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The Design and User Applications of a Low-Cost Satellite Constellation for Global Daily Imaging Revisit

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Lee Boland

The Design and User Applications of a Low-Cost Satellite Constellation for Global Daily Imaging Revisit

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Dr. R. Lane

Presented March 2004

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The Design and User Applications of a Low-Cost Satellite Constellation for Global Daily Imaging Revisit

Abstract

There are many varied sources of satellite Earth Observation and Remote Sensing data currently in-orbit. However, in general there is a distinct lack of rapid-response data for timely application. This is particularly of value in disaster situations where the value of information rapidly falls as time progresses after the event.

Micro-satellite constellations, with their low-cost and low launch costs provide a potential affordable solution to the issue of data timeliness.

This research project, supported by Surrey Satellite Technology Limited, addresses the problem of data timeliness through the development of a solution for a micro-satellite constellation to give global daily imaging revisit opportunities at a Ground Sample Distance of 30-40m in Red, Green and Near Infra-Red bands.

This thesis reviews existing Earth Observation capabilities to highlight the niche that exists for this mission. It then describes the development of the mission and spacecraft system solution as well as ground segment characteristics. The spacecraft and mission design is taken from a conceptual phase to launch and validation via in-orbit operations.

This is the first micro-satellite constellation for Earth Observation, and the first micro-satellite solution to address the rapid-response problem.

Research into potential applications for the image data is also presented, focussing in particular on disaster management applications. Wildfire management applications and flood monitoring are considered in most detail, whilst other potential application areas are addressed in brief. This research clearly indicates that there is much potential for the DMC imagery to add value, over and above the current available Earth Observation data sources, to a number of applications. It is noted that further work should be performed to validate the use of DMC data in any given application.

Acknowledgments

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Thanks also to all the staff at Surrey Satellite Technology Limited, and those who worked on the DMC project. The knowledge and experience of the many excellent engineers at SSTL has helped provide me with an invaluable experience. In particular thanks should go to Alex da Silva Curiel who, as my Industrial Supervisor, has shown solid support and advice throughout this EngD project.

And lastly thanks must go to my family and friends who have been so understanding with the lack of time I have given them during the course of this project.

The Design and User Applications of a Low-Cost Satellite Constellation for Global Daily Imaging Revisit

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1. Introduction

The satellite Earth Observation (EO) industry and applications have been established and evolving for decades. These have been traditionally performed via large programs with large budgets and using large spacecraft. Several well known, and widely used, examples are the US Landsat series and French SPOT series of satellites.

Similarly, the field of 'small' satellite engineering has been developing for decades. The sponsors of this EngD project, Surrey Satellite Technology Limited (SSTL), who have now been developing small satellites for over twenty years, have performed much of the pioneering work in this field.

Small low-cost satellites have been used for a variety of experimental EO applications in the past. Over the years the capabilities of small satellites have gradually advanced and now they are on the verge of providing operational, commercial Earth Observation missions, not just experimental imaging missions.

This EngD project is based on the Disaster Monitoring Constellation (DMC) mission, which has been described by the project sponsor as a ½ pilot-½ operational mission. This mission is 'feeling the way' for the establishment of low-cost operational earth observation services using small satellites for delivery of timely image data. The key unique quality of this mission is the combination of the rapid-revisit (daily) medium-resolution Earth observation capability, the potential to image extremely large areas, and the achievement of this using a low-cost constellation of micro-satellites.

This introductory chapter describes the origin of the project before giving an overview of the structure of this thesis.

1.1. Project Origin

The concept of a constellation of small satellites to provide global daily imaging revisit was proposed in the early 1990's by Cheng Fang-yun [1].

The concept involves a number of equi-spaced spacecraft orbiting in the same plane. The image swath of each spacecraft is sufficiently wide that there are no gaps between the swaths of adjacent spacecraft in the constellation. This essentially means that the constellation would provide a capability to image anywhere on the globe (except poles) at least once per day. Figure 1.1 provides an illustration of this 'daily' ground coverage.

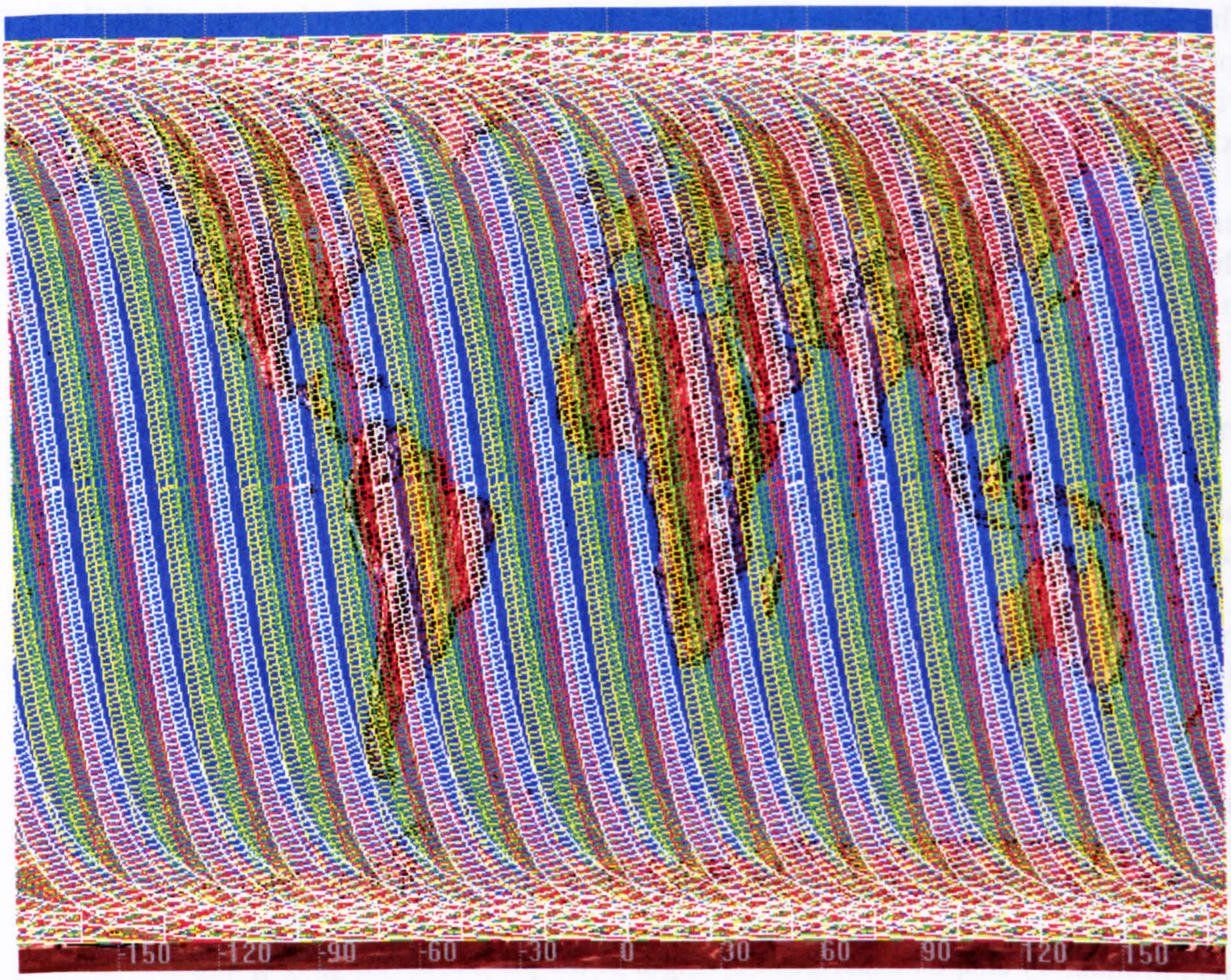

Figure 1.1 Daily Global Coverage of Satellite Image Swaths (the coverage achieved in 24 hours is illustrated. Different colour stripes represent the swaths of individual satellites in the constellation)

This concept was taken a step further by SSTL with a brief internal design study and a preliminary assessment by an independent party to indicate that image data at 30-40m GSD had potential to serve in a number of disaster application areas. Several papers [2][3] were produced on the subject and presented by the SSTL marketing team at various space conferences over the course of several years.

Although no formal study into what was available had been made by SSTL, feedback from conferences attended by the marketing team had indicated that there was currently no daily source of LandSat class imagery available to the public.

Also, from attending presentations and from discussion with members of various disaster groups, the SSTL marketing group had learnt that the value of imagery in a disaster response scenario rapidly drops off after the first 48hours. The SSTL marketing group also concluded that this need did not seem to be being currently addressed by any existing space imaging capability.

A number of potential customers showed interest in the concept and, as a result, proposals were made to various potential customers for individual satellites to form part

of a constellation. Each individual satellite would be owned by the individual customer and used for customer needs. However the satellites would also have the potential to operate as part of a constellation; the Disaster Monitoring Constellation (DMC). It was proposed that 5% of the DMC imagery be made available for free to disaster agencies in the event of a disaster. A significant advantage of the DMC concept is that each individual spacecraft mission also benefits from being part of the constellation, specifically by benefiting from the daily imaging revisit capability as well as increased imaging capacity.

The intention of the DMC mission, as mentioned earlier, is to act as a ½ pilot and ½ operational mission. The mission would provide a stepping stone on to missions where SSTL micro-satellites might lead to operational, commercial, Earth Observation rapid-response constellation missions.

At the time of the start of this EngD project, one customer had signed a contract for a DMC satellite, and several were under negotiation.

A preliminary design for the DMC mission and spacecraft existed as presented in a previous conference paper [2]. The customer contract for the first DMC satellite also stipulated certain technical requirements, although there also existed much flexibility. These are described later in this thesis when the actual DMC design is discussed. No user application requirements were provided at the start of the project.

The top-level aim of this EngD project was therefore to take the design of this novel mission from the existing conceptual stage to a real existing design, and to explore potential applications of the data.

The suitability of the DMC mission to the EngD program was considered at the very start of the project. The following are keywords or phrases taken from literature describing the aims of EngD projects and some of the main qualities desired in an EngD project:

- Ability to assimilate and assess existing knowledge
- Add to the body of applied engineering by undertaking and communicating the results of research in a systematic and ordered manner
- Appreciate fully the potential of the research in its wider economic, social, technical and environmental contexts
- Development of innovative thinking while tackling real industrial problems
- Consideration of financial constraints, timescales and personnel management
- Must make a significant contribution to the performance of the company
- Achieve an appreciation of industrial engineering and development culture including:
    - The role of research
    - Product development
    - Marketing Awareness
    - Minimisation of environmental impact

- Teamwork and leadership skills
- Communication skills
- Ability to apply skills/knowledge to new and unusual situations
- Ability to seek optimal solutions to complex or multi-faceted problems

The experience of the DMC mission and systems engineering was expected to provide a significant challenge and an ideal opportunity to cover many of the above attributes and hence to provide a solid basis for the EngD project. After reading this thesis, it is hoped that the reader will agree that the design of the DMC and investigation into potential areas of application for the image data did indeed provide an excellent basis for this EngD project.

1.2. Thesis Road Map

This EngD research and development project is based on a novel Earth Observation spacecraft and mission, the Disaster Monitoring Constellation, and the potential novel usefulness of such a mission.

The thesis document first presents background information to put this EngD project into context with current Earth Observation capabilities, and the research objectives are derived.

This is followed by a description of the DMC satellite and mission design, and the development process along with various problems encountered and the solutions derived.

The achievements of the project are then discussed with respect to user applications, and the overall project contribution to knowledge.

Several management aspects of the project are discussed in a dedicated sub-section in the final chapter. This highlights aspects that are touched upon elsewhere in the document, as well as providing discussion of a commercial context for the project.

To further aid the reader in interpreting this thesis, a brief overview of chapters is given in terms of Existing Knowledge, Work Description, and New Knowledge, as described in the following sub-sections.

1.1.1. Existing Knowledge

Following this introductory chapter, Chapter 2 provides background information that allows this EngD project to be put into context, and concludes with a definition of the Research Objectives. An introduction to the field of satellite Earth Observation and remote sensing is given. An overview is also given of existing satellite Earth observation missions. This background highlights a niche which is not addressed by existing missions and leads to the definition of the research objectives; the development of the Disaster Monitoring Constellation mission and investigation of potential user application areas.

To aid thesis readability, 'Existing Knowledge' on user applications is given in a later chapter, Chapter 5, entitled 'DMC Imagery Applications'. In this chapter, a selection of potential DMC image application areas are discussed and information presented on the main current methods and data sources used in addressing these methods.

Chapter 5 is also partly described under 'New Knowledge' in Section 1.2.2 below, with respect to the new potential opportunities provided for the selected application areas, by the DMC mission.

1.2.1. Work Description

Following the definition of the research objectives the development work itself is described.

As the Technical Lead for the DMC mission, the work of the author involved working closely with the SSTL specialist sub-system engineers and leading the technical design at a mission and spacecraft system level.

Whilst the spacecraft solution incorporates a significant amount of development in a number of individual sub-system areas, it is the system design of this unique mission that is the subject of this EngD.

Chapters 3 and 4 describe the system and mission design for the DMC mission. The design is taken from an initial concept level, as described by Ward et al [2], to a level where the first DMC spacecraft can be built, launched and operated in-orbit, hence providing proof of concept for the satellite design.

Whilst the majority of the study work is performed in the realisation of the space system, ground segment issues are also addressed.

1.2.2. New Knowledge

In Chapter 5, application of the DMC system is made to remote sensing problems to illustrate examples of the potential usefulness of this new system. This chapter highlights potential user application benefits offered by the DMC imagery over and above existing data sources. It is shown that the daily revisit capability, at low-cost, of the DMC system now provides a real potential solution to remote sensing problems that were previously not possible to address at reasonable cost with other existing Earth Observation systems. Limitations of the DMC data are also discussed in this chapter.

Chapter 6 contains a summary discussion of the project as a whole. The original rationale for the project is presented along with the achievements and limitations of the project. Chapter 6 also provides a discussion of various management aspects of the project.

Finally, Chapter 6 presents the conclusions of the project, highlighting the contribution to knowledge made by this EngD research project, as well as recommendations for continuation of this work.

1.2.3. Appendices

A number of Appendices are included with this thesis. These generally relate to a particular Chapter, with the exception of Appendix H which contains descriptions of Acronyms and Abbreviations for the whole thesis.

Table 1.1 gives an overview of the Appendices included with this thesis.

Appendix to accompany:	Appendix Number and Description
Chapter 2 Background and Objectives	A CEOS Disaster Management Support Group Technical Recommendations
	B Tables of current EO missions (Celestrak NORAD listed)
Chapter 3 Systems Engineering	C Spacecraft Configuration Control Summary Table
Chapter 4 Mission Analysis	D Assumed Launch Injection Error Probabilities
	E Launch Injection Error Analysis
	F Link Budgets
	G Power Budget
All Chapters	H Acronyms and Definitions

Table 1.1 Appendices List

1.3. Summary

This introductory chapter has described the origin of this EngD project, and described the structure of the thesis content. This is summarised at a top-level in Table 1.2.

Content:	**Found in:**
Background, context of project and Research Objectives	Chapter 2
DMC Mission and System Design	Chapters 3 and 4
Evaluation of DMC Applications	Chapter 5
Discussion of achievements, limitations, conclusions, contribution to knowledge, and recommendations for continuation of work	Chapter 6

Table 1.2 Overview of Thesis Structure

2. Background and Objectives

This chapter provides background information that allows this EngD project to be put into context, and also lays out the definition of the research objectives.

As has been mentioned in Chapter 1, the field of Earth Observation by satellite imagery has been around for many years and there exists a wide range of application areas as well as a variety of data sources. For many Earth Observation applications, imaging from space offers a distinct advantage over ground observations or airborne imaging. Key to this is the ability to image very large areas of land that would not be practically possible at reasonable cost, even should logistics allow, using ground or airborne methods.

There are numerous textbooks, journals and countless research papers published on the subject of remote sensing and satellite imagery which discuss a number of application areas for various different types of remote sensing data. Landsat data, with which DMC data has some similar characteristics, in particular has many established applications due in part to its wide availability and long history. Some examples (not a comprehensive list) are given in Table 2.1.

Agriculture, Forestry and Range Resources	Discrimination of vegetative types: Crop types Timber types Range Vegetation
	Measurement of crop acreage by species
	Measurement of timber acreage and volume by species
	Determination of range readiness and biomass
	Determination of vegetation vigour
	Determination of vegetation stress
	Determination of soil conditions
	Assessment of grass and forest fire damage
Land Use and Mapping	Land use classification
	Mapping of transportation networks
	Mapping of land water boundaries
Geology	Recognition of rock types
	Determination of regional structures
Water Resources	Determination of water boundaries and surface water area and volume
	Mapping of floods and flood plains
	Determination of areal extent of snow and snow boundaries
	Delineation of irrigated fields
Oceanography and Marine Resources	Detection of living marine organisms
	Mapping shoreline changes
	Mapping of ice for shipping
Environment	Mapping and monitoring of water pollution
	Monitoring environmental effects of man's activities

Table 2.1 Example Application Areas of Satellite Earth Observation Data
(adapted from [6])

The DMC is expected to hold relevance to a number of application areas, but primarily was conceived with the area of hazards and disasters in mind. Section 2.1 discusses the general use of satellite imagery with regard to disaster applications. Potential different

types of user for the data are then discussed in Section 2.2 as well as some potential barriers to uptake of the technology.

As the DMC is a system for optical earth observation and remote sensing, background information is given in Section 2.3 on the general use of optical imagery for Earth Observation.

Section 2.4 overviews existing and previous Earth Observation missions to provide a context for the DMC mission with respect to previously existing capabilities, and highlight that the characteristics of the DMC mission are indeed unique.

Taking into account the potential for user application of rapid response DMC type data, and the current state of in-orbit sensor capabilities as discussed in this chapter, Section 2.6 then derives the research objectives of this EngD project.

2.1. Use of Satellite Imagery for Disaster Applications

It has been estimated that the annual direct cost of natural disasters world-wide is over $400B (2000) [7]. Better information to aid mitigation, or even prevention, of disasters is clearly of much potential economic value as well as humanitarian value. Satellite remote sensing is one potential source of such information.

Much literature has been published on various potential uses of remote sensing in different types of disaster. Showalter [7] provides an excellent partially annotated bibliography, containing over 400 references on the use of satellite remote sensing for disaster and hazard applications. Some of the references listed by Showalter date back several decades. However, over the past decade or so there has developed an increased awareness of the potential for utilisation of satellite Earth imaging resources in disaster applications.

The 1990's were the UN International Decade for Natural Disaster Reduction. The UN General Assembly defined the objective of the International Decade for Disaster Reduction as follows [8]:

"The objective of the Decade is to reduce, through concerted international action, especially in developing countries, the loss of life, property damage, and social and economic disruption caused by natural disasters, such as earthquakes, windstorms, tsunamis, floods, landslides, volcanic eruptions, wildfires, grasshopper and locust infestations, drought and desertification, and other calamities of natural origin."

This was a very broad effort and not limited to satellites or even technological solutions in general. However, it undoubtedly encouraged activities in a number of areas, including the space sector.

In September 2002, Mahmood [10] provided a useful overview of a number of space programs and initiatives related to disaster management. These are listed in Table 2.2 below.

Programs and Initiatives	Acronym
Disaster Management Support Group	DMSG
Integrated Global Observing Strategy, providing links between:	IGOS
Committee for Earth Observing Systems	CEOS
World Climate Research Program	WCRP
International Geosphere-Biosphere Program	IGBP
International Group of Funding Agencies for Global Change Research	IGFA
UN Food and Agriculture Organisation	FAO
Intergovernmental Oceanographic Commission of UNESCO	IOC
International Council for Science	ICSU
United Nations Educational, Scientific and Cultural Organisation	UNESCO
United Nations Environment Program	UNEP
World Meteorological Organisation	WMO
Global Climate Observing System	GCOS
Global Ocean Observing System	GOOS
Global Terrestrial Observing System	GTOS
Global Observation of Forest Cover	GOFC
Global Observation of Landcover Dynamics	GOLD
World Weather Watch	WWW
Global Disaster Information Network	GDIN
Space Techniques for Major Risks Management	STRIM
Global Disaster Observation System	GDOS
Earth Watching	
Disaster Watch Program	
Hurricane Watch Program	
International Charter 'Space and Major Disasters'	
Global Monitoring for Environment and Security	GMES
BNSC – Small Satellites for Disaster Support*	
ASI-CNES COSMOS/SkyMed-Pleiades	
ESA-MetOp	
ESA Meteosat Second Generation	MSG
China small satellite constellation	

Table 2.2 Space Disaster Management Programs and Initiatives [10]
(*Note, the BNSC initiative essentially refers to the DMC and potential follow on missions)

In addition to the above listed activities described by Mahmood, the author has come across a number of other general initiatives and activities during the course of this research which have relation to the use of satellite imagery in disaster scenarios. Some of these are listed below, along with references as a starting point for further information:

- University of Colorado, Natural Hazards Center [11]
- Louisiana State University, Hazards and GIS initiative [12][13]
- Canada Centre for Remote Sensing: Natural Hazards [14]
- NASA Earth Observatory: Natural Hazards [15]

- Dartmouth Flood Observatory [16]
- Pacific Disaster Center [17][18]
- Reuters AlertNet [19][20]

An additional useful link for information and further links on space technology and disaster management links can be found on the UN Office for Outer Space Affairs website [22].

The above suggest that the application of remote sensing to disaster scenarios is an active field. It is beyond the scope of this thesis to describe all activities in this area, however several of the above-listed activities of particular relevance to the DMC are briefly described below.

CEOS Disaster Management Support Group (DMSG)
This is given particular attention here due to the relevance of the information resulting from this project to the evaluation of DMC potential application areas for disaster monitoring.

In 1997 the Committee for Earth Observation Satellites (CEOS) initiated the Disaster Management Support Group (DMSG) as described by Wood and Lauritson [23][24].

The CEOS DMSG effort involved expert teams dedicated to each hazard area (Drought, Earthquake, Fire, Flood, Ice, Landslide, Oil Spill and Volcanic Hazards) and over 300 participants from more than 140 organisations. The objective of each team was to compile user requirements, identify gaps and shortcomings in the provision of required satellite data, and develop recommendations. The result is a fairly comprehensive final report describing the current state of satellite EO in hazard support. The report also highlights gaps that should be addressed and the findings and recommendations of the DMSG, formulated over the four years of the study, are also presented in the report. These are also presented in Appendix A. Whilst all are of relevance in some form, of particular note with respect to the DMC mission is:

Finding: Timely disaster warning and response, and/or rapid response in support of a disaster situation, is the most important feature in the utility of satellite technology.
Recommendation: CEOS agencies should work to support rapid satellite tasking of Earth observation missions, to enhance the utility of space for disaster applications.
Recommendation: CEOS agencies should work to support fast processing and delivery of data, which will also be very important to determining the utility of space data for disaster applications.

The DMSG final report [25] was published in August 2002 and provides an excellent reference as to the use of satellite remote sensing in disaster applications.

International Charter

This initiative is given particular attention here as it is an excellent example of maximising the usefulness of resources for disaster applications via international collaboration. The principle of the initiative is similar to that of the DMC, although not focussed on a co-ordinated constellation for daily revisit, but simply making use of what data types are already available.

Near the end of the IDDR, in July 1999, the Third United Nations Conference on the Exploration and Peaceful Uses of Outer Space (UNISPACE III) called for specific actions for the implementation of an integrated, global system to manage natural disaster mitigation, relief and prevention efforts through space activities (in the Vienna Declaration on Space and Human Resources Development and Action Plan)[3].

Following this conference the 'International Charter' was founded in June 2000 by the French Space Agency, CNES, and the European Space Agency, ESA, joined shortly thereafter by the Canadian Space Agency, CSA. Since the start of the Charter, other agencies have joined and at the time of writing of this thesis the Charter members and space resources are as shown in Table 2.3.

Agency	Space Resource
European Space Agency	ERS, ENVISAT
Centre National d'Etudes Spatiale	SPOT
Canadian Space Agency	RADARSAT
Indian Space Research Organisation	IRS
National Oceanic and Atmospheric Administration	POES, GOES
Argentina's Comisión Nacional de Actividades Espaciales	SAC-C

Table 2.3 International Charter Agencies and Resources [27]

The Charter aim is to provide a unified system of space data acquisition and delivery, through authorised users, to those affected by disasters [9]. Each member agency contributes the services of space resources that can be activated upon receipt of a request from an authorised user (e.g. a Civil Protection Agency of a member country). The details of how this works are well documented in papers and on the Charter website [27]. Since being declared fully operational in November 2000, the Charter has provided imagery and information in a variety of disaster situations as summarised in Table 2.4.

		Date of Charter Activation
2004		
Flooding	Bolivia	26-Jan
2003, 14 activations		
Earthquake	Iran	26-Dec
Landslide	Philippines	21-Dec
Flood	France	04-Dec
Flood	Canada	20-Oct
Fire	Canada	07-Aug
Flood/Landslide	Nepal	07-Aig
Fire	Portugal	04-Aug
Fire	France	19-Jul
Volcano	Montserrat	12-Jul
Earthquake	Algeria	22-May
Earthquake	Turkey	07-May
Hurricane	India	24-Apr
Flood	Argentina	30-Apr
Volcano	Italy	09-Apr
2002, 15 activations		
Flood	Morroco	28-Nov
Oil Spill	Spain	14-Nov
Oil Spill	Gulf of Aden	08-Oct
Hurricane	Mexico	04-Oct
Landslide	N. Ossetia	27-Sep
Flood	France	09-Sep
Flood	Germany	22-Aug
Flood	Austria	20-Aug
Flood	Czech Republic	17-Aug
Flood	Southern Russia	28-Jun
Flood	Canada	18-Jun
Flood	Canada	13-Jun
LandSlide	Italy	06-May
Earthquake	Afghanistan	28-Mar
Volcano/Earthquake	Congo	21-Jan
2001, 11 activations		
Flood	France	31-Dec
Flood	Indonesia	01-Aug
Volcano	Italy	26-Jul
Flood	Russia	22-May
Oil Spill	Denmark	30-Mar
Oil Spill	Lebanon	30-Mar
Flood	France	22-Mar
Earthquake	El Salvador	14-Feb
Earthquake	India	29-Jan
Oil Spill	Ecuador	26-Jan
Earthquake	El Salvador	15-Jan
2000, 1 activation		
Landslide	Slovenia	27-Nov
International Charter comes into force		**01-Nov**

Table 2.4 International Charter Activations

The DMC consortium is currently in discussions regarding potential collaboration with the Charter. If such a collaboration goes ahead the DMC would provide a significant new capability to the Charter, being able to acquire 30-40m GSD images of large areas with daily imaging opportunities.

AlertNet

Reuters AlertNet aims to provide a free, web-based news and communications service for the international disaster relief community [19],[20]. Its central premise is not based, therefore, on the existence and use of satellite imagery for disasters. Rather, it recognises that satellite imagery has a potential role to play and attempts to use satellite imagery in its information service where deemed useful and practical. AlertNet is a DMC partner for DMC imagery distribution to the disaster relief community, or, more precisely, AlertNet is a DMC partner for 'information' distribution (based on use of DMC imagery, e.g. by a third party value adder).

Effectiveness of initiatives

As described above there are a number of initiatives related in some way or another to disasters.

However, despite all of the above initiatives there remain many areas of improvement needed in order to make more effective use of satellite EO data for disasters and hazards.

The findings of the recent comprehensive CEOS DMSG final report list a number of technical recommendations. These technical recommendations are listed in Appendix A. Among these recommendations was one of the key drivers for the DMC mission; improved timeliness of data, described as the most important feature for the use of satellite technology.

However, there are also non-technical considerations to be taken into account.

In his Sept 2002 report Mahmood [9] states that 'space-based support remains by and large little understood by emergency relief organisations and civil protection agencies and is still alien to disaster management conferences and fora'.

This was plainly evident to the author when attending a conference on the 'Use of Satellites and Integrated Technologies in Humanitarian Applications' at the start of the project. A definite knowledge gap existed between the humanitarian aid workers and the 'technology' (e.g. satellite) providers. It was clear that widespread use of the DMC data within the humanitarian community would involve more than just provision of technical capability. There were additional barriers to uptake of the use of satellite image data (not just DMC data) that needed to be considered. These include:

- Suspicion of motives
- Education and Training Requirement
- Availability of data

- Awareness of the technology and availability
- Resistance to Change
- Need for immediate application – no 'slack' in organisations to explore and try new unproven methods

The CEOS report suggests that there is willingness in the disaster management community to consider the use of new space technologies. However, it also points out that there is concern for introducing new, unproven technology into operational programs and often a lack of time, resources, personnel or technical understanding to do so.

Clearly these issues need to be addressed in order to fully exploit the benefits that space remote sensing has to offer the field of disaster management.

Potential barriers to uptake of the DMC data are discussed further in Section 2.2 below.

2.2. User Types and Potential Barriers to Uptake of DMC Imagery

2.2.1. DMC Imagery User Types and Constraints

Several common questions asked during the course of this project have been "what is the product?" and "who are the users?".

The basic product is essentially imagery with data characteristics and limitations as described in Sections 5.1 and 5.2.

Other value-added products, such as NDVI products, or flood boundary maps may then be created from this but these are not core products. The DMC however, makes these possible by providing the raw image data.

To answer the question of who the users are is more complicated.

DMC data can be considered in three top-level categories:

- National needs for each DMC member
- Disaster Use
- Spare capacity, e.g. for Commercial applications

National needs vary from member to member. Each DMC member tends to have their own national community of users that use the data for various applications. For example, Alsat-1 data was used as an input to a hydrology map for large areas of Algeria. Urbanisation and desertification are also areas of interest to Algeria, both of which can make use of DMC-type data.

Disaster uses, in the short-term at least, are covered by partnership with AlertNet as described in Section 2.1, although in the future additional paths to the disaster community may be considered.

The 'Spare Capacity' data could be for any user with any application.

DMC applications and potential users is an area still being explored within ongoing work at SSTL. Different users with different applications will have different specific needs. In addition to their application specific needs for technical data characteristics, users will have different levels of communications infrastructure, computing and software infrastructure, and different levels of expertise.

It is not practical to consider each and every user in isolation. However, several example users and their requirements are discussed below. In this case it does not matter, for example, whether the application is a national need, disaster, or spare capacity. The focus is on the technical requirements and needs of the user with respect to 'what data they need' and 'how to get it to them' as well their ability to actually manipulate and use the data once they have it.

Researchers

Here the term 'researcher' is taken to mean an experienced person involved in the use of remote sensing data for research purposes. This may be in any field (e.g. fire research officer, crop monitoring, flood research etc.) and may be part of an academic or professional institution. Although of course it will vary from case to case, an example typical scenario for a researcher in the field of remote sensing is given in Table 2.5.

Data product required	Will depend on nature of application but may often be L1R, or Raw (i.e. uncompressed files)
Communications Infrastructure	Highly varying. Many researchers may have good internet links being based in an academic or professional research institution. However, for those working in a remote region there may be significant issues with receipt of large image files. Each individual project would need to consider whether it was worth investing in the necessary communications equipment (e.g. VSAT terminal) to reliably access DMC data. This may be a barrier to many potential researchers.
Computing and software facilities	Should already be set up to routinely deal with and manipulate image files for remote sensing applications. Whether DMC image files present a relative capacity or performance problem will depend on the size of previous image files used, and the size of DMC images actually used. Maximum size DMC images may cause a problem for some.
Expertise in use of satellite imagery	High. Although researchers will need to understand and deal with the specific characteristics of DMC imagery, this is part of the nature of their profession and should not cause a big problem.

Table 2.5 Research Officer Data Requirements and Infrastructure Scenario

Disaster Users

There are a number of different parties that might be involved in a disaster relief situation and have potential uses for DMC data. Example parties are:

- AlertNet
- NGO Headquarters (e.g. in UK)
- NGO field operatives
- Civil Protection Agencies
- Local Emergency Authorities

Each will have their own requirements and constraints.

AlertNet

AlertNet is a distribution channel for the disaster community. Currently value adding is provided by a third party in collaboration with AlertNet. The limited capability of many disaster relief workers to receive large images has been considered, and DMC image data, in the value adding process, is to be converted into the most useful succinct information for the disaster relief community. An example would be a simple annotated image (jpeg) illustrating flood boundaries in the area of interest.

Data product required	Will depend on nature of application but may often be satisfied with compressed 'visually intelligible' files. Although, further development of value adding processes may lead to the use of e.g. uncompressed L1R files for quantitative work.
Communications Infrastructure	Good. Transfer of large image files to the value adder and AlertNet should not be a problem.
Computing and software facilities	Good. Are already set up to routinely deal with and manipulate image files for disaster applications. Maximum size DMC image files have presented some computing performance problems, but investment in upgraded computers is expected to reduce this.
Expertise in use of satellite imagery	High. The combined expertise of AlertNet and the value adders brings together remote sensing capability and the needs of the disaster community. It is accepted that lessons are still being learnt and AlertNet continues to try to better understand the needs of the community it serves. It is expected that this continued improvement and understanding will be appropriate for useful application and uptake of the DMC imagery in the disaster community served by AlertNet.

Table 2.6 AlertNet Data Requirements and Infrastructure Scenario

NGO Headquarters (e.g. in UK)

NGO Headquarters may be the users of the DMC data themselves. For example, they may wish to gain information to ascertain the best allocation of resources in a disaster

location. Alternatively, they may wish to analyse a situation and send the information (or maybe even the imagery) to local teams in the disaster area.

Data product required	Would typically require a value added product.
Communications Infrastructure	Variable. Will depend on the specific NGO. Tight funds mean that outgoings are typically kept to a minimum[1]. Whilst some may have good infrastructure, this cannot be relied upon for all.
Computing and software facilities	Variable. NGOs are not typically in the practice of manipulating remote sensing imagery and as such would not have suitable software, and are unlikely to have high specification computers, to allow value adding to image data. Smaller image files may be displayed in a commercial package such as e.g. Adobe Photoshop. However, any manipulation and value adding would need to have already taken place elsewhere.
Expertise in use of satellite imagery	Low. Manipulation in a GIS system or remote sensing software package is unlikely to be an available skill. Simple images showing flood extents or fire damage extents may be interpretable but with a risk of misinterpretation due to lack of practice and training.

Table 2.7 NGO HQ Data Requirements and Infrastructure Scenario

NGO Field Operatives

As described above, NGO personnel in the field may act on information or instructions provided by the NGO HQ, after the NGO HQ has interpreted DMC imagery. However, there may also be occasions where the person in the field would benefit from direct use of the imagery.

Consider for example a flood situation. An image displaying flood extents, within a GIS system displaying ancillary information (such as location of resources, current flood barrier locations etc.) has great potential to assist local response planning. As local information on the situation is updated, the GIS model can be updated (e.g. update to personnel locations, hospital status, locations of displaced people etc.) with this local information. There are in fact several competing commercial products to allow GIS functionality from a central image server to remote terminals via the internet. This may be a very suitable option for use by an NGO HQ as a central server with personnel in the field using remote terminals, without the need to download and process complete image files. There are some regions where there is a high probability of disaster relief being required annually (e.g. floods in Bangladesh). Such regions may be targeted for pilot projects to use DMC imagery 'in the field'.

[1] For example, one NGO commented to AlertNet that they found their web-based service particularly useful with respect to saving outgoings on telephone calls [21] - an unplanned bi-product of what was originally intended simply as an information service!

However, this is unlikely to be a capability for NGO personnel in the field in the short term.

Data product required	Would typically require a value added product.
Communications Infrastructure	Poor.
Computing and software facilities	Poor.
Expertise in use of satellite imagery	Poor.

Table 2.8 NGO Field Personnel Data Requirements and Infrastructure Scenario

Other Parties (e.g. Civil Protection Agencies, Local Emergency Authorities)
It should be noted that NGO's are not the only active parties involved in disaster scenarios. For example national Civil Protection Agencies, or local emergency authorities would typically also be involved. In many cases, especially in developed countries, either of these may be more likely than an NGO to have (although of course are not guaranteed to have) a communications and computing infrastructure, or potentially a source of funds that might enhance infrastructure if a case can be made.

It may even be the case that such parties could act as a distribution source to other local parties involved in disaster relief in a given situation.

2.2.1.1. Summary of User Types and Constraints

There may be numerous types of user for DMC imagery, each with their own requirements and constraints. Example users given in this section were:

- Researchers
- AlertNet (although, strictly speaking, is a distribution channel rather than user)
- NGO Headquarters
- NGO operatives in the field
- Other active parties in a disaster relief effort, such as Civil Protection Agencies or local emergency authorities.

It is expected that many researchers will have a suitable infrastructure as well as the necessary expertise to use DMC image data. However, it is also acknowledged that many researchers based in remote regions may lack the necessary infrastructure to easily access DMC data. Investment in a high capacity internet capacity would be necessary for these if research requires data timeliness (CD/DVD distribution can satisfy many requests with less time critical requirements). This may prevent many from taking up the use of DMC data. However, some success stories of the use of DMC data for various applications may help persuade further researchers to commit an up-front investment in communications infrastructure. It is recommended that the effort be made to support pilot projects and establish a good reputation for the use of DMC data.

Table 2.7 and Table 2.8 above suggest that it is likely that many disaster relief organisations (especially teams in the field) will lack the communications infrastructure, computing and software facilities, and technical expertise to effectively use the DMC data directly. This, coupled with the additional barriers to uptake that are discussed below, presents a bleak scenario for the uptake of DMC data in the disaster community unless efforts are made to address the issues. The DMC partnership with AlertNet mitigates this issue to an extent, as interpretation of DMC imagery and translation into useful information is performed by experienced value adders, who understand the constraints of relief workers and make efforts to minimise internet download requirements (e.g. by using small image files). However, to fully exploit the potential of the DMC, relief agencies would be able to request and work with DMC data themselves.

This would require infrastructure investment as well as training and education (in both directions, between the NGO and satellite imagery experts) to arrive at a useful operational procedure and product that the NGO can use. It is likely that the easiest first step, and perhaps also politically the best step, would be to work with the NGO HQ, with an aim to exploring potential for direct use by personnel in the field afterwards. The author would recommend investigation into potential funding (e.g. EC, or ESA) for such initiatives.

2.2.2. Barriers to uptake

Chapter 5 indicates several potential application areas for DMC imagery. However, just because a data product may be technically suitable for an application this does not mean that it will be readily adopted by the potential users. It would be easy for SSTL to simply say to the user community 'here's a data source, now just use it'. However, as should be clear from Section 2.2.1, this could easily result in a lack of widespread adoption of the data source if no further thought is given to potential barriers to uptake of the technology.

People often tend to think of technology transfer 'into' one's own organisation and barriers to this. However, one can equally apply this as a marketing exercise by putting oneself in the shoes of the potential user of technology in another organisation.

Technology transfer can sometimes be seen as simply in terms of providing access to technology. However, providing access to the technology is only a step in a process. Effort should be made to understand the needs of the organisation that is acquiring the externally developed technology [28] (in this case image data and the processes to make use of the data).

An EC high level group identified the following as barriers to technology uptake [29]:

- Technical
- Information
- Regulatory and Legal
- Financial and Commercial
- Societal

- Decision making - Political
- Not invented here
- Not subject of discussion/legitimacy
- Lack of clear license structure
- Inertia and current contentment

Technical barriers such as communications and computing infrastructure are discussed in Section 2.2 above, along with the lack of necessary expertise among many potential users. Other barriers in the EC list will come into play to a greater or lesser extent for different users. It is important that all aspects are considered for the various user groups.

It is also important to recognise that customers buy[1] benefits not technology.

Relief workers and emergency services personnel do not want imagery or new technologies. They want information to aid their decisions. Unless the imagery or new technology gives a direct and useful input to operations, then there is little point in a busy relief worker wasting time on it. It has already been highlighted that these user types are unlikely to have skills that make the usefulness of satellite imagery immediately obvious. Hence effort is required from the supply-side in order to encourage the use of the satellite imagery.

The above discussion of barriers to entry and customer need for benefits, not just technology, indicates that steps need to be taken to improve the chances of success of the DMC mission in the eyes of the end-users.

This involves assistance in removal of the legitimate barriers, e.g. technical, financial, training, availability and also addressing of the 'softer' barriers such as general resistance to change, inertia and current contentment, 'not invented here'. In doing this the users themselves must be well involved in the process in order to help overcome some of the 'soft' issues mentioned above, as well as to benefit from their expertise and better understand their real needs.

Kotter's 8 steps to transforming your organisation [30], listed below, are usually used to consider change within an organisation.

1. Establish sense of urgency
2. Form a powerful guiding coalition
3. Create a vision
4. Communicate the vision
5. Empower others to act on the vision
6. Plan for and create short-term wins

---

[1] The current intention is that 5% of DMC imagery will be donated free for disaster applications, according to specified criteria. However, this does not guarantee adoption of the data by the disaster community. Other barriers to uptake still exist and there is always a cost in terms of effort and resources to learn about and implement use of the imagery into operations. Hence, all users should be considered as 'buying' customers in a marketing exercise, regardless of the price of the data.

7. Consolidate improvements and produce still more change
8. Institutionalise new approaches

However, if one considers the potential user community as part of a DMC 'virtual' organisation, then it can also provide a useful framework to consider steps to assist adoption of DMC imagery.

Particularly key is step 6; plan for and create short-term wins. Pilot projects which produce small wins will help increase momentum and support for the use of DMC data within the disaster community. Should a few example successes be had using DMC data, demonstrating its usefulness, then this would help convince relevant parties of the usefulness in investing in whatever 'delta' infrastructure is required to receive and interpret DMC data for their particular uses.

Consideration need also be given to "the appropriate 'channels' for the communication, translation or transference of the knowledge/technology" [29]. This will help effective communication of the vision (Kotter's Step 4). Workshops with a high degree of user involvement are one potential effective communication channel. Pilot project users are another. Pilot project users would be part of Kotter's step 2 ('form a powerful guiding coalition'). Care must be taken, however, to avoid any negative influences due, for example, to competitive rivalry between members of the wider user community.

It is in SSTL's direct interest to see a useful uptake of DMC data, for potential promotion of future SSTL satellite sales, and potentially for promotion of SSTL/DMC image data as a product in its own right. However, it may also be of interest for SSTL to look wider than this. The disaster relief community barrier to uptake under consideration here is for satellite imagery in general, not just DMC data. Collaboration with other satellite data sources may be beneficial, particularly where there is a technical synergy to be had (e.g. DMC broad area coverage, and a higher resolution 'zoom-in'). In this respect, collaboration with the International Charter may be a valuable effort. Wider collaboration also somewhat addresses the end-user need for reliability and continuity of service. The DMC is only, nominally, a 5-year mission, and is also a pilot-project with limited spacecraft redundancy. Other satellite missions, and longer ongoing programs (e.g. within GMES) may mitigate the risk of the DMC-1 data alone being too short-term for serious uptake by the disaster community.

2.3. Earth Observation Using Optical Imagery

There are many textbooks available that describe the principles of remote sensing and different data types (not just optical). Sabins [31], Rees[32], Lillesand [33] and Sanchez [34] are just a small selection of examples in which further information can be found. Hence it is not the intention in this thesis to give a comprehensive discussion of this. However, as the DMC is an optical earth observation system, a very brief introduction is given in this section.

The basis of optical remote sensing is that electromagnetic waves interact with different surfaces in different ways. As far as the optical sensor on the satellite (or e.g. aircraft) is concerned, this manifests itself in each pixel receiving various levels of radiance in whatever spectral bands are being collected by the sensor.

The resulting combination of different brightness values for different pixels, possibly in multiple bands, produces an image that can then be interpreted.

There are many different properties of an image that can be useful in image interpretation. Examples are listed below:

- Shape
- Size
- Pattern
- Brightness and Tone (or hue)
- Texture
- Shadows
- Site
- Association
- Contrast Ratio
- Spatial Resolution and Resolving Power

The above might be used, for example, when using an image for a 'visually intelligible' application.

Additionally, quantitative work may be undertaken using an understanding of the different spectral response curves of different surfaces. Much work has been done in this field over many years of satellite and aircraft remote sensing and Earth Observation.

Bowker et al. [35] provides an excellent reference of different spectral reflectances for natural targets.

As an example, using data from Bowker et al, Figure 2.1 illustrates the different spectral response curves for young and mature wheat in the wavelength range 0.3µm to 1.3µm. Also illustrated are the approximate wavelengths covered by the Red, Green and Near InfraRed bands of the DMC imager.

A commonly derived parameter for pixels is the Normalised Difference Vegetation Index. This indicates the concentration of green vegetation and is obtained via a simple calculation using values of the Red and Near InfraRed bands, (NIR-R)/(NIR+R).

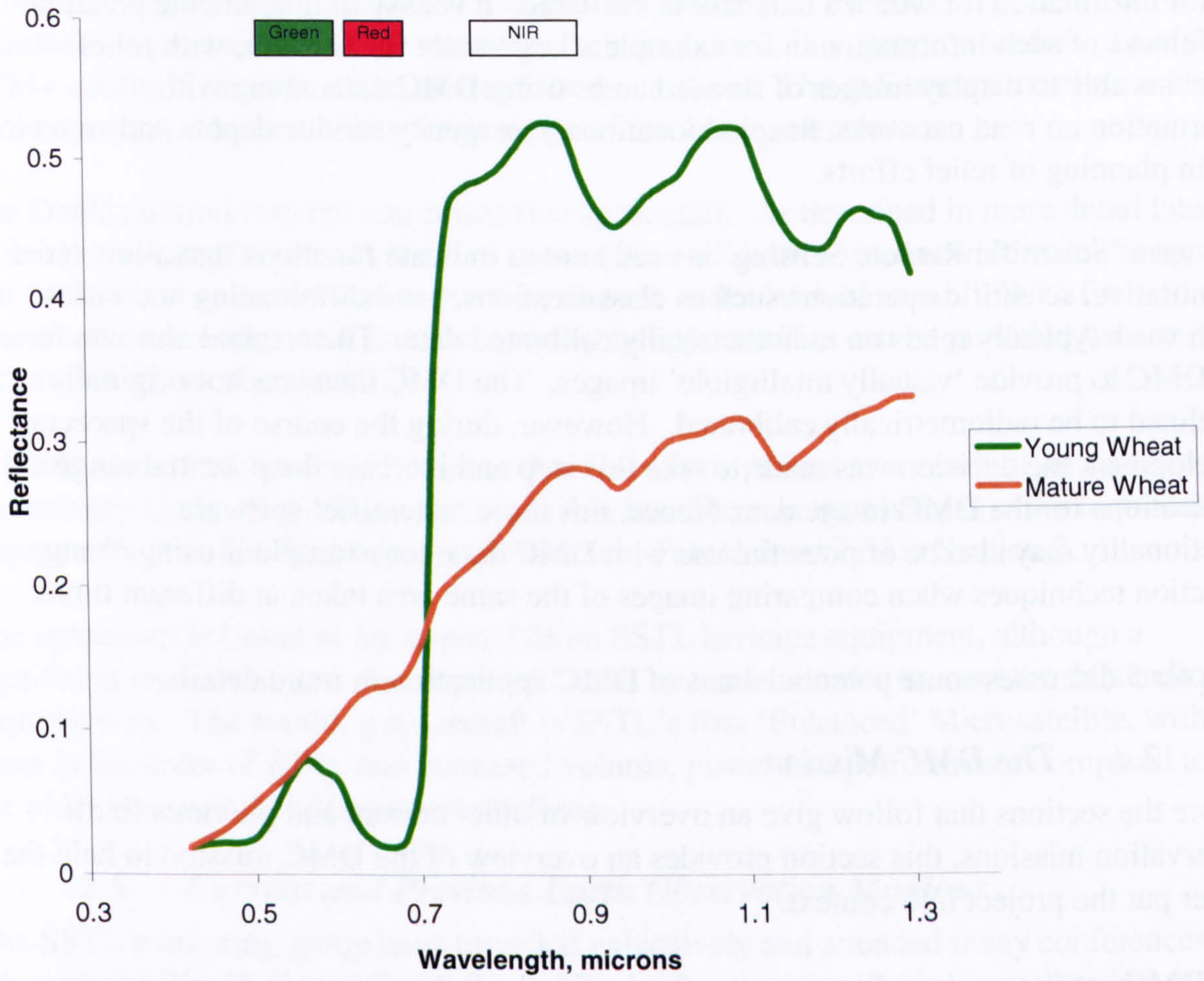

Figure 2.1 Example of Spectral Response Curves

Image Data and Value Adding

The aim of this project is the design and development of a mission capable of providing image data that can then be taken and used in various applications based on the principles described above. It is not the aim of the DMC mission or this EngD project to provide the value-added services or products based on the image data. The 'product' of the DMC mission is the basic image data that can then be used as a raw input to a value adding process.

The DMC data may be manipulated and displayed using commercial-off-the-shelf software packages. There are a number of packages available, each with its own unique combination of attributes and functionality. For the purposes of considering how image data, such as that of the DMC, might be used within such products it is useful to consider their functionality in terms of 'GIS (Geographic Information System)' capabilities and 'Scientific Remote Sensing' capabilities. Packages available typically lean towards one strength or another in this respect.

The term 'GIS capabilities' is used here to indicate functionality that allows the user to interpret visually intelligible imagery, along with ancillary information. For example, allowing the user to display different layers of information such as demographic

information, road maps, political boundaries, airport location or indeed any other such useful information for which a database is available. It is easy to imagine the potential usefulness of such information in for example a large-scale flood event, with relief agencies able to display images of flooded areas using DMC data, along with information on road networks, hospital locations, emergency service depots and so on to aid in planning of relief efforts.

The term 'Scientific Remote Sensing' is used here to indicate functions that allow more quantitative, scientific operations such as classifications, band differencing and ratios. Such work typically relies on radiometrically calibrated data. The original aim was for the DMC to provide 'visually intelligible' images. The DMC data was not originally baselined to be radiometrically calibrated. However, during the course of the spacecraft development the decision was made to take this step and increase the potential range of applications for the DMC image data. Hence, this more 'scientific' software functionality may also be of potential use with DMC data, for example if using change detection techniques when comparing images of the same area taken at different times.

Chapter 5 discusses some potential areas of DMC application in more detail.

2.4. The DMC Mission

Before the sections that follow give an overview of other current and previous Earth Observation missions, this section provides an overview of the DMC mission to help the reader put the project into context.

The DMC carries an optical imaging payload, with the following main specifications:

Swath Width:	~660km
Ground Sample Distance (nadir):	~32m
3 Spectral Bands:	Green (0.52 - 0.62)
	Red (0.63 - 0.69)
	NIR (0.76 – 0.90)
Radiometric Resolution/channel:	8 bit

The swath width requirement is dictated by the mission concept as described in Section 3.6. The actual swath width achieved during the course of this project was 660km as described above, although the requirements specification remains 600km. The achieved swath width is a consequence of the choice of components for the technological solution (mainly detector and lens).

The original target GSD for the imager at contract kick off was actually 36m. However, customer requests and consequent investigation into technological solutions (e.g. combinations of detectors and lenses) led to an improvement to 32m GSD.

The original requirements specification for the spectral bands did not dictate which spectral bands were to be provided. An easier technological solution may have been to provide Red, Green and Blue bands for which simple, but lower quality, filter and detector assemblies were available. However, the author was involved in discussions at

the beginning of the project to highlight the additional usefulness of a NIR band to provide the capability of producing a vegetation index from the data. NIR and Red were therefore adopted as two of the bands for their usefulness in vegetation studies. Landsat ETM+ quality filters were also adopted for the mission. The radiometric resolution of the image data was dictated by the heritage of the imager electronics.

The DMC mission concept comprises five spacecraft. As described in more detail later in this document (Section 4), the five spacecraft, each with a similar wide swath imager, can be flown in co-ordination to provide an even wider 'virtual swath'. With five spacecraft each with a >600km swath, imaging opportunities can be provided for any location in the world every day.

A DMC spacecraft baseline existed at the start of this project as a result of an earlier preliminary study. Significant change to this baseline was necessary in order to produce a spacecraft that met the project requirements. This is described in Section 3.

The spacecraft is based as far as possible on SSTL heritage equipment, although a significant amount of new development had to be made in order to meet the demanding requirements. The resulting spacecraft is SSTL's first 'Enhanced' Microsatellite, with a mass in the order of 85kg, and increased volume, power and performance compared to the older generation of 50kg microsatellites.

2.5. Current and Previous Earth Observation Missions

The SSTL marketing group have travelled extensively and attended many conferences at which they have discussed the DMC concept with professionals in the satellite industry and Earth Observation field. Feedback from the SSTL marketing group suggests that all spoken to agreed that the DMC would provide a new capability to the field of remote sensing and many were quite excited by the prospect of LandSat type data (albeit only three select bands) available with a daily imaging opportunity basis.

In addition, personal discussion and correspondence with experienced professionals in various satellite Earth Observation related fields indicates that the DMC mission does indeed provide a unique capability [36]-[40]. All agree that there is nothing that currently offers the very large swath coverage and the rapid revisit (daily) global imaging opportunities (at 30-40m GSD). The DMC is even more remarkable in that this is achieved via a low-cost mission solution using micro-satellites.

The above indicates that the DMC is a novel mission. However, this section is intended to provide further confidence that this is the case by over-viewing existing EO missions as described by literature such as Kramer [41] and on-line databases [43] (NORAD). Whilst not guaranteeing that every satellite ever made is considered, this section, coupled with the many discussions had by both the author and the SSTL marketing group over the last few years with EO professionals, is presented as strong evidence that the DMC mission does indeed provide a unique capability.

Appendix B contains tables of EO satellites listed in the online NORAD elements database, Celestrak [43]. This database is fairly comprehensive of today's in-orbit

satellites although it is not guaranteed that every satellite is listed. Kramer's survey [41] of Earth Observation missions has been maintained and updated over a number of years to provide an excellent history and survey of satellite Earth Observation missions. This was used, along with various other sources, as a further reference to cross-check for no major relevant omissions.

Hence the tables in Appendix B are presented as a comprehensive list of relevant satellites for comparison with the DMC.

The satellites and sensors are categorised into low, low-moderate, moderate-high, and high resolution and grouped into separate tables for ease of reference. The definition adopted for these categories is as follows:

Resolution Category	Ground Sample Distance (GSD)
Low	>500m
Low-Moderate	50-500m
Moderate-High	10-50m
High	<10m

Table 2.9 Definition of GSD Categories for Mission Comparison

Note that 'Ground Sample Distance (GSD)', rather than 'resolution', is generally used throughout this document. This is because GSD provides a less ambiguous measure for direct comparison, depending only on the spatial characteristics of the image pixels, whereas resolution can also depend on scene content (e.g. contrast between objects).

For each table in Appendix B, stars have been placed next to any satellites or sensors considered worth further mention for comparison to the DMC mission.

As the DMC satellites (at least for this first DMC generation) carry optical sensors, mainly optical sensors on other existing satellites were considered. The short-listed optical sensors are listed in Table 2.10.

Each satellite sensor listed has its own characteristics and strengths. However, for each of the shortlisted satellites it is also possible to list a specific advantage of the DMC solution.

GSD Category	Satellite, Sensor	Main reason for Shortlist selection	Main improvement offered by the DMC solution
Low	NOAA Series, AVHRR (1, 2 and 3)	Daily revisit	Better GSD
	SPOT 4 and 5, Vegetation (VGT)	Daily revisit	Better GSD
Low-Moderate	Terra, MODIS	Daily revisit	Better GSD
	Aqua, MODIS	Daily revisit	Better GSD
	IRS-P6, WiFS	Similar swath width, similar spectral bands, 60m GSD	Better GSD, multiple *low-cost* satellites improve imaging revisit
Moderate -High	Landsat series, TM and ETM+ (also note experimental ALI sensor on the NASA EO-1 satellite as the potential next generation ETM+ replacement)	Very similar GSD, Large area coverage, many established applications, and well known widely available imagery for ease of comparison of DMC imagery	Daily revisit (rather than 16 days)
	SPOT Series, HRV-HRVIR-HRG	Near daily revisit (if SPOT satellites are co-ordinated)	Wide area coverage, low-cost solution, potential availability for rapid response

Table 2.10 Shortlisted Satellite and Optical Sensors for Comparison with the DMC

* Note the term 'improvement' here is used loosely. For example, a low-resolution image may actually, in some circumstances, be better than a high-resolution image for an application (e.g. if approximate spatial detail is sufficient for the application, and ground-processing and data storage constraints exist).
It should also be noted that there may also be positive differences compared to the DMC, such as the availability of more spectral bands.

Of particular note is the recently launched (October 2003) WiFS sensor on the IRS-P6 satellite. This new WiFS sensor marks an improvement in GSD to approximately 60m, compared to the 188m WiFS sensor on previous IRS satellites, whilst maintaining the wide >700km swath width. It has similar spectral bands to the DMC sensor, plus a SWIR band (similar to the SPOT VGT instrument). However, the GSD is still approximately twice that of the DMC sensor. In addition to this the WiFS sensor itself weighs over 100kg and flies on a >1300kg platform [44]. It is not applicable therefore to make a direct comparison between this 'large' spacecraft and the small low-cost DMC micro-satellite solution, which provides an affordable solution for multiple satellite, rapid image revisit missions.

However, it is interesting to note that Ventakachary et al.[45] explain that the WiFS sensor on IRS-1C and IRS-1D is particularly useful for disaster monitoring due to its wide swath and revisit period of 5 days.

In addition to the above listed satellites there have been a number of high-resolution satellites launched and providing commercially available imagery in recent years. Table 2.11 lists current commercial high-resolution missions.

Mission	Ground Sample Distance (GSD)	Image Size
IKONOS-2	1m	13km
QUICKBIRD	60cm	17km
ORBVIEW-3	1m	8km
EROS-A1	1.8m	12.5km
SPOT-5	3 – 5m	60km
IRS-1D	6m	70km
IRS-P6	1m	8km
KOMPSAT	6m	17km

Table 2.11 High Resolution Missions

Because of the great difference in image characteristics and potential applications of these satellites they are not considered here for direct comparison with the DMC mission. Such high-resolution imagery allows a much greater level of detail to be interpreted but typically covers a much smaller image size, as seen in Table 2.11. For a disaster scenario, such missions have great potential to supply valuable complementary imagery to the lower resolution broad area coverage of the DMC. For example, the DMC may be used to provide rapid-response imagery which may assist in early top-level decision making (e.g. where to send resources), with a later 'zoom-in' on the areas of interest by high resolution satellites to provide further detail. Of particular note is the Israeli EROS mission, which is planned to be a high-resolution constellation for daily revisit. This would be an excellent complement to the DMC mission.

The DMC image data characteristics can be plotted on a chart for easy comparison with other sources of data as shown in Figure 2.2.

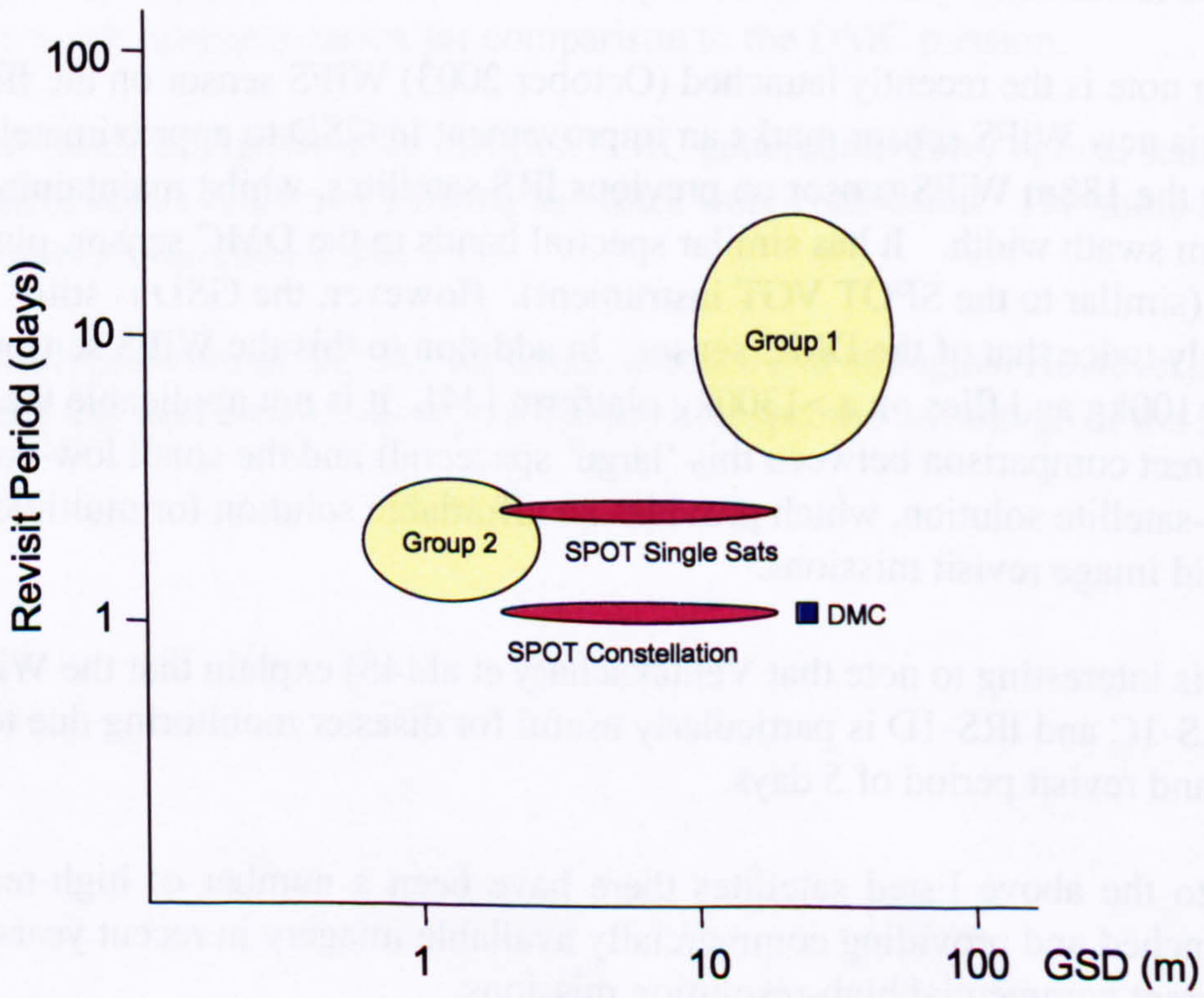

Figure 2.2 DMC Data Characteristics - comparison with other missions

Main groups of other satellite imagery have been collated to simplify the illustration. Very low resolution sensors (e.g. AVHRR at >1km) have not been included.

Group 1 contains the majority of moderate resolution satellites, including Landsat, ERS-1 and 2, Radarsat, and the IRS satellites. These typically are able to cover quite a large swath, but not quite as large as the Field of Regard offered by off-pointing satellites. Group 2 includes all high-resolution satellites. These satellites are typically quite agile, with a large Field of Regard and can hence obtain a quite good revisit frequency compared e.g. to Landsat.

SPOT is slightly individual, in the sense that it has a moderate-high sensor with off-pointing capability to give a large field-of-regard, as well as high resolution capability. Also, operated as a constellation the SPOT satellites can achieve daily revisit imaging opportunities.

The chart illustrates the technical niche that the DMC can fill, although one can see that the SPOT satellites, operated as a constellation look particularly close to this niche. Figure 2.3, however, illustrates the large differences between SPOT and DMC in image area coverage and system cost (an approximate assumption was made of 500m Euros/Spot spacecraft plus launch costs >100mEuros per spacecraft).

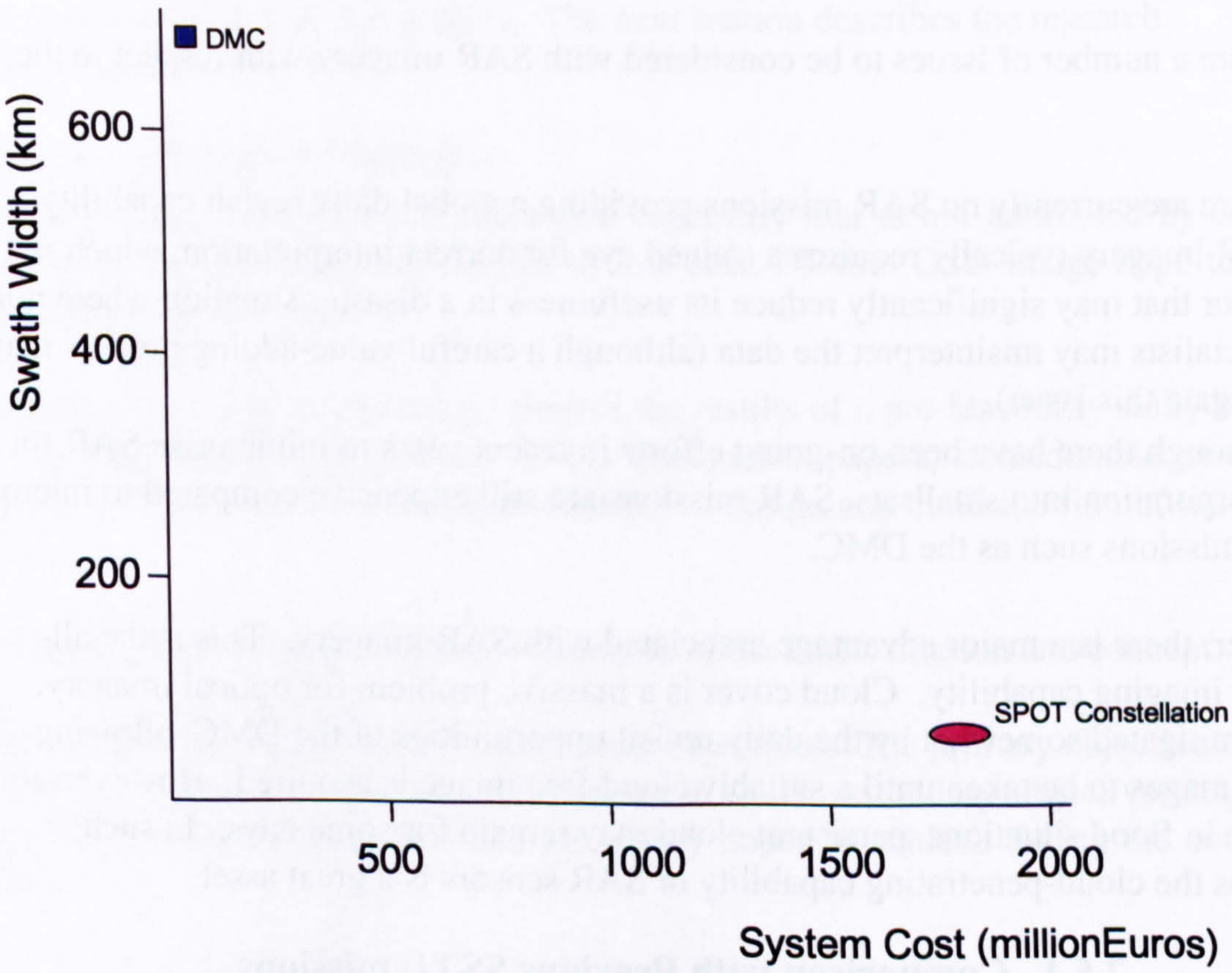

Figure 2.3 Comparison of Spot Constellation and DMC Cost and Swath Width

It is also worth noting that the SPOT satellites were not, unlike DMC designed to operate as a daily revisit constellation, but are able to exploit this opportunity due to exceeding nominal lifetimes. It is also worth noting that, as a data source, SPOT services for programmed, high priority image acquisitions are quite expensive, (e.g. approximately 6000 Euros for a 60 x 60km scene) and with 600Euros additionally charged for 24hr data delivery [46].

Optical satellites are discussed above to set a context for the DMC mission. However, Synthetic Aperture Radar (SAR) imagery should also be mentioned here. SAR sensors are currently flown on a number of satellites as listed in Table 2.12.

Mission	Ground Sample Distance (GSD)	Swath Width
ENVISAT	28m – 1km	5km-400km
ERS-1	30m	100km
ERS-2	30m	100km
JERS-1	18m	75km
RADARSAT-1	25m - 100m	10km - 500km

Table 2.12 Current SAR Missions

It is also worth noting several new SAR missions on the horizon for launch; the Canadian RADARSAT-2 and the Japanese ALOS spacecraft, both of which should provide improved resolution on the above listed sensors.

There are a number of issues to be considered with SAR imagery with respect to the DMC:

- There are currently no SAR missions providing a global daily revisit capability.
- SAR imagery typically requires a trained eye for correct interpretation, which is a factor that may significantly reduce its usefulness in a disaster situation where non-specialists may misinterpret the data (although a careful value-adding process may mitigate this issue).
- Although there have been on-going efforts in recent years to miniaturise SAR for incorporation into smallsats, SAR missions are still expensive compared to micro-sat missions such as the DMC.

However, there is a major advantage associated with SAR imagery. This is the all-weather imaging capability. Cloud cover is a massive problem for optical imagery. This is mitigated somewhat by the daily revisit opportunities of the DMC, allowing further images to be taken until a suitably cloud-free image is acquired. However, for example in flood situations, persistent cloud may remain for some days. In such scenarios the cloud-penetrating capability of SAR sensors is a great asset.

2.5.1. Comparison with Previous SSTL missions

It is worth noting that, apart from providing a new solution for daily imaging capability, the DMC satellite and mission design marks a significant development in the

performance of satellites for SSTL. Some major steps and performance parameters are listed below.

- First pushbroom imager
- First radiometrically calibrated imager
- Operationally useful butane propulsion system
- Constellation phasing and phase maintenance
- Precise orbit definition and orbit injection correction experience
- 28V power system
- 1 Gbyte SSDR (8 times improvement on previous best)
- S-Band receivers
- 8Mbps S-Band transmitter (~6Mbps effective downlink rate give almost a 50 times improvement on previous best effective downlink rate)
- Constellation Mission Planning System
- Archiving and Catalogue System

2.5.2. Current EO Missions Summary

This section has reviewed current in-orbit EO missions for comparison with the DMC.

The information given in this section suggests that there is no current mission providing low-cost multi-spectral data in the region of 30-40m GSD with a rapid response service and daily imaging opportunities. The development of a small-sat mission to satisfy this niche is the overall aim of this project. The next section describes the research objectives based on this aim.

2.6. Research Objectives

The earlier sections identify that there is a capability that is not addressed by current earth observation missions with respect to low cost, 30-40m GSD image opportunities on a frequent, e.g. daily basis.

At the time of the start of this EngD project the results of a pre-feasibility study in such a concept had resulted in several SSTL conference papers, considerable customer interest, and the signing of a customer contract to design and build the first of the DMC satellites.

This EngD project is based on the development of the DMC mission and concept.

Several categories are defined for the research objectives. The primary objectives define the technical research objectives of the project whilst secondary objectives highlight aspects of personal development that the author hopes to achieve during the course of the project.

Primary Objectives:

1.1 Perform the mission and system design of a unique low-cost micro-satellite mission to provide multi-spectral, 30-40m GSD global daily imaging opportunities - the DMC mission.
1.2 Identification of novel potential applications of the DMC mission

Secondary Objectives:

2.1 To develop the author's competence as a space mission and system engineer
2.2 To develop the author's awareness of EO application area issues and hence form a stronger link between EO mission and spacecraft systems engineering, and the end-user objectives
2.3 To develop the author's design, development and research capabilities

The success of the project in meeting these objectives is reviewed in Section 6.2.

2.7. Summary

This chapter has given an introduction to the general field of satellite Earth Observation. Example general application areas were listed and a brief background was given on the use of satellite imagery for disaster applications. It is highlighted that there are a number of potential barriers to uptake of DMC imagery, both technical and non-technical. This is particularly the case for the disaster relief community. It is recommended that significant effort be put into working with value adders and users to create useful products and services using DMC data, as well as address the numerous barriers to uptake that exist. It is recommended that funding opportunities (e.g. via the EC or ESA) to pursue such initiatives be explored. Pilot projects and planning for small wins to gain the support of the user community may be particularly beneficial.

An introduction was given to the principles of optical remote sensing, highlighting that visual interpretation of images may suit some applications whilst more scientific quantitative analysis may suit others. As such, images might commonly be manipulated in a 'GIS' software package or a 'Remote Sensing' software package in a value adding process. The DMC mission is intended to provide a unique source of imagery that can then be used as raw material for such value adding products.

A survey of the current state of Earth Observation in-orbit technical capability was made. A technical niche was highlighted for a low-cost daily multi-spectral imaging opportunity mission, with moderate (e.g. 30-40m) Ground Sample Distance. The design of a DMC mission to fill this niche would uniquely add to current in-orbit imaging capability.

From this the research objectives for this EngD project were formulated, with the primary objectives:

1.1 Perform the mission and system design of a unique low-cost micro-satellite mission to provide multi-spectral, 30-40m GSD global daily imaging opportunities - the DMC mission.
1.2 Identification of novel potential applications of the DMC mission

The following two chapters describe the design and development of the DMC mission from the concept described by Ward et. al [2] to the existence of a functioning in-orbit spacecraft providing proof-of-concept. The design process, problems encountered and solutions derived are all discussed and aspects of predicted mission system performance are given.

3. DMC System Design

This chapter gives an overview of the system design route followed during this project. Note that the mission design and spacecraft design are strongly interlinked and both were performed by the author in an iterative process. Hence both this chapter and the next are heavily linked to each other.

The design of the spacecraft and mission also, of course, involved various specialist sub-system engineers and it is important that their work, and the work of all those involved in the project in any capacity, is recognised and appreciated. However, by keeping this chapter focussed on the top-level issues it is hoped that the main considerations of the 'Systems Engineer' (i.e. the author) will be kept clear and not clouded with less relevant details to the task actually performed by the author. Hence this chapter provides a top-level overview only. Of course, during the development of a spacecraft mission, and especially one with as many new elements as in this project, there are many detailed discussions that need to take place to ensure that the system successfully comes together. As the overall project technical lead, the author was involved in many of these. However, it is not possible in a single chapter to describe all of the considerations made in every area throughout this project. Indeed, as one moves further down into the details of the different areas the contribution made between the systems engineer/technical lead and individual sub-system engineers becomes more and more blurred. It is not practical to analyse and then convey who made exactly what input to each discussion that occurs during the design process.

Hence, best efforts have been made in this chapter to concentrate on areas where the system level considerations have dominated the issues, and hence avoid moving into the details of any particular sub-system area. Acknowledgement and thanks from the author must go, however, to all of the engineers that have contributed to this project in their specialist areas, and also contributed much to the author's learning process throughout this project.

3.1. The DMC System

The NASA Systems Engineering Handbook [47] provides a useful discussion on a Hierarchical System Terminology. The hierarchy suggested is:

System
Segment
Element
Sub-system
Assembly
Sub-assembly
Part

The NASA handbook suggests that different projects may need different layers, for example an instrument may need less, or broader initiatives may require more. It also points out that every system exists in the context of a 'super-system', and that each sub-

system is a system in its own right. Hence systems engineering is performed at a variety of levels within a project.

The system under consideration in this project comprised both space segment and ground segment, and individual missions as well as the management of these missions as a larger 'constellation' mission. A top-level decomposition (down to sub-system level) for the DMC project is shown in Figure 3.1.

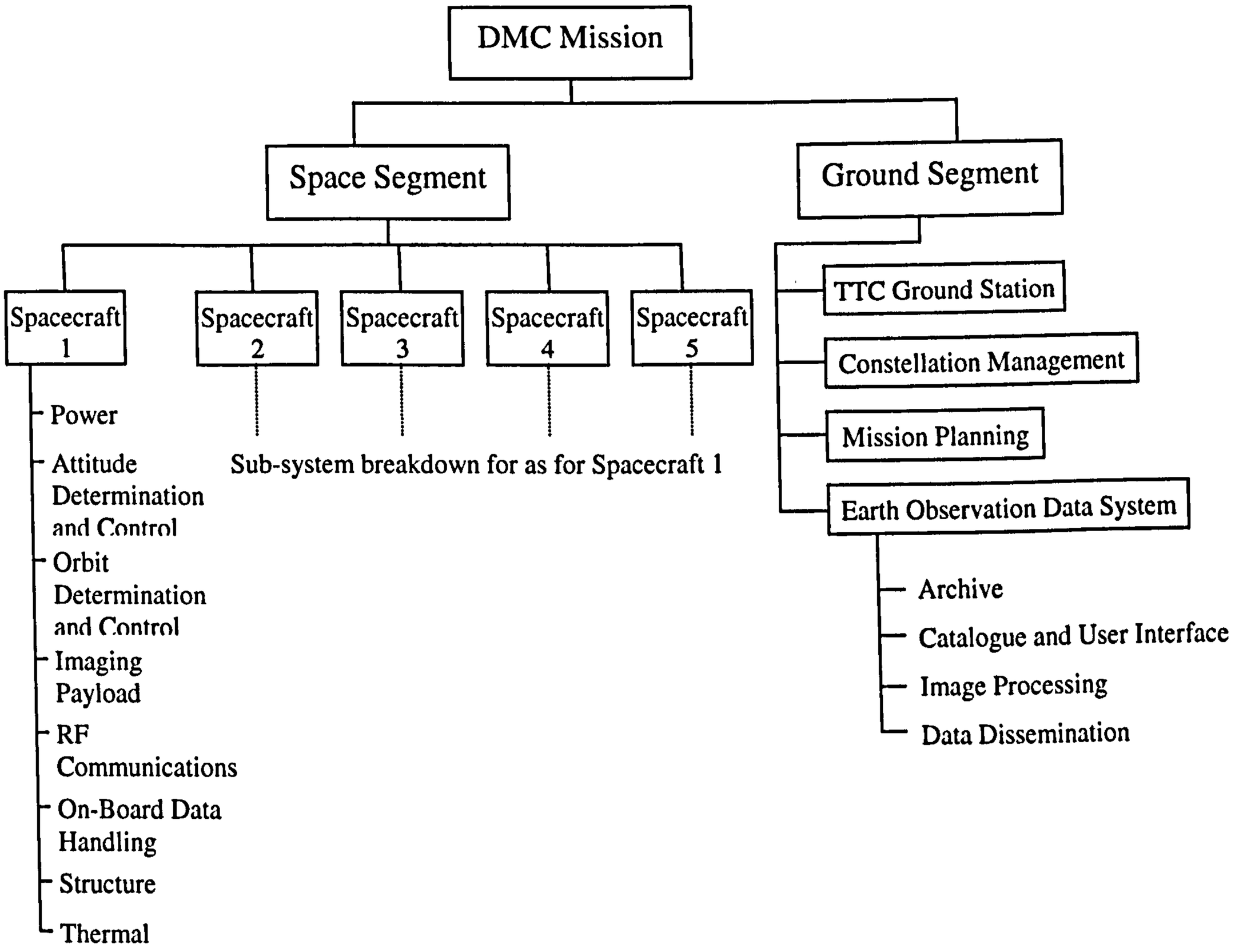

Figure 3.1 DMC System Breakdown

All areas shown were considered under the author's Mission and Systems Engineering role within this project, although the greatest emphasis and effort was spent on the Space Segment. The nature of the individual DMC member mission project contracts meant that they were designed, built and supplied as stand-alone missions, albeit with a design influence from the constellation mission concept. As stand-alone missions the contractual end-objective was to provide a spacecraft that could take images and download them to the control ground-station. This was the greatest priority. Ground image processing, and a user-friendly interface for the data user, for example, was beyond the scope of individual mission contracts. However, in parallel to the individual mission contracts a 'DMC' project was also conducted to provide improved Archive, Data Processing, Data Dissemination, Mission Planning and User

interface/catalogue capabilities. The author maintained a top-level involvement in these areas, as the DMC project Systems Engineer, but concentrated most effort on the Space Segment as mentioned above. This separate DMC 'program' also provided the constellation phasing capability, which involved considerable effort from the author.

3.2. Systems Engineering

The NASA Systems Engineering Handbook [47] provides a good discussion of Systems Engineering, as well as guidelines on performing systems engineering. It describes the objective of systems engineering as "to see to it that a system is designed, built, and operated so that it accomplishes its purpose in the most cost-effective way possible, considering performance, cost, schedule and risk". This is similar to the definition provided by French and Griffin [48] who also provide a very good discussion of Systems Engineering:

"Space systems engineering is the art and science of developing an operable system capable of meeting mission requirements within imposed constraints including (but not restricted to) mass, cost, and schedule."

Both these definitions are very broad, but that is one of the main characteristics of Systems Engineering. Both the above reference sources stress the importance of the broad, rather than deep, viewpoint of systems engineering. The NASA Handbook stresses that it is interdisciplinary and covers the system functionality from end-to-end and from cradle-to-grave. French and Griffin also stress the importance for a systems engineer to understand the goals of the project (and ensure this is passed on to the team), as any technical issue must be evaluated in context of the full system and project goals. A systems engineer must have a broad comprehension of the technical issues involved. Although not expected to be expert in all disciplines, the systems engineer must be sufficiently knowledgeable in each of the technical areas to understand the issues and make decisions. Ideally the systems engineer can perform preliminary analyses in most technical areas to be able to verify information provided and assess the effect of proposed changes.

French and Griffin make a good point that the university system can often create specialists rather than generalists. Often these specialists progress to a position that requires more of a 'systems' view. This can work well if the broad nature of the role is recognized, but there is also a danger of less effective systems engineering if a narrow 'specialist' view or bias is maintained. French and Griffin also point out that, in the real world, conflicting requirements and capabilities often do not match perfectly, leading to the need for compromise to allow project success. They point out that often some people feel that technical activities should be "pure, free of compromise, and always have a clear answer". This is of course not the case in the real world. Hence, willingness to compromise is a key characteristic of a systems engineer. Sometimes constraints (e.g. time, money, limited information, tools) mean that not everything can be analysed. Often results are ambiguous anyway, or can only be properly interpreted in context. This is an area where the broad systems engineering viewpoint and the ability to use engineering judgement is key.

The NASA Handbook also distinguishes systems engineering from what it calls 'design' engineering. It describes systems engineering as dealing with the relationships of the thing being designed to its super-system (environment) and sub-systems, whilst design engineering concentrates on the internal details of how the thing works.

All of the above-described aspects of systems engineering are relevant to this EngD project. As shown in Section 3.1, the author's role as system engineer involved working in a multi-disciplinary environment, with teams of specialist engineers and covered the end-to-end functionality of the system, albeit with greater effort expended on the space segment. The author also took the DMC project 'almost' from cradle-to-grave (the author was not involved in the preliminary study that took place before the start of this EngD project and, thankfully, at the time of writing this thesis the DMC spacecraft are still working well in orbit and have not reached their end-of-life). The spacecraft development lifecycle followed through the project, with main review gates, is illustrated in Figure 3.2.

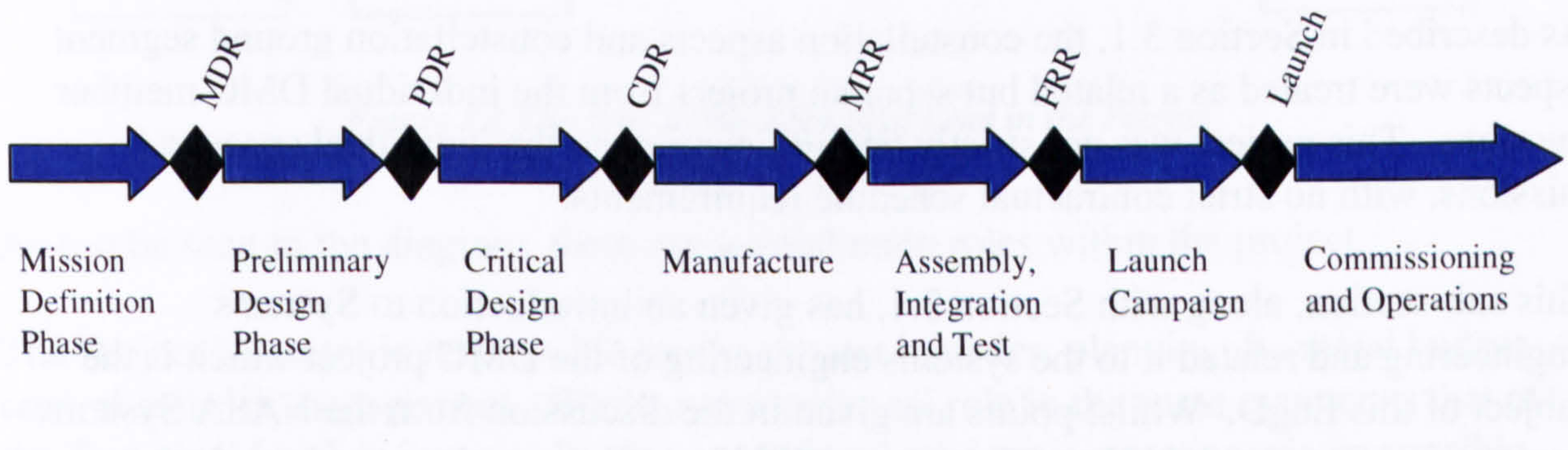

Figure 3.2 DMC Spacecraft - Project Lifecycle

Key:
MDR: Mission Definition Review
PDR: Preliminary Design Review
CDR: Critical Design Review
MRR: Module Readiness Review (entry to AIT)
FRR: Flight Readiness Review

The above SSTL process is very similar to the lifecycle for major NASA projects as described in the NASA Systems Engineering Handbook. The SSTL process does however, have slightly fewer formal reviews. For example the DMC missions did not perform a System Requirements, or System Definition Review, but instead moved from Mission Definition Review to Preliminary Design Review. One or two SSTL personnel were surprised at the Mission Definition Review by the emphasis on the mission definition and by the lack of emphasis on spacecraft design details at this point in the design process. This might suggest that in the past the Mission Definition Review at SSTL was close in nature to a System Definition Review, as listed within the NASA process. The author would attribute the difference between the DMC MDR and previous SSTL MDRs to the fact that the DMC mission demanded a larger incremental step in performance compared to previous SSTL micro-satellite missions. This demanded a previously un-envisaged step away from the SSTL standard micro-satellite solution, with associated additional work and time required in defining the spacecraft solution.

The design reviews at SSTL are treated as formal gates and are often performed in conjunction with the customer and linked to milestone payments. However, the reviews are not necessarily interpreted according to strict definition but are treated as 'snapshots in time' to step back and take a view project progress. For example, at the spacecraft CDR one might expect a number of low-risk, low development sub-systems to already be in manufacture. Equally, there may be some sub-systems with a high development effort required still undergoing final design effort, and requiring a later separate sub-system CDR before manufacture can begin. Hence CDR does not act as a strict 'clear for manufacture' gate at a spacecraft level. Clearly, the least risk scenario would be to wait until all aspects of design and analysis were complete for the entire spacecraft before progressing between stages for any sub-system, e.g. progressing to manufacture. However, by using engineering judgement on the risks, costs and benefits of 'proceeding at risk' for any sub-system at any point in the program, significant schedule and logistical efficiency savings may be made. The systems engineer plays a key role in contributing to this decision process.

As described in Section 3.1, the constellation aspects and constellation ground segment aspects were treated as a related but separate project from the individual DMC member missions. This project was not strictly tied in timescale to the individual spacecraft missions, with no strict contractual schedule requirements.

This sub-section, along with Section 3.1, has given an introduction to Systems Engineering and related it to the systems engineering of the DMC project which is the subject of this EngD. Whilst points are given in the discussion from the NASA Systems Engineering Handbook [47] and French and Griffin [48] there are a number of other good sources of information and discussion for system engineering, e.g. [49]-[52], to which the reader is pointed if interested further. Section 3.3, which follows, elaborates further on the specific role of the Systems Engineer/Technical Lead (the author's role) in the DMC project with relation to other main SSTL roles within the project.

3.3. The Role of the Technical Lead

The role of other specialist engineers in the project is mentioned briefly in the introduction to this Chapter. It is worth a few paragraphs here to illustrate the main roles within the project with an aim to setting the context of the role of the Systems Engineer/Technical Lead, and hence clarifying the contribution made by the author during this project.

Figure 3.3 illustrates the project structure.

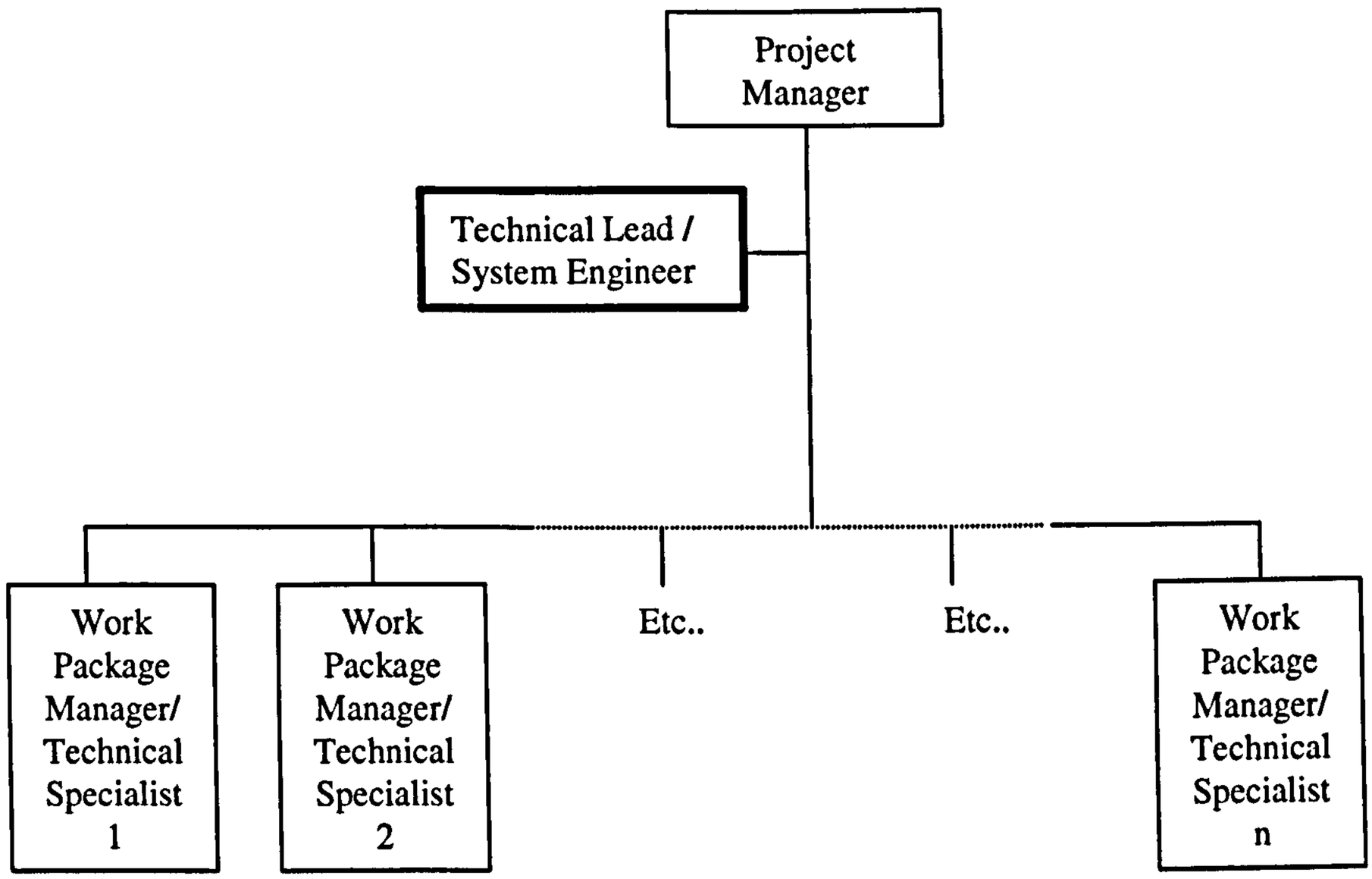

Figure 3.3 The Role of the Technical Lead in the Project

As can be seen in the diagram, there are several main roles within the project.

The Project Manager is responsible for the project logistics, planning, financial budget control and risk management. Whilst not a technical role in the same manner as that of the Technical Lead or Systems Engineer, ultimately the project manager is responsible for the success of the project as a whole. The Systems Engineer works closely with the project manager to ensure that all are happy with the decisions being made and the direction of the project as things progress.

The specialist sub-system engineers are responsible for their module, or in some instances several modules to form a sub-system on the spacecraft. Examples include an on-board computer, a transmitter, an attitude sensor, or perhaps an attitude sub-system comprising a suite of sensors and driver electronics.

In addition to the project structure roles shown above, the 'DMC Programme' Manager is a role specific to the DMC activity within SSTL. The DMC is a constellation of satellites (each with their own groundstation). Each satellite and groundstation are elements of a stand-alone mission for each DMC customer, and the development of this is managed by the Project Manager for that mission. However, the DMC members agree to pool certain resources (e.g. satellite imaging capability) and operate as a constellation in addition to their own 'stand–alone' mission. As well as posing additional technical requirements for consideration by the author, this requires co-ordination and management between projects. This is the role of the 'DMC Programme Manager'. The Systems Engineer also works closely with the DMC programme manager, in a similar manner as described for the Project Manager.

The Systems Engineer/Technical Lead was the role of the author in this project.

From personal experience, and in particular due to the new nature of the role at SSTL, there can be confusion over what the role of a systems engineer is within a project. Section 3.2 gives a general discussion of systems engineering and refers the reader to several texts on the subject.

The role can of course vary from case to case depending on what definition is adopted. Within the DMC project, which is the basis of this EngD project, the term Systems Engineer is used synonymously with the term Technical Lead. The job description for this role provided by SSTL at the start of the project is as follows:

> "As a Systems Engineer on this constellation for multiple customers, you will be expected to resolve technical conflicts and work closely with the customer, SSTL project and SSTL programme manager. You will be in a position where you provide strong leadership to the project engineers; both SSTL and technology transfer customers."

Whereas individual module engineers or analysts might develop a specific process or item, the systems engineer or technical lead develops the mission as a whole, ensuring that everything fits together in the best way to meet the objectives of the mission. Indeed, it is the spacecraft design and mission as a whole that provides the unique ground-breaking capability of the DMC and is the subject of this EngD project.

At an implementation level this involved close collaboration with all specialist sub-system engineers to understand the possible solutions, constraints and drivers in their areas. Close contact with the customers was also required in order to be able to understand their requirements, and hence make sensible design trades as the design progressed. As the development progressed, continued Systems Engineering involvement was necessary to drive the proper review of module and sub-system designs and deal with any non-nominal situations as they arose.

Also, in this instance the majority of the mission analysis was owned by and performed by the author. This combined mission analysis/systems engineering role can allow a quick understanding of the impact of any spacecraft design changes on the expected mission performance[1].

The areas of responsibility of the technical lead encompass all aspects of the mission. The majority of the focus in this project has been on the development of the space segment to the point where three of the 'standard' DMC spacecraft designed in this project are flying and operational in orbit, providing proof-of-concept. However, the ground segment also needs consideration for a successful mission and this was also considered within the scope of this project. However, the author has expended less

[1] Although it should be noted that on occasion, if not carefully managed, this can also sometimes hinder progress if too many analysis tasks, as well as other system tasks, simultaneously fall to the single individual. This risk can be mitigated by the involvement of other individuals in various tasks, albeit at a potential expense of efficiency.

effort in the details of the ground segment compared to the space segment. This is not due to a lack of importance attached to this area. The constraints of overall project timing and management beyond the control of the author meant that many ground segment issues were addressed later in the project. In addition, it was possible to partition the work involved into relatively large easily manageable blocks that could be allocated to specific Work Package Managers. These could be progressed directly under the Programme Manager with continued contact from the author as the project Systems Engineer. The role of the author has been primarily at a top-level in the definition of the project ground segment requirements and constraints.

In addition to the above role as the project Technical Lead the author also took on the additional role of Assembly, Integration and Test manager of the UK-DMC satellite. This provided very valuable, practical experience, dealing with numerous logistical, pragmatic and technical issues as the spacecraft build and testing progressed. This was not only a very valuable experience, but also a very satisfying one, allowing the author to work more closely with the hardware results of all the preceding hard work that had gone into the design.

This sub-section has given an overview of the author's role within the DMC project. This should, when read in context with the mission and system design description, and the applications research described in the rest of this document, allow the reader to better understand the author's contribution to the DMC project and hence the work presented as the basis of this EngD project.

3.4. Mission and Spacecraft Design Process

This EngD project has taken the mission and spacecraft design from the level of an initial feasibility study to a realisable spacecraft that is fully designed, built, tested, launched and operated successfully in–orbit, providing a comprehensive proof-of-concept. The design starting point at the beginning of this EngD project was therefore the design as it stood at the end of the initial feasibility study. The most comprehensive description for this starting point is given in a paper by Ward et al. [2].

The feasibility of this starting point was assessed and as a result the spacecraft design evolved significantly as described in Section 3.7. This occurred in the context of the mission objectives described in Section 3.5 and the mission concept described in Section 3.6.

As mentioned previously, the spacecraft design evolved significantly throughout this project. As described in Section 3.2, the DMC project followed a similar milestone review strategy to many previous satellite projects at SSTL. Major milestones include:

MDR	Mission Definition Review
PDR	Preliminary Design Review
CDR	Critical Design Review
FRR	Flight Readiness Review

The above reviews are typically related to customer milestone payments. Additional smaller reviews, typically unrelated to payments, also took place along the way, for example the author arranged a number of additional Peer Reviews for areas of particularly critical and/or new development.

In addition to the process described above it is worth noting a number of major additional items that were addressed along the way.

Compensation for long-term orbit perturbations
Previous SSTL missions have typically piggy-backed on launches without very specific orbit requirements, and a limited amount of consideration of the long-term evolution of the orbits has been performed in the past. However, for several reasons additional orbit analysis was performed for the DMC mission in choosing the target orbit for launch:

1. The DMC mission was to be launched on a dedicated launcher, and SSTL had the opportunity to define exactly what parameters were required
2. A higher level of performance was desired for the DMC mission compared to previous missions
2. The implication on the mission of the long-term lunar-solar gravity effects was realised during the course of the mission design. Considerable effort was made to understand and quantify these effects in choosing a final target orbit for the launch.

Change of launch strategy
During the course of the mission development it became clear that delays in the kick-off of various contracts for the different DMC members would cause a significant delay in the launch of the first DMC spacecraft unless another strategy could be found. An opportunity to launch the constellation using separate launches at different times became available. Additional unplanned analysis to evaluate the acceptability of this approach (as the spacecraft design was largely fixed by this stage) and to follow this approach was also required.

Launch injection errors from the first DMC launch
The launch of the first DMC spacecraft in November 2002 was a great success. The spacecraft operated well and commissioning progressed relatively smoothly considering the amount of new development involved in this project. The orbit Local Time of Ascending Node was very accurate, as was the inclination. However, there was a significant error in the orbit apogee radius. This was much larger than the quoted 3-sigma error and would result in the spacecraft orbit deteriorating significantly in the course of a few years. A significant amount of additional effort was required to evaluate the situation and produce and implement a recovery plan, which eventually involved an almost full correction for the apogee error using the spacecraft propulsion system.

DMC Consortium Meetings
Also during the course of the project, the author has attended a number of customer DMC Consortium meetings:

DMC Consortium Meeting 1 in Surrey, England
DMC Consortium Meeting 2 in Algiers, Algeria
DMC Consortium Meeting 3 in Abuja, Nigeria
DMC Technical Symposium 1 in Surrey, England

These typically take place at least 6 months apart and are attended by delegates from each of the DMC member countries and allow project progress and future plans to be discussed at a top-level.

3.5. Mission Objectives

The DMC technical performance requirement specifications were defined at the start of the project as:

- 30-40m Ground Sample Distance
- MultiSpectral (3-4 spectral bands)
- Global Daily Revisit
- No specific image quantity requirement, but the constellation should be designed to provide as much imagery as possible within cost, schedule and reasonable risk constraints.

These were adopted as the mission objectives, and the starting point for the mission design.

3.6. Mission Concept

The DMC mission concept comprises 5 spacecraft equi-spaced within the same orbit with a wide imaging swath width to provide global daily imaging revisit. Adjacent imaging swaths, imaged by adjacent satellites in the constellation, overlap to provide seamless coverage of the globe (excluding poles) at least once per day as depicted in Figure 1.1.

The following sections describe the System Design to meet these mission objectives.

3.7. Spacecraft System Design

A significant amount of work was involved in this project in moving from the preliminary feasibility study design to the actual realisable design that was subsequently built, flown and tested in-orbit during the course of this project.

Figure 3.4 and Figure 3.5 illustrate the significant changes necessary. These changes came about through requirements imposed by additional mission analysis, as well as pragmatic decisions driven by non-technical considerations (examples include export license risks, resources constraints etc.).

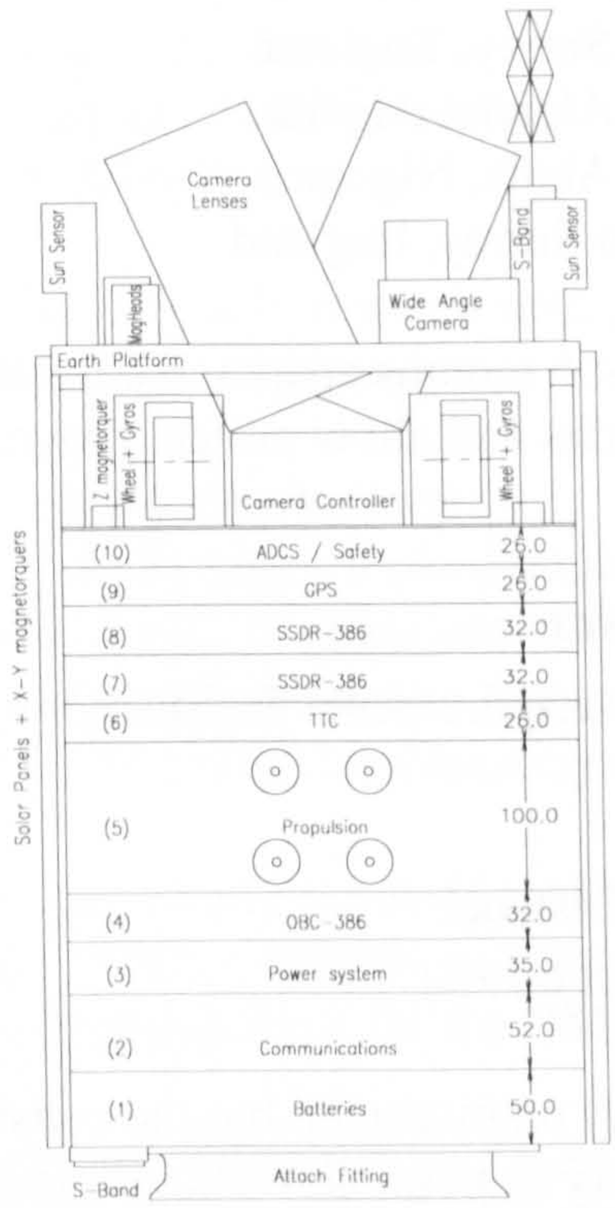

Figure 3.4 DMC satellite after preliminary feasibility study

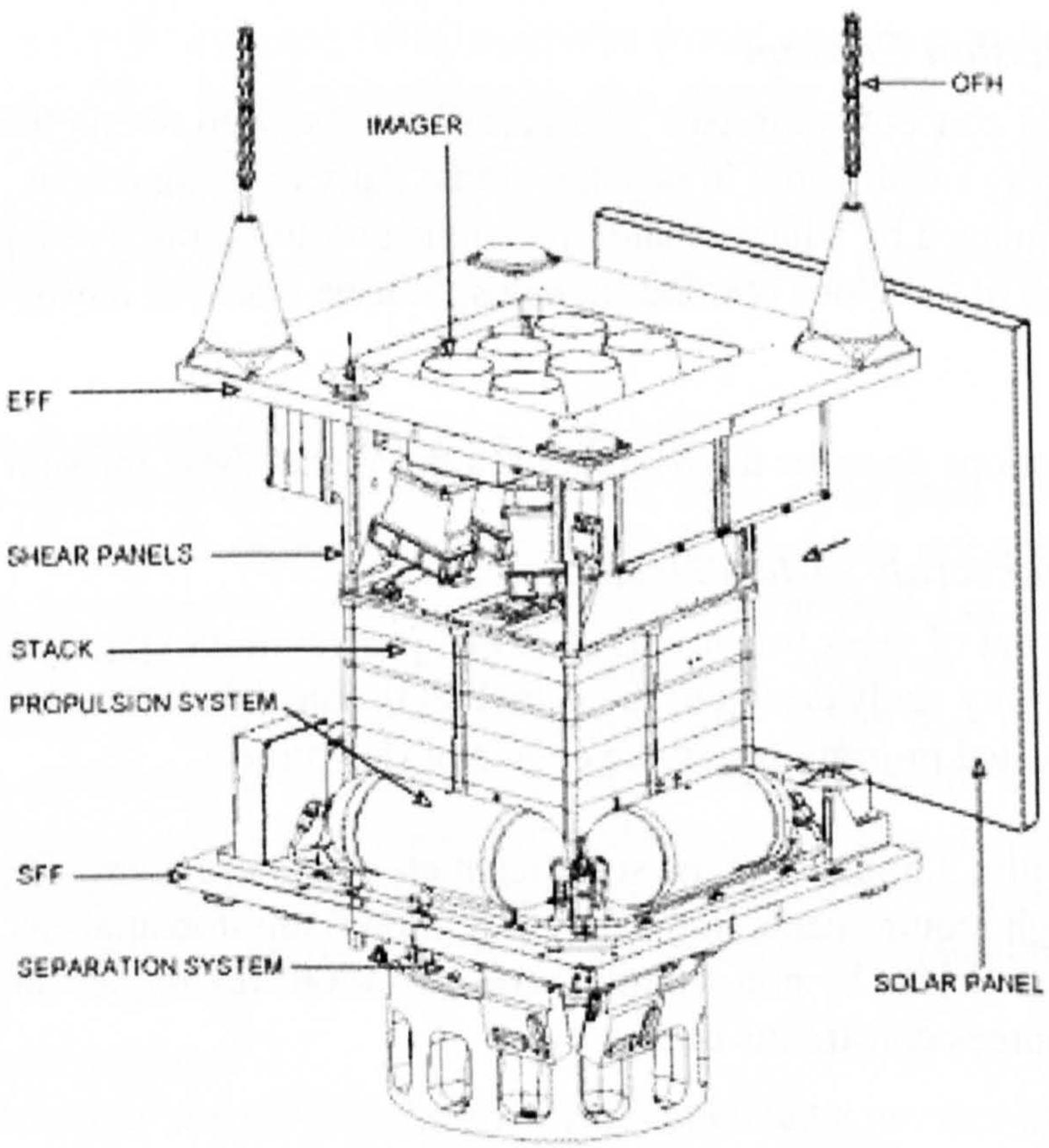

Figure 3.5 Actual DMC satellite as designed during the course of this project

As described in Section 3.1, the task of the author was to lead the system and mission design of the DMC. This was done by starting with an analysis of the requirements and assessing the impact of these at a spacecraft level.

The mission concept gives rise to certain requirements for the DMC spacecraft:

- Large imaging swath width (e.g. approx 600km for a 5 spacecraft constellation to provide daily imaging revisit)
- 30-40m Ground Sample Distance
- Propulsion to acquire and maintain the satellite's constellation formation
- ADCS pointing accuracy such that gaps do not occur between adjacent spacecraft imaging swaths

The DMC mission analysis is described in Chapter 4.

The mission analysis suggests an orbit of approximately 700km (686km) and this is used in the baseline spacecraft design. Sensitivity to an altitude change is borne in mind throughout the design process (for example, an imager that works at 686km but does not work at, for example, +/-10km from this would clearly present a risk to the mission). If any items were particularly altitude sensitive, or sensitive to any variation in orbit parameters then this would be flagged up and the suitability of the design considered. For the DMC mission there were no systems that were critically altitude sensitive. The greatest sensitivity to altitude is the imager swath width (for daily revisit) and Ground Sample Distance (with an initial 'target' of 36m).

Several top-level spacecraft requirements were used as an input to the spacecraft design process. These are listed in Table 3.1 as requirements and, where not so critical, as targets.

	Justification/Origin of Requirement/Target
Requirements	
Global Daily Revisit for constellation	Primary DMC Mission Objective
~600km swath push-broom imager	In Contract
3 Spectral Bands	In Contract
Visually Intelligible Imagery	Discussed with customer prior to project Kick Off
GPS receiver included	In Contract
S-Band Uplink and Downlink	In Contract
Propulsion system for phasing	In Contract
DeltaV of 10m/s	Inherited requirement from previous SSTL analysis. This requirement was revisited during the course of the project.
3.6m ground-station antenna	In Contract
Targets	
36m Ground Sample Distance	In Contract

5-year lifetime	In Contract
Downlink Data Rate ~8Mbps	Inherited requirement from before project Kick Off. Arises from SSTL evaluation of technical feasibility in preliminary study and discussions with customer before project Kick Off.
Imaging capacity (e.g. images/day) as high as possible within project constraints	Desired by customer. Desired by SSTL marketing group.
Constraints	
Mass: <100kg	To allow potential use of commercially available spacecraft adaptor which had a 100kg limit. This limit was also regarded as a reasonable 'ballpark' figure to allow: a) a dedicated launch with 5 DMC spacecraft on the same launcher b) a secondary launch, if necessary
Volume: No strict constraint, but as small as reasonably possible. Dimensions to be considered on a case-by-case basis of proposal.	To allow accommodation of 5 DMC spacecraft on the same launcher. Also as small as reasonably possible to maximise potential opportunities of a secondary launch if necessary.
In addition to the technical constraints listed above, cost, risk and schedule were also constraints during the design process.	

Table 3.1 Top-level Spacecraft Requirements and Targets at Project Kick-Off

The above listed *top-level* requirements, targets and constraints were the starting point for the spacecraft and mission design. Other requirements are not listed above as top-level requirements. This is because other requirements are derived requirements. For example, there was not a strict requirement to have a 4Ahr battery, 55W solar panels, or a given ADCS configuration. These were derived requirements in order to best meet the *top-level* requirements and targets listed in Table 3.1 above. The process of derivation of these further requirements is described later in this chapter.

The above describes the requirements, targets and constraints at project Kick Off. Requirements and targets were also tracked throughout the spacecraft development. For example, the (desirable) requirement to radiometrically calibrate the imager was discussed and introduced part-way through the project.

The following sub-sections give a top-level overview of the impact of the listed items in Table 3.1.

3.7.1. Payload Requirements and Targets

When considering mission requirements and their impact on the spacecraft the payload is the best place to start. After all the reason for the rest of the spacecraft platform is to support the payload. The requirements of the payload should therefore be understood.

Due to the new nature of the imager design (extremely wide swath, push-broom) and also somewhat due to the fact that the most experienced SSTL imager design engineer left the company at the start of the project, the imager development was perceived as a particularly high risk. As a result, in general, efforts were made to accommodate the preferred design of the imager team, as far as possible.

The requirement of a 600km swath with a Ground Sample Distance of 36m (eventually 32m), and three spectral bands leads to a preferred imager design solution as shown in Figure 3.6.

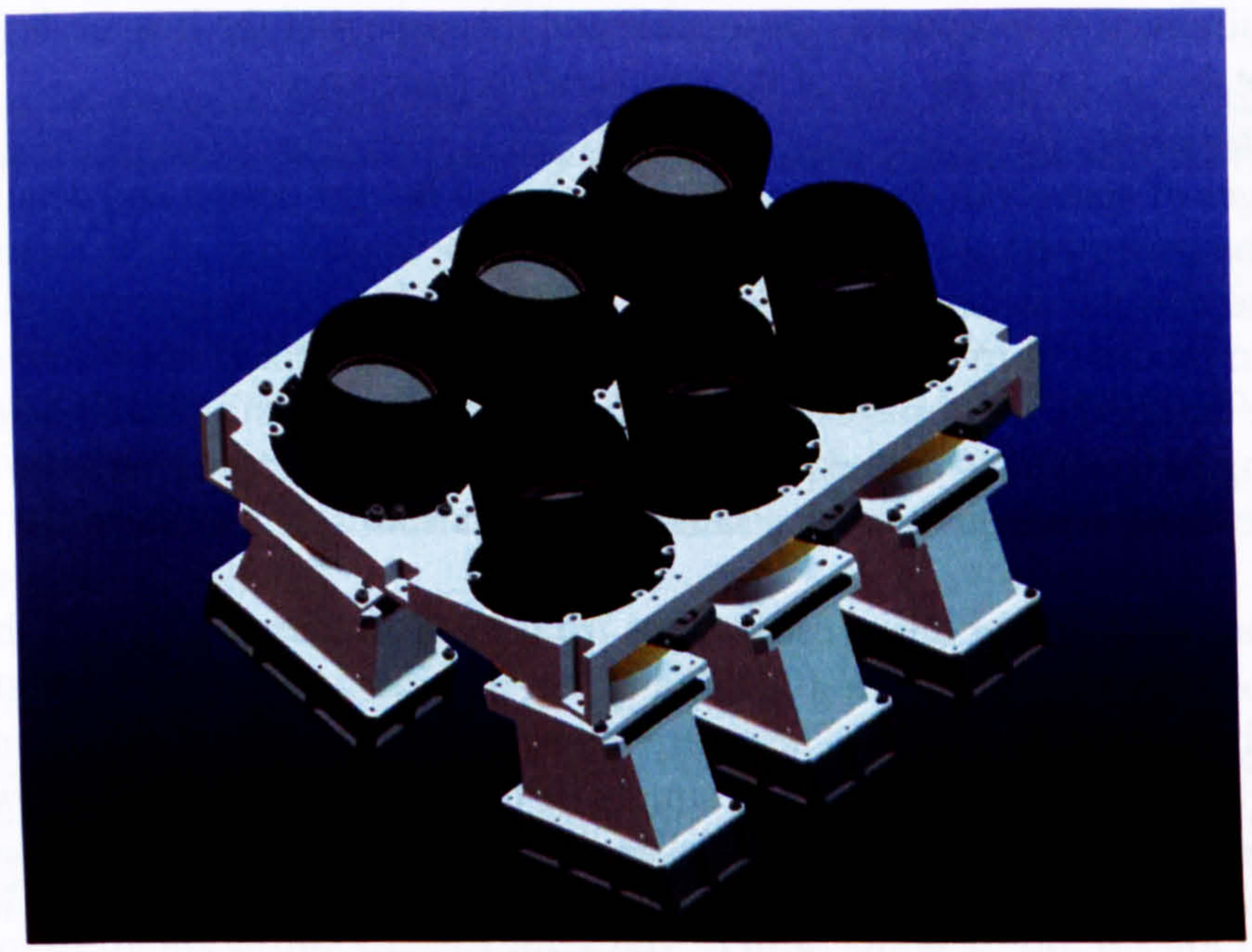

Figure 3.6 DMC Imager Design[1]

This imager design imposes certain requirements on the rest of the spacecraft. In particular:

- Attitude stability
- Thermal environment
- Data rates
- Power Requirements
- Accommodation requirements

In the early stages the imager design may be revisited if any showstoppers or great difficulties are highlighted in other areas of the spacecraft design. However, this was not necessary in the case of this design. It was also the case that the alternative imager design options did not necessarily relax any of the requirements on the spacecraft.

Each of the above requirement areas are examined in Table 3.2 below.

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[1] It is interesting to note the similarity in the solution for the DMC imager and also the recently launched WiFS sensor on IRS-P6. The WiFS sensor is the most similar sensor to the DMC currently in-orbit (in terms of swath/GSD combination), with a similar swath, and a 56-70m GSD. Both imagers use a two-bank solution, with each bank offset from nadir to provide two 300-400km adjacent swaths.

Attitude Stability
Attitude stability requirements are stated as nominally 5mdeg/s in all axes. The derivation of this requirement is basically aimed at minimising the image processing effort to recombine the separate image bands on the ground. The imager group set themselves a target alignment accuracy for the image band alignment on the spacecraft and this, combined with attitude rates during imaging results in a variable offset between the image bands. Attitude rates of approximately 5mdeg/s will result in this offset being only 0.5pixels at the edge of the 600km image swath. Should attitude rates be greater than this then the offset will be greater and hence additional image processing effort may be required. Discussions with the ADCS group indicate that a stability of 5mdeg/s in each axis is achievable via a number of attitude control solutions. Hence this requirement is accepted as reasonable and this aspect of the imager design is therefore acceptable as far as the rest of the spacecraft is concerned.
Thermal Environment
In the early stages of spacecraft design, with both detailed imager design and detailed thermal analysis yet to be performed, it is difficult to have a precise knowledge of the thermal range to be expected, and also the thermal range that may be tolerated by the imager design. In this case it is necessary to proceed at risk with limited knowledge and attempt to iterate the solution as best as possible during the early stages. An initial starting point would usually be established from engineering judgement or past experience, then preliminary thermal analyses and imager design would be iterated to converge on a satisfactory solution. In the case of the DMC imager initial estimations from past experience were that the imager might be able to tolerate a range of +/-10degC and that the thermal design should attempt to provide a stability that matched this. The centre temperature would ideally be at ambient to make testing of the imager easier (i.e. could simply be tested at room temperature with no modifications necessary to adjust for the actual centre temperature expected in space). On the other hand the cooler the centre temperature, the less thermal noise and higher the image quality. After a number of iterations the thermal analysis settled on a centre temperature of approximately 5degC and a stability of approximately +/-5degC. The 'target' range for the imager design remained at +/-10degC and the centre point was fixed at approximately 5degC.
Data Rates
The requirement of the imager results in a very high data rate being produced from the imager during imaging. Even with the preferred imager design of six separate channels, each sending their own data out separately, this data rate could not be received by any existing SSTL technology at the start of the DMC mission.
Power Requirements
Initial estimates from the imager group for the power consumption of the imager were in the order of 90W when imaging. This could provide a significant thermal issue, in particular considering the thermal stability requirements of the imager. Hence the core 'high power' imager electronics are thermally decoupled from the imager channels by being accommodated in a microtray on the central spacecraft stack.
Accommodation Requirements
The imager solution is larger and heavier than originally envisaged in [2], with six physical channels rather than two, and drive electronics that require a microtray or equivalent.

Table 3.2 Payload Requirements and Targets

3.7.2. Impact of Payload Requirements and Targets on Spacecraft Design

The above payload requirements have the following impact on the spacecraft design:

Attitude Stability
No significant impact. The specified attitude control and stability requirements may be met via a number of ADCS control solutions.
Thermal Environment
The imager channels should be thermally decoupled from the rest of the spacecraft and coupled with the Earth to provide stability. The core 'high power imager electronics' should be thermally coupled to the stack to allow reasonable dissipation of the generated heat. Operational limits on the imager due to temperature increases should be expected due to the high power consumption.
Data Rates
The data rates produced by the imager banks have a large impact on the spacecraft. The high rates mean that the original expected solution of an SSDR386 based on the SSTL OBC386 (or even a slightly modified version) would not be possible. The recommended solution as a result of consideration of various options by the OBDH group is the Power PC SSDR. The switch from an OBC386 based SSDR solution to a PPC based solution provides a significant change to the entire OBDH system envisaged for the spacecraft and also a significant change in the expected power consumption levels of the OBDH system.
Power Requirements
The power requirements of the imager are high. These suggest, but do not dictate, a preference for a higher spacecraft bus voltage, i.e. at 28V the imager will be drawing half the current from the power system than if at 14V to meet the same power requirement. The imager group also suggested a preference, although again not a strict requirement, for a voltage supply that was above 15V.
Accommodation Requirements
The larger imager opto-mechanics solution allows no room on top of the stack for other equipment, such as reaction wheels. The increased mass also increases the loading on the stack. The imager electronics in a microtray increases the height of the stack which also increases loading on the stack.

Table 3.3 Platform Impact of Payload Requirements and Targets

3.7.2.1. Summary of Impact on Imager and OBDH Solution

Having considered the above requirements the following solutions are arrived at for the Imager and OBDH system, as described in Table 3.4.

Item	Solution	Comment
Imager	microtray for main electronics	higher imager power than originally envisaged, main electronics should be relatively thermally decoupled from the imager channels
		Increased imager volume and mass requirement
	six channel solution	Increased imager volume and mass requirement
		Increased channels mean more drive electronics required, hence full microtray required
OBDH	Two Power PC SSDRs	Higher Power than baseline SSDR386
		Single microtray required rather than 2 microtrays for 2 SSDR386
	One OBC386	As baselined
	One OBC186	Additional microtray required
	One SA1100	Additional ½ microtray required

Table 3.4 Imager and OBDH Solution Derived from Stated Requirements and Targets

The main points to take from Table 3.4 are that, compared to the original envisaged microsatellite solution:

- An additional 1.5 microtrays are required (note that even if the imager electronics are not accommodated in a microtray they will need an equivalent PCB 'real estate', and hence a similar volume and mass impact)
- There is a higher power requirement than originally envisaged (Orbit Average Power and instantaneous)
- There will be a larger imager mass and volume on top of the stack

3.7.3. Communications Requirements and Targets

3.7.3.1. Downlink data rate of 8Mbps

A target downlink data rate of 8Mbps necessitates a new development for the project. Existing work on a High Power Amplifier unit, could be combined with a transmitter exciter development module, based on a heritage S-Band design. This solution is based on nanotray size PCBs or smaller.

This nanotray configuration provides the opportunity to reduce the stack height by accommodating the RF transmitter systems outside the stack. This is advantageous as the imager solution has already added a microtray to the height of the stack and also increased the mass of the overall imager on top of the stack by the addition of four more physical imager channels (and also the structural shear panels to support them).

The initial power consumption predictions of the high rate transmitter are in the order of 45W as opposed to an original estimate of approximately 16W when the original baseline spacecraft solution was envisaged. This increases the Orbit Average Power requirement for a given transmitter duty cycle as well as the instantaneous power requirements during transmission.

The preferred voltage supply of the high rate transmitter is also 28V due to the transmitter heritage design. This is considered along with the voltage supply requirements or preferences of other items as described in Section 3.7.6.1.

3.7.3.2. Commercial S-Band Uplink and Downlink

The platform implications of the high rate transmitter are considered above in the discussion of the 8Mbps target data rate. However, the requirement for a commercial S-Band uplink also has an impact on the spacecraft design. Specifically this is in the power consumption. The power consumption prediction for the original spacecraft was 1W for the spacecraft receivers. The actual initial prediction for power consumption from the S-Band receiver engineer at the start of the receiver design was actually 2W per receiver, giving a total prediction of 4W (peak power and Orbit Average Power) for receiver power consumption.

3.7.4. Propulsion Requirements and Targets

3.7.4.1. DeltaV requirement of 10m/s

The reasons behind the DMC propulsion system design and changes from the original baseline can be briefly summarised as follows:

- the DeltaV requirement is higher than originally envisaged (10m/s rather than 7m/s)
- the original baseline high pressure nitrogen system was perceived as a high technical and programmatic development risk compared to the liquid butane system

Because of the above, the propulsion system is larger than originally envisaged, and therefore accommodated outside the stack.

3.7.5. Summary of Initial Top-level Design Process

The Top Level Design Process so far can be summarised as follows:

Payload

- Imaging requirements → imager solution
- Imager solution → OBDH solution
- OBDH solution and Imager solution → increased power requirements
  Increased stack height

Communications

- 8Mbps and S-Band Up and Downlink → RF comms solution
- RF Comms solution → increased power requirements

		Accommodation outside the stack preferable

Propulsion

• 10m/s deltaV requirement	→	Propulsion system solution
• propulsion system solution	→	accommodation outside stack may be necessary (not just preferable)

The above design decision process was influenced <u>directly</u> by the listed requirements and targets in Table 3.1. The above described design decisions then influence the design decisions for the rest of the spacecraft, described in the sections to follow. Hence, the design decisions described in the following sections are influenced indirectly from the initial requirements and targets listed in Table 3.1.

3.7.6. Top level Design Process, 2nd level Derived Platform Requirements and Solutions

The first level of derived design impacts the Imager, OBDH, RF Communications and Propulsion as described in above. This section describes further derived design for the satellite. The first level of design leads to certain requirements or preferred solutions for the Power, ADCS and TTC systems. The accommodation issues for all systems should then be considered in the structural configuration.

3.7.6.1. Power System

The main characteristics of the power system solution are:

- 4 body-mounted 55W GaAs/Ge solar panels
- 4Ah NiCd battery
- 28V unregulated bus
- 5V regulated bus

Several of the main 'drivers' behind the power system changes to the original baseline are summarised below:

- Increased power requirements compared to the original baseline (as described above, due to the changes in the OBDH system and also the higher than expected power consumptions of the S-Band RF systems)
- Recent evidence suggested uncertainty in the original baseline battery cell technology. The preferred technology as a result of research from the Power Group is a 4Ah cell.
- The 28V bus allows a reasonable battery capacity using the preferred 4Ah cell, and also allows the use of an existing 22cell SSTL battery design.
- Significant number of modules would prefer a 28V supply (although some would prefer 14V).

Use of the existing SSTL battery design would require accommodation outside the central stack.

3.7.6.2. Attitude Determination and Control System

The main characteristics of the ADCS solution are:

- 2 reaction wheels: 1 Z-wheel (Yaw), and 1 Y-wheel (Pitch)
- 3 magnetorquer rods
- 1 Gravity Gradient boom
- 4 sun sensors
- 2 x 3-axis magnetometers
- 28V module electronics

The most significant change to the ADCS solution from the original baseline is the addition of a Gravity Gradient boom. When the original baseline design (before this project) was conceived it was not expected that a GG boom solution would be adequate. Further consideration during the course of the development suggested that this was not the case as long as the boom is used in conjunction with reaction wheels. The addition of a boom provides a number of advantages:

- Wheel lifetime reliability is improved as the wheel duty cycle can be reduced
- The option of 'barbecue' ADCS mode is made available for non-imaging periods, which may be of use to reduce thermal gradients
- ADCS requirements can be met with either a pitch or yaw wheel
- The spacecraft centre of mass with the boom deployed provides a convenient solution for the thruster positioning and alignment

In addition to the above, SSTL has a wealth of experience and heritage in gravity gradient stabilised control systems that can be called upon in the development.

3.7.6.3. Telemetry and Telecommand System

The telemetry and telecommand solution is based on a distributed system, with each electronics module on the spacecraft having a dedicated CAN node, rather than a single dedicated TTC module electronics tray for all satellite command and telemetry reception and distribution.

This is a departure from previous SSTL microsatellites, and is predominantly a result of the fact that many of the sub-system designs to be used in the DMC solution already had a CAN node within the design anyway. Without the redesign of a number of modules, the use of a centralised system would have introduced additional power requirements as well as mass and volume.

3.7.7. SA-1100 SSDR

The PPC SSDR uses a processor that does not have SSTL flight heritage. Although there is no reason to suspect that this processor would perform badly in the space environment, it was decided that it would be prudent to add a second redundant data recorder, based on a different processor technology. Also the SSDR was to use DRAM, which due to its nature might lose whole rows or columns due to single event upsets. The Strong-Arm processor has flight heritage on the SSTL SNAP-1 mission. Hence it

was decided to include an SSDR based on the Strong-Arm processor in the spacecraft design.

The performance predictions of the SA-1100 SSDR would not meet the stated mission objectives of 8Mbps downlink, and would not support a 512Mbyte memory. However, a graceful degradation would be possible, with a predicted 4Mbps downlink output possible to the HRTX, and a 128Mbyte SRAM storage capacity. The interfaces to both the imager and the HRTX were to be via FPGAs.

3.7.8. GPS

Whilst there is no strict requirement for the inclusion of a GPS the mission can benefit from this in several ways:

- increased on-board timing accuracy
- improved orbit and position knowledge

Hence a GPS is included in the spacecraft solution, with NORAD two-line elements as a back-up solution.

3.7.9. Structural Configuration

Increases to the stack height are necessary, due to the changes described in previous sections, as follows:

Imager:	1 microtray
Power system (not including battery):	1 microtray

There are also, however, several items that were originally baselined to be in the stack but would benefit from accommodation outside the central stack:

- RF Systems
  - To accommodate the RF systems in the stack would result in additional RF module redesign.
- Propulsion system
  - To accommodate the propulsion system in the stack would not have been possible in a reasonable volume using a liquid butane propellant.
- Battery
  - To accommodate the battery in the stack would require additional battery redesign.

By moving all of these systems outside the stack, the stack height is actually reduced. This reduces the risk of structural issues with the stack, which is particularly beneficial given the increased mass of the imager and associated supporting shear panels for the imager.

In addition, larger solar panels are required to support the higher Orbit Average Power. This means that the spacecraft volume needs to be increased to accommodate the solar

panels. Work by the mechanical Design Office revealed that the sizing of the solar panels and also all of the accommodation issues for the above mentioned sub-systems could be solved by increasing the dimensions of the spacecraft body to approximately 600mm x 600mm x 600mm. It was considered unwise to greatly exceed these dimensions in order maintain a good prospect of accommodation on a piggy-back launch should this ultimately prove necessary.

It is worth noting that the prospect of using Carbon Fibre Substrate solar panels was considered, rather than the original baseline Aluminium substrate. Whilst Aluminium was the baseline due to heritage, carbon fibre panels were identified as a potential opportunity due to several positive technical characteristics; primarily lower mass and expected lower co-efficient of thermal expansion to more closely match the solar cells. This is an example of a relatively simple trade-off and provides as good an example as any to describe the nature of trade-offs in a little more detail.

The NASA Systems Engineering Handbook describes a trade study process to allow selection between alternative design concepts. The general aim of a trade study is to assess design alternatives against the system goals such as effectiveness, cost, schedule and risk (both quantified and otherwise). The main steps of the process described by NASA are:

- define systems goals and objectives and identify constraints (in early phases this will be in general operational terms, later on it may be performance requirements that must be met)
- perform functional analysis (i.e. what functions does the system need to perform to meet the goals and objectives)
- define measures and measurement methods for system effectiveness, system performance, or technical attributes, and system cost
- define a Selection Rule (how to combine and interpret the results to formulate a decision)
- define plausible alternatives
- collect data
- compute estimates of system effectiveness, performance and system cost
- make tentative selection
- ...do not accept the answer blindly. Perform a reality check.

The NASA handbook points out that trade studies can be enhanced by developing system models. An example would be a quantitative method of scoring different attributes and applying a mathematical Selection Rule to output the optimum solution. However, NASA also points out that there are problems in using models, primarily around the fact that they do not always necessarily represent reality. For example, a model might be chosen more for its mathematical convenience rather than to accurately represent the real needs of the system. This is why any such selection output should be considered tentative and a Reality Check must be made to support or reject the tentative selection.

The trade-off of Carbon Fibre substrates against the Aluminium baseline was a relatively simple process. A quantitative analytical method or selection rule was not used, although the general procedure above was followed.

Goals and Objectives
Support solar cells
Provide protection (mainly radiation) for spacecraft internals
Provide mounting for magnetorquers (internal)
Low Mass

Constraints
Cost
Schedule
Risk

Functional Requirements
Provide suitable surface for laydown of solar cells
Provide suitable co-efficient of thermal expansion to match solar cells
Provide suitable co-efficient of thermal expansion to match rest of spacecraft structure (Aluminium)
Allow re-work of inserts
Allow re-work during solar cell laydown process
Provide radiation shielding
Provide suitable stiffness to survive launch vibration loads

Measures and measurement methods
This step was not formally followed in this case. Qualitative discussion of the relative performance of the proposed solutions proved sufficient to lead to a selection.

Define Selection Rule
Again, this was not formally considered in this case. The selection was arrived at purely through verbal discussion and not a formal analytical process. In actual fact a selection rule *must* have been applied, otherwise no selection would have taken place. However, in this case it was not a formal, documented, or mathematical rule but a rule in each of the engineer's heads. Each engineer may not even be aware that they are applying a selection rule and it will most likely not be tightly defined in their heads. However, in this case no engineer had any doubt or indecision about whether the right selection was made. This indicates that the 'sub-conscious' selection rule for each engineer was fairly robust. Each engineer involved in the discussion may have also had a slightly different rule, or applied a different weighting in their head to the different decision criteria under discussion. However, in this case, it was found that a unanimous conclusion was reached, and without reservations for each person involved. This suggests that a robust and sufficiently consistent selection rule was applied (in their heads) by each engineer involved in the trade-off discussion.

Define plausible alternatives
In this case this was done before the whole trade-off process began; Carbon Fibre, or Aluminium. In fact, the reason for the trade study taking place was that a new alternative to the baseline had been identified.

Collect Data
This occurred mainly qualitatively by discussion of the functional requirements and goals, objectives and constraints and how well each of the alternatives met these, as shown in Table 3.5.

Attribute	Aluminium	Carbon Fibre
Low Mass	Acceptable	Good
Cost	Acceptable	Unknown
Schedule	Acceptable	Unknown
Risk	Acceptable	Unknown
Provide suitable surface for laydown of solar cells	Acceptable	Expected to be acceptable
Provide suitable co-efficient of thermal expansion to match solar cells	Acceptable	Expected to be good
Provide suitable co-efficient of thermal expansion to match rest of spacecraft structure (Aluminium)	Good	Expected to be bad
Allow re-work of inserts	Acceptable	Expected to be bad
Allow re-work during solar cell laydown process	Acceptable	Unknown
Provide radiation shielding loads	Acceptable	Unknown
Provide suitable stiffness to survive launch vibration	Acceptable	Expected to be good

Table 3.5 Carbon-Fibre vs. Aluminium Substrates

Compute estimates of system effectiveness, performance and system cost
This step occurred, as described above, in the heads of the engineers involved in the discussion. However, as indicated by the table above (under the step Collect Data), it was not possible at the time to create an accurate comparison in all areas.

Make tentative selection
The selection was that of the original Aluminium baseline. Due to heritage experience, these were considered a low risk to meet the project technical, cost and schedule criteria. The main weighting in the decision criteria was that of schedule risk. Another high rating was that of Technical Risk. The lack of understanding of the risks and issues involved with Carbon Fibre panels is evident in Table 3.5 and presented a risk. It may be that Carbon Fibre panels would be fine, or better than the Aluminium panels. However, there was no resource to investigate the unknown areas. Even if a resource had been available, to delay decision until the investigation was complete would have impacted the schedule for the mechanical design team, which was considered

unacceptable. These factors overwhelmed the other technical considerations (for some of which it was not possible to make concrete comparisons between the options due to limited information).

Reality Check

A mathematical model was not used, and the entire selection process was based on discussion and engineering judgement. Hence, reality was never really moved away from during the selection process. However, a reality check of any decision is always recommended, regardless of how it is arrived at.

It is not always quite as straightforward to reach a trade-off conclusion. If it is a closer decision than the example above, then it may be that more effort is made to define and separate the decision criteria. However, in most cases during this project quantitative analytical system models were not typically created. Instead, the results of the different decision criteria were holistically considered using engineering judgement to arrive at a decision, rather than using a mathematical, quantitative selection rule.

An example of where it was particularly difficult to identify the best solution this way was in the selection of the imager technology. In this case a quantitative system model was used as a tool. In this case a simple point scoring system was used depending on system goals such as component heritage, risk, cost, and performance to provide the best combination for the imager. An amount of subjectivity is always present in such exercises unless unambiguous and detailed measures can be defined. However, if performed as a group exercise then the result is more likely to be less influenced by any individual bias.

In this case of the choice of technology for solar panel substrates, other factors may have come into the measures for the system performance or effectiveness. For example, longer-term technical strategy and research and development needs may be included in the mix. Carbon Fibre offers several advantages including mass and a low coefficient of thermal expansion and in the longer term it may be wise for SSTL to adopt this technology. However, it was not considered necessary or acceptable to make the move on this customer project whilst there was such a limited time in the schedule to evaluate and fully understand the issues involved.

The thermal analysis of the spacecraft was performed by an SSTL thermal engineer. Close contact was maintained between the author, the mechanical design office and the thermal engineer to ensure that the mission structural and thermal design was suitable to meet the mission needs.

The above sub-sections describe the top-level payload and platform requirements and targets. The following sub-sections describe the evolution of the spacecraft solution.

A 'Configuration Control' table can also be found in Appendix C which summarises, at a system level, the main final spacecraft design changes from the original baseline starting point.

3.7.10. Spacecraft Solution at PDR

Figure 3.7 to Figure 3.12 illustrates the physical configuration of the DMC spacecraft design as at the PDR stage of the project (all 3D spacecraft drawings are provided courtesy of the SSTL Mechanical Design Office).

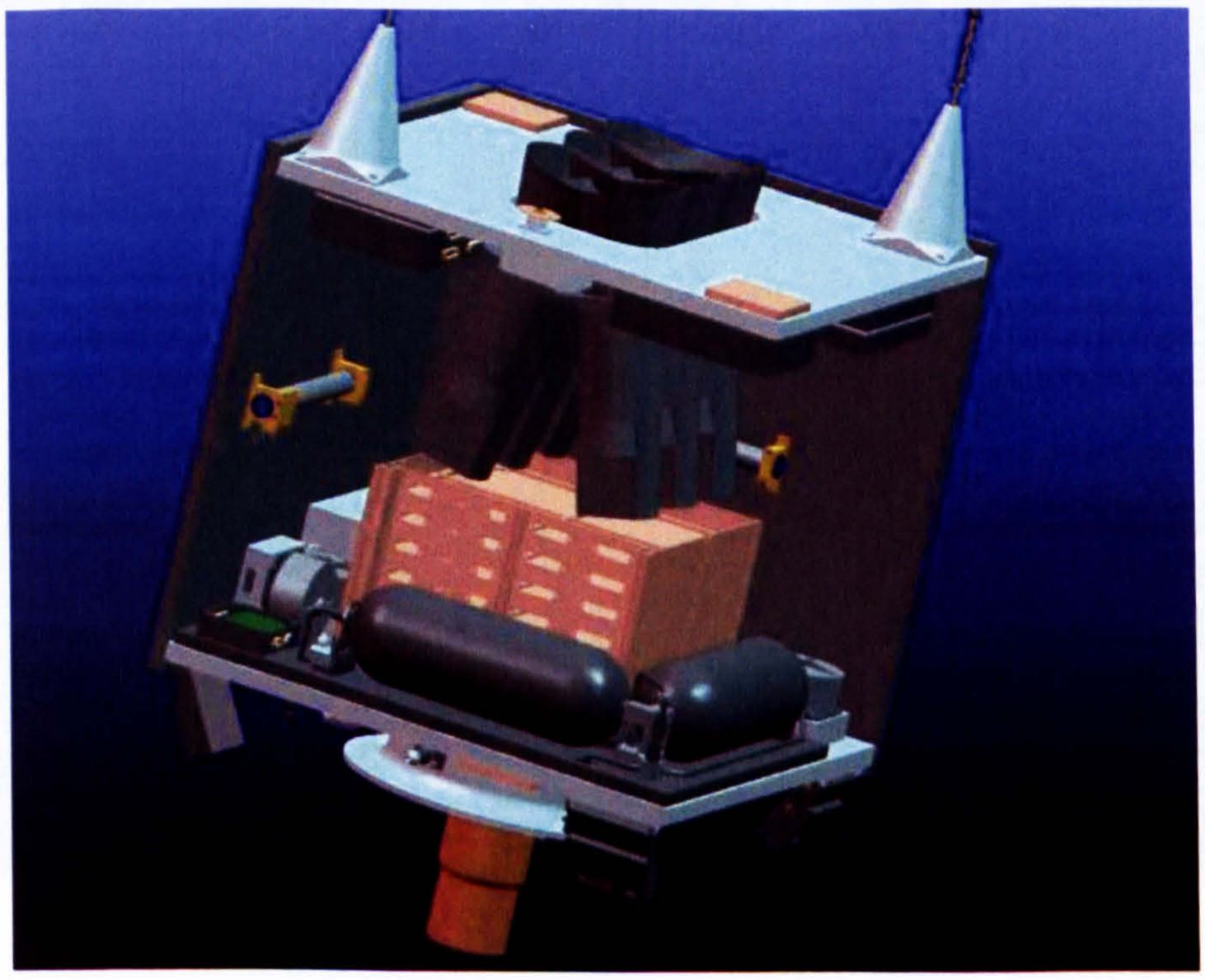

Figure 3.7 DMC Satellite Internal Physical Configuration at PDR

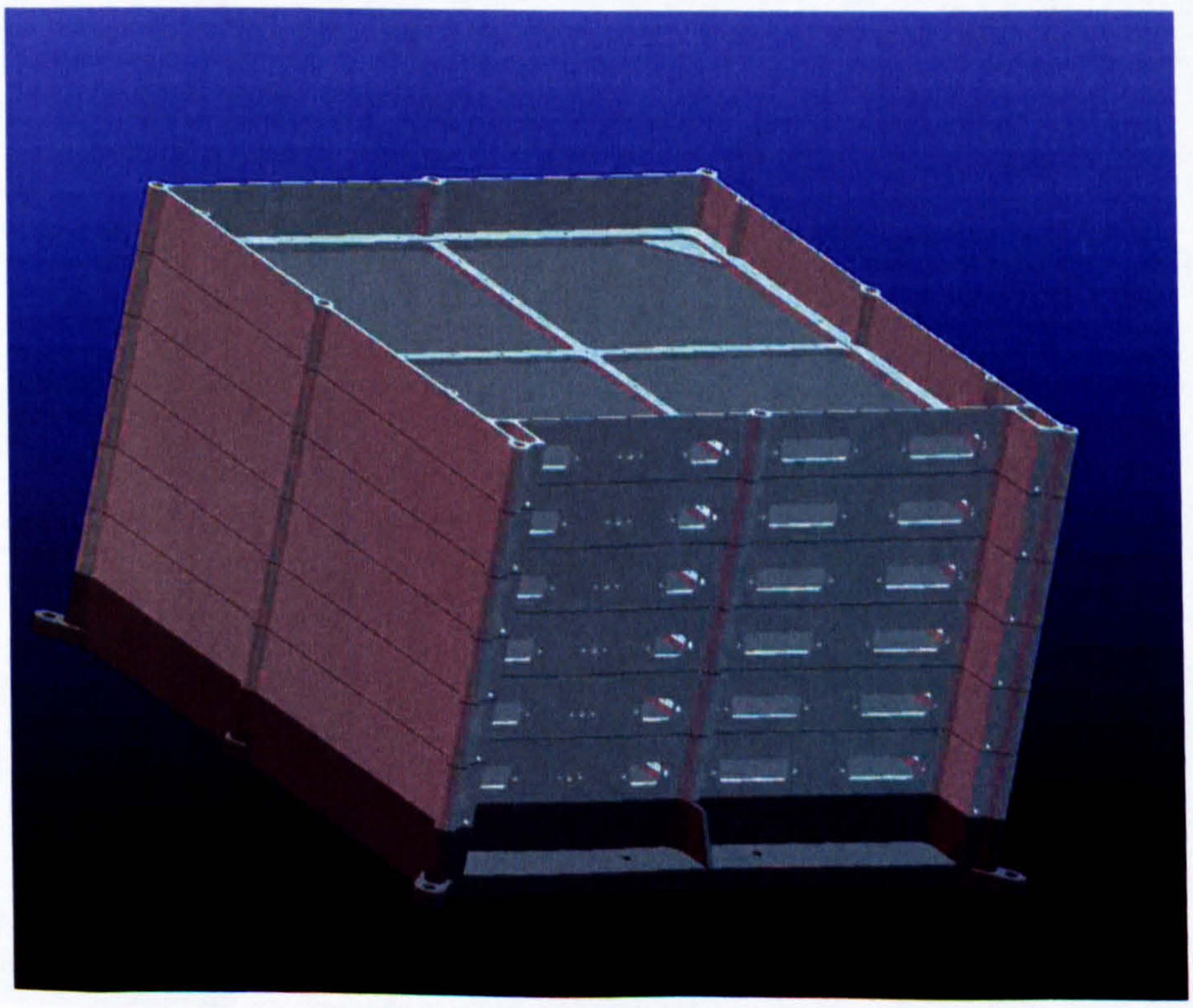

Figure 3.8 Module Stack at PDR

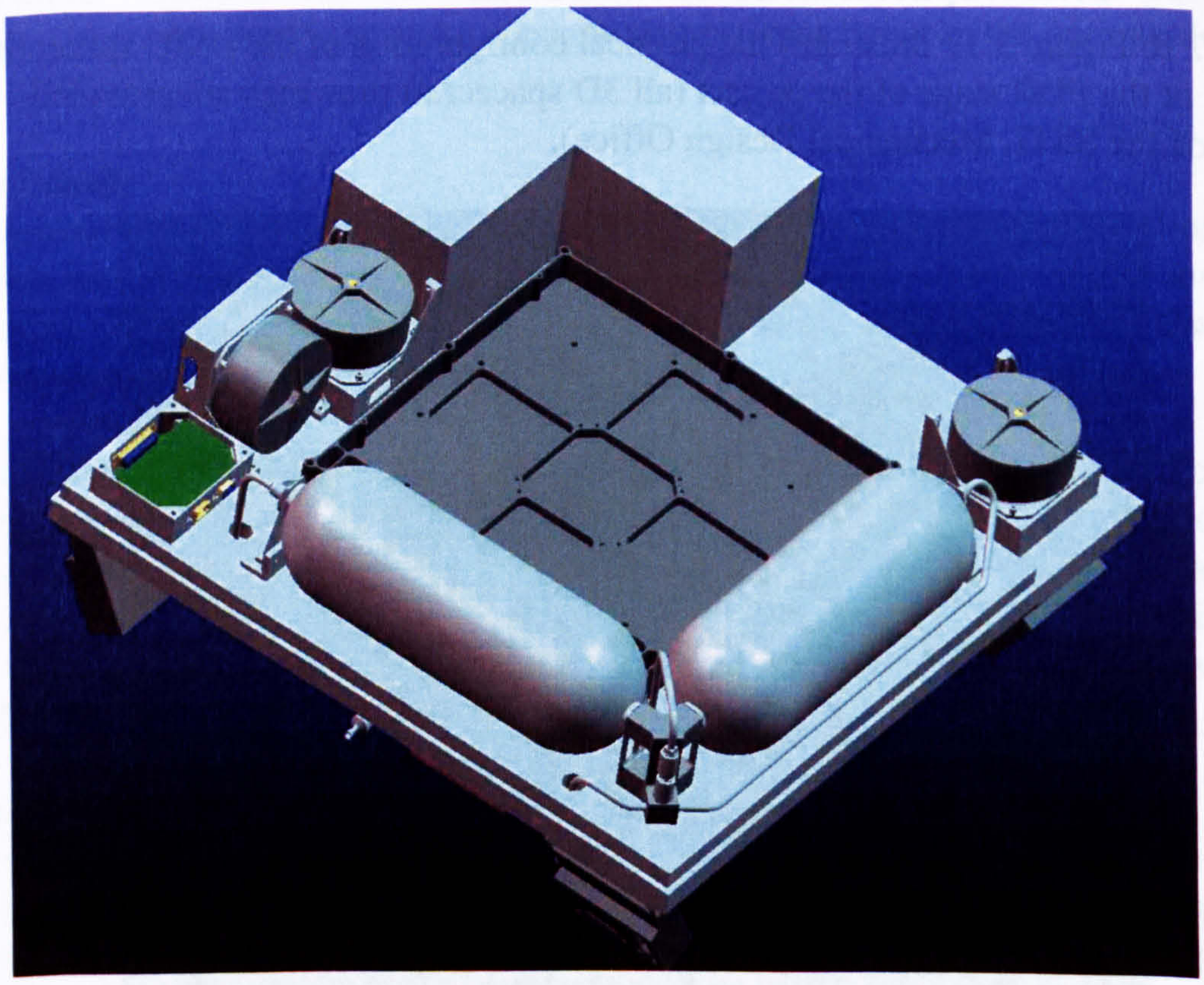

Figure 3.9 Space Facing Facet at PDR (Internal)

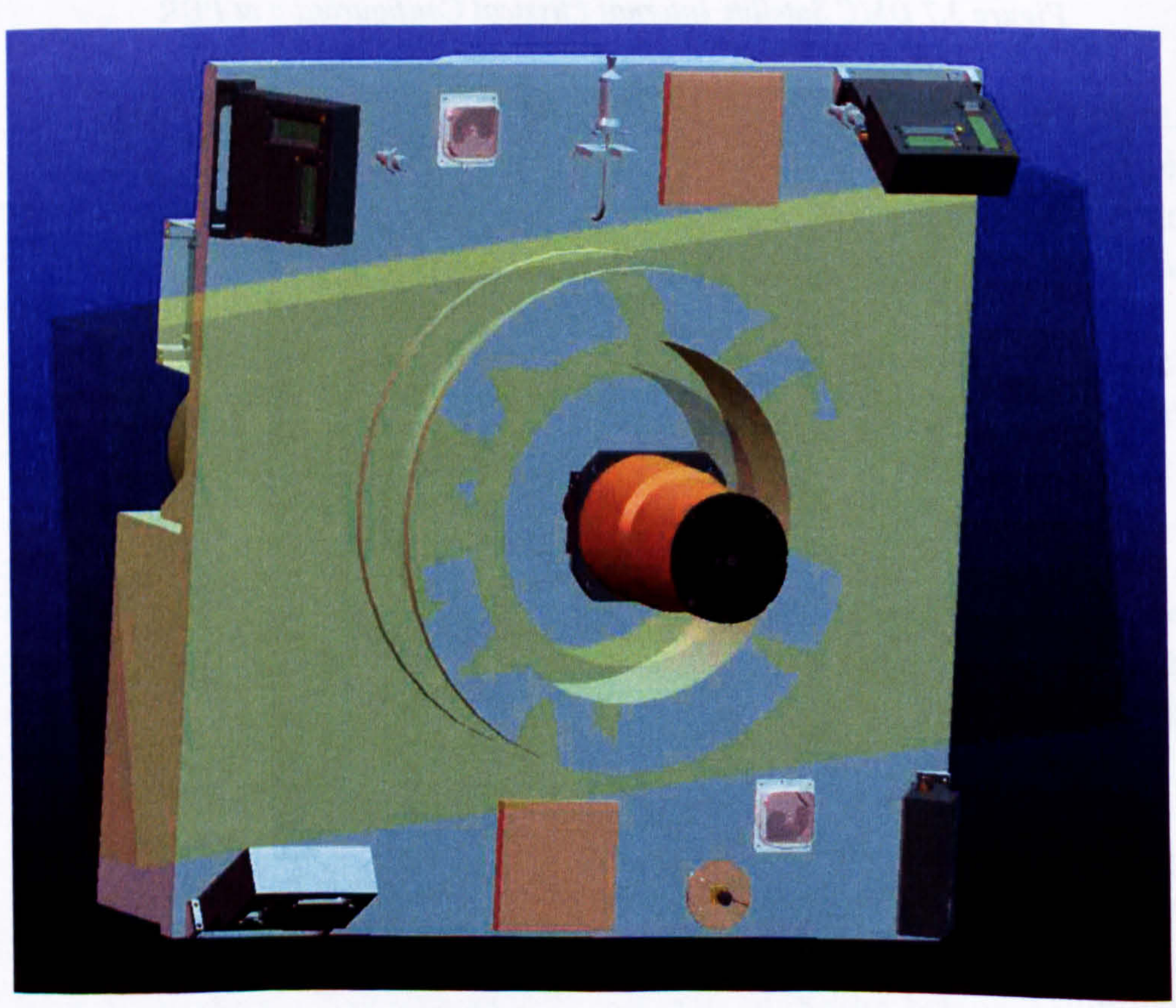

Figure 3.10 Space Facing Facet at PDR (External)

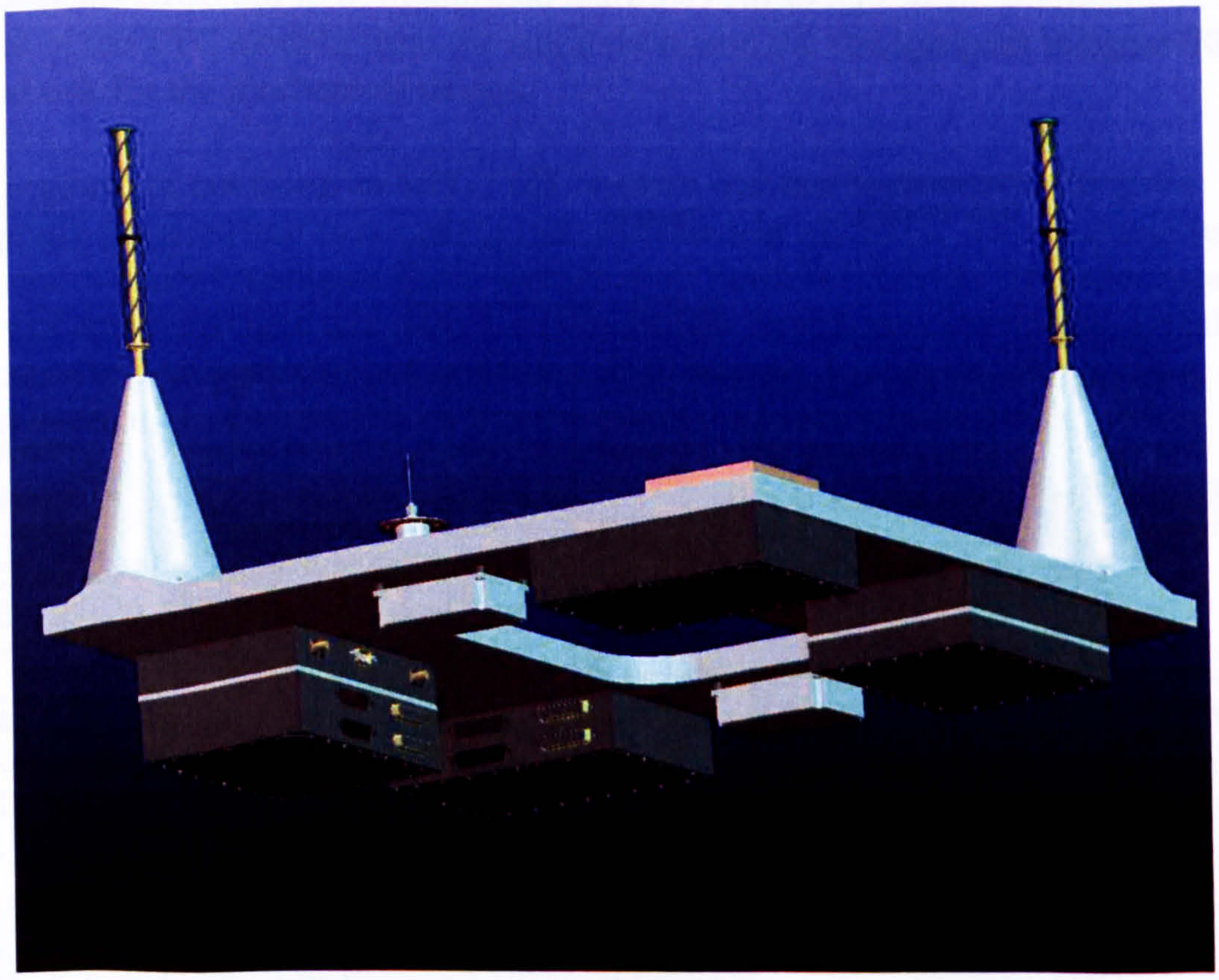

Figure 3.11 Earth Facing Facet at PDR (Internal)

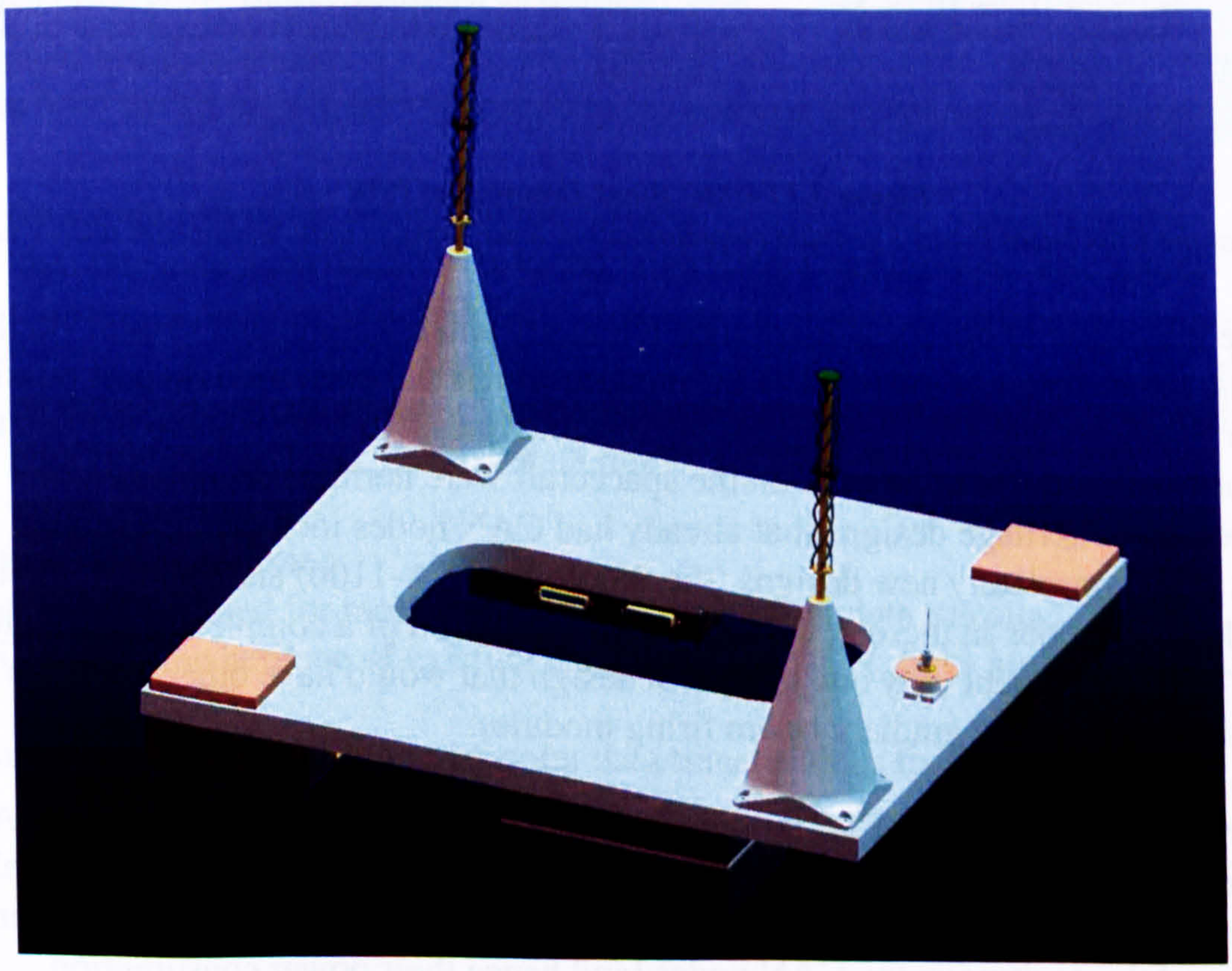

Figure 3.12 Earth Facing Facet at PDR (External)

Figure 3.13 illustrates the design of the electrical configuration of the DMC satellite as at the PDR stage of the project.

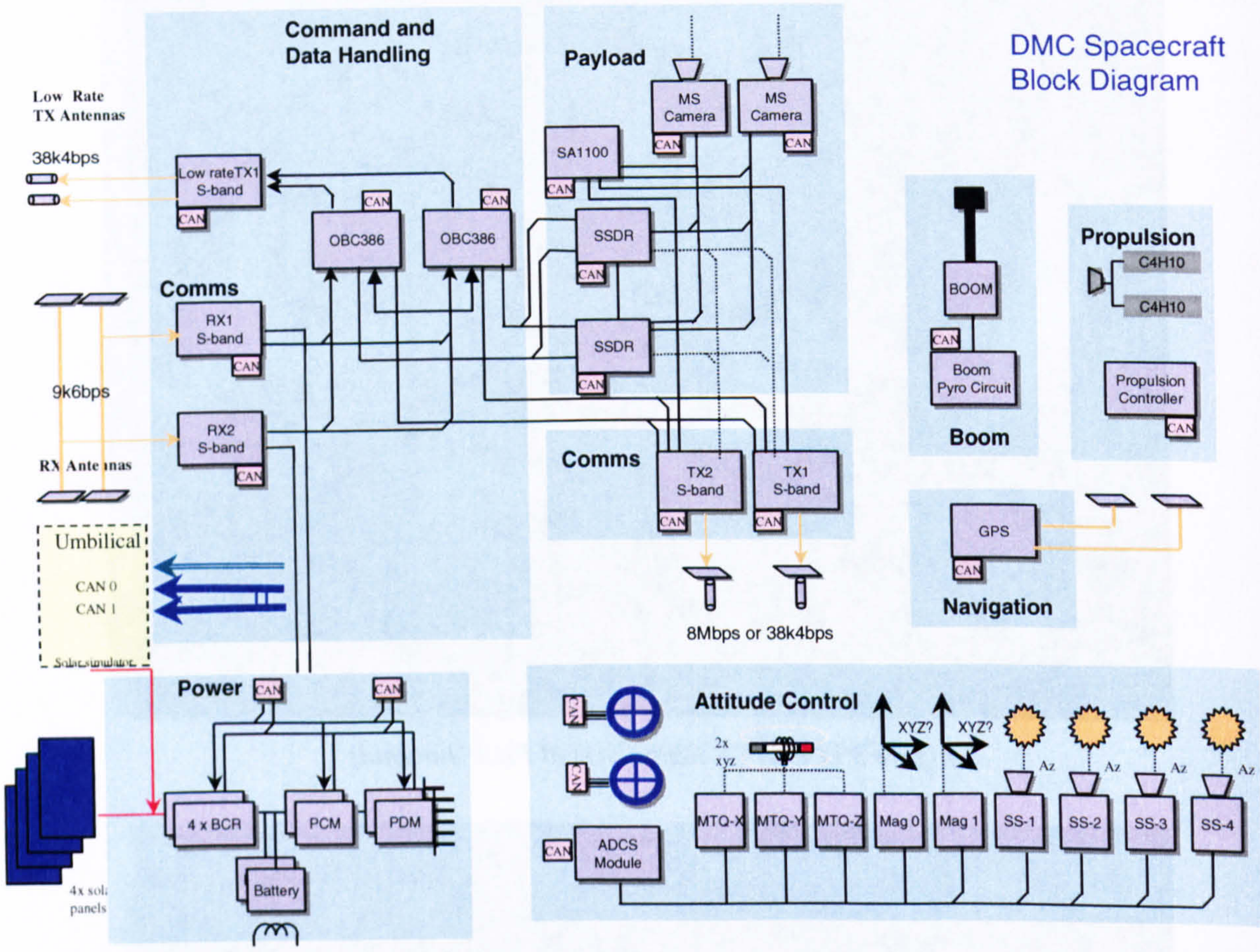

Figure 3.13 DMC Block Diagram at PDR

(note that the CAN buses 0 and 1 provide communication links between units shown with a CAN node)

A choice was made to opt for a distributed telemetry and telecommand system via the CAN bus, rather than use the SSTL TTC module which had been used on past missions to gather telemetry and send commands via discrete lines. This was due to the fact that the majority of modules to be used on the spacecraft were heritage designs or modifications of heritage designs that already had CAN nodes included. Several modules were completely new designs (the SSDRs and SA-1100) and hence it was easy to include CAN nodes in these new designs. The adoption of a completely distributed CAN TTC system meant only one module redesign that would have otherwise been unnecessary (the gravity gradient boom firing module).

The power consumption of a TTC module was greater than that of the additional CAN nodes required for the new designs and the boom-firing module to allow a completely distributed TTC system. It was not considered a serious option to redesign the other heritage modules to remove the CAN nodes (and hence their power consumption contribution) and implement discrete telemetry lines, due to the large cost, risk and schedule impacts. Hence a distributed architecture was the most favourable option in terms of power, as well as redesign cost, risk and schedule impact. The distributed

architecture was also the most favourable in terms of mass and accommodation volume. Removal of the TTC module from the stack shortened the stack height, which reduced technical risk for the mechanical design.

A disadvantage of not using an SSTL TTC system was that there was no longer a permanently powered unit to collect temperature data at all times. This is discussed slightly more under "Analogue Data, Temperature Sensors", below. The additional capacity of spare analogue telemetry lines that might have been used for additional temperature sensors was also not available. This was discussed and considered to be an acceptable price.

Power

The power supplies available on the spacecraft are a 5V regulated bus and a 28V unregulated (26.4V – 34V), as described in Section 3.7.6.1.

Digital Data

Control Area Network (CAN)

The TTC system is a distributed system based on the CAN, as described in Section 3.7.6.3. A dual CAN bus is used for dual redundancy. A direct CAN independent uplink command route is provided, via a TTL link from the receiver to the power system. This would allow low level commanding (e.g. switching on and off of malfunctioning units) in the event that problems are experienced via the usual commanding routes.

High Speed Point-to-Point

LVDS is used for all high links. The high-speed links on the spacecraft include:

- data output from the camera to the SSDRs
- high rate data from the SSDRs to the High Rate Transmitters. The actual transmitter data rate is 8.1408Mbps but may be simply referred to at places in this thesis as the 8Mbps communications link (8.1408Mbps is a multiple of 38.4kbps, therefore allowing the capability to switch between the low heritage data rate and the high '8Mbps' data rate)

Low Speed Point-to-Point

TTL interfaces are used for most low speed point-to-point data transfer. This is primarily due to the heritage of existing equipment. All TTL links are opto-isolated.

There are several low speed point-to-point data transfer links that are LVDS:

- RX0 and 1 to PPC SSDRs and SA-1100 (uplinked commands and data destined for SSDRs or SA-1100)

The reason for this is that these links are newly designed anyway (whereas the TTL links listed above took advantage of existing design as far as possible). There is no particular reason why opto-isolated TTL could not be used for the RX-SSDR links.

However it was decided that new designs should use LVDS where possible for the following reasons:

- LVDS allows higher link speeds at a lower power consumption than opto-isolated TTL (although note, at low speeds (less than 1Mbit/s) LVDS actually draws more power than opto-isolated TTL)
- Due to its differential nature LVDS exhibits a higher level of noise immunity than opto-isolated TTL
- Due to its differential, low current nature, LVDS radiates less noise into the surrounding environment than opto-isolated TTL
- Due to its differential, low current nature, LVDS will exhibit the above characteristics across poorly twisted, badly matched cable. Where as opto-isolated TTL will radiate and pick up noise unless the cable is very well made

GPS Pulse Per Second

The GPS pulse per second is distributed using 4 TTL links and one LVDS link. This is simply due to the fact that these were the available types of link on the heritage GPS unit. The two OBCs already had the facility to receive a TTL PPS signal. Hence the PPS links were allocated as follows:

OBC386	(TTL)
OBC186	(TTL)
PPC SSDR0	(TTL)
PPC SSDR1	(TTL)
SA-1100	(LVDS)

Analogue data

Temperature Sensors

All units on the spacecraft provide their own temperature sensors and read these themselves, for distribution over the CAN. This is with the exception of the propulsion controller which actually has its temperature sensor read by the ADCS module (due simply to the availability of lines to read the temperature sensors).

However, as all units read their own temperatures this means that temperature information for these units is only available when the unit is powered on. This is not considered to be a big problem, although operational procedures should be considered to minimise the possibility of switching on a sub-system if at either too high or too low a temperature. However, one issue is that the data available on the ground for trend analysis of spacecraft temperatures is not likely to be gathered at a continuously predictable steady interval.

At one point there was a suggestion to include a permanently powered CAN node dedicated to reading temperature sensors. However, as each module could provide its own temperature sensor readings when switched on, plus the ADCS module (which is generally permanently powered on) could provide temperature sensor reading for a number of other lines, this was decided against so as to save spending unnecessary power, or overcomplicating the design of any module and also the harness.

The ADCS module provides the option of reading up to 5 analogue lines (typically temperature sensors). The spacecraft thermal engineer selected to use four of these to read sensors placed at points around the spacecraft and hence provide reliable temperature telemetry data for trend analysis on the ground.

Data Umbilical Interface

The spacecraft data umbilical interface is used during Assembly, Integration and Test to provide a data path to and from the spacecraft independent of the RF link. The umbilical carries:

LRTX Data
HRTX0 Data
HRTX1 Data
12V Supply
GPS Pulse Per Second
Primary CAN
Secondary CAN

When deciding on the umbilical functionality the prospect of adding a line to allow the high rate data downlink from the SSDR to be sent via the umbilical as well as via the HRTX was considered. This was decided against as it was considered that in order to be able to test anything more than one could test on the bench, one needed the High Rate Transmitter in the path anyway. The benefit of not including such a line in the umbilical is simply that it reduces the harnessing complexity (note the SSDR harness connections are extremely dense).

Spacecraft Isolation and Grounding Policy

The spacecraft isolation and grounding policy was decided after a series of meetings discussing the risk of EMC interference issues and also any implications for unit redesign and unit power consumption.

The easiest way to minimise the possibility of EMC problems occurring during AIT is to isolate everything using opto-isolated data links and also isolated power supplies (and hence individual DC-DC converters for all units). However, this has two main disadvantages:

- High (and possibly wasteful) Power Consumption
- May require redesign of a module (e.g. adding a DC-DC converter/opto-isolators) if not already isolated

Hence, the sensitivity of each module to EMC, as well as their potential contribution to EMC problems, was considered in discussions alongside the power consumption and re-design implications for each module.

3.7.11. Spacecraft Solution at CDR

Figure 3.14 to Figure 3.19 illustrate the physical configuration of the DMC spacecraft design as at the CDR stage of the project (as before, all 3D spacecraft drawings are courtesy of the SSTL mechanical Design Office).

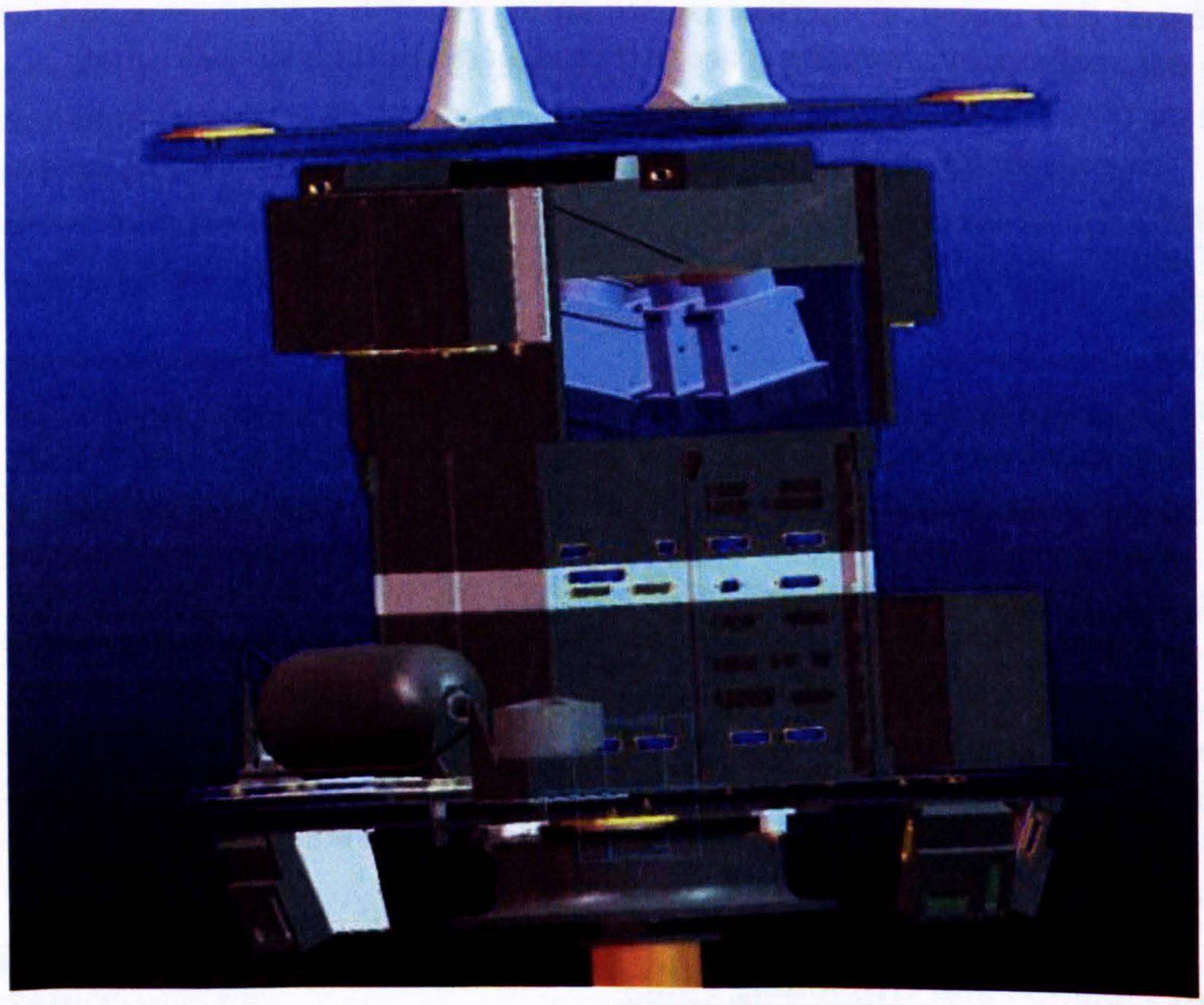

Figure 3.14 DMC Satellite Internal Physical Configuration at CDR – View 1

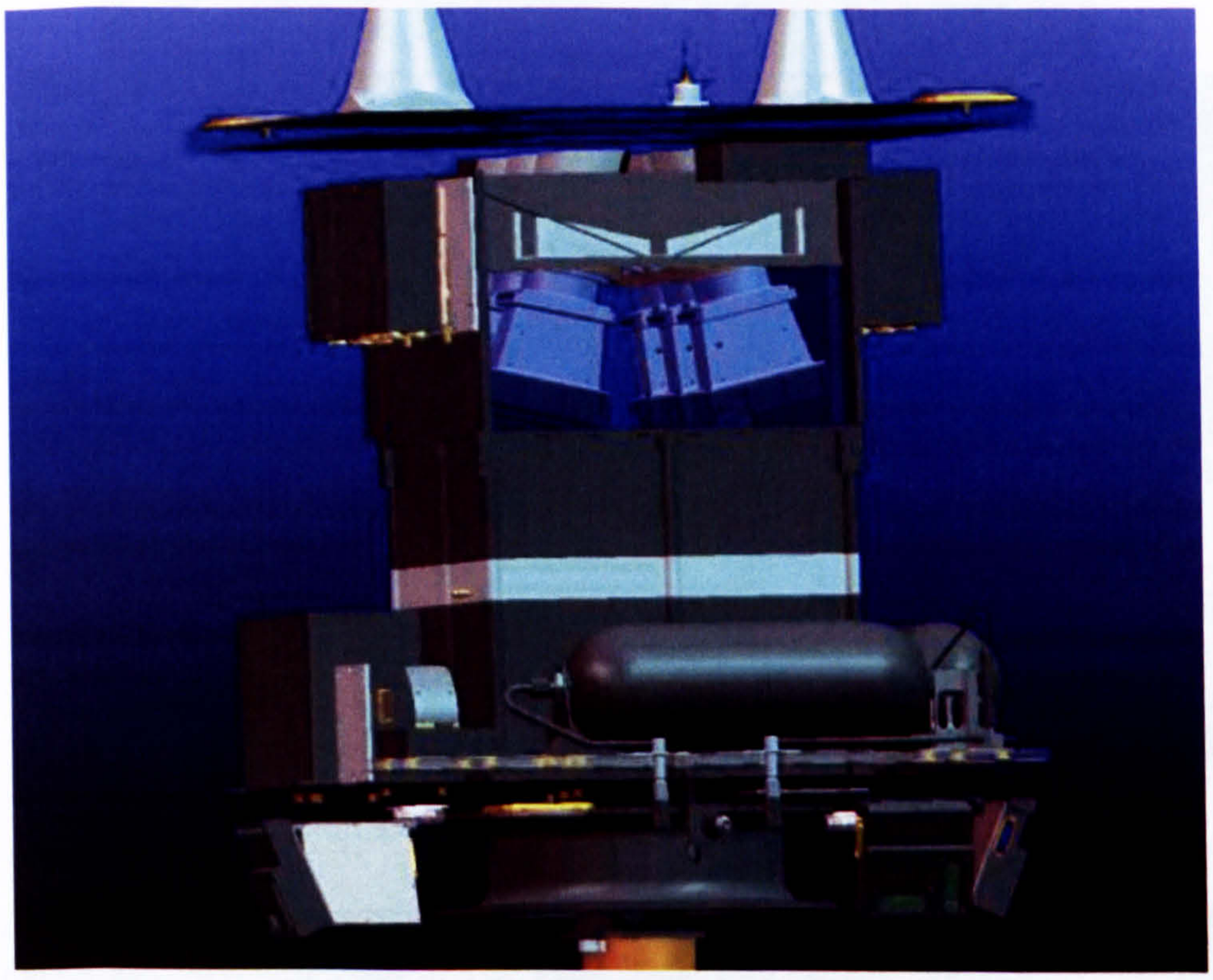

Figure 3.15 DMC Satellite Internal Physical Configuration at CDR – View 2

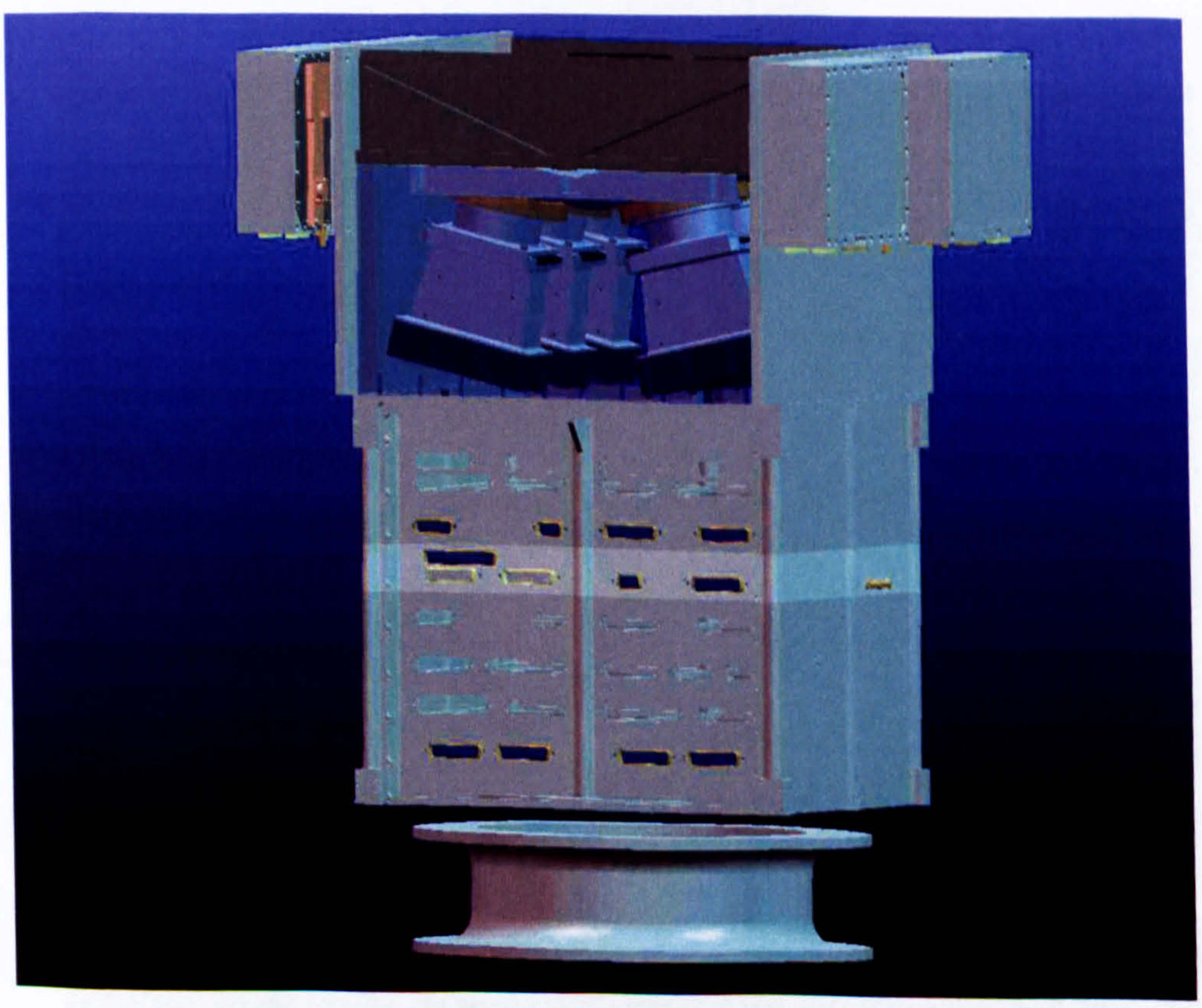

Figure 3.16 Stack Configuration at CDR

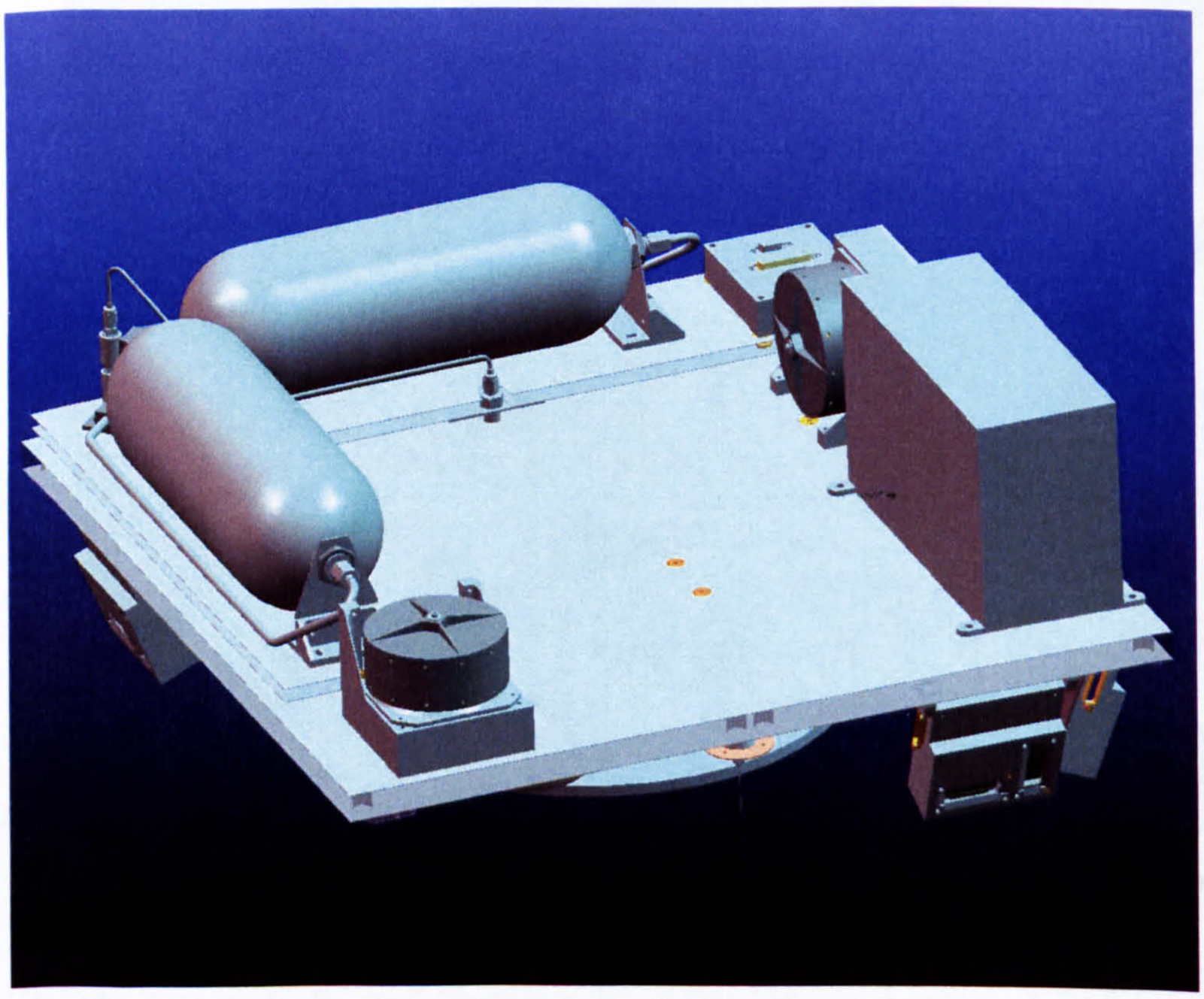

Figure 3.17 Space Facing Facet at CDR (Internal)

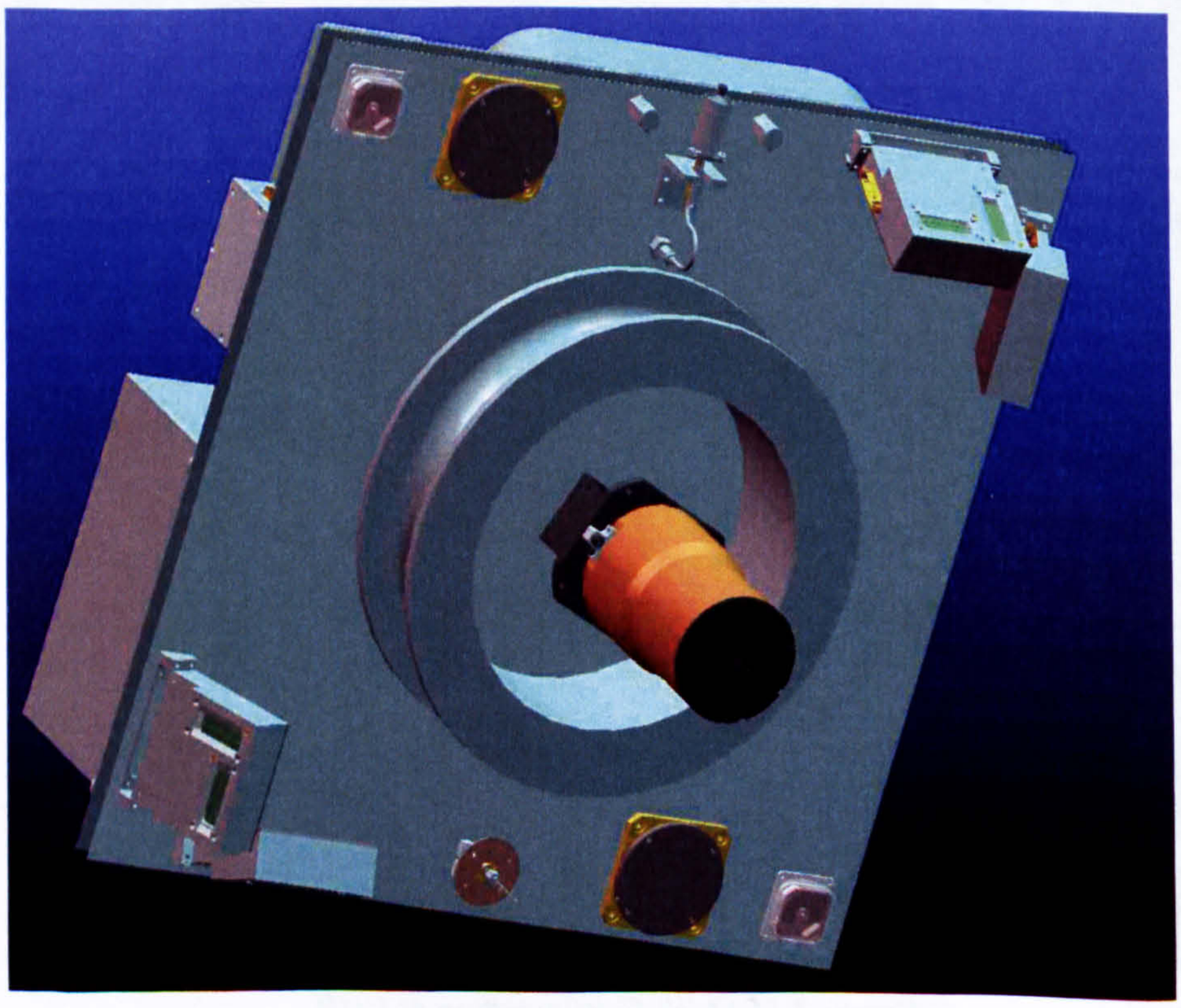

Figure 3.18 Space Facing Facet at CDR (External)

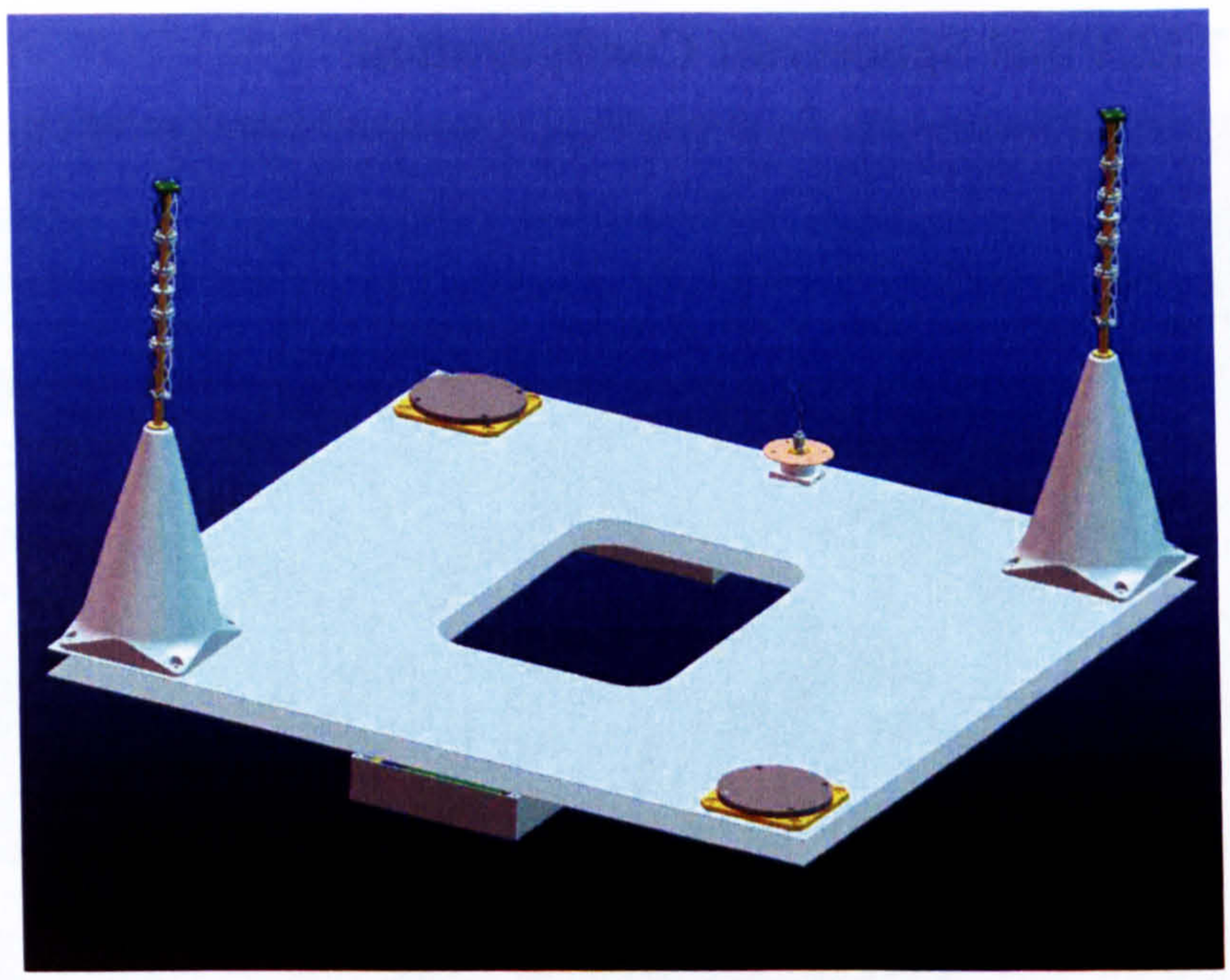

Figure 3.19 Earth Facing Facet at CDR (External)

Figure 3.20 illustrates the design of the electrical configuration of the DMC satellite as at the CDR stage of the project.

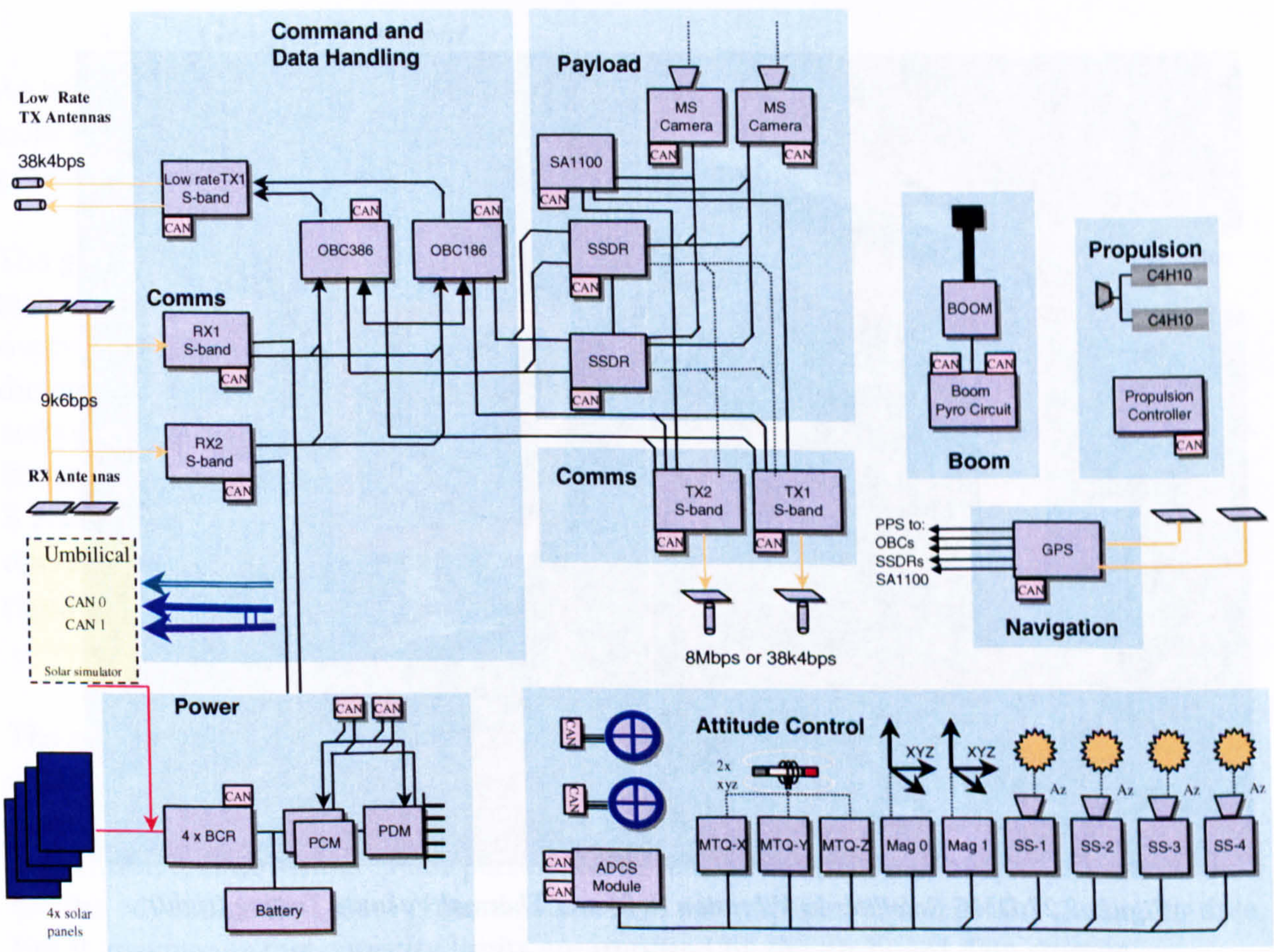

Figure 3.20 DMC Block Diagram at CDR

(note that the CAN buses 0 and 1 provide communication links between units shown with a CAN node)

3.7.12. Final Spacecraft Configuration

Figure 3.21 to Figure 3.23 show the final physical spacecraft configuration.

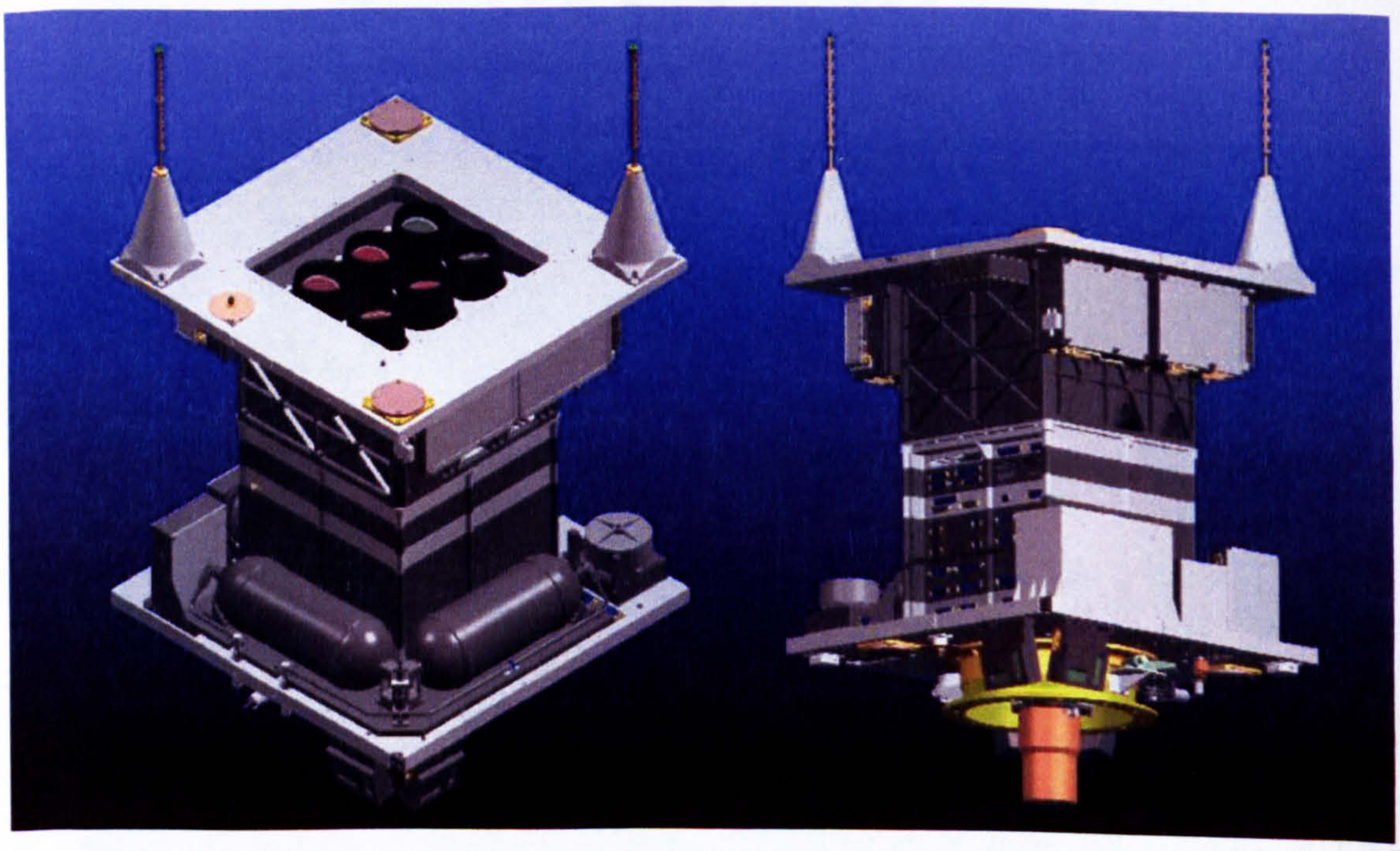

Figure 3.21 Illustrations of final DMC Spacecraft Configuration

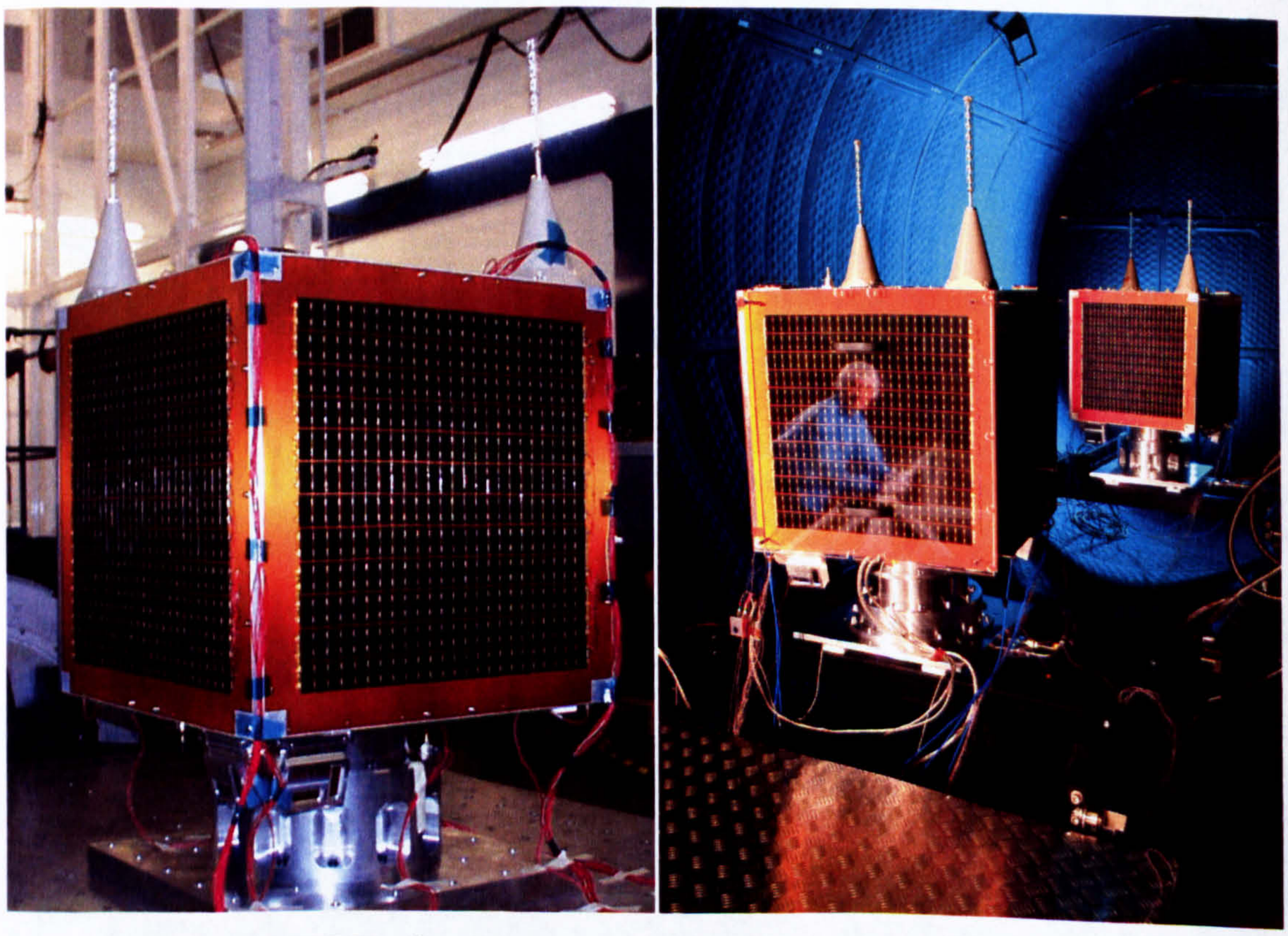

Figure 3.22 DMC Satellites in Vibration (left) and Thermal Vacuum Testing (right)

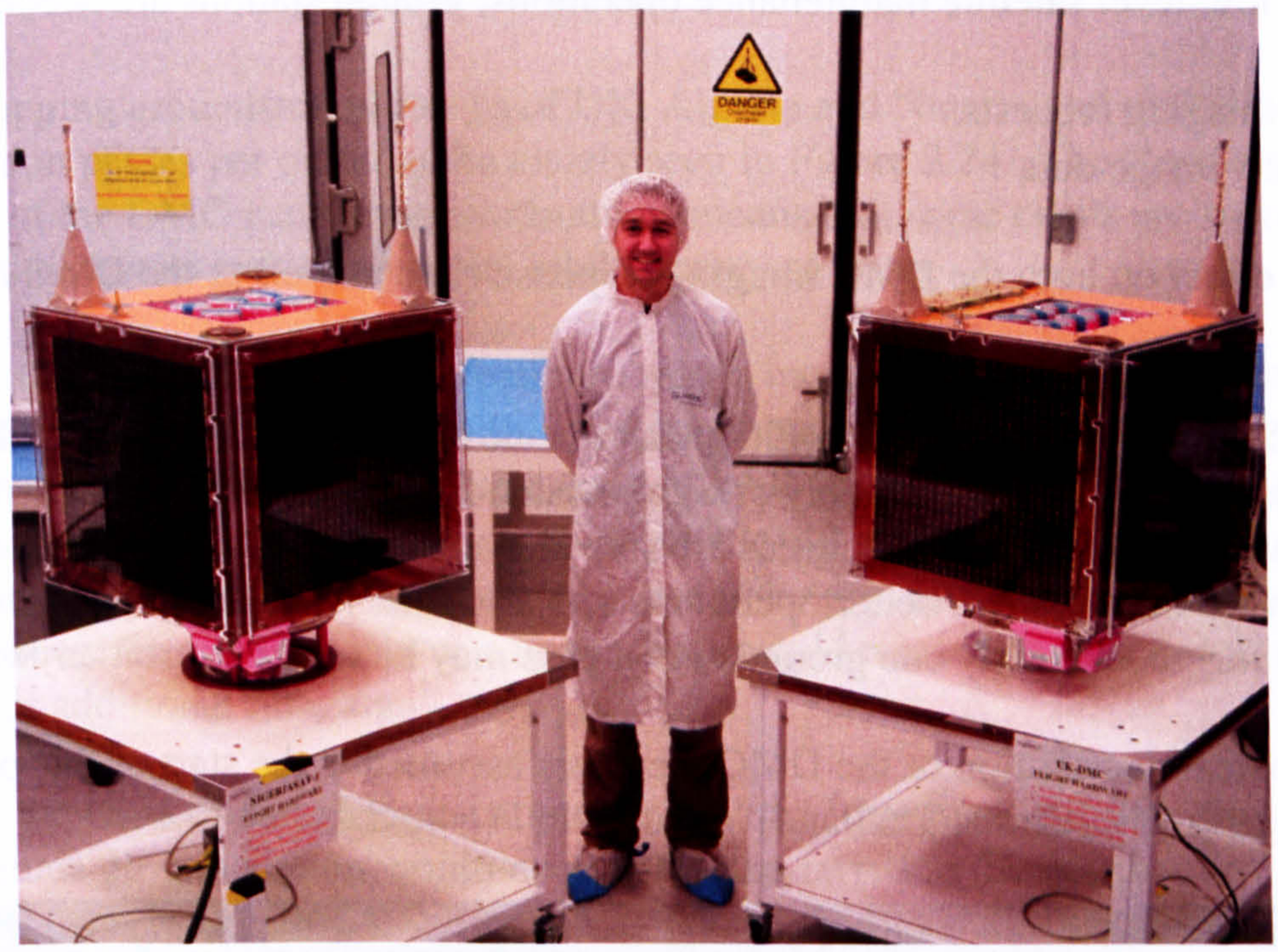

Figure 3.23 The author with UK-DMC and Nigeriasat-1

3.8. Ground Segment

As briefly described in Section 3.1, it is the responsibility of the author to ensure that all technical elements of the mission are appropriately addressed. There are a number of ground segment elements. These are briefly described in the following sub-sections.

The ground segment elements are not presented here in detail as part of the thesis. The task of the author as the mission systems engineer was simply to keep the top-level overview, ensuring that the elements tied together to meet (evolving) mission aims as dictated by SSTL marketing and the DMC consortium. As with the space segment the author inevitably became involved in the details of the various ground segment elements to varying degrees, and it is not practicable to 'detail' all work performed in this report. It is hoped, however, that the following descriptions will help to clarify the DMC operations and ground segment concept and illustrate the technical feasibility of the rapid response DMC mission and the ability to serve users in various locations.

3.8.1. Ground Station locations and performance implications

The operations concept for the DMC involves imaging discrete areas, as requested by command from the ground. These images are then stored in the on-board memory and downlinked to the ground when in view of a DMC groundstation. Hence the image acquisition and downlink is not performed in real time. This Store and Forward method has the advantage that local groundstations are not required to image any particular area. But it also means that capacity limits are imposed by the on-board data storage capability and downlink opportunities to DMC groundstations.

The distribution of groundstations has an impact on the DMC mission in several ways. Aside from low-level satellite maintenance operations, ground stations are needed to;

- Upload imaging requests
- Download image data

This has an effect on both the DMC imaging response time as well as the DMC imaging capacity.

The power constraints of a DMC satellite mean that downlink time using the high rate transmitter is limited to approximately one groundstation pass per orbit. Hence if the satellite groundstation pass opportunities are spread evenly throughout the spacecraft's day then this would provide a better operations scenario than if the pass opportunities are bunched together, as only one groundstation pass may be used per orbit anyway.

The geographical distribution of the DMC members assumed at the start of this project (Algeria, Nigeria, UK, China, Thailand) is shown in Figure 3.24.

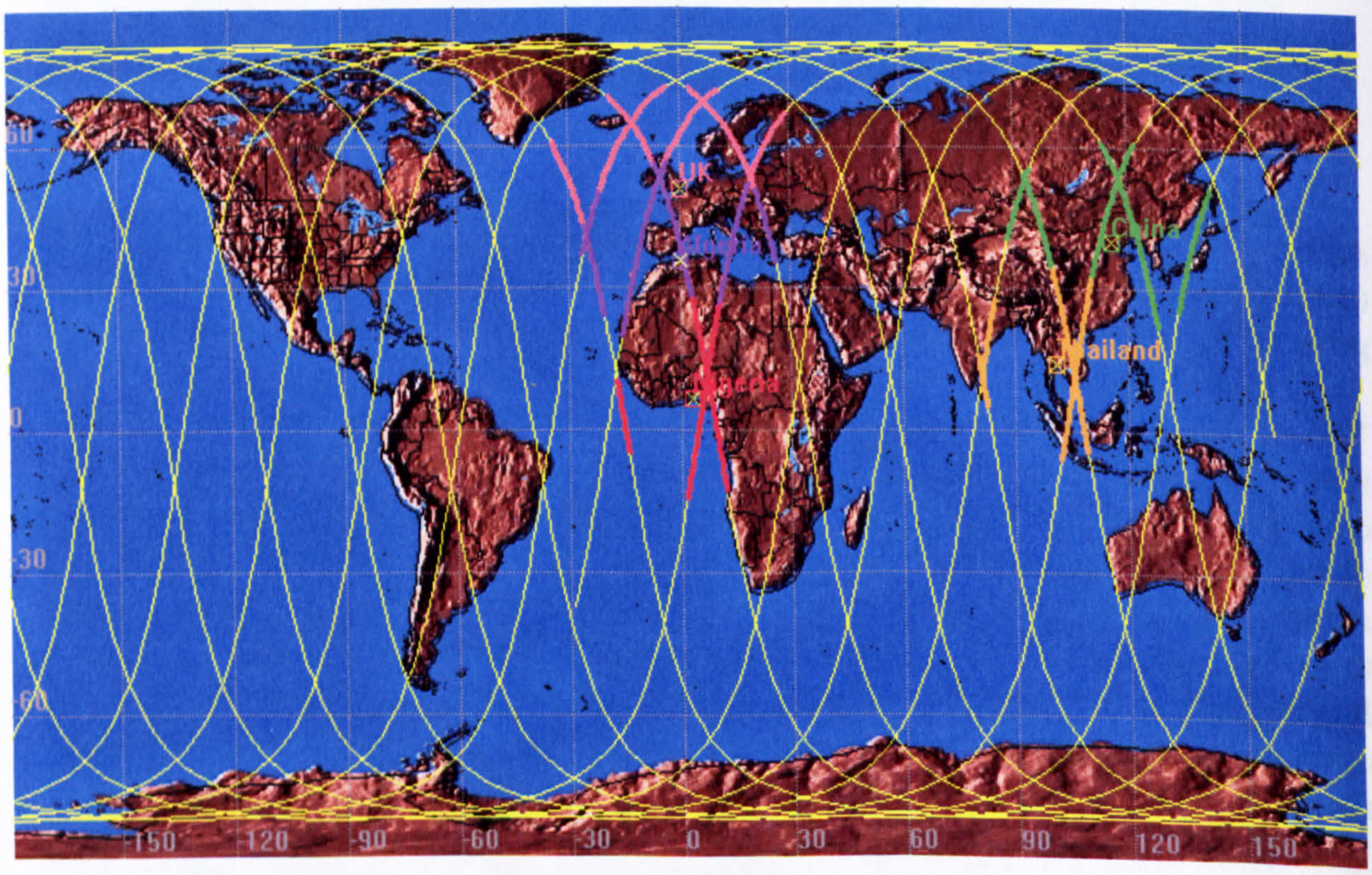

Figure 3.24 DMC Member Groundstation Distribution
The orbit tracks are shown with a light yellow line and the ground station accesses are shown in thick lines coloured by groundstation (Algeria - Purple, Nigeria - Red, UK - Pink, China - Green, Thailand - Orange).

Since this time, various contractual delays have meant that UK-DMC, Nigeriasat-1 and Alsat-1 have launched but the Chinese and Thai spacecraft are yet to be launched and there are no DMC ground facilities in these countries at the time of writing this thesis. However, a Turkish satellite, BILSAT-1, was built by SSTL and launched on the 2nd DMC launch as an associate DMC member. A DMC compatible ground-station is now

present in Turkey and is being integrated into the DMC ground networked infrastructure.

The overlapping groundstation masks of UK, Algeria and Nigeria and multiple groundstation passes per orbit can be clearly seen in Figure 3.24. The close longitudinal proximity of the DMC member groundstations means that some orbits see more than one communications pass opportunity whilst some see none.

A high latitude groundstation, e.g. Svalbard would increase the communications opportunities per day, with the possibility of commanding the satellite, or downlinking data, on every orbit. This would give a more reliable imaging response time (with a guaranteed chance to command an image acquisition at least once every orbit) and would increase the constellation potential capacity by providing downlink opportunities on orbits where there previously was none. This would release on-board storage capacity for additional imaging.

However, the issue of data dissemination must not be forgotten. All data downlinked to a high latitude ground-station would need to be transferred to the destination archive/user. The feasibility and cost of this should be considered if serious consideration is to be given to the use of high latitude ground-stations in the future.

3.8.2. Ground Segment Architecture

At the time of writing this thesis the DMC ground segment comprises facilities in four separate countries; UK, Algeria, Nigeria and Turkey. These are the DMC countries with DMC satellites in orbit (with Turkey being an associate member with a non-DMC type satellite). A Chinese DMC spacecraft will be joining the constellation in 2005 at which point additional constellation ground resources may be available in China.

The ground segment in each country currently supports their respective spacecraft as part of an independent stand-alone national mission. However, current plans are underway to implement a ground segment suitable for proof-of-concept for the DMC as a collaborative mission. Current plans are that, when complete, the ground segment in each DMC member country will comprise:

- Command and Receive Groundstation, including Antenna
- Data Archive and Catalogue software
- Image Processing Software
- Mission Planning System

In addition, constellation orbit management software will reside in the groundstation at SSTL.

The ground segment facilities in each member country are connected via the internet. This is to allow sharing of groundstation resources for satellite command and control, and payload downlink, as well as catalogue co-ordination and transfer of selected payload image data between different archives.

Figure 3.25 illustrates the ground segment architecture.

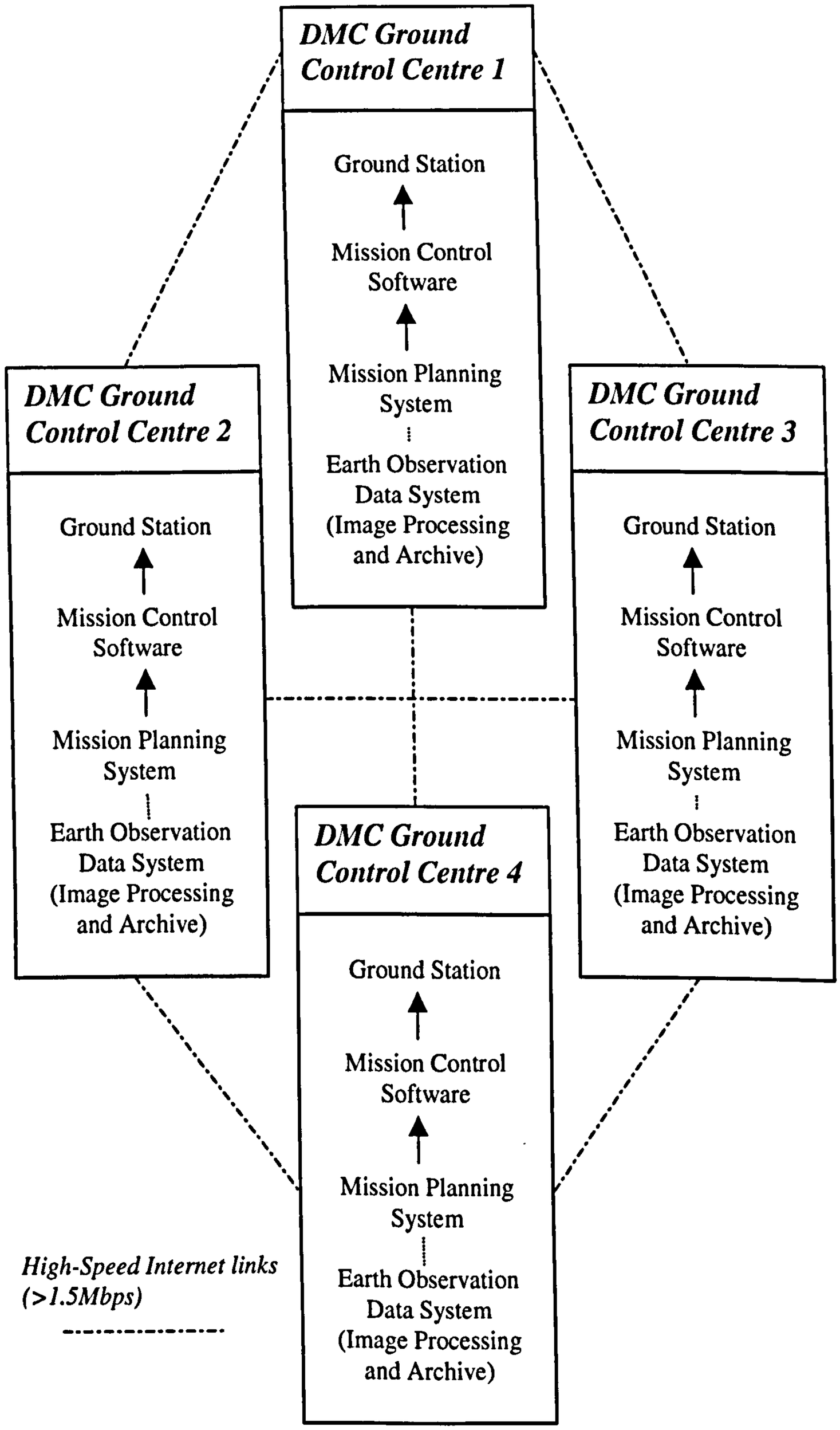

Figure 3.25 DMC Ground Segment Architecture
(The groundstations are functionally identical with the exception of the Constellation (Orbit) Management software which resides only in the SSTL groundstation)

3.8.3. Data Processing

DMC image processing software has been developed by SSTL to perform basic image processing on the raw data received from the spacecraft.

This software processes DMC data to a point where DMC image files can be usefully imported into a COTS software GIS or remote sensing product. Any further processing or value adding is then down to the user for individual applications.

3.8.4. Data Archiving

Each member mission of the DMC has the ability to archive its own imagery. Imagery can then be transferred and shared among the DMC members as required via the internet.

The archive solution essentially comprises hardware for data storage (e.g. tape library) and software for data catalogue management.

A common database structure has been agreed for image catalogue software, giving each DMC member the technical freedom to tailor their catalogue user interface as they desire. The user interface to the catalogues and DMC image sharing mechanism is currently on-going work.

Now that the DMC satellites are launched, operating well and returning good imagery, DMC data policy is being discussed in earnest. The possibility of a shared centralised archive for all imagery designated 'DMC' imagery (as opposed to private 'national' imagery) is also under consideration.

Of course this has implications for network bandwidth requirements as 'all' DMC images would need to be transferred to the central archive. A distributed archive would mean that only images needing to be transferred were those downloaded to a groundstation which does not hold the final destination archive.

The technical solution to collaborative operations, and data archiving and data sharing on the ground, is of course intertwined with the chosen Data Policy solution. This is currently on-going work. Now that data policy issues are being fully discussed and the customer needs in this area are being properly assessed, the preferred solution for this is expected to become clearer in the coming months.

3.8.5. Data Dissemination

Once an image has been acquired and downloaded to the relevant ground-station it also has to be disseminated to the end-user. The definition of end-users is discussed in more detail in Chapter 5.

Data distribution is mainly to be performed via Internet. In certain circumstances images may be written to CD or DVD and distributed via courier or post. However, any rapid-response applications will require a good Internet connection.

Images are composed of a number of image 'tiles', with each image tile (~80km x 80km) being approximately 19Mbyte in size. A large image e.g. 24 tiles, will occupy nearly 0.5Gbyte of memory. Transfer of such a file would not pose a problem for a good internet connection, e.g. 1.5Mbps would transfer the file in 5 to 6 minutes. However, with a 56kbps modem, such an image would take in the region of 2.5 hours to transfer (assuming a constant 56kbps transfer rate which is likely to be over-optimistic).

Each spacecraft in the constellation should be capable of imaging in excess of 100 tiles/ day downloaded to the various groundstations. Assuming an even split between groundstations, the data received by each groundstation during the day would be in excess of 2Gbytes/day. Referring to figures in the above paragraph, we can see that such an amount of data could be easily transferred from site to site assuming a high speed (e.g. 1.5Mbps) connection, but would be difficult with a slow and/or unreliable internet connection.

An outlet for Disaster imagery is to be provided by the Reuter's Foundation[1] via their Alertnet website. This website provides a service to the relief community as described in Section 2.1. Disaster images requested by AlertNet are to be downlinked to the Guildford groundstation and transferred via internet to the service provider for the AlertNet website. These will then go through a value adding process as deemed appropriate by the AlertNet service provider before being posted to the AlertNet site for use by the disaster relief community. In this case, the Guildford groundstation–AlertNet service provider internet link is good and reliable. The internet link that serves the various user communities that access the AlertNet service will be variable. The AlertNet service provider considers this in trying to distil and convey information from the imagery provided by the DMC.

A possible additional outlet for DMC imagery for disaster application is via the International Charter. Discussions are on-going regarding possible collaboration of the DMC with this international initiative. In the event this collaboration does go-ahead, it is envisaged that DMC data will be distributed to the Charter project manager, or service provider, for any given image request via internet. Value adding and use of the image data would then be performed by the service provider and the resulting product distributed to the end-user in the most appropriate way (as established by the project manager within the International Charter for that particular event).

The above illustrates several examples of DMC data dissemination. It must be recognised that rapid response imagery requires the image data user[2] to have a good internet connection.

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[1] The Reuters Foundation is a registered charity, primarily but not entirely funded by Reuters Limited. The priorities of the charity are the advancement of education, humanitarian aid and the environment, focussing in particular on areas where Reuters skills and expertise in news and information services can be put to use. [19]

[2] Note that the DMC image data user is not necessarily the end-user of the resulting product. For example, an event project manager in the International Charter may receive and use DMC image data to produce a product. This may be an image file, a paper map, or simply information that is then distributed by whatever means to the end-user.

It is acknowledged that for a number of users this may be a barrier to use of the DMC data.

An alternative approach is that taken by the NOAA with AVHRR data. In this case users may make a one-off investment in an affordable receiver station (LARST - Local Application of Remote Sensing Techniques) and could then rely on receiving imagery each day as desired. This is because the satellite would be continuously imaging the ground below and transmitting the data to the ground.

However, power constraints, bandwidth limitations, frequency regulation limitations, as well as ground station cost mean that this is not feasible for this generation of DMC satellites and this operations concept was not seriously considered from the start. This concept has however, been considered for other proposed constellation concepts in the past [54].

Whilst the LARST/AVHRR approach certainly has an advantage it is not expected that the need for a good internet connection will cause a technical barrier to the uptake of DMC imagery.

If users are able and willing to invest in a receive ground-station then it is considered reasonable to assume that they should be able to invest in a decent internet connection. The issue may be less technical than it is political and commercial. If a project can make a case for funding and acquire a LARST transmitter, for example, then it is almost guaranteed to have access to AVHRR data throughout the lifetime of its project. However, if a project has to make new requests for DMC data as it progresses throughout the project then this may cause issues, particularly if funding for the data acquisition is obtained as the project progresses rather than as an up-front agreement. The more links in the chain in any given project, the more chance there is of the project plug being pulled at any point in time. This is a concern pointed out by an experienced AVHRR data user [55].

This is a point to be taken on-board and efforts made to understand and address the barriers to uptake of the DMC imagery. It is not necessarily enough to simply make the technology available and expect users to use it. This point is discussed a little further in Chapter 5.

3.9. Summary

This chapter has explained the technical role of the author in the DMC mission and has given an overview of the System Design for the DMC spacecraft and ground segment. The next chapter overviews the mission analysis activities of the project which should be read in conjunction with this Chapter for a fuller understanding of the design.

4. DMC Mission Analysis

Decisions made during the satellite and mission system design described in Chapter 3 must be based on appropriate mission analysis. This section describes various core aspects of mission analysis performed during the course of this project.

4.1. Concept

The mission concept has already been described in Section 1.1 as involving a constellation of satellites, equi-spaced in the same orbit to provide global daily coverage. Figure 4.1 and Figure 4.2 illustrates the swath of a single DMC satellite.

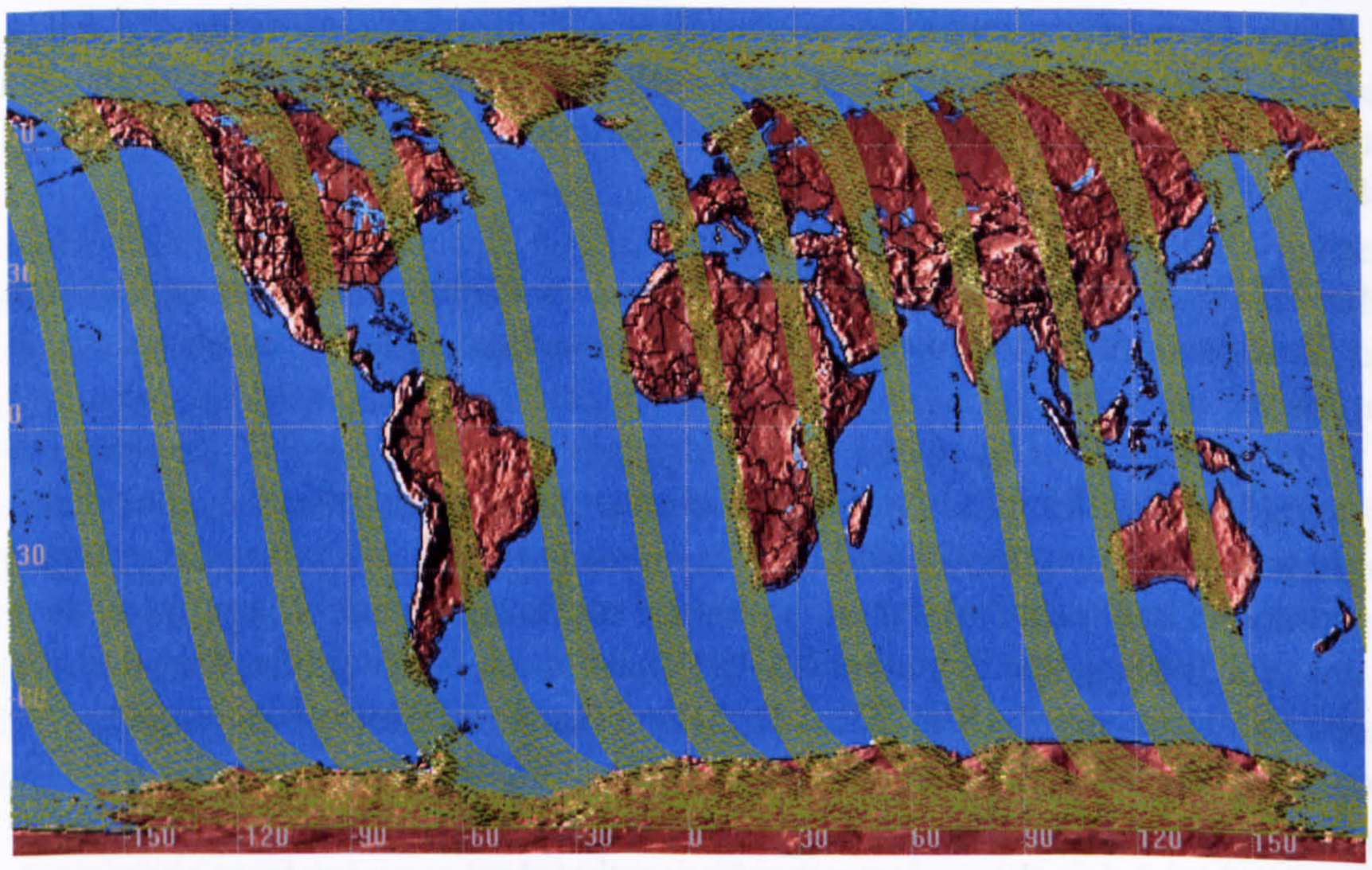

Figure 4.1 Single DMC Satellite – Daily Swath Coverage 1

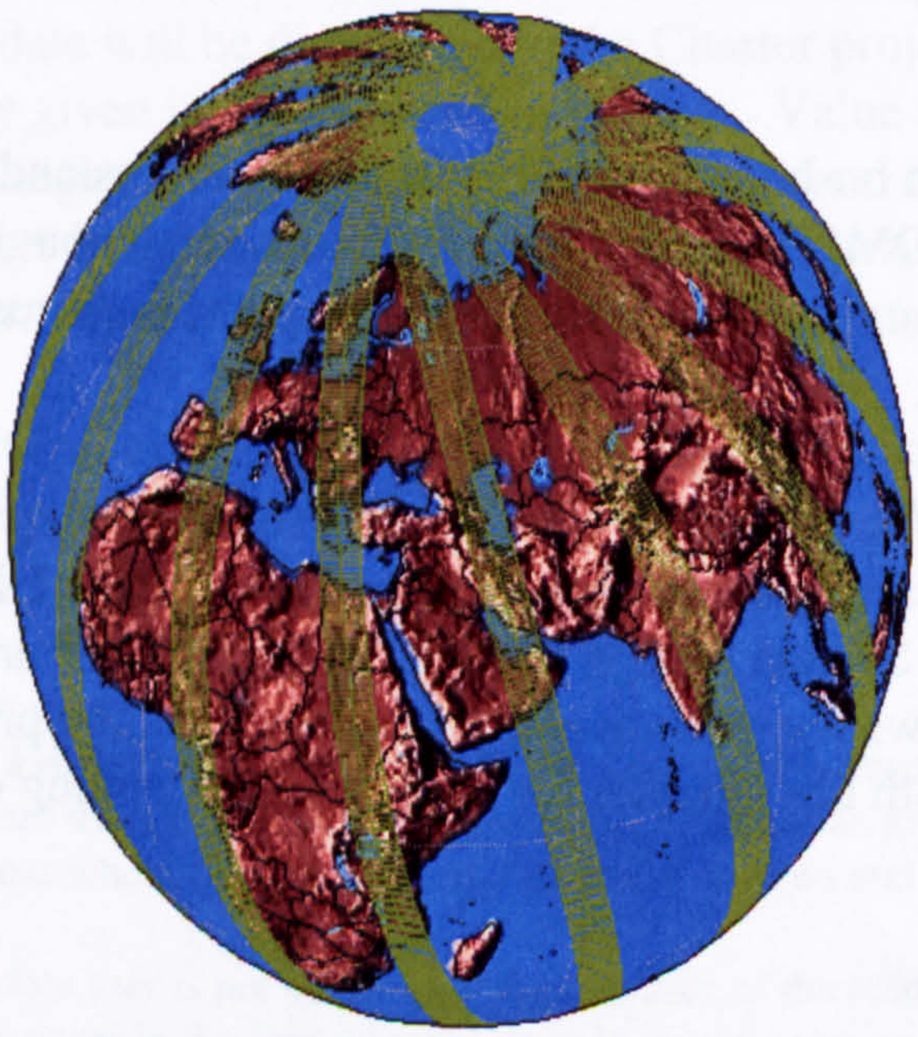

Figure 4.2 Single DMC Satellite – Daily Swath Coverage 2

With five satellites equi-spaced in the same orbit, the satellite ground tracks will also be equi-spaced. If the imaging swaths of the satellite sensors are wide enough then there will be no gaps in daily coverage at the equator.

The swath width is dependent primarily on the number of satellites in the constellation.

Station keeping errors and attitude control errors, are additional factors that need to be taken into account and margins need to be added onto the swath requirement to account for these.

4.2. Launch

The original proposal for the DMC constellation was that of launching all 5 spacecraft on a dedicated launcher to a sun-synchronous orbit.

In the early stage of the design, five launchers were short-listed as the main potential candidates for a single dedicated DMC launch, and also possibly secondary launches in the event of a change of launch strategy:

- Dnepr (considered the most likely and assumed as the baseline)
- Cosmos
- Long-March 2C
- Eurockot
- Strela

There are a number of considerations when choosing a launcher, both technical and commercial. For example:

- Cost
- Politics (for example, a Chinese institution is a DMC member and China has a national launch vehicle included in the list above. If contract timings had worked differently this might have been an influential factor in the launch vehicle choice)
- Commercial considerations (for example, occasions may arise where launch costs may be negotiated against the supply of a satellite if the launch provider is interested in satellite ownership)
- Reliability (e.g. with a proven track record)
- The availability and quality of launch campaign facilities
- Ability to launch to the desired orbit (mass capacity)
- Ability to launch to the desired orbit (regulatory –for example not all launchers listed above were able guarantee the approval to follow a flight path to give a sun-synchronous orbit (due to the need to drop rocket stages in other countries during the launch).
- Vibration and acoustic environment (want to minimise)
- Fairing accommodation envelope (want to maximise)
- Orbit injection errors (want to minimise)

If designing for secondary launches, prospective availability of regular launch opportunities is another major factor. Whilst the DMC baseline was to launch on a dedicated launcher the option of secondary launches was also kept in mind.

In the early stages of a project when design decisions are still yet to be made, the non-technical drivers of launcher selection dominate and the technical characteristics of commercially suitable launch vehicles may influence the design. However, the associated cost, risk and schedule impact of any particular technical requirement imposed by a launch vehicle should be considered. Hence the list of launch vehicles that are 'commercially' suitable may be whittled down due to 'technical' non-suitability.

For example, the satellite structure was to be designed to be compatible with as many of the five listed launchers as possible, but with the option to leave out any 'outliers' if they presented particular design difficulties, such as a particularly difficult vibration specification that significantly differed from the other listed launchers.

COSMOS and Dnepr were considered the two most likely launchers from a non-technical standpoint. Dnepr was considered the most likely and was adopted as the baseline launcher.

Injection error probabilities are given in Appendix D for Dnepr and COSMOS.

4.3. Orbit Analysis

4.3.1. Orbit Selection

There are a number of factors that need to be taken into account when choosing the orbit for a mission. The main factors and their main effect on the DMC mission are summarised in Table 4.1.

In addition, the long-term orbit perturbations need to be taken into consideration. The initial combination of orbit altitude and inclination was given particular attention in order to get the desired sun-synchronicity throughout the mission lifetime for the DMC.

Factor to consider	Effect on DMC mission
Sun-synchronous vs. Non sun-synchronous	Power profile variation Imaging illumination variation Thermal variation
Altitude	Propulsion requirements Link budget Ground Sample Distance • Imager Data Rate and clocking frequency • Image volume and storage requirements • ADCS pointing requirements Repeat ground track potential
Local Time of Ascending Node (Time)	Power profile Image illumination Cloud Cover
Local Time of Ascending Node (a.m. or p.m.)	Imaging Ground Track Geometry Timing of ground station passes in eclipse Timing of ground station passes in a working day
Eccentricity	GSD variation throughout orbit Variation in spacecraft relative spacing throughout orbit

Table 4.1 Factors in Orbit Selection for the DMC Mission

The launch target for the first DMC launch was chosen as:

Altitude	686km
Inclination	98.23°
Eccentricity	Zero
LTAN	10:00am

This combination of altitude and inclination provides a 'near' sun-synchronous orbit with a LTAN that is predicted to vary between 10:00am and 10:20am during the 5-year target mission lifetime, without the need for expensive altitude or inclination maintenance manoeuvres.

4.3.2. Delta-V Budget

The Delta-V budget for the DMC mission has changed throughout the mission development. The original estimate made for the pre-feasibility study was 7m/s. This then rose to 10m/s, which was the starting figure when the author took up this DMC project.

At this time, the expectation was, as mentioned in Section 4.2, to launch all five DMC satellites on a single launch. The breakdown of manoeuvres accounted for in the 10m/s budget are described in Table 4.2.

Manoeuvre Name	When	Meaning	Why
Circularisation (4m/s)	LEOP	To remove, as far as possible, eccentricity/altitude launcher injection errors	Eccentricity means that the spacecraft will bunch together slightly at certain parts of the orbit and disperse at others. However, this should not be a strong effect and should have minimal implication on e.g. station keeping operations. Eccentricity would increase altitude variations and hence imaging GSD variation throughout the orbit. Again this should be a small effect. If the semi-major axis can be controlled accurately enough then a repeat orbit may be acquired, which may allow easier operations planning.
Station Acquisition (1m/s)	LEOP	To manoeuvre the spacecraft from the singular starting point to being equispaced (within certain accuracy limits) throughout the orbit. For 5 satellites this means 72° spacing between satellites.	The spacecraft need to be equally spaced (within certain accuracy limits) so that the imaging swath on the ground at the equator is adjacent to the preceding spacecraft in the constellation. With the right swath width and number of spacecraft this will provide Daily Global Coverage for imaging revisit.
Station Keeping (4m/s)	Throughout the mission after LEOP	To maintain the correct inter-satellite spacing throughout the mission	To maintain imaging coverage as described above for Station Acquisition.
Margin (1m/s)	**Total = 10m/s**		

Table 4.2 Baseline Manoeuvres for the DMC Mission

4.3.3. Multiple-launch Orbit Analysis and Revised Delta-V budget

Delays in funding and contract kick-off for the individual missions that comprise the DMC eventually became so significant that alternative options were considered for the launch strategy.

The circularisation, station acquisition, and station keeping strategy described above were all re-evaluated, along with any other potential requirements that may arise from a multiple launch solution. If a multiple launch solution were feasible it would allow the

first DMC satellite to be launched and used by the customer, without needing to wait almost a year before others were ready.

In this instance, as the satellite solution had already been designed, the question was not so much 'How much DeltaV do we require?' but 'What can we do with the DeltaV that we have, and is it acceptable?'. Table 4.3 illustrates the evolution of the Delta-V budget to this point. If one follows the arrows in the table one can see:

- starting with the single launch scenario to arrive at a requirement of 10m/s
- producing a propulsion solution with an expected performance of 12.6m/s
- and allocating the expected 12.6m/s to meet station acquisition and station keeping requirements, leaving 7.3m/s available for injection error correction

Propulsive Manoeuvre	Baseline dV est. (m/s) (Single Launch)	Comment	Revised dV (m/s) (Multiple Launch)	Comment
Injection Correction	4	Circularisation	7.3	Semi-major axis & inclination
Orbit Phasing	1	Est. ~ 9 - 10 weeks	1	Time TBD (Dependent on phasing strategy)
Orbit Phase Maintenance	4		3	Estimate 2 m/s - as DMC launch in solar min. Extra 1 m/s to account for uncertainty in atmospheric density
Margin	1		1.3	E.g. finite burn losses
Total	10		**12.6**	Propulsion system performance may exceed this, dependent on a number of factors

Table 4.3 DeltaV allocation: Single launch vs. Multiple launch

An analysis was then performed to evaluate the suitability of a multiple launch solution, using either a Dnepr or COSMOS, based on a 7.3m/s potential for launch injection error correction.

Appendix E gives further details on this, but the conclusion was that a multiple launch was a satisfactory way forward. COSMOS was the chosen launcher. The probability of having fully correctable altitude and inclination launch errors was estimated to be better than 97.5%.

4.3.4. Station-Keeping Strategy

The station keeping strategy initially budgeted for in the Delta-V budget involved altitude maintenance. Theoretically, if all satellites have the same semi-major axis, and hence same orbital period they will maintain a fixed phase formation.

During the mission development, once it had been decided that a repeat orbit ground-track was not a requirement, the option of 'relative' orbit maintenance rather than 'absolute' orbit maintenance was also considered. This had the potential to save a significant amount of the station keeping propellant budget.

The author worked alongside the Astrodynamics group of Surrey Space Centre to produce a software solution to allow station-keeping to be performed. All software coding and many simulations were performed by the Astrodynamics group, with the author providing a top-level guidance in order to meet the mission needs.

The software produced allows the production of 'firetables' that allow the relative orbits and relative phasing between the satellites to be controlled. Hence it is used for injection correction, phase acquisition and phase maintenance throughout the mission.

4.3.5. Orbit injection error correction for the first DMC launch

It is worth pointing out here that, although the launch of the first DMC satellite was extremely successful in most respects, a significant amount of effort had to be expended in dealing with a much higher than expected apogee.

As a baseline, it had been planned to perform no manoeuvres until after the 2nd DMC launch, in order to allow optimal use of propellant between the satellites. However, uncorrected this apogee error would have resulted in a significant degradation of the orbit LTAN within just a few years, and would certainly not provide a suitable profile for the other DMC satellites to join.

A better than predicted performance of the propulsion system allowed the error to be almost fully corrected whilst still maintaining sufficient propellant to meet the needs of the mission.

However, this would leave the first DMC spacecraft with significantly less Delta-V capability than the remainder of the DMC satellites after the 2nd launch. It was decided that the strategy for all manoeuvres after the 2nd launch could only sensibly be done after the launch had taken place and orbit characteristics were known. In the event, as described in Section 4.3.6, the 2nd launch was remarkably precise, leaving the constellation in an excellent position with respect to propellant.

4.3.6. Station Acquisition after the 2nd DMC launch

As mentioned in Section 4.3.5 above, the results of the 2nd DMC launch were very good. The altitude and inclination were accurate, and the satellites were in a relative phasing as illustrated in Figure 4.3.

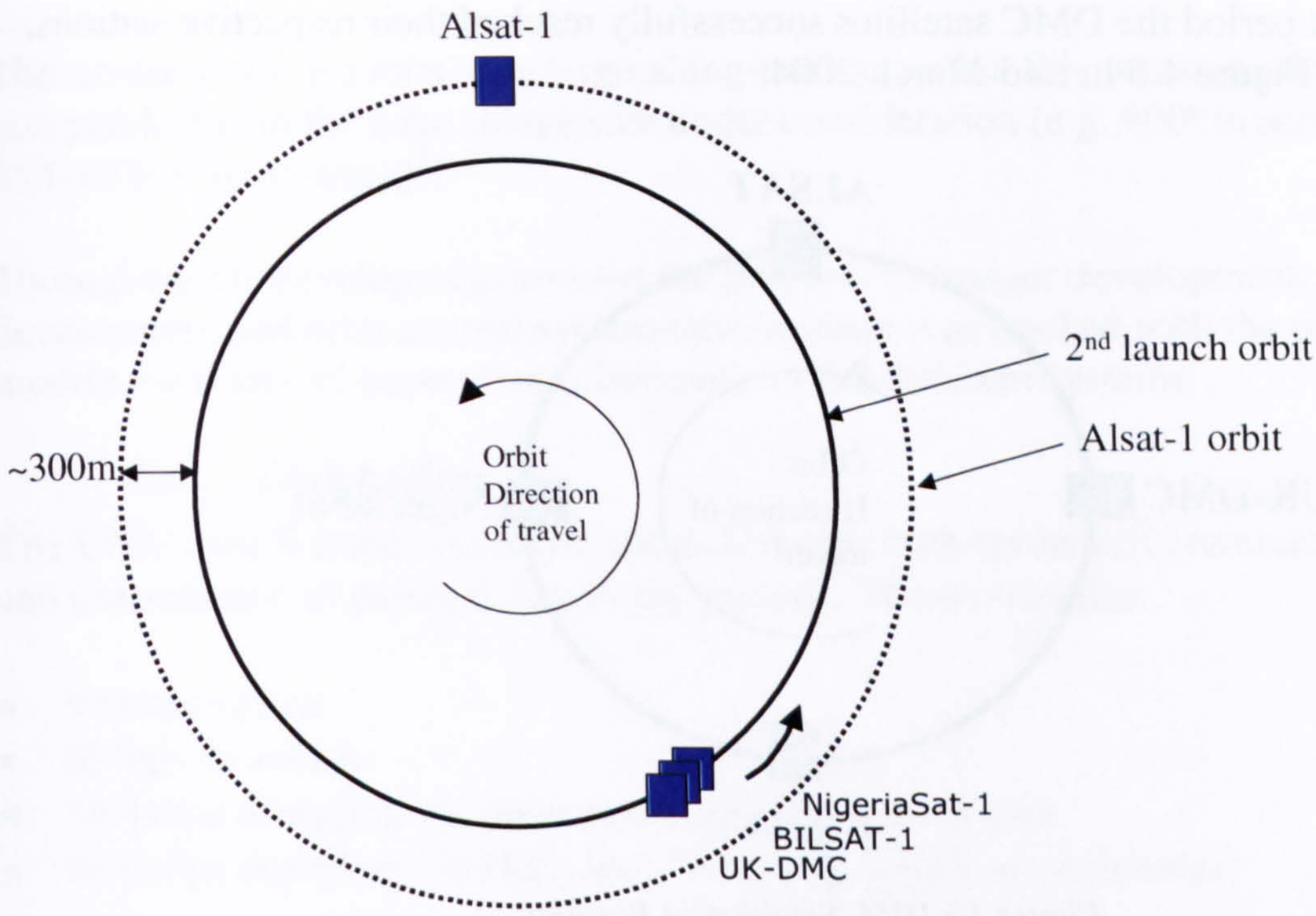

Figure 4.3 DMC Orbit Status following 2nd DMC launch

This allowed a nominal station acquisition strategy to be followed as depicted in Figure 4.4.

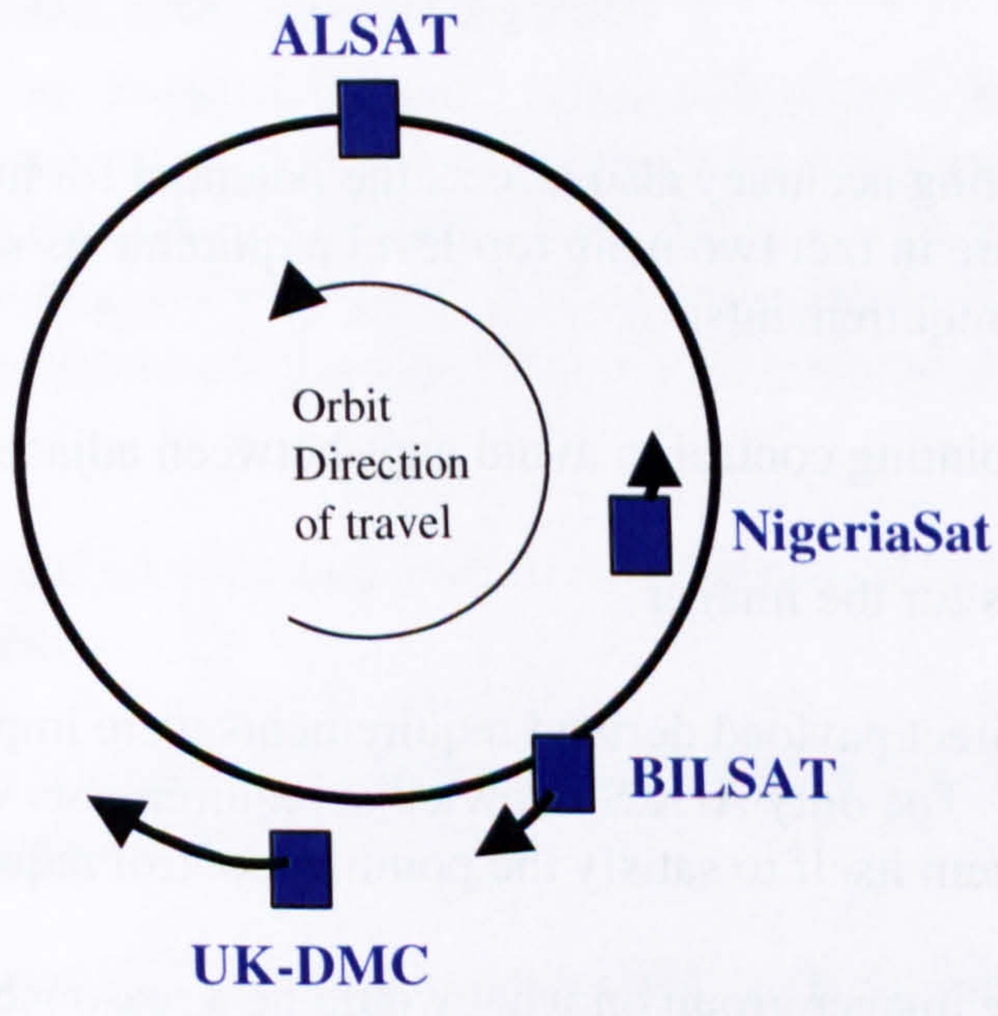

Figure 4.4 DMC Station Acquisition Strategy

The software mentioned in Section 4.3.4 was used to perform simulations and analyse the situation to allow derivation of a suitable implementation plan. A plan was agreed with the DMC partners and implemented. After a planned long duration (approximately

3-months) coast period the DMC satellites successfully reached their respective stations, as illustrated in Figure 4.5 in mid-March 2004.

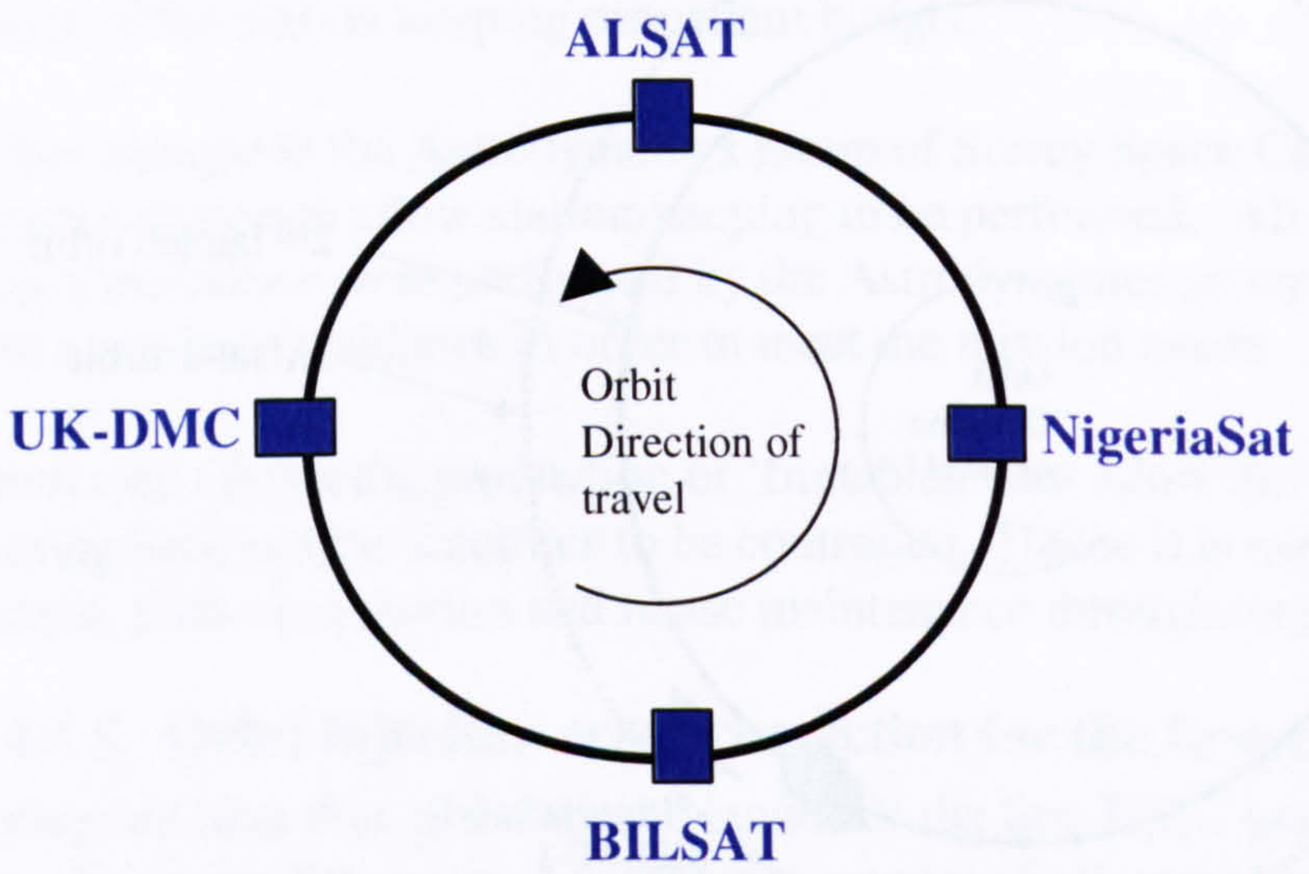

Figure 4.5 DMC Satellites in Position

4.4. AODCS Requirements

The station keeping window requirement set for the DMC was 1 minute, which equates to approximately 3.5degrees. If a satellite is 1 minute out-of-phase along track with respect to its adjacent satellite then this translates to an across track error in ground track placement of approximately 27km at the equator (maximum at equator). Hence 27km margin is included in the imager swath width in order to maintain coverage without gaps at the equator.

The attitude control pointing accuracy also affects the potential for image targeting error on the ground. There were in fact two main top-level requirements set for the ADCS knowledge and pointing requirements:

- Sufficient absolute pointing control to avoid gaps between adjacent satellite swaths in the constellation
- Stability requirements for the imager

In the first instance, no direct payload derived requirements were imposed on ADCS knowledge requirements. The only ADCS knowledge requirements were those required by the ADCS control system itself to satisfy the pointing control requirements.

After discussions with the imager group on what would be a reasonable maximum swath target (600km), and also assuming a 1-minute station keeping window, the following (2σ) requirements were set for ADCS pointing control accuracy:

Pitch: 2°
Roll: 1°
Yaw: 2°

This could result in a relatively large along-track error but this was considered acceptable due to the large image size under consideration (e.g. 600km across track by 250-300km along-track)[1].

Throughout the development process the progress of imager development, ADCS development and orbit control system development was tracked with the potential to modify the trade-off between requirements on the different systems.

4.5. Link budget

The DMC uses S-Band communications links for both spacecraft command and control and transmission of payload data to the ground. These comprise:

- 9.6kbps uplink
- 8Mbps downlink
- 38.4kbps downlink via dedicated Low Rate Transmitter
- 38.4kbps downlink via High Rate Transmitter (in low rate mode)

A baseline link budget for the uplink and the 8Mbps downlink was inherited at the start of the mission, based on an SSTL spreadsheet tool. Through the course of the mission development this link budget tool was evaluated and corrections and adjustments made in order to provide a confident evaluation of the predicted link performance.

Appendix F contains details of the final pre-launch link budgets.

4.6. Data Flow and Storage Analysis

The high rate transmitter downlink data rate is approximately 8 Mbps as described in Section 4.5 above. However, during the mission design it was expected that the actual effective payload data throughput efficiency could be as low as 70% depending on link quality and actual overheads of the newly developed protocol implementation. The best estimate of the OBDH team was that a 6.5Mbps effect effective data downlink rate was achievable.

This nominal throughput would mean that a full SSDR could be downloaded in approximately 11 minutes.

A mean pass duration is approximately 9 minutes so, simplistically speaking, 80% of an SSDR can be downloaded in an average pass.

A ½ Gbyte SSDR is capable of storing an equivalent area of 600km x 290km at 32m GSD in the 3 spectral bands at 8bit resolution. Early in the mission design an additional overhead (and hence reduction in storage capacity) was expected to be potentially

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[1] Subsequently, a windowing function allowing smaller images to be taken was introduced. The progress of performance of the ADCS simulations was tracked indicating that ADCS control was expected to exceed requirements and allow reasonable pointing accuracy for smaller images.

necessary for Reed-Solomon correction. However, operational experience has proved this to be not necessary.

The above figures can be used, along with power constraint considerations, communications statistics, and consideration of imaging opportunities to estimate the imaging capacity of the spacecraft. This is discussed further in Section 4.8.

4.7. Power Analysis

The power analysis for the mission is critical in determining many aspects of the spacecraft configuration. The results impact on the choice of voltage rails (e.g. whether 14V, 5V or 28V). It has re-design implications on individual heritage modules and impacts the battery solution and solar panel solution. Hence the power analysis has large impacts on the entire mechanical design and electrical design of the spacecraft.

Appendix G contains details of the final pre-launch power budgets.

The power budget has been considered on an orbit-by-orbit basis in terms of operations concept. This is representative for a scenario with an even distribution of ground-stations around the world, or perhaps a high latitude ground station. In this case one could envisage the spacecraft imaging payload, data storage units, and high-rate transmitter (also high power consumption) operating in most orbits.

The spacecraft is, however, power constrained and safe operational constraints need to be imposed. For example:

- GPS use should routinely be limited to e.g. 10 minutes/orbit if payload and high rate transmitter activity is expected in an orbit
- High Rate Transmitter operations should be limited to a single communications pass per orbit (even if multiple passes are available with different groundstations)
- Payload and High Rate Transmitter operations should not take place in the same orbit as propulsion system operations
- High Rate Transmitter use should be limited in eclipse to between 5 and 10minutes depending on season and location of groundstation
- Data storage units should be powered off when not in use

The amount of available power changes with the seasons and the exact details of the necessary constraints vary also, but the above list gives a top-level idea of the sort of operational constraints involved.

4.8. Imaging Capacity

If one considers the power constraints and other spacecraft and mission characteristics then it is possible to evaluate the potential imaging capacity of the solution.

It was agreed with the operations team that simple and safe operations rules should be adopted at the start of the mission. It was decided that the safest rule would be to always switch off the data recorders after a communications pass. This conserves power

and limits battery discharge and can actually allows a greater downlink time, as it frees power to operate the high rate transmitter for slightly longer in each orbit. Hence maximum downlink opportunities can be realised and maximum data acquired.

The big disadvantage of this is that it severely reduces flexibility in imaging. It assumes an equal interest in imaging any part of the globe at any time. It is not always possible to download a full data recorder on a communications pass. The 'average' pass opportunity would actually allow only 80% of a data recorder to be downloaded. Hence, one might have the opportunity to image an area of interest, however the amount of imagery that can be taken and downloaded in that instance is limited by the duration of the subsequent communications pass.

This should work efficiently in principle if individual images are relatively small and there is an even geographical distribution of imaging interest. However, if interested in only a select region, e.g. Europe, then 'useful' imaging capacity will be lost if the data recorder is switched off after a pass. In this instance it would be better to leave the data recorder on between passes and use more conservative downlink durations to safely download the entire data recorder. This would reduce the maximum capacity for 'global' imaging, but perhaps focus resources in the most desirable geographical region.

Imaging interests vary for the different DMC customers but do tend to be focussed more regionally than globally. Hence, in practice, data recorders are typically kept on between ground-station passes, albeit with slightly more strict power constraints on downlink time.

Once some operational experience, especially with respect to constellation collaborations, is gained operations rules and constraints are expected to be revisited.

The maximum 'global' (assuming equal interest in all regions) imaging capacity, for a single DMC spacecraft, is estimated as 80 imaging tiles[1]/day, based on the number of ground station passes and satellite power constraints.

4.9. Summary

The mission and spacecraft design work performed during this EngD project have been described in this Chapter. This, along with the system design information in Chapter 3, shows that a micro-satellite mission is capable of supporting the payload, power, accommodation, communications and spacecraft attitude and orbit control requirements necessary to meet the DMC daily imaging mission objective.

[1] A 'tile' is defined as 2500 pixels across-track by 2500 pixels along-track, equivalent to a ground cover of approximately 80km x 80km

5. DMC Imagery Applications

Previous chapters have described the Systems and Mission Design for the DMC. The DMC has been designed to provide a unique low-cost solution for daily global imaging revisit at 30-40m GSD in the Green, Red and Near Infra-Red bands (G, R, NIR).

The technical uniqueness of the DMC lies in the combination of its main attributes; the low-cost of the mission, the rapid response/timeliness and availability of image data, potential large image size, combined with the spectral and geo-spatial data characteristics. There are currently no other missions that combine these attributes to provide affordable 'Landsat' class imagery on a rapid response basis. In discussions over many years with potential users the SSTL marketing team concluded that this is a highly desirable niche that was not being filled.

As a result, the DMC is the first dedicated micro-satellite constellation designed for daily imaging revisit.

However, is this useful?

This chapter provides some insight into potential applications for such a source of data. The chapter first describes the main characteristics and limitations of the DMC image data, before considering potential applications for the data.

In order to investigate potential usefulness of the DMC service, a number of application areas are investigated. These include various hazard application areas with several of the areas (Fires and Floods) investigated in more detail, whilst others are more briefly addressed to indicate potential areas that may be worth further study. Also briefly addressed are some non-hazard related application areas such as monitoring of insect breeding grounds, or elephant movement monitoring due to bushfires. This is in order to indicate the potential diversity of applications that such a source of data may provide. The potential application areas described here are by no means exhaustive, but are intended to illustrate some of the potential uses of the DMC mission and follow-on missions.

It should be noted that this Chapter also does not address potential applications of DMC data that do not necessarily benefit from the most unique aspects of the system, i.e. the rapid response/daily revisit or large swath. However, it is worth remembering that the DMC satellites provide image data very similar to that of LandSat in the spectral bands of Red, Green, Near InfraRed (hence of particular interest to vegetation studies). A DMC satellite costs in the order of less than $10million compared to the LandSat7 $600-700million cost. Hence potentially for some applications that are based on these spectral bands the DMC 'satellites' could be considered as a low cost alternative to the LandSat 'satellite'.

The DMC mission is intended as a ½ operational and ½ pilot mission. Future missions based on the experience of the DMC mission may provide various different characteristics, for example, additional or different spectral bands, or a different Ground Sample Distance. This Chapter also highlights some potential improvements to the DMC system where an application would benefit.

5.1. DMC Images: Main Characteristics

The main characteristics of DMC images are summarised in Table 5.1.

Geometric	
Maximum Swath Width	~660km
Windowing capability	Window sizes in multiples of 2500 pixels may be selected
Tile size	2500 x 2500 pixels (~80 x 80km)
Ground Sample Distance (nadir)	~32m
Spectral and Radiometric	
Spectral Bands (μm)	Green: 0.52 – 0.62
	Red: 0.63 – 0.69
	NIR: 0.76 – 0.90
Radiometric resolution	8 bit (256 levels)
Temporal	
Image Revisit Time	Daily
Image Processing Levels and Formats	
Raw	Band Interleaved SSTL specific format
Radiometrically corrected	TIF
Geometrically corrected	TIF
Compressed files	ECW

Table 5.1 DMC Image Characteristics

Figure 5.1 shows the spectral bands of LandSat 7, SPOT 5 and AVHRR 3 for comparison to the DMC. The thermal Infra-Red bands provided by the LandSat 7 ETM+ and the AVHRR 3 greatly extend the scale and make comparison of similar spectral bands difficult, hence a zoom-in on the wavelengths below 2.5μm is given in Figure 5.2.

Figure 5.3 shows one of the first images taken by the first DMC satellite. This image is of the South-Western USA, reaching from Los Angeles to the Grand Canyon.

An indication of the Landsat and SPOT HRG scene size is given for comparison. The SPOT scene size shown is also of the same order as the largest scene size of any previous SSTL satellites.

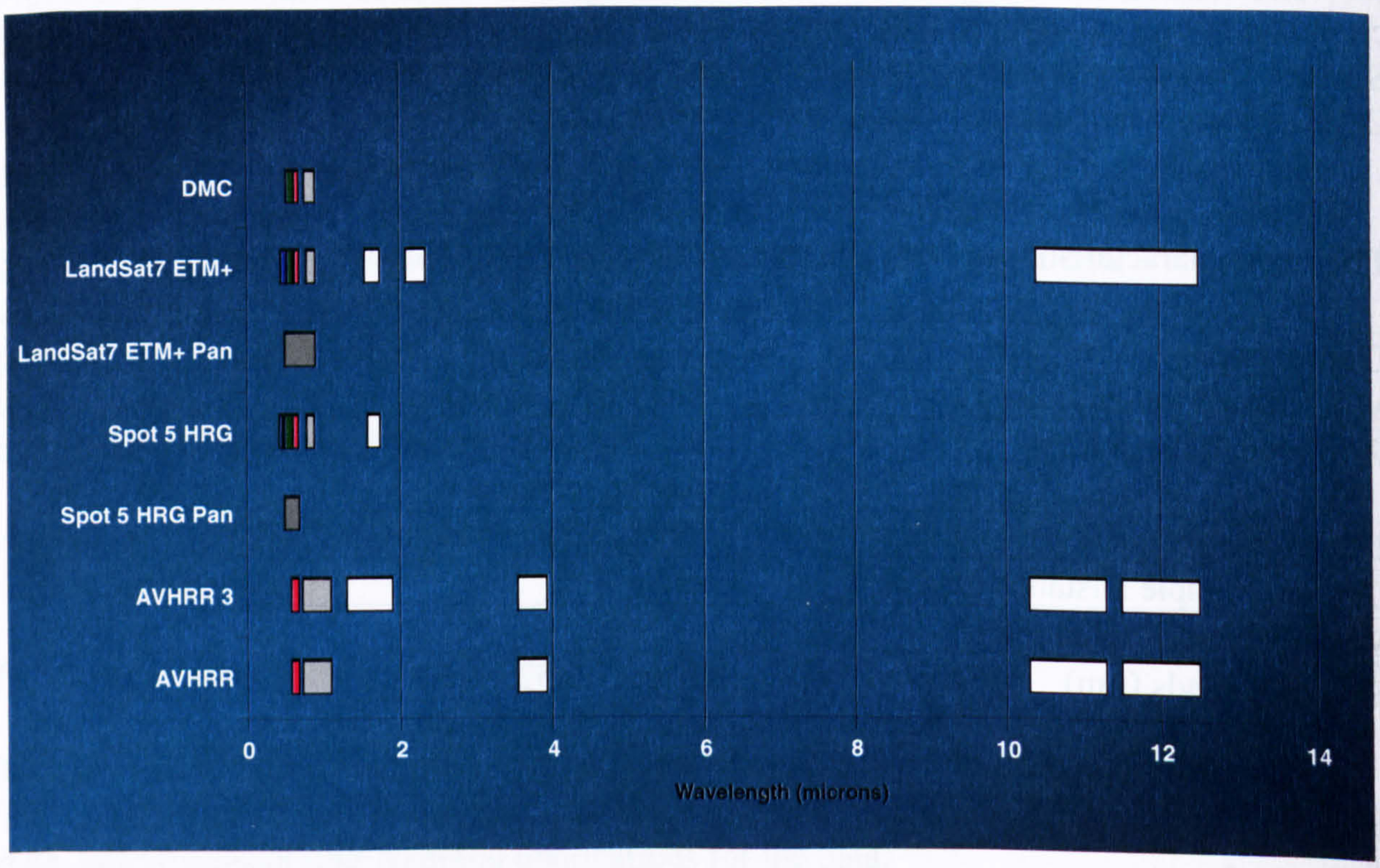

Figure 5.1 DMC Spectral Band Comparison

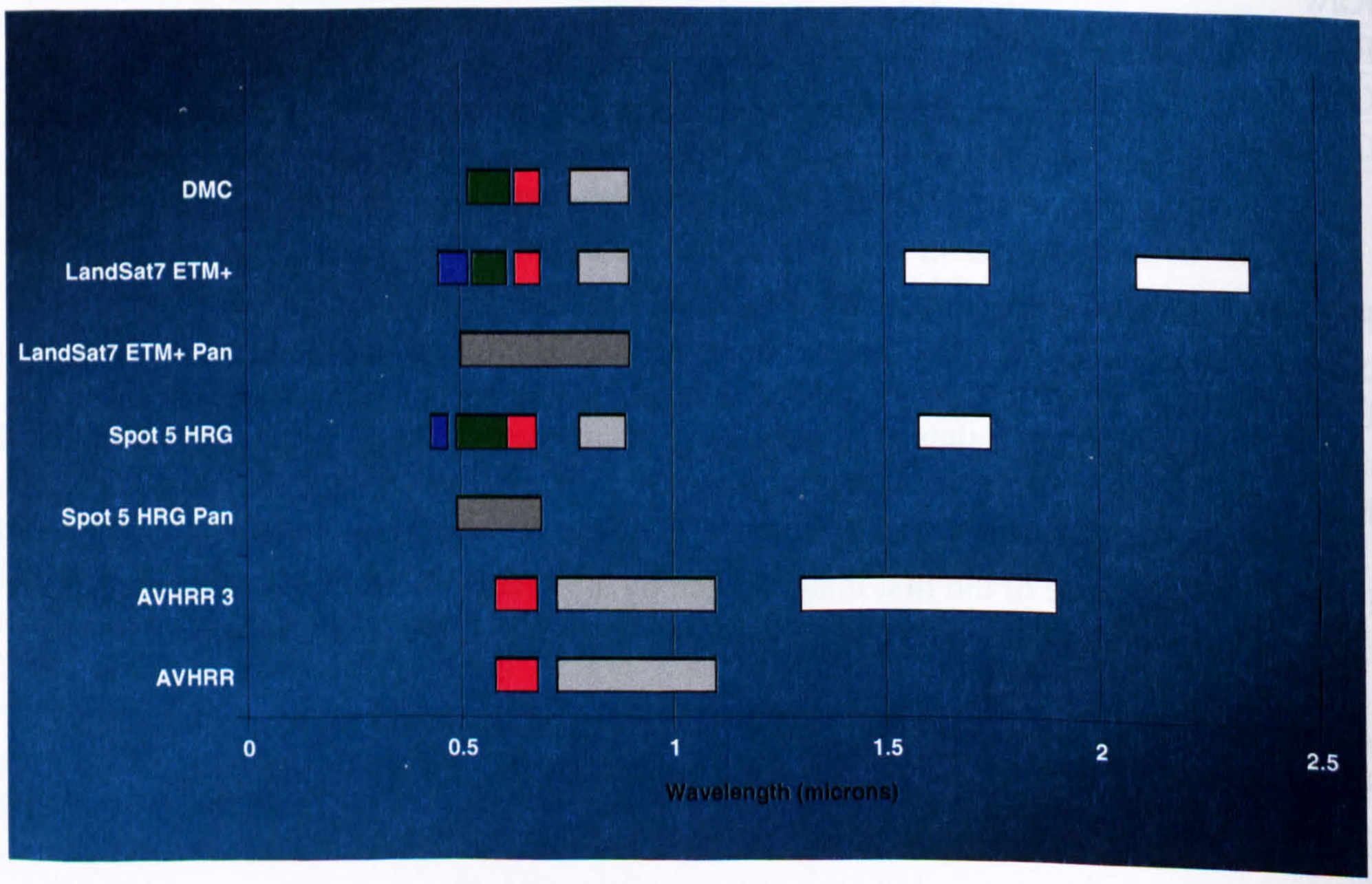

Figure 5.2 DMC Spectral Band Comparison (zoom in)

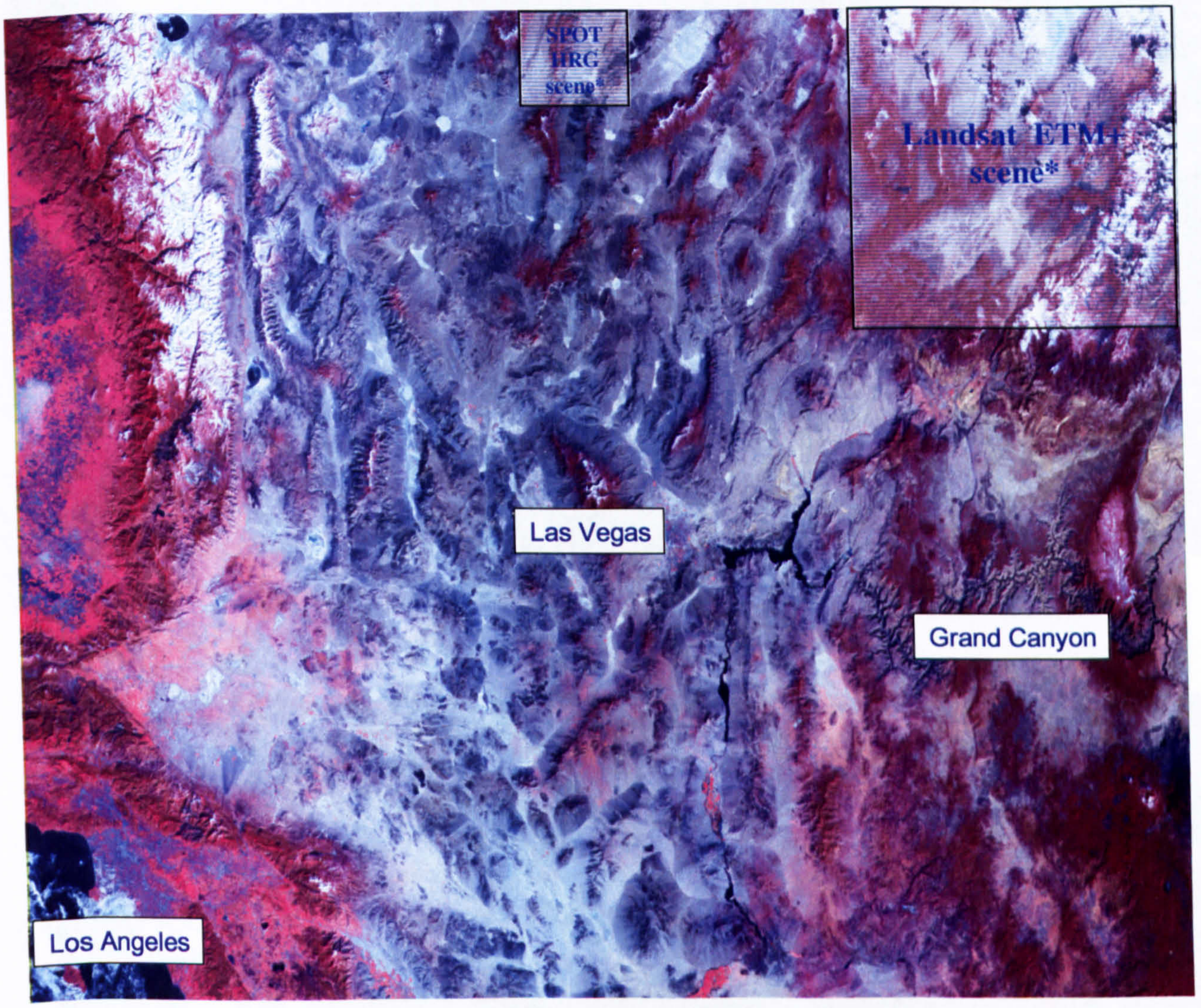

Figure 5.3 DMC Alsat-1 Image of South West USA
**approximation for illustration only*

The DMC is the only satellite capable of covering such a large area in a single image with a GSD in the order of 30-40m, allowing the detection of urban infrastructure and even roads and railways.

The DMC is almost capable of imaging the entirety of England in one single image. Interest has already been expressed by users, for example, in imaging all of Greece in a single image at the beginning and end of the fire season, illustrating the usefulness of such a large image size.

Figure 5.4 to Figure 5.6 show a progressive zoom in on the Las Vegas area in Figure 5.3.

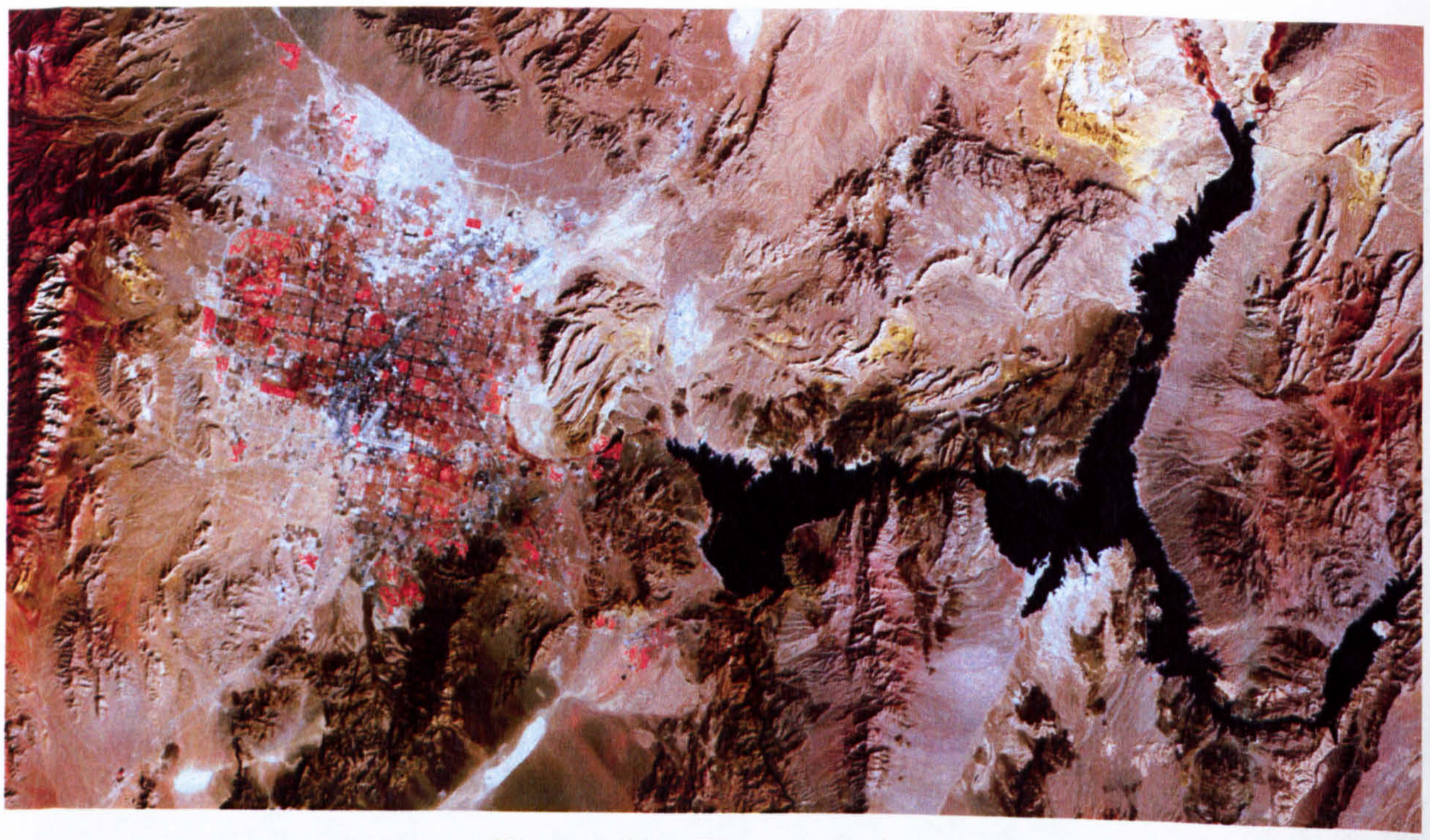

Figure 5.4 Las Vegas: zoom in 1

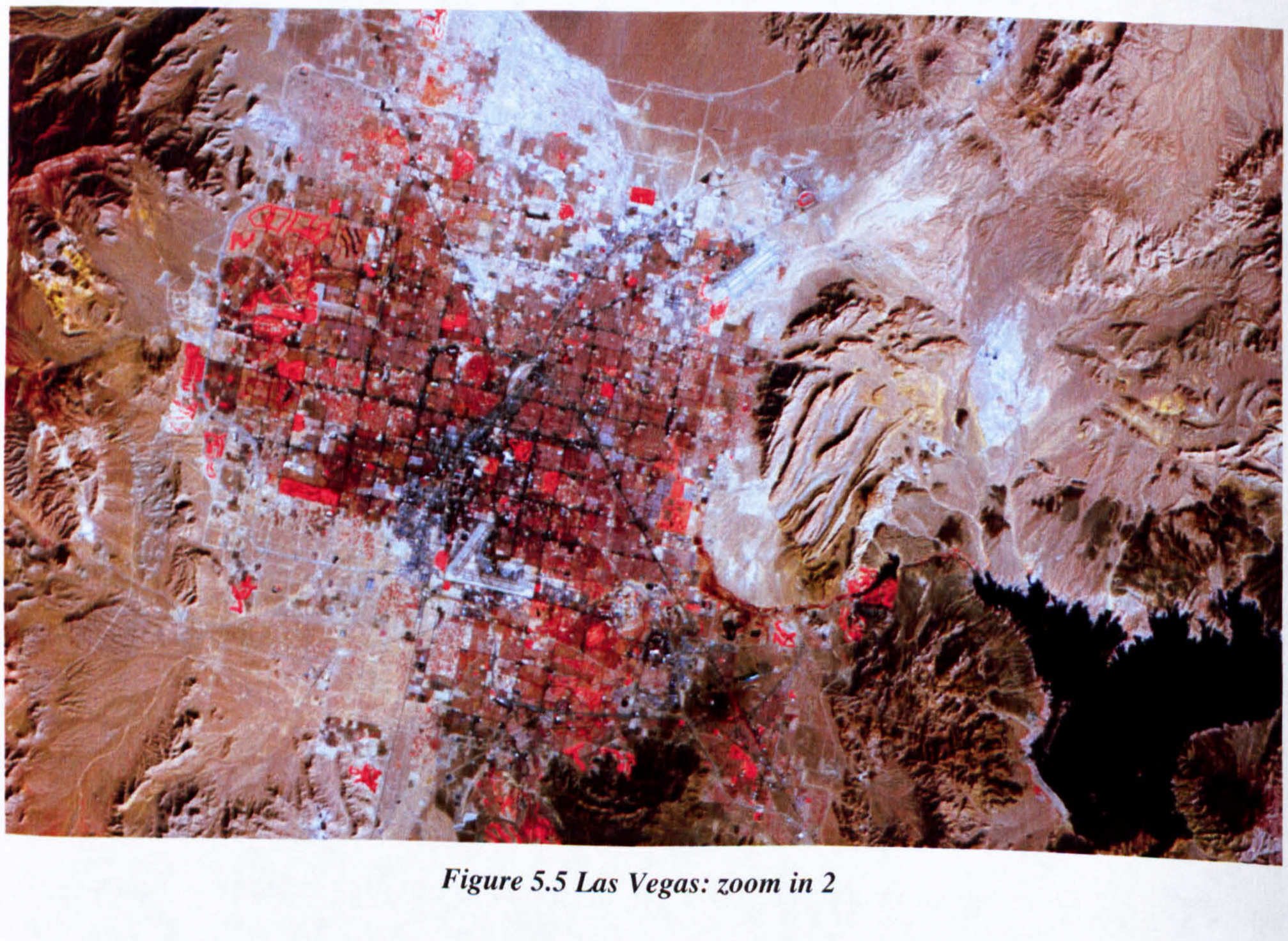

Figure 5.5 Las Vegas: zoom in 2

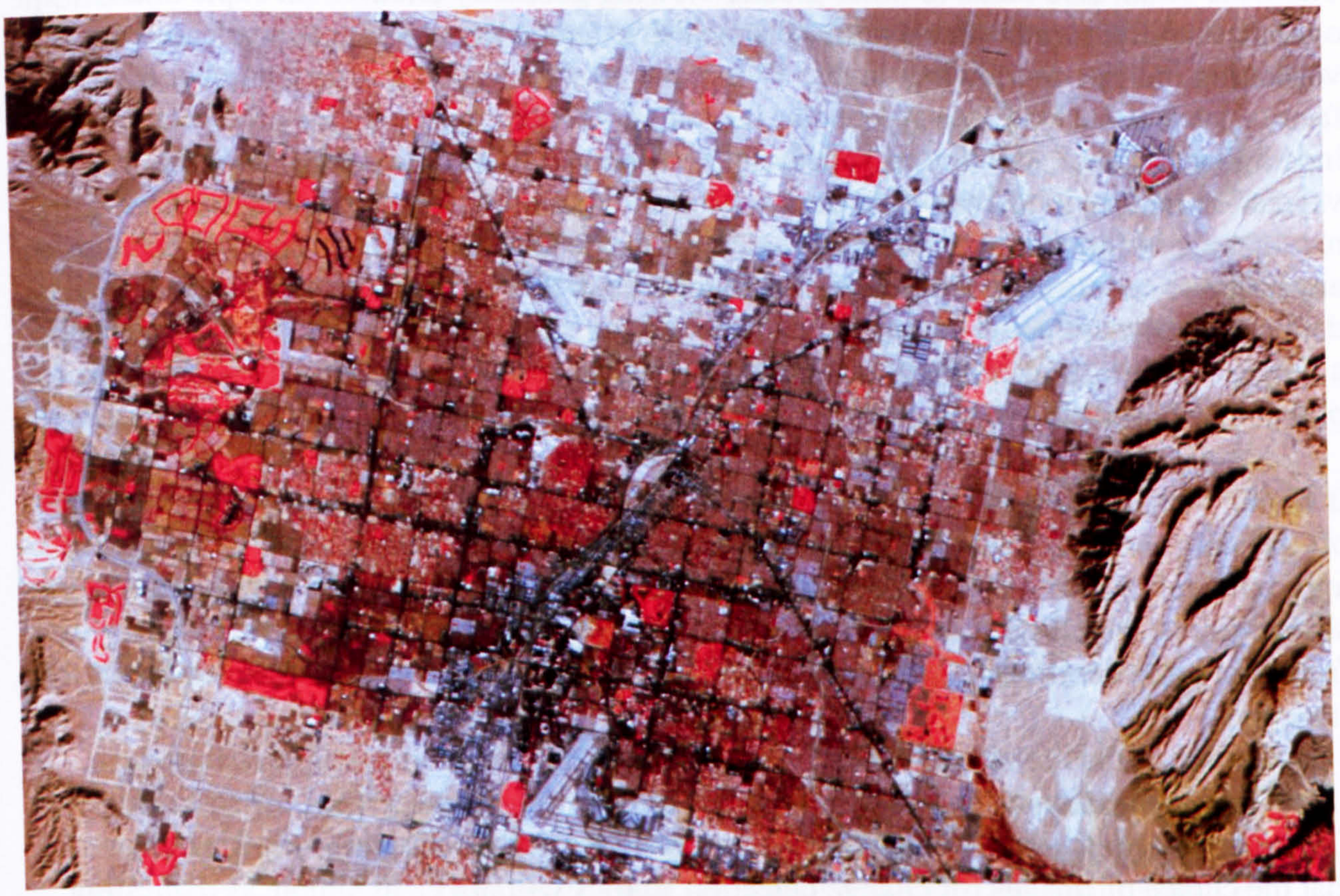

Figure 5.6 Las Vegas: zoom in 3

With a full complement of DMC satellites in constellation formation it would be possible to image the entire breadth of the USA, for example, at 30-40m GSD in a single morning. This sort of capability has never before been achieved.

5.2. DMC Image Data Limitations

DMC has the same bands as Landsat ETM channels 2, 3 and 4 (Green, Red, NIR). It also has a similar GSD, e.g. ~32m at nadir, compared to Landsat's 30m.

For this reason there are a number of applications that the DMC imagery can 'inherit' from the experience and research gained by the large Landsat user community over the decades of Landsat operations.

There are, however, a number of issues that should be considered for any scientific studies that require more than a simple visually intelligible image. None of these issues are necessarily show-stoppers for the various applications but care should be taken to ensure their proper consideration for any application.

DMC wide swath

The large swath of the DMC means that the GSD changes over the swath width. This can be geometrically corrected, but it should be noted that the effect over the full DMC swath is greater than over the Landsat ETM swath (simply as the DMC swath is >3times that of the Landsat ETM).

The wide swath also leads to other greater viewing geometry effects than experienced over the Landsat swath. For example, Staenz et al [86], describes the dependence of vegetation indices on viewing angle. Whilst the effect is dependent on a number of factors, such as surface area type, solar illumination conditions and type of vegetation index, Staenz concluded that in general approximately 70% of the variation of the vegetation indices investigated in the study can be explained by viewing angle. The natural conclusion from this for the DMC is that care should be taken when performing any accurate quantitative studies with the DMC data. For example, broad earthquake damage assessment using change detection relies on small changes only, which requires a diligent viewing angle/solar illumination angle compensation approach to reduce the probability of misclassification error.

It should be noted that these effects are even greater for the SPOT satellite, which has an off-pointing sensor to take a 60km swath anywhere on a cross-track path of approximately 900km, than they are for the DMC. However, due to the particular similarities of the DMC data to Landsat data, and the potential to draw comparisons from past Landsat studies, the issues are pointed out here with respect to the Landsat imagery.

DMC image location

DMC image acquisitions are not based on a World Reference System grid. This means that the choice of images for change detection studies will not be as simple as requesting two images from a grid reference. The region of interest must be specified and the images are likely to be only part overlapping. Once it has been established that the area of interest is covered by an image in the archive, any programmed imaging request simply needs to ensure that the image acquisition covers at least the referenced area. This is not necessarily a big issue, but is a difference to the Landsat image acquisition and cataloguing system and is hence noted here.

It should also be noted that for change detection studies, as well as potentially being imaged at a different time of year (and hence different solar illumination angle) the area of interest may also be imaged with different viewing angles for the two images being compared. Hence, viewing angle effects must be taken into account for maximum accuracy.

Image size

The largest single image acquisition achievable by a DMC spacecraft is in the region of >660km x 500km, which corresponds to approximately 1Gbyte of data. The processing demands of using such an image on user computers is high, and relatively high-specification machines would be required by users wishing to manipulate imagery of this size.

5.3. Study Approach to Specific DMC Application Areas

This chapter addresses the potential of the DMC in various user application areas under separate sub-sections. The intention of the chapter is not to provide a detailed overview of all application areas but simply to provide sufficient information to demonstrate the potential usefulness of the DMC. Hence, a more detailed discussion of several

application areas is provided, with a number of other areas just touched upon in order to demonstrate the potential breadth of use of DMC data, subject to more detailed study in each area.

The major hazard areas are covered under the titles of Fire, Ice, Flood, Landslide, Oil Spill, Volcano, and Earthquake, in line with the team structure and final report of the recent CEOS Disaster Management Support Group. The areas of Fire and Flood are the areas selected for the more detailed treatment in this Chapter. The remaining hazard areas are not treated in such length but instead are briefly discussed to indicate where the most likely potential areas of use are foreseen. Whilst this thesis is primarily based on the engineering of the DMC solution and illustrating some of its potential, it is recommended that future studies be performed that are dedicated to exploring DMC 'applications' in order to add detail to the areas raised in this report. Several non-hazard user application areas are also covered under a separate sub-section to demonstrate that the DMC data has potential uses beyond disaster monitoring.

For the two selected hazard areas of Fire and Flood the following is provided:

- an overview of the current state of use of satellite remote sensing data for the hazard type. In particular it is necessary to understand what data sources are currently available to allow the DMC to be put into context. This draws heavily, although not exclusively, on the descriptions given in the 2002 CEOS DMSG final report [56]. Again, this is not intended to give a comprehensive description but just sufficient information to allow the reader to understand the main current data sources to provide a context for the new DMC data source.

- an overview of the relevant characteristics of different data types and their limitations, referring to the results of existing research into specific application of the various data types. Emphasis is given to optical data, with some main points also provided on other relevant data types. Optical and SAR data are discussed for floods, whilst Thermal IR is also briefly discussed for fire applications due to its particular relevance for fire detection. This is not meant to comprehensively describe all research in each area, but instead to give sufficient information to provide the reader with an insight into the capability and limitations of the DMC data with respect to the particular application and put this into context with other data types.

- a discussion of where the unique advantages of a mission such as the DMC might fit into the existing current state of satellite earth observation for hazard support. The potential new capability provided by the DMC data is highlighted.

5.4. General DMC Data Use in Disaster Management

Disasters can be broadly categorised into slow-onset (e.g. drought), and rapid-onset (e.g. earthquakes, flash floods).

Walter [56] quotes the "International Agreed Glossary of Basic Terms related to Disaster Management" from the Department of Humanitarian Affairs, United Nations Offices in Geneva to define three elements of disaster management:

- Prevention
- Preparedness
- Relief

It is worth mentioning that the rapid response of the DMC is targeted primarily with the idea of 'monitoring' a rapid-onset type disaster once occurred rather than 'detection' of a disaster.

The majority of the DMC applications considered here therefore fall into the 'Relief' category but it should be noted that the entire disaster management cycle should be considered as a feedback loop, and lessons learned in the relief phase (including e.g. information from the use of remote sensing data) may well feedback into prevention and preparedness for future disasters.

As will be described later, there may also be some 'slow-onset' disaster applications where the reliability of timely data could aid the preparedness phase, for example as a data input to a Famine Early Warning System (FEWS).

Walter [56] also stresses the importance of distinguishing between operational and research/prototype missions for use in disaster reduction, stating that it is important that operational users can rely on a continued supply of data. This reinforces the need for operational reliability raised earlier in this thesis and is a point that needs serious consideration, in particular for a low-cost small satellite mission. The International Charter operates on a best-efforts basis. This would also need to be the case in particular for a small satellite mission such as the DMC that would not tend to be designed with as much redundancy as a traditional mission.

It is important that satellite and mission designers work with disaster relief agencies to understand operational needs and to define a service of sufficient reliability and/or operational procedures that are sufficiently robust to take advantage of satellite data if available, but cope if it is not.

This is beyond the scope of the first DMC mission, as a ½ pilot-½ operational mission, but is a point that should be considered for any future operational missions that might be fully dedicated to disaster relief.

Williams [59] also stresses the importance of understanding real user needs in the use of satellite data for disaster management, stating that often scientists try to produce quantified results when sometimes decision makers need just qualitative information of a different nature. For example, in a flood situation it may be practically more useful for the decision maker to know simply whether the flood is likely to get better or worse, rather than a detailed quantification of flood extents.

In 1994, a concept similar to the International Charter was proposed by Kessler et al. [60] whereby existing EO capabilities would image disaster areas at high priority. Standard (hence allowing processing to be carried out most quickly) disaster-specific processed products would be delivered to relevant disaster relief authorities. Kessler also suggested that details of standard products be updated as experience is gained in collaboration with aid and relief agencies. This would be an excellent target to aim at for the DMC data exploitation to maximise the benefit of the rapid-response information.

The above points out several areas for consideration in the general use of DMC data for disaster applications. The following sections discuss specific potential application areas.

5.5. Fires

This section discusses the use of space remote sensing and application of DMC data in application to wildfire management.

The economic cost of fires can be immense, illustrated by several US fires in just two months of 2002. In May 2002, a fire in New Mexico consuming over 12,000 acres of land took 800 firefighters, 4 air tankers and 12 helicopters to control it [62]. A fire in Arizona the following month consumed almost half a million acres and cost more than $30million before being contained [63].

As well as the economic cost, wildfires also impact the global and local environment and population safety and security.

For example, as described in the above mentioned Working Group report, vegetation loss due to wild-fires can lead to loss of soil protection, wind and water erosion of the site, increased water run-off causing floods, landslides, and water quality/availability issues. The damage from wildfires can cause problems in sustainable development for rural societies and this, in fact, was one of the reasons for the formation of the UN ISDR-IATF Working Group on Wildland Fire.

The UN Working Group stated in a draft 2002 position paper [61] that:

"Several hundred million hectares of forest and other vegetation types burn annually throughout the world, but most of these fires are not monitored or documented. Informed policy and decision-making clearly requires timely quantification of fire activity and its impacts nationally, regionally and globally. Such information is currently largely unavailable."

"there is a paucity of accurate and timely information on the numbers of fires, area burned and phytomass consumed annually at national, regional and global scales"

"Recent Intergovernmental Panel on Climate Change (IPCC) reports have emphasized the fact that climate change is a current reality, and that significant impacts can be expected, particularly at northern latitudes, for many decades ahead. Model projections

of future climate, at both broad and regional scales, are consistent in this regard. An increase in boreal forest fire numbers and severity, as a result of a warming climate with increased convective activity, is expected to be an early and significant consequence of climate change. Increased lightning and lightning fire occurrence is expected under a warming climate. Fire seasons are expected to be longer, with an increase in the severity and extent of the extreme fire danger conditions that drive major forest fire events. Increased forest fire activity and severity will result in shorter fire return intervals, a shift in forest age class distribution towards younger stands, and a resultant decrease in terrestrial carbon storage in the boreal zone. Increased fire activity will also likely produce a positive feedback to climate change, and will drive vegetation shifting at northern latitudes. The boreal zone is estimated to contain 35-40% of global terrestrial carbon, and any increase in the frequency and severity of boreal fires will release carbon to the atmosphere at a faster rate than it can be re-sequestered. This would have global implications, and must be considered in post-Kyoto climate change negotiations."

and also concluded that:

"...there is an obvious need for more reliable data on fire occurrence and impacts. Remote sensing must and should play a major role in meeting this requirement. In addition to the obvious need for improved spaceborne fire-observation systems and more effective operational systems capable of using information from remote sensing and other spaceborne technologies, the remote sensing community needs to focus its efforts more on the production of useful and meaningful products."

The above UN working group statements indicate the importance of being able to monitor fire activity on a global and regional scale, as well as the current lack of information and also the feeling that space remote sensing has a significant role to play in providing this information.

There are a number of ways in which space remote sensing can and has contributed to both fire research and fire management:

- Damage assessment/Burn Scar Mapping
- Fuel Maps
- Fire Risk/Danger Maps
- Fire Detection

These areas are addressed in the following sub-sections, which describe the technical application of different types of space remote sensing data to fire applications as well as existing space remote sensing data sources for fire applications. Finally, the potential contribution that the DMC mission can make in this field above existing capabilities is described.

5.5.1. Current Image Data Sources for Fire Applications

This section describes several of the most relevant existing missions/sensors for fire applications and lists other existing sensors with potential for fire application.

The DMSG CEOS Fire Hazard group listed available EO data sources for seven areas of application as given in Table 5.2.

Fuels Mapping	Fire Danger Assessment	Rapid Detection	Local Fire Monitoring and Mapping	Global Monitoring of Wildfires	Local burned area assessment	Global burned area assessment
LandSat	LandSat	DMSP/OLS	None	DMSP/OLS	LandSat	LandSat
Spot	Spot	GOES	-	IRS-WiFS	Spot	Spot
Ikonos	Ikonos	MeteoSat	-	GMS	IRS	IRS
ATSR	ATSR	GMS	-	MeteoSat	ERS	ERS
MODIS	MODIS	MODIS	-	MODIS	MODIS	MODIS
NOAA-AVHRR	NOAA-AVHRR	NOAA-AVHRR	-	NOAA-AVHRR	NOAA-AVHRR	NOAA-AVHRR
ADEOS-II /GLI	ADEOS-II	-	-	SPOT-VGT	SPOT-VGT	SPOT-VGT
-	-	-	-	GOES	JERS-1	JERS-1
-	-	-	-	-	Ikonos	GOES
-	-	-	-	-	ALOS*	ALOS*
-	-	-	-	-	ATSR	ATSR
-	-	-	-	-	ADEOS-II /GLI	-
-	-	-	-	-	IRS-WiFS	-
-	-	-	-	-	IRS-P4	-

Table 5.2 CEOS DMSG Fire Hazard Group, listed EO Data Sources
*planned

The DMC could be added to this suite of sensors as a new rapid-response, daily revisit data source for fire applications. Some specific areas in which the DMC may contribute are outlined in Section 5.5.3 below.

In addition to the satellites listed in the above table it is worth noting the FUEGO proposal. A brief description of this is given below. A brief description of the BIRD mission is also given, which is an existing micro-satellite demonstration mission for fire detection. Finally a brief description is given of the RapidFire service offered to the US Forest service by the MODIS sensors.

FUEGO (from [90])
Whilst this section is primarily dedicated to existing capabilities, it is considered worthwhile to mention the FUEGO proposal, due to its dedicated application to fire management and the fact that it is a current proposal (The ESA Council in November 2001 approved the Consolidation phase for Fuegosat [91]).

FUEGO is a proposed system dedicated to early fire outbreak detection and monitoring. The concept involves a system of 12 mini-satellites (~240kg) launched to 3 different planes (47° inclination) in order to provide a 15-minute mean detected time.

Risk areas to be observed can be updated every day by users. The proposed products would include:

Detection Product: hot spot detection with fire alert warning
Monitoring Product: fire-front imaging product

In addition there would be Fire Risk Index Maps (using NDVI with auxiliary data, e.g. meteorological data), and Damage Assessment information produced.

The FUEGOSat Field of Regard would be up to 2500km and the choice of bands would be as described in Table 5.3.

Band	Function
MIR	Hot spot detection
VISNIR	Filter false alarms due to sun-glints. Products to help manage the pre- and post-crisis activities.
TIR	Information on cloud presence. Helps to refine detection tests.

Table 5.3 Proposed FUEGOSat Image Bands and Functions

MODIS RapidFire

The MODIS sensor is a wide swath low/moderate spatial resolution imager that allows global coverage every 1-2 days [92]. It currently flies on the Aqua and Terra satellites, one imaging in the morning and one in the afternoon.

The MODIS sensor has 36 spectral bands, including Red and NIR at 250m resolution. Other bands are at a lower resolution, e.g. 500m or 1km.

A daily active fire detection product is produced within 4 hours of acquisition which is provided to the US Forest Service and others via a Global Observation of Forest Cover project.

A recent press article [93] described newly developed NASA software that will automatically allow observations of interest from one satellite to result in a responsive image request to another satellite. MODIS operations are given as an example with a scenario where a hotspot is detected by ground processing of MODIS data (via the RapidFire system). The hot spot detection, along with scientific criteria could be used to automatically request the EO-1 satellite to take more high resolution images. This is not designed just for one phenomenon and is also not just envisaged to better facilitate operational services (e.g. fire-fighting). It is described as a first step to allow users to specify the type of data they want (for example, forest fires, or floods) rather than to simply request an image of a geographical area.

This is a potentially exciting development, in particular for the field of operational hazard support (and indeed hazard research). However, ultimately one is restricted by the sensors available in space to collect data. Consider the example given. EO-1 is just a single experimental spacecraft with a swath of 185km (similar to Landsat 7), and a similar revisit period (16-17days) as Landsat 7. New initiatives such as this would

allow the benefits of a rapid-revisit imaging system such as the DMC to be best exploited.

BIRD

The BIRD (Bi-spectral InfraRed Detection) mission is a demonstrator micro-satellite mission aimed at fire detection [41][94]. Due to an absence of IR detector saturation, the BIRD mission is able to improve false alarm rejection and also give quantitative information on hot spots, such as effective fire temperature and area [95]. This is a capability improvement welcomed by Lynham [38] as a fire research officer.

Its payload comprises a Hot Spot Recognition Sensor which operates in the MWIR (3.4 – 4.2μm) and Thermal IR (8.5 – 9.3μm), as well as a Wide Angle Optical Stereo Scanner (NIR, 0.84 – 0.90μm).

Nadir ground resolution is 185m for the NIR channel and 370m for the MIR channels. In the first 15months of operation the smallest man-made fires detected by BIRD had an area of $12m^2$ at daytime and $4m^2$ at night. It can detect hot targets 7 times smaller than those detectable by MODIS and AVHRR. Like the DMC this mission is an excellent example of the improving capabilities of micro-satellites and their potential operational usefulness.

5.5.2. Application of Different Data Types

5.5.2.1. SAR Data

Several areas are discussed in Section 5.5.2.3 regarding use of optical data for fire applications. These are not discussed in detail for SAR data. It is beyond the scope of this thesis to comprehensively research the methods of SAR application to the various applications under consideration. Ultimately, there is still not a daily revisit capability available from any SAR mission, and hence the DMC has a unique benefit it can bring to any application requiring timely data. However, several points are mentioned below to indicate that SAR data should not be forgotten, in particular with respect to its cloud penetrating capability, when considering solutions to these remote sensing problems.

SAR data has been studied for use in production of fire danger maps. Leblon et al [64] noted the problem of cloud cover for optical data in fire danger estimation and suggested that SAR data be considered as a complementary data source to optical data. The fuel moisture content is related to the fuel dielectric constant, which in turn is related to the radar backscatter characteristics. The discussion given below for optical data and fire danger indices indicates that this is a complex area that already makes use of a number of data inputs to arrive at a reliable estimation of fire risk. Further research may indicate that SAR data produces more (or less) reliable results than optical data. However, the availability of timely SAR data would need to be considered before adding it to a model for fire danger assessment.

SAR data has also been studied for the mapping of burn scars. Siegert and Ruecker [65] performed a study in which burn scars could be identified visually in multitemporal principal component analysis enhanced ERS SAR colour composites. Bourgeau-Chavez

et al. [66] also discuss the use of SAR data for burn scar mapping. They refer to a study in which a method using AVHRR NDVI data was compared to a method using ERS SAR data, with a priori knowledge of fire scar locations. The AVHRR method was found to be more accurate than the SAR method (70% - 54%) in this case. The use of the SAR data in combination with the AVHRR data yielded an improved result of 81% accuracy. The SAR data, however, actually gave a better estimation of area burned (96% - 82%). This may be due to the relatively coarse spatial resolution of the AVHRR - an area where the DMC can introduce improvements. The AVHRR was mentioned as particularly useful due to its daily revisit and compositing techniques. A 15-day composite product was used in the referenced study. The DMC has the daily-revisit capability to allow this. However, this first DMC mission has not been designed as a commercial, high capacity mission and the imaging capacity necessary to produce such products should be borne in mind when considering proposals.

Bourgeau-Chavez et al. [66] described that the main problem encountered in mapping fires in Canada using SAR was in separating fires from wetlands, for which a combination of SAR and multi-spectral data was suggested as a solution. A combination of large footprint multi-spectral data, followed up by higher resolution SAR or multi-spectral data was also proposed as a solution in recognition that the use of ERS or Radarsat would be a costly and time consuming solution alone for burn-scar mapping.

5.5.2.2. Thermal Infra-red Data

Thermal infra-red data is useful for fire detection capability. This is not discussed here, as the DMC is not being considered for fire detection capability due to its lack of thermal and mid-wave IR channels (although, Li et al [73] discuss the use of NDVI and burn scar detection for fire detection after the event). However, thermal data is also useful to provide information input for other fire applications such as fire danger/risk indices and also for burn scar mapping. This is discussed further below.

5.5.2.3. Optical Data[1]

This section discusses the use of optical data in:

- Burn Scar Mapping
- Fuel Maps/Fuel Models
- Fire Danger Mapping/Indices
- Blow-down events

Fire Detection is not discussed in detail as the DMC does not have any thermal IR or MWIR channels. In addition, the DMC is not intended as a 'detection' system.

Burn Scar Mapping
Wide swath optical satellite imagery from both Spot VGT and the ATSR is already used operationally in burn scar mapping.

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[1] See Appendix H for a definition of the term 'Optical' as well as different wavelength ranges as used in this document.

The Global Burnt Area –2000 Initiative (GBA-2000) [67][68] uses 1km resolution SPOT Vegetation imagery to derive statistics of burnt area for different types of vegetation cover.

The GLOBSCAR project [67] uses ATSR data in burn scar mapping. The method uses the following physical variations:

- A strong reflectance decrease in the NIR (0.7-1.3micron) after a fire.
- An 7-8K increase in temperature over a burnt surface during the day-time (due to the presence of ash and carbon, preventing the cooling evotranspiration process)

Whilst the DMC does not have a thermal channel as does e.g. ATSR, the DMC does have an NIR (0.76-0.90μm) channel, and also a red channel providing an NDVI capability.

NDVI has been used with good effect as a measurement in studies on burn scar areas [69]. Similarly to the ATSR example above, other bands, such as thermal and reflective bands have also been used in studies, sometimes alongside NDVI, in order to attempt to improve classification accuracy [70]-[74]. In a study by Stroppianna et. al [75], good results were also achieved using just the NIR band (0.78-0.89μm) of SPOT VGT. Smith et al. [76] also found using a single ATSR band (NIR, 0.87μm) that texture appears to be a useful image variable in identifying burn scars, although also stated that their method did not produce benefits over the comparison intensity based algorithm.

Salvador et al. [77], however, state that, of all sensors and bands, NDVI is in fact the most commonly used in studies of burned area detection. Salvador goes on to point out that NDVI uses both red and NIR radiometric information, minimising the effect of different solar angles and relief effects. It is also available from most Earth observation sensors. Salvador also suggests that its general response to green biomass regardless of plant species makes it a useful tool to quantify the total vegetation cover. A drawback pointed out is that soil properties can affect results. However, whilst other more complex indices have been proposed, NDVI is widely used for regional scale studies since soil information is typically not available on such scales (and may change with time) in any case.

One weakness highlighted in the study by Salvador et al. was the consequence of a long time period between the fire and the acquisition of the first image. In this case, re-growth of vegetation in the burned area can conceal the drop in NDVI and distort the results, particularly in areas where vegetation was not initially dense in the first place.

This is clearly a case where the DMC can provide value, with its daily imaging revisit opportunities.

Fuel Maps/Fuel Models and Fire Danger Mapping/Indices

Fuel maps and models have been produced in the past using satellite data. Wagtendonk and Root [79] quote an example where a single Landsat TM NDVI image was used to

classify fuels in Yosemite National Park. Despite apparent discrepancies in the maps, fire management operations were helped by the timely availability of fuels information. Wagtendonk and Root also give an example where multiple LandSat TM NDVI images were used to classify a Yosemite National Park fuel model including six different fuel types:

- Short annual and perennial grasses
- Tall perennial grasses
- Medium brush and evergreen hardwoods
- Short-needled conifers with no heavy fuels
- Long-needled conifers and deciduous hardwoods
- Long-needled conifers with a component of heavy fuels

Sannier and Taylor [80] present a study using AVHRR NDVI data for biomass estimation as an input to fire risk assessment for Etosha National Park in Namibia. Whilst acknowledging that further work is required to refine relationships between biomass and NDVI for different vegetation types, they point out the usefulness of the timeliness of the AVHRR data and rapid local processing to use as a timely input for fire management. The DMC imagery is, unlike AVHRR, not available for direct local reception. However, it does provide a daily revisit opportunity and, particularly due to its relatively high resolution (30-40m compared to the >1km AVHRR GSD) may hold great potential for such an application as long as image distribution can be smoothly achieved.

As well as fuel models, satellite imagery has also been studied to assist in estimation of fire danger mapping and risk indices. Fuel water content is one of the critical factors affecting fire ignition and propagation. Fuel moisture content is defined as the proportion of fresh weight, versus dry weight of a fuel sample, and although not the only technical measure of water content, is a measure recommended by a wide range of fire researchers [81].

Leblon [64] questioned the use of NDVI for droughtness (moisture deficiency) estimations for fire danger estimation. However, in a later study by Chuvieco et al. [82] an empirical estimation of live fuel moisture content was generated using AVHRR NDVI, Relative Greenness (derived from NDVI), and surface temperature. This was proposed as an input to fire danger programs and regional planning for fire prevention. However, the spatial resolution of AVHRR was noted as a weakness. Although surface temperature data would need to come from elsewhere for such a model, the DMC could offer an improvement over the AVHRR resolution in this instance.

Also noted as a potential improvement, would be the use of a SWIR band which could more directly measure the Fuel Moisture Content. These are now available on a daily basis on more recently launched sensors such as MODIS (although only at 500m GSD).

In addition to fuel models and maps, and e.g. NDVI measurements, weather information is also a valuable input to fire danger assessment models [25][83]. Carlson and Burgan [84], for example, list the integration of weather forecast information into their models

as part of their future plans to be able to predict future fire danger conditions across Oklahoma.

In summary, it can be seen that the assessment of fire risk is not a simple process and a number of information inputs are required. Whilst there are improvements to be had by the use of a SWIR band, studies have indicated the usefulness of NDVI measurements in estimation of Fuel Moisture Content and hence fire risk.

Damaged Forest Areas/Blow-down Events

Blow-down events occur when high winds result in fallen trees. With time, areas of fallen trees may become drier than healthy living forest and therefore become a greater fire risk. It is useful for the forestry services to ascertain the extent of blow-down damage as soon after the event as possible in order to evaluate the potential change to fire danger assessment.

Research into blow-down damage assessment using change detection methods using DMC spectral bands has been performed in the past. The results of several studies are discussed in the paragraphs below. However, the results described are not sufficient to conclusively recommend whether DMC data is, or is not, a potential useful data source for this application. The results do suggest that further investigation is required to make a more concrete judgement on the potential DMC data usefulness in this area.

Kundu et al. [85] demonstrated the use of NDVI change detection to assess damage after a super-cyclone. In this instance there was a four-week difference between the pre-cyclone and post-cyclone image. The NDVI change was used to classify areas unaffected, moderately affected and highly affected by the cyclone. Unfortunately, Kundu did not discuss an evaluation of the success of this particular study. Should it be proved a sufficiently reliable technique, this could be a useful method to assess blow-down areas in forests. One point to note however, is that in order to assess NDVI change due to a blow-down, one needs to somehow account for any natural NDVI change between the first image and second image, or justify why it is not accounted for. Kundu assumed insignificant NDVI change over the four-weeks as there was little rainfall.

Another study by Mukai et al [86], used two images from 1 year before damage and 8 months after for the change detection analysis, along with aerial photographs for ground truth. Good weather Landsat TM data acquired in the same season could not be found. In this study, the change in spectral characteristics used were a decrease in NDVI and a prominent increase in bands 5 and 7, resulting in an accuracy of 90% in extracting damaged areas. The significant increase in bands 5 and 7 was attributed to the drying out of the trees. A relatively small change in the NIR was attributed to the fact that the fallen trees kept their leaves, even after 8 months.

Takao [87] compared MOS MESSR images from April 1991 and November 1991 to estimate the damage from several September typhoons in Japan. He found that there was no clear difference in the infrared bands or the NDVI between damaged and non-damaged pixels, suggesting that this was due to the fact that there had not been much

time for any change in the leaf cover on the fallen trees. However, the most clear differences appeared on the Red band and reasonably accurate results, although slightly underestimated, were reported.

Mukai suggested that a few months were necessary for the spectral characteristics to change. This study would therefore suggest that in this instance the rapid revisit of the DMC would not be of great benefit, although the ability to ensure availability of an image immediately after the blow-down event may be useful (for comparison with the later image in a change detection analysis). The Mukai study also concentrated on SWIR bands which the DMC does not have. However, the results from Takao indicate that DMC data (Red band) may be useful. The Mukai study was for a largely coniferous damaged area. As the pre-damage and post-damage spectral characteristics of different tree types will differ, further investigation would be required to better understand the potential of DMC data in this application.

5.5.3. DMC Application

Section 5.5.1 described examples of recent and current initiatives in use of space remote sensing data for fire management and availability of suitable data from existing space sensors in-orbit. Section 5.5.2 described the potential of various optical data, SAR data, and thermal IR data with respect to various fire applications. This section highlights areas where the DMC data specifically may contribute to the area of fire management.

Fire Damage Mapping and Burn Scars

The daily monitoring of the burn scar damage would provide a source of imagery that may be used for fire research purposes to model fire growth [38]. The DMC data would provide a simple and cost-effective way of acquiring such data for research.

Currently some agencies use Landsat to map large fires. However, in order for Canada to have a comprehensive map of area burned each year a higher repeat rate is required. In this case the DMC would offer a definite advantage.

By the end of the season, the geo-locations of most fires are known and this could be used to minimise the imagery required to cover the major fires. Of course Canada is not the only country that is affected by fires. In 2003, up until the end of June, Russia had over 19 million ha of fires and this was before the Summer fire season begins. Previously the worst year has never seen above 15million ha. Remote sensing from space holds a clear advantage over other methods in being able to monitor such a large area. Above this the DMC offers a clear advantage in being able to offer the repeat rate necessary to be able to image the affected areas in a timely fashion at the end of the fire season. The problems associated with vegetation re-growth after a fire and their distortion of accurate burn scar assessment have already been mentioned in Section 5.5.2 above.

Near daily imaging is available from e.g. the NOAA AVHRR or the SPOT VGT instrument. This data would allow burn scar mapping on a scale of 1km ground sample distance. However, there is a lot of potential for classification inaccuracy in this case due to the coarse spatial resolution. The situation is improved by the MODIS sensor

which also provides near daily imaging revisit on the NASA Aqua and Terra satellites. This has a GSD of 250m in the Red and Near Infra-Red, although for other spectral bands the GSD increases to 500m or greater. However, the DMC clearly has the potential to provide a much more detailed picture of burn damage than these sensors.

An example of DMC application to burn scar identification is shown in Figure 5.7. This image was taken by the UK-DMC satellite in Summer 2003. The image covers a large area showing a distribution of fires in the San Bernadino area. Burn scars can be identified even as the fires are still burning.

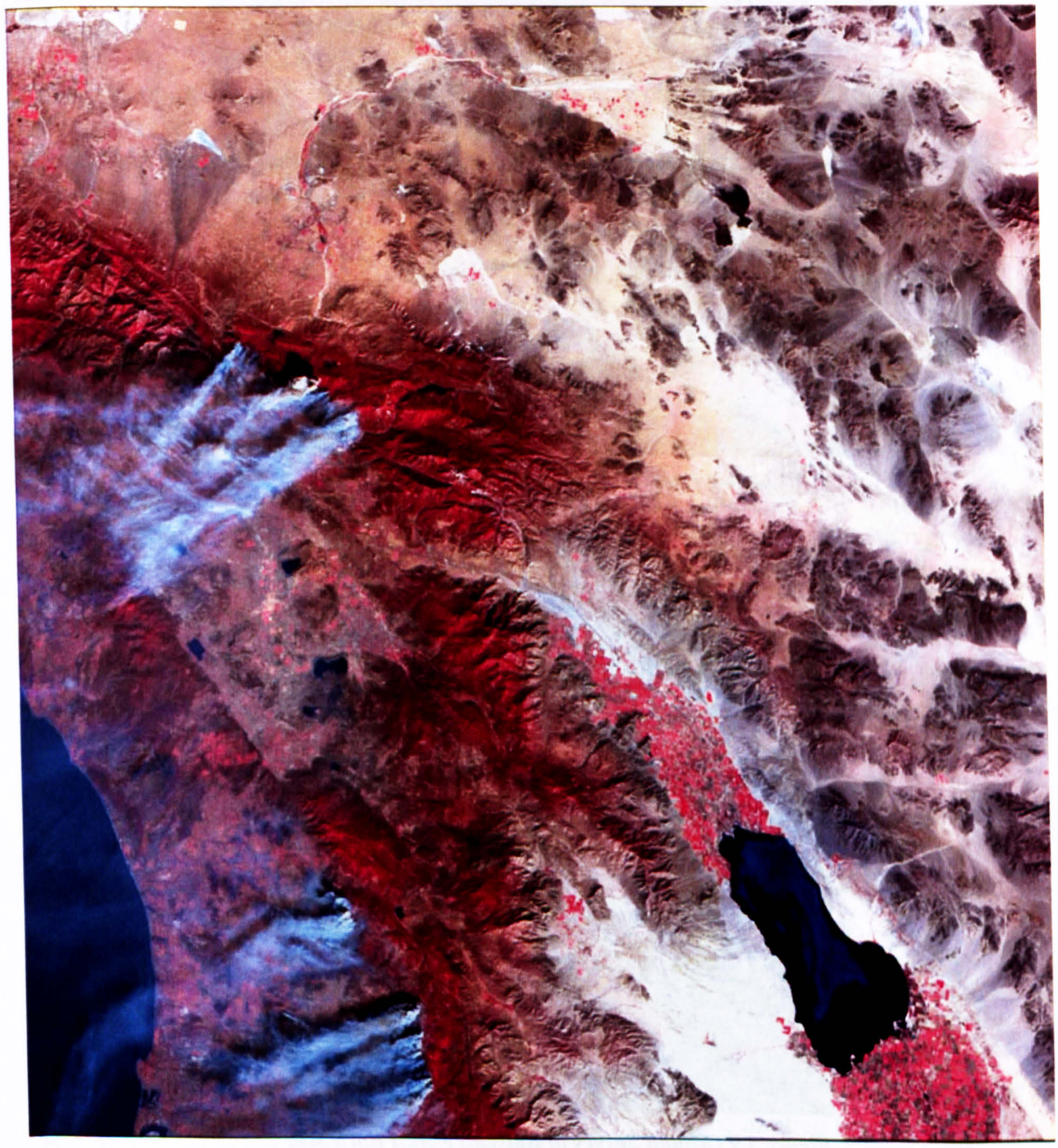

Figure 5.7 Summer 2003 California Wildfires

The usefulness of the DMC for burn scar mapping is also demonstrated by the Alaskan forest fire images shown in Figure 5.8 and Figure 5.9. In this case the DMC estimate of burn scar area was very close, but slightly less than that of the ground survey. It is believed that this is due to the fact that the DMC image could identify unburnt spots within the damaged area, whereas the ground survey assumed all forest within the damage perimeter was burn scar.

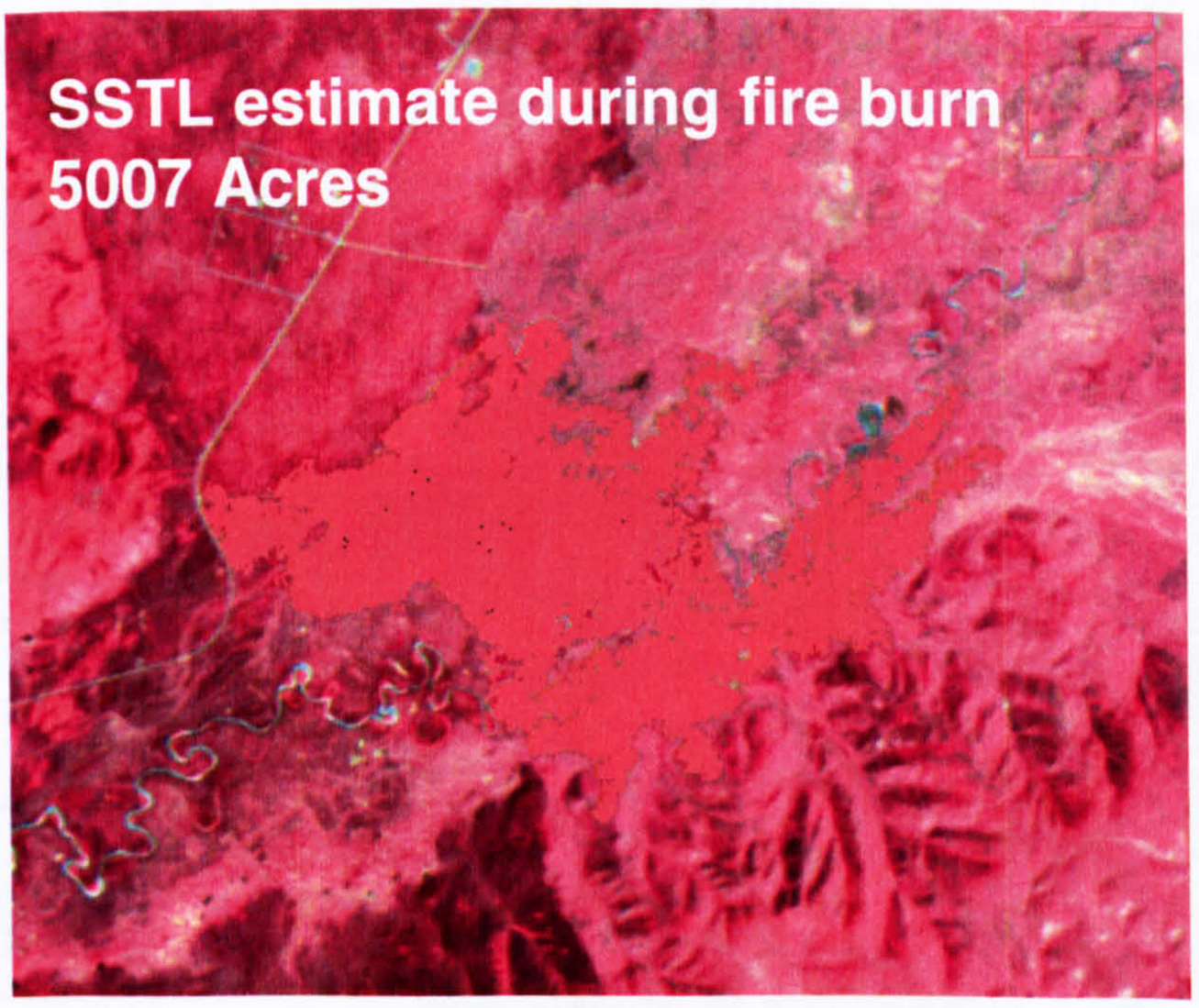

Figure 5.8 DMC Image of Alaskan Forest Burn Scar

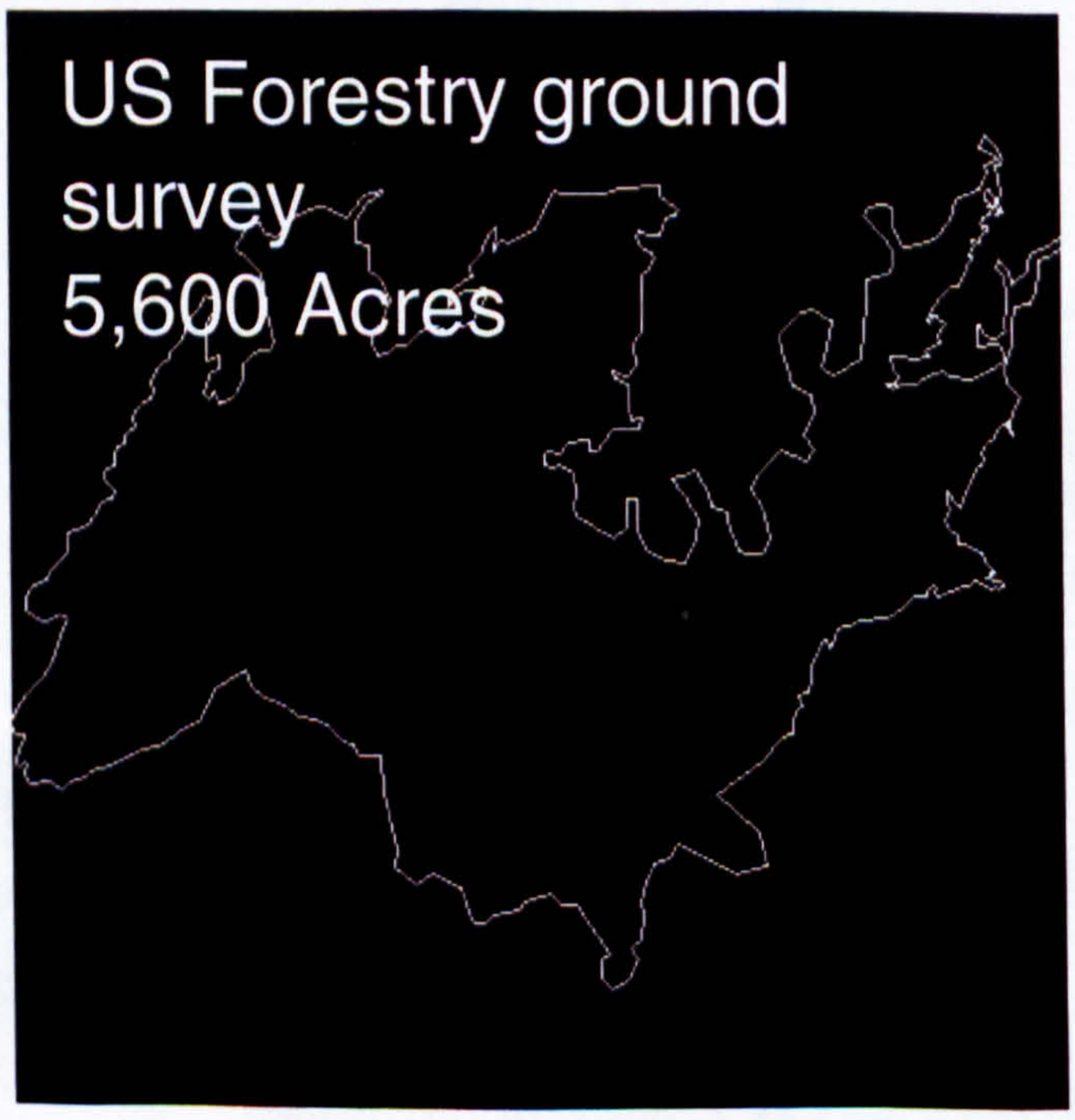

Figure 5.9 Ground Survey of Alaskan Forest Burn Scar

Fuel Maps/Models and Fire Danger Maps/Risk Indices

The Canadian Forest Service (CFS) and Canadian Space Agency (CSA) is funding a project to build a Land Cover map of Canada using Landsat, as part of a project called Earth Observation for Sustainable Development of Forest (EOSD). Often a Land Cover map is the starting place for creating a Fuel Type map.

It is estimated that it will take approximately 3-4 years to acquire all the LandSat images for the map [38]. This is an area where the DMC, with its daily revisit and wide-swath coverage could be of some value.

The frequent imaging opportunities of the DMC could also be used to provide regular timely, large area updates of NDVI to fire danger/risk index models. Ancillary information for such models (e.g. surface temperature (for Fuel Moisture Content, as calculated by Chuvieco) and weather information would need to come from other sources. Ideally the DMC would have a SWIR band to help such applications. This is something that could be considered for future DMC missions.

Damaged Forest Areas:

Blow-down Events

Another application is that of 'blow-downs'. ie where areas of forest are blown over by high winds. This increases the fire hazard of the area affected. The main value of the DMC is in being able to rapidly acquire a cloud-free image soon after these events to map the damage. This is currently not possible in a quick timescale with Landsat due to the 16 day revisit, and is possible only with only a very coarse accuracy with e.g. the MODIS sensors. The suitability of DMC data for this application requires further investigation as described in Section 5.5.2.3.

Research into Insect/Disease Spread in the Forest

Another issue for fire monitoring and particularly fire research is that of insect infestation in the forest. It is quite possible for an area to be temporarily infested by leaf-eating insects and rapidly stripped of leaves before the insects move on to a new area. In the course of a week or so the leaves grow back and hence the insect visit may not be apparent from one LandSat image to the next (with a revisit time of 16 days). However, in the time that the leaves are stripped, the area becomes an increased fire hazard.

The MODIS sensors which provide near daily revisit are too coarse to accurately monitor the situation. The DMC with its 30-40m Ground Sample Distance and daily revisit could potentially be used to update fire hazard maps with such phenomena. However, it is also important to be able to capture the insect infestations in order to be able to study the pattern of insect outbreaks. This can also be applied to other diseases. This data could then be used to help model future infestations.

5.6. Summary of Wildfires and DMC Application

The above discussion indicates that there a number of areas where satellite remote sensing and earth observation has application to wildfire management. The potential data sources include SAR, Thermal IR, and optical data each of which has its own strengths but is not by itself a universal panacea.

With respect to the application of optical data, there are subtleties to be considered such as which particular spectral bands provide the best results for a particular application with a particular forest type. However, NDVI using Red and NIR bands (as available on the DMC) has been widely used in a number of studies to good effect.

AVHRR data has also been used in a number of studies due to its daily revisit capabilities. However, the low spatial resolution has typically been mentioned as a limiting factor. Recent improvements have been made by the availability of the MODIS sensors in orbit, on the NASA Aqua and Terra spacecraft. However, these still provide only 250m resolution.

The discussion in this section indicates that the DMC has great potential to add value to applications such as burn scar mapping and evaluation of damaged forest areas due to e.g. blow-down event or insect infestation. It also has potential to act as a source of NDVI data for input to fire danger models.

Potential improvements to future DMC constellations, of particular value for fire applications, would be the addition of SWIR (for more direct measurement of fuel moisture content), and Thermal IR channels (for fire detection and to assist burn scar mapping). Also, increased imaging capacity to allow routine production of e.g. 10day composite products over a given area would be beneficial to more effectively exploit the daily revisit capability and reduce the effects of cloud cover.

Hence in summary, the unique daily imaging opportunities and large image areas of the DMC hold clear potential for application to wildfire management.

5.7. Floods

The following quoted information taken from the NASA Earth Observatory Natural Hazard service [15] for a period in 2002 and 2003, highlights the potential devastating impact of floods:

- May 2003, heavy rains in Argentina led to devastating floods that displaced 35,000 people and killed over 25 people in the province of Santa Fe.
- May 2003, snowmelt from the Cacaucus Mountains combined with heavy rains led to flooding in Azerbaijan. The floods displaced thousands of people along the Araks and Kura rivers and caused over $50 million in damage.
- April 2003, heavy rains in Afghanistan led to floods that killed 30 people and displaced hundreds.
- March 2003, heavy rains in Zambia led to floods that displaced over 10,000 people and destroyed thousands of valuable acres of farmland.

- Madagascar January 2003, floods throughout the country killed 13 people and forced several thousand from their homes.
- Unusually heavy rains hit Morocco in late November 2002, giving rise to floods that killed more than 60 people.
- During the summer of 2002, frequent, heavy rains gave rise to floods and landslides throughout China that killed over 1,200 people and affected millions.
- August 2002, heavy rains in Central Europe led to some of the worst flooding the region witnessed in more than a century. The floods killed more than 100 people in Germany, Russia, Austria, Hungary, and the Czech Republic and led to as much as $20 billion in damage.
- August 2002, heavy monsoon rains led to massive flooding in eastern India, Nepal, and Bangladesh, which killed over 500 people and left millions homeless.
- July 2002, S.E Texas. At least seven people were killed by floods, and hundreds were evacuated from their homes. The governor declared 28 counties a state disaster area.
- June 2002, heavy rains inundated southern Russia, giving rise to floods that killed up to 83 people and drove thousands from their homes.
- June 2002, Zeyzoun dam in northern Syria ruptured and collapsed, killing 20 people and leaving thousands more homeless.

Clearly, the damage from floods is not something that man has yet managed to successfully control in all circumstances. Any information that can help in the mitigation of the effect of floods clearly holds value. Satellite technology is already used somewhat in the prediction and monitoring of flood events. This is discussed in the following sections along with the additional capability made possible by the DMC.

5.7.1. Current Image Data Sources for Flood Applications

The description given in the DMSG final report [56] breaks down the Flood Disaster Management Cycle into stages of Prevention, Mitigation, Preparedness/Warning, Response and Recovery.

The flood application area of most relevance to the DMC imagery, and in particular relevant to the data timeliness, is that of estimating flood extent and areal coverage during the Response phase of a flood emergency response.

Whilst satellite meteorological data is used to a great extent in flood management activities (e.g. precipitation forecasting), this area of application is not described here as it is so far removed from the potential DMC application area.

One other flood application area perhaps worth a mention though, is that of the Soil Wetness Index as a useful input to flood models. The lack of a SWIR band on the DMC means that this is not possible with the first DMC constellation. However, along with a number of other application areas, this might be a useful application should it prove feasible to include a SWIR band on a future DMC constellation. The SSM/I on the DMSP is described in the DMSG report as providing an experimental Soil Wetness Index product, available in real-time on a twice daily basis. However, the report also

notes that this does not have the resolution of SAR missions, SPOT or Landsat data (which in turn do not have the temporal resolution of the DMSP product).

With respect to the main foreseen flood application for DMC data, i.e. flood extent monitoring, there are a number of satellites in orbit that are able to provide useful imagery.

Current satellite SAR sensors and optical sensors with useful optical bands (e.g. VNIR/SWIR) for flood monitoring are listed below, as listed by the flood hazard team in the CEOS DMSG final report [25].

Satellite System	Description
ALOS*	Optical, Radar
DMSP	Optical, IR
ENVISAT	Radar, Optical, IR
ERS 1 and 2	Radar
Ikonos 1 and 2	Optical
IRS	Optical
KVR-1000	Optical
Landsat 5	Optical
Landsat 7	Optical
NOAA-GOES	Optical
NOAA-POES	Optical, IR
OrbView	Optical
Quickbird	Optical
Radarsat-1 and 2*	Radar
Resurs-01	Radar
SeaWiFS	Optical, IR
SPOT 1-5	Optical

Table 5.4 Satellite data sources for flood applications, as listed by CEOS DMSG
* planned

Not listed above but of particular note, and currently used by Alertnet, is the MODIS data from the Aqua and Terra satellites. These recent satellites now provide 250m-500m GSD optical imagery in the morning and afternoon of every day (including suitable bands for flood monitoring).

Among the conclusions of the DMSG Flood Hazard Team final report were:

- Increase temporal frequency of polar orbiting satellite data acquisitions
- Decrease time required to acquire and deliver remotely sensed data
- Lower the cost of remotely sensed data

These are areas that should benefit from the DMC mission.

Another area of recommendation from the DMSG Flood Hazard Group was that of improved international co-ordination of data acquisitions, although this has been addressed somewhat in recent years by the commendable efforts of the International Charter.

The DMSG Flood Hazard Group also derived tables listing a number of flood applications, along with the phase of the flood management cycle to which they are relevant, and the useful data types along with threshold and optimum values for spatial resolution and temporal resolution. The particular areas relevant to the DMC as a data source are listed below.

Application	Threshold*	Optimum**
Land Use (Pre-flood) multi-spectral imagery	30m	4-5m
Flood development and flood peak (during flood/post flood) SAR/multi-spectral/visible panchromatic/IR	≤30m	≤5m

Table 5.5 DMSG Flood Hazard Group: Data Spatial and Temporal Threshold and Optimum Values

* Threshold refers to the level below which there is no significant usefulness

** Optimum refers to the level above which there is no significant improvement in usefulness

The threshold presented in Table 5.5 proposes 30m. However, is 32m really a significant difference? Or even 40m? It is difficult to draw a solid threshold for an application such as flood extent monitoring, particularly without any reference to the scale of the flooding under consideration. Hence it is assumed here that the DMC data GSD of 30-40m is not far enough below the DMSG defined threshold to significantly reduce its usefulness.

5.7.2. Application of Different Data Types

5.7.2.1. SAR Data

SAR data has the advantage of being able to penetrate cloud-cover which can be a significant advantage in a flooding event.

In addition to being able to overcome cloud cover, Wang [101] explains that radar data can, to some extent, penetrate forest canopy. L-Band is better than C-Band (Note RadarSat-1 and 2 are C-Band) but in any case, this is a capability not offered by optical data. Wang does however, conclude that ultimately a flood monitoring scheme that used optical, radar, DEM and river gauge data would be better than any of the methods on their own. An interesting satellite in this respect will be the ALOS satellite which is designed with an optical, radar and DEM capability all-in-one.

One of the advantages of the DMC data is the daily revisit. However, Brivio [102] describes a method using topographic data that can be used to retrospectively estimate the maximum extent of a flood, using an example of an ERS SAR image acquired 3 days after a flooding event when only 20% of the affected area was still flooded. In

principle such a method could be considered using optical imagery also. However, this would not aid early emergency response efforts, for which more timely data is required.

One disadvantage of radar sensors raised by [102] is that there can be a different classification of the acquired signal due to complex variables. This is especially so for single band, single polarisation radars. Hence multi-temporal change detection is best. Multi-temporal change detection is also a useful exercise with optical data. However, in the event that a suitable archived image is not available for change detection, an image based on optical data is typically more interpretable to an untrained user (for example a single NIR image might be used to indicate a delineated water boundary, depending on the scene).

The above points are made to highlight the fact that, although SAR data has a massive advantage in a flood situation due to its cloud penetrating capability, it does not, alone, provide a perfect solution to the flood monitoring problem. Hence the potential complementary use of SAR data and optical data should be considered.

5.7.2.2. Optical Data

Although the use of space based optical remote sensing can be compromised by cloud-cover, a significant amount of flood monitoring research has been performed in the past using optical imagery. A number of studies have particularly made use of the low reflectance of water in the NIR and SWIR bands, which make water bodies appear very dark in the image.

A research exercise by Colby et al. [96] after Hurricane Floyd concluded that a reliable method to identify floodwater can be achieved using change detection methods with LandSat 7 TM data. This exercise indicated that TM4 (0.76-0.90) + TM7 (2.08-2.35) (addition of) gave the best results. TM4 alone could allow confusion between water and asphalt areas (e.g. road pavements/rooftops) which could both appear black, whereas TM7 provided a difference. DMC does not have a Reflected IR band, and would hence be limited to the use of TM4 (plus TM2 and TM3). This would suggest that flooded areas with significant asphalt surfaces would need very careful interpretation, as the DMC data would not necessarily distinguish well between the two.

However, this research exercise also touches upon the main strength of the DMC system. A pre-flood image of the flooded area was used from July 1999. A flooded image was taken on September 30th, whilst the flood peak was estimated to be September 21st. It is explained that no other images were obtained during the flooding due to the 16day revisit of LandSat.

In the exercise by Colby et al. [96], it was found that the ability to delineate flooded boundaries under forest canopy was limited. The integration of DEM data along with river gauge readings helped model floodplain inundation and also helped identify flooded areas underneath the forest canopies. The DEM therefore allowed additional information that could not be obtained from the image data alone. The final product clearly showed flooded areas and nominal water areas, over a background image (TM7) showing non-flooded areas. Such a method could equally be used with DMC data.

This method is also described in [100] which also adds several notes of caution when using DEM data. Firstly the accuracy of the estimated extent of flooding using this method will depend on the DEM accuracy. If a figure of ±1m vertical accuracy is assumed (the RMS USGS DEM error quoted in [100]) then this can vary the estimated flood area depending on where in this range the actual topography lies. Secondly, this method can only be used within a reasonable distance of the river gauge reading being used. The sensitivity to both of these issues depends on the actual terrain of the area under consideration, being most sensitive in cases of low relief.

Sheng [101] suggested that this DEM method might be used to overcome local patches of thick cloud in optical imagery, whilst also pointing out that this technique may only be used where DEM data is available, which is not necessarily always the case, particularly in developing countries. However, in the case of the US for example, DEM data is widely available.

Whilst the above-mentioned studies concentrate on the spatial accuracy of flood extent monitoring using various spectral bands and ancillary data, Sheng [99] also stresses the importance of revisit times for dynamic flood monitoring. Sheng states that Landsat, NOAA/AVHRR and radar images are often used in flood monitoring. However, as floods can devastate in a short period of time, it is not easy to study flood dynamics with LandSat, ERS-1, JERS-1 and Radarsat. Sheng describes studies using NOAA AVHRR data to study the extent and area of inundation at different times, pointing out that during the two months of the flood, AVHRR provided a series of useful images whereas other satellites did not. Whatever the reasons may be for this, it is clear that there was not an easily available, timely source of data for this study other than the AVHRR data for which the relatively coarse resolution (>1km) is a disadvantage, a characteristic that the DMC could clearly improve upon with its 30-40m GSD. Interestingly, Brivio [102] also notes that sometimes AVHRR is also sometimes the only available source of information.

Sheng also mentions that cloud cover is a major obstacle to flood monitoring using AVHRR but goes on to point out that a ratio image (Channel 2/Channel 1, or NIR/Red) can be used to reduce the effects of thin cloud clover, a technique that could also be considered for the DMC, using the DMC NIR/Red bands (note that the DMC Red and NIR bands are not identical to the AVHRR bands and hence this should be evaluated in more detail, but the possibility is mentioned here).

Techniques should be applicable to MODIS. However, note MODIS is still only 250m GSD (and 500m GSD for the SWIR band is that is used).

So in conclusion with respect to optical data it can be seen that:

- NIR and SWIR bands have previously been used for flood monitoring studies with good results due to their low reflectance for water bodies
- SWIR allows better water delineation than NIR in the presence of asphalt surfaces

- Cloud cover is an issue with optical data
- Thin cloud cover effects might be reduced by using a band ratio method
- Daily revisit can help overcome some of the problems with cloud cover, and data timeliness to allow a level of dynamic flood monitoring.

5.7.3. DMC Application

Both literature and SSTL discussions with aid agencies have indicated that information on the extent of flooding and its daily progress can help improve disaster response, logistics planning, and direction of relief effort.

An example is illustrated by a description given by Pine [98] of the experiences of the local emergency services after a local snow-storm that led to flooding:

"For emergency service personnel, response to calls to the 911 Center were complicated by a lack of information on high water along roads, bridges, or areas inaccessible because of the snow. In addition, local officials had no local information to predict the extent of flooding or information on which to base warnings to residents on high water in their area."

From the discussion in the sections above it is apparent that, whilst an improvement may be made by the addition of a SWIR band, the NIR band of the DMC data can provide good water body delineation in a number of cases and may be of potential use for monitoring the extent of floods.

Optical data is often considered ineffective for progressive monitoring due to the inherent cloud cover problems [103]. The daily revisit capability of the DMC however will largely alleviate this problem compared to existing 30m solutions such as Landsat7 which provides a 16 day revisit. In addition to being interpreted on a daily basis, a daily image at 10:00 local time could also, for example, be used to create a weekly mosaic, through gaps in cloud cover, in order to give the most complete view on a weekly basis, plus incremental part cloud covered views on a daily basis of the changing extent of flooding.

A very quick visual interpretation of the data could indicate the probable water-covered areas (e.g. simply by looking at the black areas in the NIR image). If the observer has a knowledge of nominal water coverage in the area this would give an immediate idea of newly flooded areas and hence where to focus efforts. Even if not 100% accurate, in this instance some information is better than no information as it would simply improve the 'probability' of focussing efforts in the best areas. As mentioned above, such an image could be updated daily to provide information on the progress of the flood boundaries.

More useful and easily interpretable information may be obtained from the DMC data if used in a value-adding process. For example, a change detection process may be performed using pre and post-flood images to plot nominal water bodies and flooded areas in clearly differentiating colours over a base map. However, such a process should be kept simple enough to be performed rapidly, bearing in mind the importance of data

timeliness. An automated value adding process would be ideal, although the potential presence of clouds in the image may cause some issues for such an automated scheme, particularly due to the lack of a SWIR band (although if the clouded image is used as the base image on which to overlay the detected water-covered areas, the clouds should still be made visible in the image to aid user interpretation). A SWIR band on future DMC missions might also add much value in providing soil moisture content information, which can be particularly valuable in a flood scenario, when combined with precipitation forecasts.

Consideration should be given to the use of a ratio product for flood applications to reduce the effect of thin cloud cover.

SAR data provide a large advantage in the event of cloudy weather above the observation area. However, there are currently no SAR missions that can provide a global daily revisit opportunity. RADARSAT has a mode that allows a 500km swath with ~100m spatial resolution which allows good revisit times, but unfortunately not global daily revisit. In addition, it is not necessarily always the case that SAR data will be available for any given flooding event, particularly in an on-demand rapid response scenario.

MODIS data is currently used by Alertnet [104] due to the timeliness of the data (almost daily) and its availability. This has proven to provide useful information in terms of a coarse idea (250m pixels) of the region affected, but could be greatly added to with the availability of 30-40m data.

The maximum DMC image size is in excess of 600km swath width and 500km along track. This allows very large areas to be surveyed, enabling regional coverage in a single pass. Yet the image resolution allows details of infrastructure to be detected sufficient to discriminate e.g. roads and rail lines cut off by floods.

Hence, it is concluded that the daily revisit opportunity for the DMC data, together with its potential large image size combined with a 30-40m GSD, makes the DMC a unique potential tool for flood extent valuation and monitoring that might be used alongside other space systems, such as SAR systems.

5.8. Other DMSG Hazard Classes

Whilst fires and floods were looked into in more detail, some other hazard areas, as categorised by the CEOS DMSG have been looked at very briefly. The purpose of this is to give a first level discussion of the areas that might most obviously benefit from application of DMC data, as well as to highlight those that do not stand out as areas warranting priority study effort. As with fires and floods, further study would be required to lead to actual useful application of the data, for example in pilot projects.

5.8.1. Earthquakes

Earthquake infrastructure damage can be assessed directly by using high-resolution imagery, such as that available from the IKONOS satellite. This is not possible with 30-40m GSD imagery.

However, studies have been performed using SPOT and Landsat data [105][106] that illustrate the usefulness of lower resolution data in damage detection from earthquakes. This is based on a change detection technique, whereby a small increase in brightness can be detected for damaged areas. In the Landsat study [106] it was shown that the brightness value for damaged areas increased significantly in the red and near-infrared bands (although the mid-infrared, TM Band 5, showed an even greater change). [105] used the SPOT HRV near infra-red channel to detect change in brightness and concluded with an 83% coincidence ratio. However, care must be taken with this technique as if pre-and post earthquake imagery is not sufficiently calibrated, e.g. to account for differing solar azimuth, then significant misclassification errors may creep in. For example, one study using a change detection technique with SPOT data obtained a positive confirmation of only one out 30 predicted possible damage areas when using high resolution IKONOS data for direct damage assessment as the truth [56].

However, if done carefully, the potential for data of a DMC Ground Sample Distance to ascertain areas of infrastructure significantly affected by earthquake damage is indicated by these previous works.

Potentially therefore, using the DMC, one could perform a rapid wide area assessment a day or so after an earthquake hits, to highlight the probable worst affected areas. This could aid in overall planning of the strategic response to a major earthquake (especially if combined with a suitable GIS product e.g. for demographics and infrastructure details) and potentially assist planning further high resolution acquisitions. Even if there are false alarms as well as positive identifications in the imagery, the technique could be used to at least improve the probability that the right areas will be investigated (even if not a 100% probability). In this case, as in many emergency response scenarios, some information is better than no information as long as the image interpreter and decision-maker understand the limit of the information.

After an earthquake, valuable information using a direct damage assessment method may be obtained from high-resolution space systems such as the IKONOS or Quickbird satellites. However, these space systems do not provide a rapid revisit capability and it may be a number of days before such information is available. The DMC cannot provide information as detailed as the high-resolution systems mentioned. However, using the change detection methods described the DMC has the potential to provide a rapid response (e.g. within one day or two) to assist in an initial early assessment of the scale of earthquake damage.

A quote from a news article [107] indicates the usefulness of a large scale method of ascertaining earthquake damage:

"Jones quoted one experience of the International Federation of the Red Cross. Responding to an earthquake in Turkey in 1999, they found the affected area stretched far beyond their expectations, stretching 110 km across. A satellite image would have identified the true scale of the disaster far sooner."

5.8.2. Landslides

The CEOS DMSG final report suggested that landslide assessment would typically require very high-resolution imagery for direct damage assessment. This suggests that the DMC data would be of limited, if any, use for this application. During the course of this research no evidence to suggest otherwise was discovered. However, very limited effort was put into researching this field due to time constraints.

5.8.3. Ice

The DMC mission has not been specifically designed with the imagery of ice in mind. In particular due to its cloud penetrating capability, SAR data is considered of particular use for ice mapping. For example, the design of the RADARSAT SAR instrument was largely driven by the Canadian Ice Service [108].

However, as with a number of applications SAR data does not necessarily always provide a complete answer to the problem.

The CEOS Ice Hazards team states that it is "extremely important that all ice centers have access to EOS data in the various spectral ranges (e.g. visible, infrared and microwave) to allow the most accurate analysis of ice conditions". Although RADARSAT produces excellent data, SAR data is not always able to give unambiguous interpretation. Here one could see the value of DMC as a potential complement to other sources. However, one would need to consider the application carefully. In particular, if intended for operational decision-making (e.g. for shipping) then it is unlikely that a newly programmed acquisition would be timely enough for its purpose, even with the DMC daily revisit. Images would most likely need to be routinely acquired alongside the primary SAR images e.g. of RADARSAT. In addition, the use of such imagery would need to be integrated into the operational procedure. The Canadian Ice Service for example already has a fairly well developed procedure and processing system for the use of RADARSAT data.

However, it should also be considered that not everyone has access to e.g. RADARSAT data where and when they want it. Optical data is not ideal in cloudy conditions but studies [109] using Landsat TM data have demonstrated the usefulness of optical data, particularly using the NIR band (as available on the DMC).

It should also be remembered that RADARSAT is a >$600million ($Canadian) mission. Although not necessarily ideal for ice applications, the DMC mission is another source of data available to the user community.

5.8.4. Oil Spills

The DMC image characteristics are not optimised for Oil Spill applications. Use of the farther Reflected IR bands differentiates between Oil and Water much more clearly and may be considered for future constellation missions but these are not flown on the current DMC. Also, optical bands are of limited use over clouded areas, whereas SAR does not have this disadvantage. However, it is often the case that when one looks closely at what is available and thinks carefully one can make much use of what exists.

Remote sensing methods, whether SAR, optical, or Thermal InfraRed, can provide False Positives (i.e. oil spills can be interpreted where none actually exist) and False Negatives (i.e. actual oil spills are not detected). Jones [110] and Fiscella at al.[111], for example, explain how SAR imagery may be falsely interpreted due to natural films such as algal blooms, or simply due to variations in wind speed and hence surface waves.

A combination of Remote Sensing methods (i.e. SAR/optical) might be used to reduce the number of false interpretations. Whilst not specifically designed for Oil Spills it is expected that the DMC imaging data may have the possibility of providing a valuable complement to, for example, the SAR data of other missions. Whilst Bands 2 and 3 do not allow much differentiation between an oil 'mousse' and water, band 4 does begin to differentiate. Looking at each band on its own does not allow the mousse to be easily seen. However, there is evidence that the oil spill can be detected by simply displaying a band ratio of 4/3 as described in Sabins [57].

This preliminary investigation indicates that there is potential for a use to be made of DMC data in this area. To verify this, further research is required and a dedicated study using actual DMC data on a number of Oil Spill applications is recommended.

5.8.5. Volcanoes

The DMSG Volcano Hazard group considered two classes of volcanic hazard, each with quite different requirements:

- Volcanic Ash
- Proximal Hazards

Volcanic Ash
Francis [112] points out that information on the height of volcanic plumes and their rate of spreading is also needed as an essential input to volcanic ash dispersion models.

In addition, the application of volcanic ash plume monitoring is quite well serviced by other satellites (e.g. at 1km resolution) as described by the CEOS DMSG volcanic hazards group.

Whilst the DMC imagery can be used to detect volcanic ash, it does not, in the opinion of the author, really add a great deal more value to existing solutions for this application.

Proximal Hazards
No obvious major application is highlighted here with respect to improving operational response to volcanic hazards. The ground sample distance of the 32m DMC satellites is too coarse for direct-damage assessment, for which a high resolution satellite such as IKONOS or Quickbird would be necessary.

The DMC also does not have any thermal channels for hot-spot detection.

However, the DMC would provide the potential to be able to acquire multi-spectral 32m daily imagery from the start of an eruption event. This has not previously been available. If this were to occur, then the imagery could be studied in more detail to ascertain with more confidence whether there was any direct use in a relief operational scenario.

Cloud cover, must however be considered as an issue. Briole et al. [113] presented statistics on cloud cover for volcanoes around the world, stating that the long-term percentage varies from 33 to 70% of visibility. However, it was also stated that the best time for imaging, in terms of low cloud cover probability was between 10am and 12noon local time, which is satisfied by the DMC.

Francis [112] suggests that remote sensing has a role to play in the event of a major eruption in providing an overview of the situation, such as which roads and bridges are passable, where flooding has occurred, and which areas are most affected. Francis suggested that the most important requirement is that the data is available immediately. The cloud penetrating capability of SAR is somewhat offset by the fact that untrained users, such as relief workers, find SAR images more difficult to understand than optical images. This discussion suggests that, if the DMC data is the only data available, then it can add value to a situation in which large scale infrastructure damage has occurred. However, the hazards, e.g. lahars, would need to be quite large in order for the DMC data to successfully distinguish the affected areas.

Francis also touched upon various barriers to uptake of satellite imagery, suggesting that satellite data was too expensive for routine use. Francis also suggested that with a maximum frequency for general purpose sensors like Landsat determined by orbit repeat (e.g. 16days) the data would be no good even if affordable as it is just too long a time scale. The delays involved in scheduling a satellite (if not a routine acquisition) added a further issue.

Francis also praised the AVHRR system, saying that at time of writing the paper only one type of satellite data was routinely and reliably available, using simple turn-key ground equipment ($2-3000). This allowed real time images of plumes and large thermal anomalies and such equipment is becoming part of the normal facilities of many hazard study agencies.

5.9. Agriculture

The European unit, Monitoring Agriculture using Remote Sensing (MARS) [114] has several main activities:

- fight against fraud within the EU and the Candidate Countries as an element of the Common Agricultural Policy (CAP) and the 'Acquis Communautaire',
- crop yield forecasts in Europe and food security linked to crisis situations outside Europe in the context of the Global Monitoring for Environment and Security initiative.

Whilst the DMC NDVI may also be of general help in the first of these activities, it is the second activity of crop yield forecasts and food security where the DMC is expected to hold particular potential due to its revisit frequency.

Food Security
Timely information is needed on the food and crop situation by the EuropeAid Co-operation Office (AIDCO) for implementation of the European Food Aid and Food Security policy. Currently Spot-Vegetation data is received and processed on a regular basis, along with Global Meteorological models.

Spot-Vegetation data has a Ground Sample Distance of approximately 1km, in the same bands as the DMC but with an additional SWIR band. The main bands of interest for vegetation studies, however, are the Red and Near Infra-Red. A 30-40m GSD could, in many cases, be used to increase the classification accuracy. There is the potential for the DMC data to contribute as a complement to the Spot-Vegetation data, with the low resolution Spot data being used to routinely assess extremely large areas, with problem areas highlighted being then imaged by the DMC at the higher resolution. The rapid response and daily revisit plus the large swath of the DMC would all contribute to the particular usefulness of the DMC in this scenario.

The potential usefulness of the DMC in this example scenario, as a rapid zoom in on areas highlighted to be of interest by the SPOT Vegetation instrument, has been confirmed by the Sector Head of Food Security [115]of the MARS program at the EC Joint Research Centre.

Crop Yield Forecasting
It is expected that DMC data could add value to crop monitoring activities.

It has already been mentioned that the MARS group is interested in crop yield forecasting. Canada also regularly monitors crops (e.g. potatoes) in other countries so that they can compare the potential yields to those expected by Canadian growers.

In paper on operational crop forecasting, Glick et al. [116] suggested that a 16-17 day repeat period does not provide a sufficient revisit frequency, particularly once missed chances due to cloud cover are taken into effect. Glick presented a study using AVHRR data. The daily imaging capability of AVHRR means that one has a much greater chance of obtaining images on e.g. a weekly repeat timescale. It was pointed out that AVHRR covers a very large viewing angle (~56°), but that a procedure had been developed that accounted for this. A similar thing would most likely need to be done for the large viewing range of the DMC data. Glick described a correlation between AVHRR Channels 1 and 2 (Red and NIR) and crop yield. Glick also suggested that if the satellite data is used to indicate the time of heading of wheat, then this information could be used to more closely track meteorological data around that period. Weather conditions at the time of heading of wheat are critical in determining the final yield. Hence Glick concluded that AVHRR data could be used to provide useful information on crop phenology and also has potential as a useful input to a yield model. The DMC also has Red and NIR bands, and a daily revisit capability, but has a 30-40m GSD rather

than a >1km GSD. Hence, monitoring could potentially be performed more accurately at a smaller scale.

5.10. Other Application Examples

Elephant movement monitoring with respect to bushfire activity
SSTL has received enquiries about the potential use of DMC data to assist in the study of elephant movement in relation to bushfire activity. The movement of elephants can be monitored fairly easy by simple electronic tagging. However, up until now, it has not been possible to monitor bushfire activity on a frequent enough basis for correlation with elephant movements. The DMC, subject to further study, might provide a solution to this problem.

Mapping e.g. all of Greece's fires in one or two images
SSTL has received enquiries with respect to the potential use of the DMC large area coverage capability to image, at 30-40m GSD, all of the fire affected areas of Greece in a single image. This would allow the mapping and damage assessment of burn scars at the beginning and end of the fire season without the need for mosaicing of numerous, e.g. Landsat images, with the associated image processing, as well as data availability complications.

Insect breeding grounds in the desert:
Locusts breed such that new locusts hatch just as vegetation starts to appear. By monitoring NDVI, looking at vegetation growth and combining this with knowledge of rainfall areas and also wind direction potential locust breeding/hatching grounds can be predicted.

AVHRR data has been used in the past [117] for such applications but is limited by its low resolution. The 30-40m GSD of the DMC imagery can pick out much more detail and allow much better targeting of areas. This would allow a ground truth team to enter and apply pesticides relatively accurately to prevent locust hatching.

Landsat has been unable to satisfy this application due to its long revisit period. For example, imagery would be wanted every 10 days or so of the potential locust breeding grounds (typically in the same broad regions annually). Although Landsat has a 16day revisit period, one instance of cloud cover then means that there would be over 30 days between images, by which time vegetation and locust hatching may well have advanced too much.

Forest clear-cutting
In Canada, forest clear-cutting is a big issue [38]. DMC data has potential use for environmental groups to monitor forest activities. Once a month might be adequate, but in the past Landsat imagery has been is too infrequent to provide reliable updates. With the daily revisit of the DMC constellation this is an area where the DMC would be able to greatly improve upon the currently available data sets in terms of timeliness, coverage and costs.

Droughts

Whilst the DMC was envisaged for monitoring of rapid-onset disaster situations after the event, there is potential value for DMC to act as a tool in prediction and mitigation of drought disasters. The potential of DMC data to assist in food security has been mentioned in Section 5.9. It has been suggested [55] that DMC data, via its potential to provide regular and timely (e.g. weekly or fortnightly) images of vegetation development, would provide a useful tool for prediction of drought and famine conditions, and might be of interest as an input to the Famine Early Warning System (FEWS).

Cloud Cover

One of the biggest issues with Landsat data is cloud cover. With a revisit time in the region of 16 days, the time to acquire a largely cloud free image of any given area rapidly in the event of several cloudy images in succession. For example, the first image may take up to 16 days. If this is cloudy then the next one may come after 32 days. If there is cloud in this second imaging event then the next one may be after 48 days from the time of originally wanting the image, and so on. With the DMC mission the potential delay due to cloud in achieving a suitable image is much less as imaging opportunities arise daily.

General

In addition to the applications described above, which concentrate on the daily revisit, rapid response and/or large swath width, it should be remembered that the DMC provides a low-cost alternative solution with respect to many other Landsat applications that require the Red, Green, and Near Infra-Red bands. Even if these applications do not rely on the rapid response nature of the DMC imaging and thus could be currently satisfied by e.g. Landsat[1], it may be considered that the DMC mission is a large step towards a micro-satellite mission that can provide a real operational level of service that can meet the needs of a user community, at a fraction of the cost of larger missions.

Whilst Landsat7 is an excellent technical achievement and the technical specifications exceed those of the DMC, the $600-700million USD cost of Landsat7 should also be compared to the <$10million USD cost of a DMC satellite. The DMC mission is a significant step towards the demonstration of the real potential usefulness of micro-satellites in the field of Earth Observation. Future developments along this trend may well mean that many user community needs can be addressed at an order of magnitude less cost (total solution cost, not data price) than current solutions, allowing the high specification, high-cost missions to be focused on applications that specifically require the additional technical benefits of the more expensive mission.

5.11. Summary of DMC Applications Considered

This chapter has given an overview of the main DMC data characteristics and limitations.

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[1] Note that at the time of the writing of this thesis Landsat7 had experienced a significant degradation in image quality due to a problem with its scan line corrector

The chapter also describes potential use of DMC data in each field of disaster management. In addition, several non-disaster related potential application areas are described. The chapter concentrated on the unique aspect of the DMC mission, i.e. the low-cost rapid response mission objective, daily imaging revisit and the large area swath with 30-40m Ground Sample Distance.

The applications described in this Chapter are listed in Table 5.6 below. Table 5.6 also indicates whether the application is made possible, or facilitated more easily, by any or each of the unique DMC aspects; Rapid Response, Daily Revisit, Large Area, Low Cost.

Application	Rapid Response	Daily Revisit	Large Area	Low Cost
Natural Hazards Disasters				
Fires				
Daily monitoring of progress of fire boundary (for research into fire growth models)	Y	Y		Y
Burn scar damage assessment – throughout fire season		Y	Y	Y
Burn scar damage assessment – end of fire season		Y	Y	Y
Insect infestation monitoring and research	Y	Y		Y
Floods				
Daily monitoring of flood boundary to assist with operational flood response	Y	Y		Y
Assessment of flooding situation over a large region (e.g. 600km wide)	Y	Y	Y	Y
Ice				
Daily monitoring of ice	Y	Y	Y	Y
Ambiguity check for other satellite data, e.g. SAR data	Y			Y
Oil Spills				
Ambiguity check for other satellite data, e.g. SAR data	Y			Y
Daily monitoring of progress of oil slick/continued ambiguity check	Y	Y		Y
Earthquakes				
Large scale assessment of locations of earthquake damage	Y	Y	Y	Y
Landslides				
No application identified	-	-	-	-
Volcanoes				
No firm application identified.	-	-	-	-
Drought				
Detection of signs of drought, via monitoring of vegetation development		Y	Y	Y
Agriculture				
Food Security	Y	Y	Y	Y
Crop Yield Forecasting (e.g. Potato)		Y	Y	Y
Other applications				
Monitoring elephant movements due to fires		Y	Y	Y
Large Area Mapping of Burn Scars		Y	Y	Y
Locust breeding grounds		Y	Y	Y
Environmental monitoring – forest clear cutting	Y	Y	Y	Y
General - overcoming cloud cover issues		Y	Y	Y

Table 5.6 Summary of DMC Applications Considered

The chapter is by no means intended to provide an exhaustive description of all potential DMC applications, or limitations, but instead the chapter illustrates that a definite potential exists for the DMC mission to provide a new and unique source of low-cost rapid response imagery that can be applied to improve upon the solutions already available for existing problems in areas of disaster management as well as other application areas.

The original expected emphasis of the DMC rapid-revisit applications was towards the operational use of the DMC data in monitoring and managing hazard situations. However, it is clear from this research into potential applications for the DMC that there is potential for the DMC data to add value to as a new research tool for several areas, rather than just as an operational tool for disaster response.

The chapter has successfully highlighted a number of potential areas where the DMC imagery may add unique value as a data source for various applications. To fully capitalise on this, value added products and services should be developed making use of the baseline DMC products for various applications.

6. Discussion and Conclusions

6.1. Rationale

The field of Earth Observation and remote sensing from space has been developing for many decades. Satellite platforms and sensors (optical) have been improving in many respects including Ground Sample Distance, choice and number of spectral bands, spectral resolution and radiometric resolution.

However, image data timeliness is still an issue to overcome. Although proposals have been made for moderate resolution[1] geostationary imaging platforms [118], it is still a general rule that for moderate-high resolution imaging more satellites are required if increased imaging revisit is required. The cost of traditional large satellite systems has, so far, meant that the design of an earth-imaging LEO constellation for global daily imaging revisit at a moderate-high GSD has been financially prohibitive.

The French SPOT system is a good example. The SPOT satellites, if operated together as a constellation, are actually capable of providing a daily revisit, but this is a fortunate side-effect of greatly extended mission lifetimes for the earlier SPOT satellites. The cost of SPOT-5 (not including definition phase) was in the order of 500million Euros [119] so it can be seen that to launch a dedicated constellation of e.g. 3 SPOT satellites would be extremely expensive. In addition the SPOT constellation images a relatively small image area. High Priority programmed SPOT acquisitions are also very expensive.

So, whilst SPOT and many other large satellites offer excellent quality imagery satisfying many current user applications, there is much financial expense in designing a mission for rapid-imaging revisit due to the expense of the satellites themselves, and the expense of launching them.

Micro-satellites, with the potential of launching a constellation in a single launcher hold great potential for cost-effective constellation missions.

When researching this EngD it was clear that there were no satellite systems in place that could offer a global daily imaging revisit at e.g. 30-40m ground sample distance, with wide area coverage. It was expected that such a source of data could assist a range of user applications, particularly in the area of disaster monitoring.

Having identified this technical niche, a number of objectives could be derived for this project as listed in Section 2.6. These objectives mainly involved the successful development of a practical low-cost engineering solution to the daily imaging revisit problem, as well as further investigation of potential applications of the resulting image data. Associated personal development objectives were also defined.

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[1] Note: 'moderate' resolution is the terminology used by the Geostationary mission proposers and in this context refers to ~500m GSD. No Geostationary mission has yet been proposed to supply image data with a GSD in the order of 30-40m, as provided by the DMC.

Section 6.2 discusses the success in achieving these objectives.

6.2. Achievements

This section reviews the achievements made during this EngD project with respect to the original project objectives described at the end of Chapter 2.

These objectives were:

1.1 Perform the mission and system design of a unique low-cost micro-satellite mission to provide multi-spectral, 30-40m GSD global daily imaging opportunities - the DMC mission.

1.2 Identification of novel potential applications of the DMC mission

2.1 To develop the author's competence as a space mission and system engineer

2.2 To develop the author's awareness of EO application area issues and hence form a stronger link between EO mission and spacecraft systems engineering, and the end-user objectives

2.3 To develop the author's design, development and research capabilities

Objective 1.1

During the course of this project the author has performed the mission and system design for the Disaster Monitoring Constellation, as described in Chapters 3 and 4. The result is a design for a novel low-cost micro-satellite constellation that allows daily imaging revisit. The first of the DMC satellites, Alsat-1, has been launched and operated successfully in-orbit for well over a year, returning imagery that is being eagerly used by, and receiving good comment from, the Earth Observation user community in Algeria. DMC satellites for Nigeria and the UK were launched more recently.

The DMC imagery provides the unique opportunity to image, at 30-40m GSD, in Red, Green and Near Infra-Red bands a swath in excess of 600km, up to a maximum image size in the region of 600km x 500km. This allows very large areas to be surveyed, enabling regional coverage in a single pass. The image resolution, however, allows details of infrastructure to be detected sufficient to discriminate e.g. roads and rail lines. This capability was not previously available from any in-orbit data source.

The intention of the DMC mission is to act as a ½ pilot and ½ operational mission, providing a stepping-stone on to missions where SSTL micro-satellites might be used in fully operational Earth Observation rapid-response constellation missions. The DMC satellite has provided a giant leap in performance over previous SSTL satellites as described in Chapter 2, and the experience of the DMC mission development has certainly provided a valuable platform for SSTL to move onto further constellation missions.

As well as performing the satellite and top-level mission design, the author also worked closely with a team of astrodynamics experts to enable a mission suitable solution for constellation management.

The mission design and systems engineering for the Disaster Monitoring Constellation also involves consideration of the ground segment solution.

The result is a novel end-to-end design solution for a low-cost micro-satellite mission to provide multi-spectral, 30-40m GSD global daily imaging opportunities. Hence Objective 1.1 was met.

Objective 1.2
The author identified that a technical niche existed for 30-40m daily revisit imagery. Further research was then performed to provide evidence that this technical niche held new potential for a number of user applications.

Chapter 5 has described a number of potential applications for the DMC image data. This concentrated on the unique qualities of the DMC mission, i.e. the daily revisit capability (at 30-40m Ground Sample Distance) and the very wide swath capability, coupled with the fact that this is provided by a low-cost mission solution. It is clear that a number of applications could benefit from such a data source. Hence Objective 1.2 was met.

Objective 2.1
The engineering of the DMC mission, working with a range of excellent SSTL specialists, has provided invaluable experience for the author. It is rare for anyone to have the opportunity to act as the Technical Lead for three individual satellites taking them from the conceptual phase to launch and successful operations in such a short space of time. It is even more rare to have the opportunity to lead the design activities to operate the satellites as part of a constellation mission with the associated orbit analysis, control and operational implications. In addition to this the 'hands-on' work as the Assembly, Integration and Test Manager for the UK-DMC satellite has provided invaluable experience to contribute to 'closing the loop' on the systems engineering and ensuring a greater understanding of the practicalities of actually physically building and testing the spacecraft design.

During the course of this project several of the spacecraft were built with Technology Transfer customers on site, and the author had several customer engineers as students throughout much of the project. There is an old saying that it is not until you try to teach something that you really realise what you do and do not know. This was certainly found to be true and the teaching of the DMC systems engineering to these students was a very valuable experience, forcing the questioning of reasoning and knowledge in many areas along the way.

At the start of the project the author was a Systems Engineer with theoretical knowledge and various elements of practical experience but with no experience of leading a

mission and spacecraft design. This project has allowed the author to progress to a confident Systems Engineer.

Objective 2.2
The research into various potential application areas for the DMC image data was extremely valuable. The understanding of the author of the advantages and limitations of various types of image data is greatly increased as a result of this project, and as such the project has certainly increased the effectiveness of the author in considering Earth Observation missions at the user requirements level.

It also importantly highlights without doubt the fact that the engineering of the satellite and mission technical solution to provide a raw data source is just a part (albeit a large part in terms of effort) of a bigger picture. For each user application the whole supply 'chain' to get the product to the user in it's requisite format (e.g. whether raw data, annotated maps or simply information in text), is important and should be considered when considering specific applications.

Objective 2.3
This project has provided an excellent challenge and experience for the development of the author's design, development and research capabilities. To demonstrate, it is useful to comment on some of the EngD requirements that were listed earlier in the thesis in Section 1.1.

- *Ability to assimilate and assess existing knowledge.* The research into existing missions, Earth Observation and remote sensing practices, and user applications was a massive exercise in information assimilation and assessment. The wealth of material and information available covering a diverse range of topic areas provided a great challenge in information assessment, distillation and final interpretation for the core purposes of this project. In addition to this, the design of the DMC satellite and mission itself involved a significant amount of assimilation and assessment of existing knowledge of the various sub-system engineers within SSTL.
- *Add to the body of applied engineering by undertaking and communicating the results of research in a systematic and ordered manner.* The DMC mission provides a unique new spacecraft and mission design and unique new data source, adding to the body of applied engineering. As technical lead for this mission, the author was responsible for the successful mission and system design of the solution. The system design and development of the spacecraft and mission was a significant effort. The research into potential applications was also a significant effort, requiring a systematic and ordered approach in order to identify particular areas where the DMC data may benefit potential users. The author has also co-authored several marketing conference papers on the DMC during the course of the project, one of which was selected for a special publication of Acta Astronautica [120].
- *Appreciate fully the potential of the research in its wider economic, social, technical and environmental contexts.* There are various potential impacts of the DMC in each of these areas. The potential new user applications each have their own potential economic, social, technical and environmental impact. In addition, the DMC is a step on the way towards more capable, operational small, low-cost

satellite systems. As small satellites become ever more capable there is a real potential for them to complement and even replace *some* of the functionality currently provided by traditional large satellites. Feedback to the SSTL marketing group indicates that the DMC has helped alert a number of people to the serious potential for small satellites to provide useful operational services. This recognition in itself has the potential to contribute towards the continued development of the satellite industry and peoples perception of future solutions to future problems.

- *Development of innovative thinking while tackling real industrial problems.* The DMC mission certainly posed a real industrial challenge with various real problems along the way.
- *Consideration of financial constraints, timescales and personnel management.* This EngD project was based on the DMC mission, which was a commercial project within the sponsor company. As such the project was operated with significant importance attached to financial constraints, timescales and personnel management. The author worked closely in conjunction with the DMC project and programme managers to ensure the proper consideration of these factors.
- *Must make a significant contribution to the performance of the company.* For much of the duration of this EngD project, the DMC satellite projects constituted a large part of the company turnover and profit. In addition, the strategic importance of the DMC mission as the company's first constellation mission means that this EngD project has made a significant contribution to performance of the company.
- *Achieve an appreciation of industrial engineering and development culture including:*
  - *The role of research*
  - *Product development*
  - *Marketing Awareness*
  - *Minimisation of environmental impact*

  The author was essentially immersed in a large industrial project, with significant product development. During the research and development, close contact was maintained with the company Head of Research and Development, as well as with all project stakeholders, including the customers, project managers and SSTL marketing group. This experience provided an excellent experience of the SSTL industrial engineering and development culture. Environmental impact of the DMC was also considered. For example, an orbit lifetime analysis was performed to illustrate the orbit decay within an acceptable period of time, and hence limit the constellation time as potential space debris in the future.
- *Teamwork and leadership skills.* Acting as the Technical Lead for the mission, and working with a number of engineers, customers and other project personnel provided an excellent basis for the development of teamwork and leadership skills.
- *Communication skills.* As above, the development of good communication skills, was essential to the success of the project due to the amount of teamwork and stakeholders involved in the project.
- *Ability to apply skills/knowledge to new and unusual situations.* As a significant new development, and the company's first constellation mission, this EngD presented many opportunities to apply the author's skills and knowledge to new and

unusual situations. This was particularly the case with the orbit control issues, which is a particularly new area to SSTL.

- *Ability to seek optimal solutions to complex or multi-faceted problems.* In the opinion of the author it is one of the most important skills of a systems engineer to be able to deal with complex and multi-faceted problems to arrive at the best solution. The DMC mission and system development inevitably required consideration of all sub-systems and mission parameters, including performance, cost and schedule (and human factors as mentioned in a bullet point above) when addressing any problem.

6.3. Management Aspects

There are many aspects of this EngD project for which the EngD management studies were helpful. For example, some potential barriers to uptake of the DMC image data were discussed earlier in the thesis.

An area that was also found to be particularly useful to the author was the study of Organisational Behaviour and Human Resource (HR) factors. The increased level of self-awareness, and awareness of others from such models as Belbin, MBTI, power and politics, 'not-invented here', role definition and other HR study areas certainly benefited the author in the recognition and dealing with related issues.

The MBA studies, along with the EngD taught courses on technical innovation, also helped the author in understanding the inter-relation between the companies innovation strategy, company culture, organisational relationships, knowledge management strategy, mission stakeholders and marketing objectives, all of which had an influence on the DMC mission development process.

This EngD project also provided excellent experience of working as a central figure, alongside the project manager(s), in a large project. Experience was gained into project management lessons learnt along the way. The MBA project management studies provided useful background information to consider the strengths, weaknesses and potential areas of improvement in the project management of the DMC mission. In the opinion of the author the areas of greatest improvement could be had from increased involvement of the various project engineers early on in the mission to assist in a feeling of ownership and accountability for their units (including schedule) and the mission as a whole, and improvement of goal-congruence. A more substantial project start-up phase or workshop might assist in this area. Another area that could have greatly benefited the project would be training of engineers in project management activities such as schedule planning. This was found to be a weakness in this project, in particular due to the high number of new starters at SSTL. Ultimately, this programmatic issue may be partly translated into a technical risk, with less time available for testing, and necessary in-orbit development of some software functionality.

The project would have also benefited from a more clear definition of roles. The role of systems engineer was new to SSTL. The exact definition of the systems engineering role and in particular the relationship between the systems engineer, project manager and sub-system engineers was only loosely defined at the start of the project. This fact

was recognised but a clear solution was not presented. It was decided to proceed with the project and with this level of role ambiguity for the systems engineer and learn lessons along the way. The lack of clarity in role and responsibility caused various communication difficulties along the way that ultimately influenced project progress and project results. With the experience of this project it should be possible to learn from this and more clearly define the Technical Lead and Systems Engineering role for future projects.

It is not practical in this thesis to elaborate in detail on all of the areas mentioned above. This section instead mainly concentrates on providing a commercial context for the DMC using various frameworks and analysis tools from the EngD MBA studies as an aid.

- A business environment analysis (PEST, Porter's Five Forces) is performed for the small satellite market (and specifically with Earth Observation satellite constellations in mind).

Then internal influences are considered:

- A SWOT analysis is provided for the DMC mission in the context of the core business objective of the project – to demonstrate the potential usefulness of small satellite constellations and establish SSTL as a leading provider of small satellite constellations
- Perceived User Value (PUV) of customers for satellite constellations is considered

It is important in each of these discussions to be clear on whether the subject is SSTL as a small satellite supplier (current core business), or SSTL/DMC Consortium as an image data provider (new area for SSTL). Both are discussed here, as there is dependence between the two issues. The discussion of the commercial context of the DMC is given in Section 6.3.1.

6.3.1. The Commercial Context of the DMC Mission

The DMC is an important mission in the context of the company business strategy.

The SSTL marketing team describe constellations as the 'killer' application for small satellites, simply because large satellites are typically much more expensive to make and launch. This generally makes missions based on constellations of large satellites economically unfeasible, or at least difficult to make a funding case for. Small satellites might be considered an 'enabling' technology for constellation missions and the benefits they can bring.

SSTL's core mission statement is 'affordable access to space' and SSTL is already widely acknowledged as a world leader in provision of low-cost small satellite missions. The DMC mission is intended to establish SSTL's reputation as a leading supplier of small satellite *constellation* missions, and lead to future sales of small satellite constellations for SSTL. This may even be via a DMC-2 mission, which can build on the experience gained by the first DMC mission.

The DMC will be the first low-cost small satellite constellation for rapid-revisit earth observation, demonstrating the feasibility of using micro-satellites for an operational constellation EO mission. It is hoped to be a key component in demonstrating the potential of small satellite constellations and, along with other concept papers presented at conferences by the SSTL marketing group, stimulate further ideas in potential customers in the Earth Observation market. Hence the DMC is intended as a tool to help 'create' the small satellite constellation market in which SSTL hopes to prosper.

The Porter's Five force analysis presented below indicates that small satellite constellations may be a favourable market for SSTL (although it does not assess the market demand).

The move into the constellation market via the DMC mission is a good example of the strategic 'stretch' approach (i.e. 'Identification and leverage of the resources and competences which yield new opportunities or provide competitive advantage'[121]), and mirrors SSTL's product development approach.

Environmental Analysis

A PEST and Porter's Five Forces Analysis help identify the key business environment impacts on SSTL in the constellation market.

PEST

Table 6.1 presents a PEST analysis for the small satellite market, with particular attention given to small satellite constellations, although the issues are broadly the same.

The PEST analysis is useful when considering the issues involved in, for example, the management of an international collaboration to achieve a constellation mission. As can be seen from Table 6.1, it is clear that there are a number of areas, e.g. regional economic performance, political pressures, that can affect the signing of a mission. This is the experience of the first DMC mission where contract signing and Kick Off did not occur in the originally planned timescales for all satellite projects (hence the resulting multiple launch strategy due to individual mission delays). The PEST is useful to increase awareness of the potential interfering factors in order to be able to consider methods of risk mitigation. In some instances with different combinations of customers, it may be for example that the probability of program success is not acceptable and efforts should be focussed on a different framework for a mission solution.

Political / Legal	**Economic Factors**
-Possible relaxation of US export license laws in provision of hi-tech products to certain countries -Options for launch often limited by politics which continuously vary, particularly with regard to former Soviet Union rockets -There is generally a preference for any national space agency to look first to the industry in its own country to implement a space mission. -Political relations between countries amy help or hinder multi-national 'constellation' collaborations -Political uncertainties (e.g. elections) can delay contract signatures	- The strength of Sterling (business is mainly export). - Commercial/Operational missions are providing increasing pressure for the spacecraft manufacturer to share in the risk and financing of the mission until in-orbit delivery takes place -Regional economic situations can affect programs (e.g. delays), e.g. Asian Pacific region. The impact of such risks on a multi-national collaborative constellation would depend on the technical and commercial solution employed.
Socio-cultural factors	**Technological**
- Increased demand from taxpayers lead to tighter financial budgets for large space agencies, e.g. NASA/ESA. This is actually moving in favour of SSTL as they occupy a 'cost-effective' rather than ultimate-performance niche. However, it is also putting pressure on larger more traditional companies to move into this type of market and may increase competition - A lack of supply of well-educated young engineers produced by the UK education system is a resource problem	- With increasing emphasis on smaller missions worldwide the pace of technological change is increasing as larger risks are taken with new technologies on more frequent but smaller missions. Conservatism is still predominant in the industry, however, and revolutionary advances are rare. -Certain countries, e.g. France, have significant govt spending on space programs that provide their industries with an advantage in new technology development.

Table 6.1 PEST Analysis of the Small Satellite Sector

Porter's Five Forces Analysis

A Five Force analysis is given for SSTL as a small satellite provider, and as a small satellite constellation provider in Figure 6.1 and Figure 6.2 respectively.

The analysis indicates that there are some changes in the balance of forces depending on whether SSTL is acting simply as a small satellite provider, or whether SSTL is acting as a small satellite constellation provider.

As a constellation provider, although it is a generalisation, SSTL's power as a buyer increases due to the larger volume of business, hence reducing relative supplier power.

The barriers to entry for a new entrant to the satellite market are even greater for constellation missions due to the additional technical performance requirements and know-how over and above that required for a single-sat mission. Also, the financial stakes are generally higher than for a single satellite mission hence heritage and reputation can hold even more influence with potential customers.

In fact as the first small satellite constellation, the DMC mission establishes SSTL as the only current existing small satellite provider with experience of designing, building,

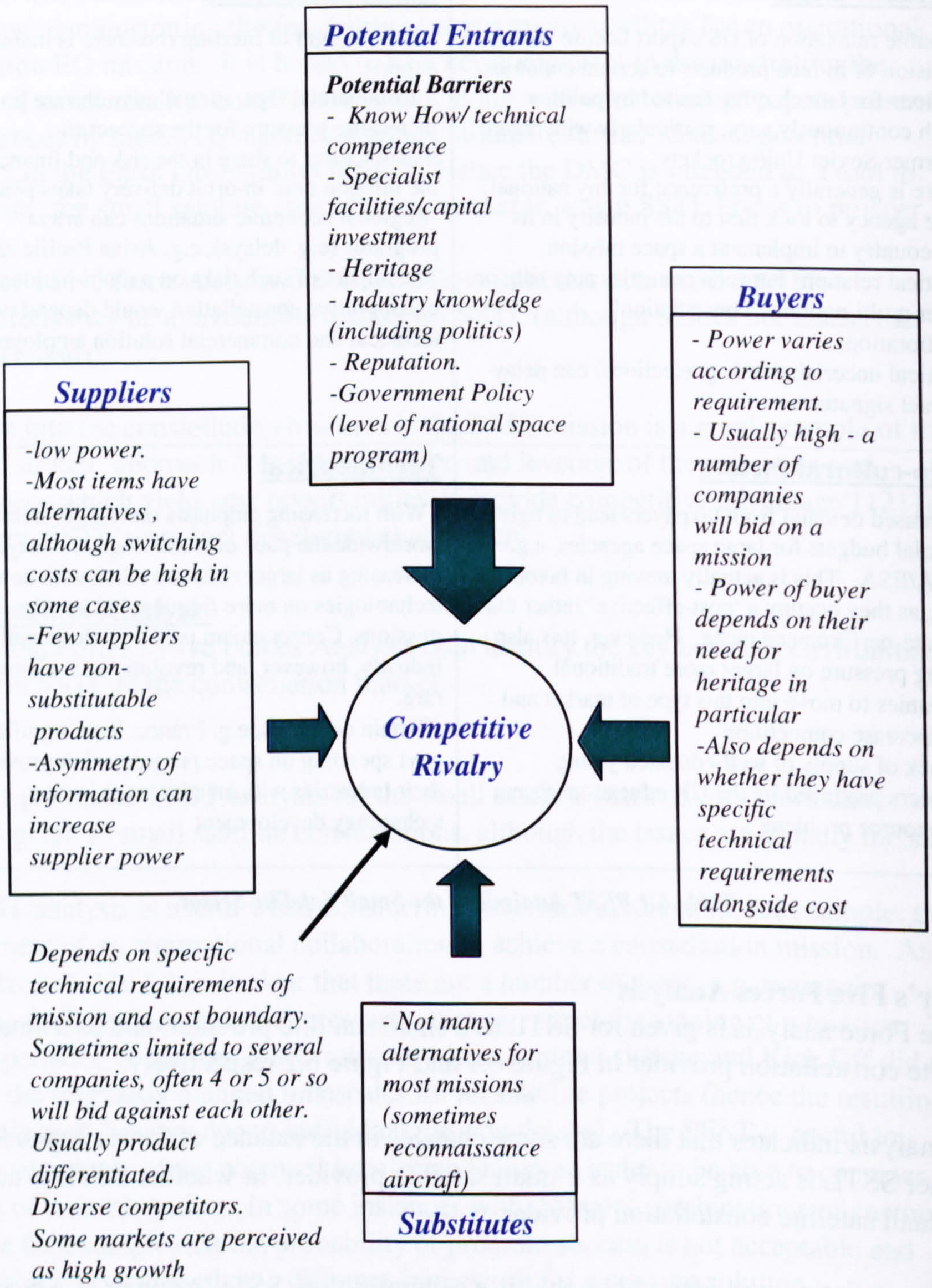

Figure 6.1 Five Forces Analysis – SSTL as a small satellite provider

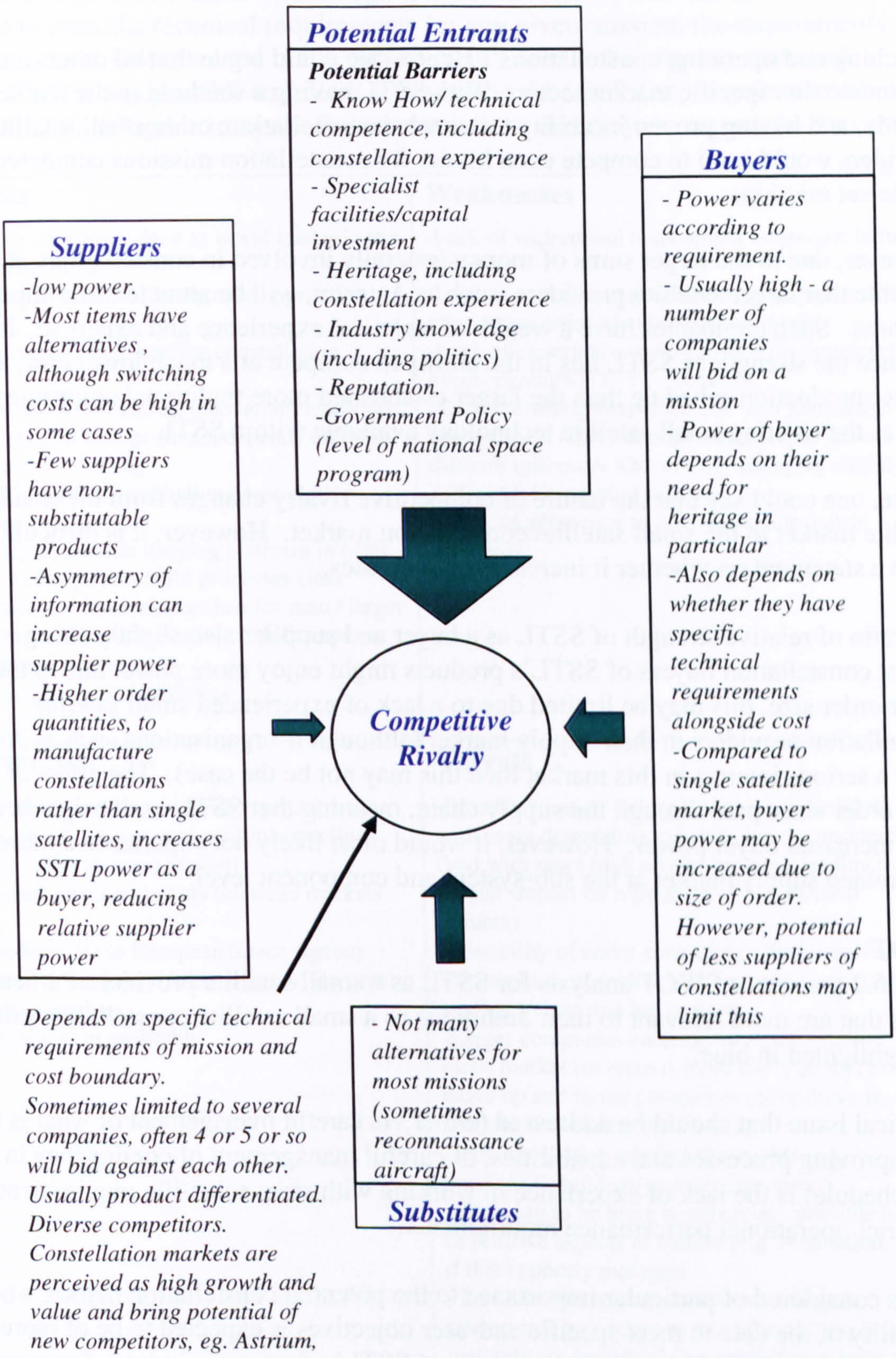

Figure 6.2 Five Forces Analysis – SSTL as a small satellite constellation provider

(The balance of forces changes for SSTL as a constellation provider, shown above, as opposed to a single-satellite provider as shown in Figure 6.1. In general, SSTL's power as a buyer increases, barriers to entry increase, and the power of buyers from SSTL slightly decreases due to the lack of other small satellite constellation providers with heritage)

launching and operating constellations[1]. Hence, one could argue that all others are new entrants to this specific market sector. With SSTL having a foothold in the market already, and having proven its ability to launch a constellation, other small satellite providers would need to compete even harder for constellation missions compared to single-sat missions.

However, due to the larger sums of money generally involved in constellations, it is possible that larger satellite providers, such as Astrium, will be attracted to compete for business. Such companies have a wealth of technical experience and expertise. In this instance the strength of SSTL lies in the ability to compete at a much lower cost, and shorter production schedule than the larger established more traditional companies, as well as the existing small satellite technology available within SSTL.

Hence, one could say that the nature of competitive rivalry changes from the small satellite market to the small satellite constellation market. However, it is difficult to make a statement on whether it increases or decreases.

The ratio of relative strength of SSTL as a buyer and supplier also slightly changes. Whilst constellation buyers of SSTL's products might enjoy more power due to the larger order size, this may be limited due to a lack of experienced small satellite constellation providers in their supply market (although if organisations such as Astrium show a serious interest in this market then this may not be the case). The effect of the large order sizes pass through the supply chain, meaning that SSTL itself might benefit from increased buyer power. However, it would most likely not experience a more constrained supply market at the sub-system and component level.

SWOT

Table 6.2 presents a SWOT analysis for SSTL as a small satellite provider. Particular points that are more relevant to their ambitions as a small satellite *constellation* provider are highlighted in blue.

A critical issue that should be addressed (either via careful management of what is taken on, improving processes and capabilities, or careful management of contingency in costs and schedule) is the lack of experience in working with strict scientific requirements, and strict operational performance requirements.

This is considered of particular importance to the potential constellation market where the ability of the data to meet specific end-user objectives is expected to be of more importance (see PUV discussion) than many of SSTL's previous missions, for example

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[1] For example, some particular issues for which SSTL can now demonstrate heritage, further differentiating itself from other small satellite providers include:

- Ability to manage the manufacture of multiple satellites
- Operationally useful propulsive capability on a microsatellite
- Ability to use this propulsive capability; injection correction and constellation orbit management
- Experience in launching and operating a constellation of satellites in a co-ordinated manner

which had a large KHTT aspect. Although it is not necessarily the case that it would be a problem to meet the technical requirements for any given mission, the requirements and expectations of all involved in the project would need to be properly managed. With the DMC it was possible to follow a 'best efforts' basis for any requirement above that of visually intelligible images. For other missions this may or may not be the case.

Strengths	**Weaknesses**
-Reputation - acknowledged as world leader in the small satellite market - successful 23 satellite history over approx 20 years -first to launch a small satellite constellation (DMC) -Culture (fun, collaborative, innovative, learning) -Marketing relationships (much depends on CEO contacts and reputation) -Technical capability (including constellation experience) -Ownership of satellite imaging platform in orbit -Innovative design and build processes (less bureaucratic and burdensome than for many larger companies more used to dealing with European Space Agency missions) -Academic links with University	-Lack of widespread commercial awareness in the company -Lack of experience in designing payloads and missions to strict scientific requirements -Lack of experience in operational (as opposed to experimental/KHTT) missions -Tacit knowledge/expertise and tacit knowledge management (KM) strategy makes rapid growth difficult (although KM strategy changing slightly still much knowledge is tacit) - Lack of adherence to international technical standards
Opportunities	**Threats**
-Constellation markets (establish reputation as first port of call for low cost, multiple satellite missions) (large forecast market) -Operational mission markets (increase markets served) -Increase business to European Space Agency -Penetrate US market (NASA business) (largest world space market) -Focus innovation profitably	-Possible mission failure becoming more likely with more demanding missions being considered (and with more high profile missions leading to greater impact on reputation of any mission failures) -Possibility of under-estimating effort involved in moving to more technically demanding missions leading to loss making projects -Larger companies entering the small satellite niche market (overlap is more likely as SSTL move up and larger companies move down in satellite size and performance) -New companies entering the market (e.g. previous technology transfer customers) -Changing to be more commercial - possible loss of positive aspects of culture (e.g. innovation, fun) if this is poorly managed - Possible loss of competitive advantage in operational procedure as more formal, explicit methods are employed (e.g. may 'throw baby out with the bathwater') - Must watch out for change from 'culture of responsibility' to 'culture of blame' as the company grows and becomes less personal, with more commercial pressure and focus

Table 6.2 SWOT Analysis of SSTL

Perceived User Value

It is worth bearing in mind that the value of a satellite mission to a customer is not necessarily just based on the end application for the data, although this is usually a large factor. Other example factors that come into play for a typical small satellite mission are illustrated in the PUV diagram shown in Figure 6.3. It should be noted that this is intended to be purely illustrative and is not based on quantitative data. It is simply meant to illustrate that the value of a mission is perceived to be across multiple areas, not just the obvious end applications. As an example, for the DMC mission, an additional bar could be added for Disaster Response applications to indicate the perceived value of this benefit.

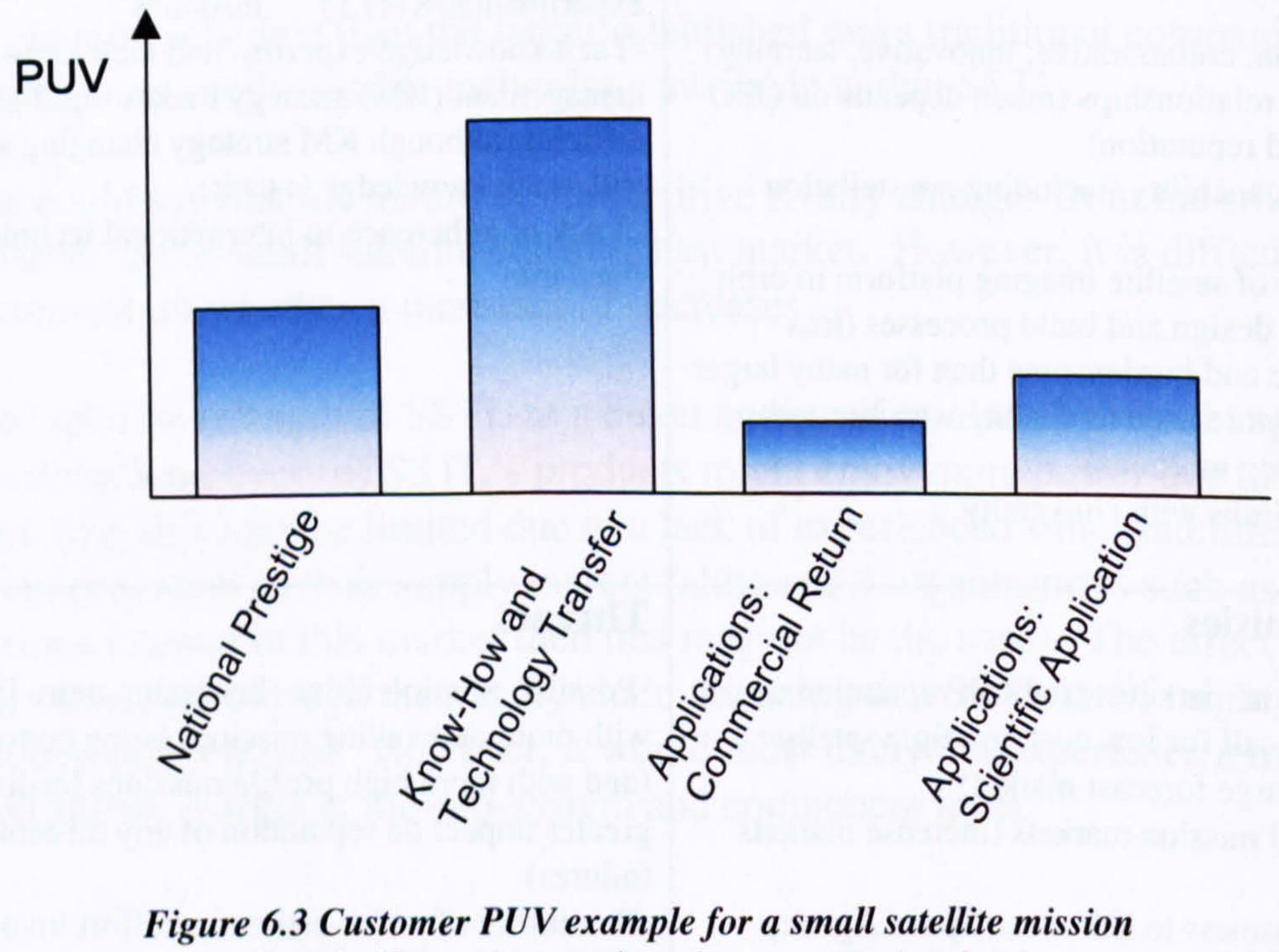

Figure 6.3 Customer PUV example for a small satellite mission
(purely illustrative, not based on quantitative data)

For the DMC mission, in the author's opinion, KHTT was a large PUV element for the individual missions involved. This may or may not also be the case for future constellations based on a similar model of collaboration of individual missions. This may lessen the need for strict requirements on payload scientific quality, or operational efficiency, described as potential risks in the SWOT analysis and allow a mission with 'best efforts' and 'targets' to be aimed at rather than strict requirements. It may also be the case that multiple individual customers for the same platform are potentially more profitable than a single customer, as any stand-alone substitute mission would cost the customer a significant sum. However, the environmental risks highlighted by the PEST analysis should not be forgotten.

For future satellite constellations with a single customer, it is expected that the usefulness of the mission for specific target applications will be a very large part of the customer PUV. The author believes that a greater knowledge in user applications and needs can benefit the long-term success of SSTL, particularly in the constellation

markets, where the end-user application may have a greater weight in the PUV than in many of SSTL's previous missions.

A greater understanding of user needs and imagery applications will allow SSTL to:

- More effectively direct R&D (for example on instrument development)
- More effectively market constellation missions (and other missions)
    - Allowing targeting of feasible missions
    - More effective discussion with potential customers, addressing their real needs and requirements
    - Encourage potential end-users to support SSTL, whether decision makers or influencers in the decision process.
- Reduce project risk that user needs and expectations will not be met

A further potential benefit is to assist in the potential venture into the image data provision market via the DMC image data.

Currently SSTL has very limited knowledge in the area of user applications for Earth Observation. However, it is considering its options with regards to acting as a data provider via the DMC mission.

The provision of DMC data is being approached in a collaborative manner by the DMC Consortium, which comprises the owners of the member missions. Data policy and collaboration principles are still areas of ongoing discussion.

Note that the incentive for SSTL to enter the data provision market is not necessarily profit. For SSTL, it is driven also by the need to ensure that the DMC data is exploited by user communities and hence help to demonstrate the usefulness of small satellite constellations. There is a balance to be found between underselling the DMC capabilities to potential data users, and overselling it and hence actually damaging the SSTL reputation in this area.

SSTL have recognised the importance (to the future business of further small satellite constellation sales) of the successful user uptake of DMC image data and demonstration of its potential usefulness. To this effect the company has recently appointed a DMC business manager who has the task of working with the user community to make the DMC a successful demonstration mission.

6.3.2. Summary of Management Aspects

This section has highlighted that the DMC mission and systems engineering has provided a valuable learning experience in related management aspects. Some points that have been mentioned earlier in the thesis are barriers to uptake of technology of DMC data and the importance of working effectively within a supply-chain. It was also mentioned that the project, combined with the management studies of the EngD provided an appreciation in many areas including various aspects of human resources, organisational behaviour and self-understanding, the influence of company culture, knowledge management, innovation strategy, and project management practice.

However, the main thrust of this section was to provide a commercial context for the DMC mission. Analysis tools were used to discuss the importance of the DMC mission to SSTL. The DMC mission is of strategic importance to SSTL in one of their major business objectives – to create, exploit and lead a market for small satellite constellations.

6.4. Limitations

This project has been successfully completed and the project objectives met as described in Section 6.2. A successful design has been performed for a novel low-cost global daily revisit mission, and a number of potential applications discussed for the resulting data. Three satellites of the project design are currently flying and successfully operating in-orbit.

However, there are several limitations of the solution and the work performed in this project that are particularly worth noting. These are discussed in this section.

User Barriers to Uptake and needs of the Disaster Relief Community
Potential barriers to uptake of the DMC imagery have been discussed earlier in this thesis. It was noted that one can provide a technical solution (DMC) to provide the data but this does not mean it will be successfully used.

This EngD project has highlighted the existence of potential barriers to uptake. In the opinion of the author, these barriers now pose the main obstacle in the potential successful widespread use of DMC data, within the disaster relief community in particular.

Whilst this EngD has provided top-level recommendations, such as pursuit of joint initiatives and pilot projects with disaster relief parties, solutions to the issues have not been explored in detail. Further work needs to be performed, perhaps within pilot projects, to think through and address the details of the potential barriers to uptake of the DMC imagery.

The DMC as a Commercial Mission
It was mentioned earlier in this thesis that the DMC is intended as a ½ pilot – ½ operational mission. It is intended to act as a demonstration mission of the potential capabilities of small satellite constellations - a step on the way to a mission that can provide a fully operational rapid imaging service.

As such the DMC has not been designed or evaluated as a commercial mission. The image throughput capacity and potential image demand has not been considered in a business context. This would of course be necessary if such a mission were to be considered as a business venture.

The fact that this commercial evaluation was not performed is not as strange as it may first seem. If one considers the Perceived User Value for the DMC satellite customers as described in Section 6.3, commercial return from imagery sales does not rate highly.

For several of the DMC customers the Know How and Technology Transfer aspect of the mission was extremely important. For them, this is their first steps into space - a beginning of a long-term program to build an indigenous space industry capability. Each country also has national applications for the satellite data, rather than a desire for commercial sales. In this aspect the project has been a great success. In addition, feedback to the SSTL marketing department indicates that the DMC has successfully demonstrated to many in the Earth Observation community the potential usefulness of small satellites, and that such daily-revisit imaging capability is a real possibility at an affordable cost.

A logical next step would be to evaluate potential data users and a business case for a follow-on mission, as well as improvements that may be made to the mission technical solution. For a commercial mission there are several technical aspects of the mission that should be given particular further consideration in order to approach such a venture prepared:

- Image throughput capacity/unit time (e.g. increase on-board data storage capacity, increase payload data downlink rate)
- Limitations of DMC image characteristics as described in Section 5.2.

The limitations of this first DMC demonstration mission generally arise from commercial or time constraints on the project. Whilst spacecraft performance can generally be enhanced with more design work and more money, one would need to be careful to not end up on a slippery slope to a much larger and more expensive spacecraft design. Each enhancement to the spacecraft platform or payload to improve performance needs to be evaluated in terms of overall spacecraft and mission impact. It is the job of the Systems Engineer to perform this in the context of the mission objectives. In this case, the DMC performance was taken as far as the project commercial limitations would allow.

User Application of the DMC Data

The original intention of the DMC mission at the start of this project was to provide 'visually intelligible' imagery. During the course of the project it was also decided that radiometric calibration should be performed on the payload in order to open up potential for further applications.

At the end of this project, there is much good feedback from users of the data already. Indeed, feedback from users of the first DMC data in Algeria indicates that for many of their needs the DMC data is as good as Landsat data. These customers are delighted to have the control and flexibility to schedule and receive images from their own satellite.

However, it must be acknowledged that the DMC imager design has not been driven by scientific requirements from the start. A significant amount of effort was expended in this EngD project in surveying a range of potential application areas that would benefit from the DMC data. However, for the more scientific and quantitative applications, detailed study and pilot projects would need to be performed in order to more confidently ascertain the suitability of the DMC data to the particular application.

A number of the above-listed limitations inevitably lead into recommendations as listed in Section 6.7.

6.5. Conclusions

A number of conclusions can be drawn at the end of this project:

- The primary project objectives have been met. The author has led the system and mission design of a novel low-cost solution to provide global daily imaging opportunities at 30-40m GSD, and potential user application areas have been identified. The secondary project objectives, related to the author's personal development, have also been met.

- The author has researched and highlighted a number of potential user application areas where the DMC mission offers an advantage over existing missions as a result of its unique combination of attributes; low cost, daily imaging revisit, large-swath, multi-spectral, 30-40m GSD. The DMC therefore has the potential to act as a useful complement to existing Earth Observation missions.

- The first DMC satellite, Alsat-1, has been launched and is operating well in-orbit. After more than a year in operation, feedback from the owner national Earth Observation user community indicates that the data returned is proving of much use. UK-DMC and NigeriaSat-1 have also been launched and are operating well, although have not been in service for long enough to receive feedback from user communities.

- The DMC provides the first low-cost solution for a global daily imaging revisit at 30-40m GSD.

- The DMC is the first civil application of Earth Observation micro-satellites designed to fly in a co-ordinated constellation.

- The DMC has the largest 30-40m GSD imaging swath capability ever achieved by a civil satellite.

- A significant amount of system and mission design work by the author was necessary to fully understand the scope of the problem presented in actually realising a suitable spacecraft design for the DMC mission. This is demonstrated by the difference in spacecraft solution presented in the original DMC papers after a pre-feasibility study [2], and the actual final design as a result of this project.

- The DMC mission demonstrates that collaboration between individual spacecraft owners, to operate in a co-ordinated constellation effort, can provide significant benefits to all. Whereas none of the individual DMC members might have afforded

a dedicated constellation of satellites, the pooling and co-ordination of resources provides otherwise unrealisable technical advantages for these customers.

6.6. Contributions to Knowledge

In this EngD project the author has identified a technical niche in the market that was not served by existing Earth Observation solutions in-orbit.

The author has then performed the system engineering for a new satellite design, and mission design, to enable daily opportunities of obtaining high-quality images anywhere in the world (excepting poles). This provides a brand new capability using a low-cost micro-satellite solution.

The research conducted by the author indicates that there is no other data source with the revisit times, wide coverage and ground sample distance to match that of the DMC. The unique combination of characteristics give the DMC image data the potential to act as a valuable complement to the already existing Earth Observation resources in-orbit.

The satellites designed in this project have been launched and operated successfully in-orbit, including constellation orbit manoeuvre operations led by the author, providing proof-of-concept that such a mission and capability can indeed be achieved using low-cost micro-satellites. Before this project, such a mission had been theoretically proposed at a basic concept level, but never attempted.

In this EngD project, the author has also identified applications that might benefit from the rapid response capability of the DMC mission. A number of applications that were previously not feasible are now feasible as a result of the DMC mission. Examples are wide-area rapid burn damage assessment after a wildfire, daily monitoring of flood boundaries, and timely monitoring of vegetation growth for locust population prediction and control.

Hence, this project has provided proof-of-concept that a low cost micro-satellite mission can provide a new capability for daily imaging that allows new, previously unserviceable applications to be considered.

In addition to this, the feedback received by the SSTL marketing group indicates that massive leap in performance made the DMC mission compared to previous micro-satellite missions has demonstrated to many just how far micro-satellites have come since the earlier days of purely experimental imaging missions. It is hoped that the DMC mission will indeed pioneer the way for a new wave of operationally, useful low-cost micro-satellite imaging constellations for rapid revisit.

6.7. Recommendations

Whilst the project objectives of this EngD have been successfully met, there are still many areas where further work would be useful. A brief bullet point list of ideas is given below:

- Work into the promotion of the use of satellite imagery and understanding of the factors that are preventing the widespread uptake of satellite imagery to aid decision-making in disaster relief work. Application of this to the DMC imagery.

- Further investigation into DMC image potential applications. Pilot projects, studies and trials using the actual DMC data.

- Development of value-added DMC Data Products, e.g. flood product and integrated process with ancillary data.

- Similar constellation design with additional channels for improved applicability to a number of user applications. Detailed study on implications on satellite platform demands for adding 1.5µm and then perhaps even 3 - 4µm channels.

- Study of DMC augmentation missions - e.g. additional satellites with smaller (but pointable) swath, high resolution, sensors, sensors in different bands, radar, observation at different local times.

- Study steps to increase system capacity and reliability for follow-on missions and improve commercial viability - e.g. X-Band transmitter for higher data rate to allow real-time data download, increased on-board storage, decreased power constraints, accommodation of redundant GPS unit etc.

- Study of on-board image compression to allow greater system capacity (although, note, if high latitude ground station used with downlink opportunity on every orbit, limited processing time available on-board to take advantage of this).

- Review of image direct user reception benefits vs. store and forward, along with in-line data compression options.

- Evaluation of the importance to the user of a World Reference Grid system approach (e.g. similar to Landsat), and potential implications to spacecraft propulsion solution and orbit control design (e.g. altitude maintenance required giving propulsion system redundancy concept implications).

- Consider potential for increased scheduling autonomy for future constellation missions; on-board scheduling of propulsion manoeuvres, on-board image scheduling based on target definition.

- Development of efficient logging and billing system for future commercial use.

- Evaluation of the commercial case for future missions similar to the DMC.

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APPENDIX A Findings and Recommendations of the CEOS DMSG

The following are the findings and recommendations of the CEOS Disaster Management Support Group as published in their August 2002 Final Report:

• *Finding*: There is a visible willingness within the disaster management and response community to give due consideration to new space technologies that will improve their operations. This tendency is reflected in the notable participation and interest of the community in the DMSG.

Recommendation: The space sector should be pro-active in responding to the receptiveness of the disaster management and response community.

• *Finding*: There is a general reluctance among the disaster management community to assimilate new technologies and information quickly, due to concern for introducing new, unproven technology into operational programs. They also often lack the time, resources, personnel, or technical understanding to do this.

Recommendation: In order to promote wider acceptance and use of space systems by disaster management users, the space and services communities must create the appropriate tools and continue to perform compelling demonstrations.

• *Finding*: Space technology has been demonstrated conceptually, however, the viability of operational reliance has generally not been fully demonstrated to the disaster management community. The central challenge relates to the promotion of mutual understanding and dialogue between the disaster management and space sectors.

Recommendation: The space agencies and applications community should invest in familiarizing themselves with the needs of the disaster management users and work together to the smooth transition from research capabilities to operations.

Recommendation: Recognizing the reluctance and lack of familiarity of some users to the use of satellite data, effort to be as accurate as possible in describing the capabilities and limitations of space-based observations must also be done. One should not oversell, and at the same time not understate, the true value of remote sensing.

• *Finding*: Timeliness, cost, accessibility, ease of use, reliability, repeatability, and demonstrated operational capability are all critical factors that affect successful incorporation of space systems and data into disaster management programs.

Recommendation: Space agencies should address each factor on its own merits, since user acceptance does not necessarily increase by trading one factor off against another.

• *Finding*: Several teams have identified the need for a broad-based data policy that would improve and assure access, timeliness and affordability of data, including (or especially) high-resolution data streams.

Recommendation: CEOS agencies should work together to advance common data policies, where possible, to facilitate ready, affordable access to Earth observation satellite data for emergency use. (The data charter, announced at UNISPACE-III by ESA and CNES, may provide a starting point for such a policy.)

• *Finding*: Timely disaster warning and response, and/or rapid response in support of a disaster situation, is the most important feature in the utility of satellite technology.

Recommendation: CEOS agencies should work to support rapid satellite tasking of Earth observation missions, to enhance the utility of space for disaster applications.

Recommendation: CEOS agencies should work to support fast processing and delivery of data, which will also be very important to determining the utility of space data for disaster applications.

• *Finding*: Typically, users can benefit from satellite data that is provided from more than one agency. Initial project efforts to develop information tools to demonstrate timely access to satellite-derived data and information products received positive reactions. It was recognized that there is merit for moving in a collaborative fashion towards a more integrated approach to mission planning.

Recommendation: Initial steps should be taken towards sharing technical information and developing tools for satellite tracking and tasking that are more user friendly for disaster management support purposes.

• *Finding*: While it is not yet a practicality, the goal of mirroring information from agencies in different areas of the world holds promise for providing timely access to essential information on missions, as well as useful educational information.

Recommendation: Mirroring of information currently contained on the project information server may be a productive operational demonstration of this concept.

• *Finding*: Disaster management is an area that can greatly benefit from an integrated approach to space technology applications.

Recommendation: There is a need to integrate non-space information with space imagery and other satellite data, including the use of appropriate geographic information system tools, to facilitate integrating those data quickly and in a seamless fashion.

Recommendation: It is recognized that each team, and the project in general, must continue to endeavor for broader geographic and disciplinary representation, especially in terms of interacting with specific users, to determine their desired information needs.

APPENDIX B Tables of Current Earth Observation Missions

This appendix includes tables of Current Earth Observation Missions, categorised into High, Moderate-High, Low-Moderate, and Low Resolution.

The GSD category classification definition is as follows, as described in Section 2.5:

High	<10m
Moderate-High	10-50m
Low-Moderate	50-500m
Low	>500m

Each table is highlighted in a different colour, according to the resolution category. This is not of interpretable significance but simply a visual aid to minimise incorrect classifications when working within the spreadsheet used to create the tables.

Stars (★) are placed next to spacecraft sensors that are short-listed for discussion in Section 2.5.

An arrow (⇦) is placed next to the DMC satellites to highlight them for the reader.

High Resolution Missions

Satellite	Instrument	Description	GSD Class	GSD at nadir	Swath (km)
HELIOS 1A		French Military	Hi	1 - 5m (?)	
HELIOS 1B		French military	Hi	1 - 5m (?)	
MTI	MTI	MS Imager VNIR, SWIR, TIR	Hi	5 - 20m	12 x 12
SPOT 5	HRG	Pan Imager	Hi	3-5m	60 - 80
	HRS	Pan Imager for stereo imaging	Hi	10 x 5m	120
IRS-1C	PAN	Pan Imager	Hi	6m	70
IRS-1D	PAN	Pan Imager	Hi	6m	70
ADEOS	AVNIR	Pan Imager	Hi	8m	80
TUBSAT (DLR)	1000mm	Pan Imager	Hi	6	6 x 4.6
IKONOS-2	OSA	Pan Imager	Hi	1m	13
		MS Imager VNIR	Hi	4m	13
QUICKBIRD 2	BGIS-2000	Pan Imager	Hi	0.61m	17
		MS Imager VNIR	Hi	2.5m	17
KOMPSAT	EOC	Pan Imager	Hi	6.6m	17
EROS-A1	PIC	Pan Imager	Hi	1.8m	12.5
ORBVIEW 3	OHRIS	Pan Imager	Hi	1m	8
		MS Imager VNIR	Hi	4m	8
IRS-P6	LISS 4	MS Imager VNIR,SWIR, plus mono	Hi	6m	24 - 70 (mono)

Table B.1 High Resolution Satellite Sensors

High-Moderate Resolution Missions

Satellite	Instrument	Description	GSD Class	GSD at nadir	Swath (km)	
PROBA 1	CHRIS	HyperSpectral imager VNIR	Hi-mod	25m	19	
	HRC	Pan Imager	Hi-mod	10m	10	
ALSAT 1	SLIM 6	DMC MICROSATELLITE	Hi-Mod	30 - 40m	>600	
UK-DMC	SLIM 6	DMC MICROSATELLITE	Hi-Mod	30 - 40m	>600	⇦
NigeriaSat-1	SLIM 6	DMC MICROSATELLITE	Hi-Mod	30 - 40m	>600	
BILSAT-1	Pan	Pan Imager	Hi-Mod	12m	25 x 25	
	MSI	MS Imager VNIR	Hi-Mod	26m	55 x 55	
SEASAT 1	SAR	SAR	Hi-Mod	25m	100	
	SMMR	Microwave Radiometer	Hi-Mod	22km	600	
LANDSAT 4	TM	MS Imager VNIR, SWIR, TIR	Hi-Mod	30 - 120m	185	
LANDSAT 5	TM	MS Imager VNIR, SWIR, TIR	Hi-Mod	30 - 120m	185	★
LANDSAT 7	ETM+	Pan Imager	Hi-Mod	15m	185	
		MS Imager VNIR, SWIR, TIR	Hi-Mod	30 - 60m	185	★
SPOT 1	HRV	MS Imager VNIR	Hi-Mod	20m	60 (x2)	★
		Pan Imager	Hi-mod	10m	60 (x2)	
SPOT 2	HRV	MS Imager VNIR	Hi-Mod	20m	60 (x2)	★
		Pan Imager	Hi-mod	10m	60 (x2)	
SPOT 3	HRV	MS Imager VNIR	Hi-Mod	20m	60 (x2)	★
		Pan Imager	Hi-mod	10m	60 (x2)	
SPOT 4	HRVIR	MS Imager VNIR, SWIR	Hi-Mod	20m	60 (x2)	★
		Pan/Mono Imager (B2 of MS Imager)	Hi-mod	10m	60 (x2)	
SPOT 5	HRG	MS Imager VNIR, SWIR	Hi-Mod	10-20m	60 - 80	★
MOS 1A (MOMO 1)	MESSR	MS Imager VNIR	Hi-Mod	50m	185	
OKEAN-O	MSU-V	MS Imager VNIR, SWIR, TIR	Hi-Mod	50 - 250m	195	
MOS 1B (MOMO 1B)	MESSR	MS Imager VNIR	Hi-Mod	50m	185	
ERS-1	AMI	SAR	Hi-Mod	30m	100	
		Wind Scatterometer	Hi-Mod	50m	500	
IRS-1A	LISS-II A/B	MS Imager VNIR	Hi-Mod	36m	74 (x 2)	
IRS-1B	LISS-II A/B	MS Imager VNIR	Hi-Mod	36m	74 (x 2)	
IRS-P2	LISS-IIM	MS Imager VNIR	Hi-Mod	32 x 37m	131	
IRS-1C	LISS-III	MS Imager VNIR,SWIR	Hi-Mod	23 - 70m	142 - 148	
IRS-1D	LISS-III	MS Imager VNIR,SWIR	Hi-Mod	23 - 70m	142 - 148	
RESURS O1-3	MSU-E	MS Imager VNIR	Hi-Mod	45 x 33m	80	
ERS-2	AMI	SAR	Hi-Mod	30m	100	
		Wind Scatterometer	Hi-Mod	50m	500	
RADARSAT-1	SAR	Synthetic Aperture Radar	Hi-Mod	25 - 100m	10 - 500	★
ADEOS	AVNIR	MS imager VNIR	Hi-Mod	16m	80	
TECHSAT 1B	ERIP	Pan Imager	Hi-Mod	52 x 60m	25 x 31	
SUNSAT	HRI	MS Imager VNIR	Hi-Mod	15m	51	
UOSAT-12	SHC	Pan Imager	Hi-mod	10m	10 x 10	
	MSI	MS Imager VNIR	Hi-Mod	32	60 x 30	
KITSAT-3	MEIS	MS Imager VNIR	Hi-Mod	15m	50	
CBERS-1	HRCC	MS Imager VNIR	Hi-Mod	20m	113	
		Pan Imager	Hi-Mod	20m	113	
TERRA	ASTER	MS Imager VNIR, SWIR, TIR	Hi-Mod	15-90m	60	
EO-1	ALI	Pan Imager	Hi-mod	10m	185	
		MS Imager VNIR, SWIR (potential ETM+ success	Hi-Mod	30m	185	
	Hyperion	Hyperspectral imager VNIR, SWIR	Hi-Mod	30m	7.5	
SAC C	HRTC	Pan Imager	Hi-Mod	35m	90	
ENVISAT	ASAR	SAR	Hi-Mod	30m - 1km	100 - 400	
IRS-P6	LISS 3	MS Imager VNIR,SWIR	Hi-Mod	23 - 70m	142 - 148	
JERS-1	SAR	Synthetic Aperture Radar	Hi-Mod	18m	75	
	OPS	Radiometer VNIR, SWIR	Hi-Mod	18m x 24m	75	
SUNSAT	HRI	MS Imager VNIR	Hi-Mod	15m	50	

Table B.2 High-Moderate Resolution Satellite Sensors

Low-Moderate Resolution Missions

Satellite	Instrument	Description	GSD Class	GSD at nadir	Swath (km)	
LANDSAT 4	MSS	MS Imager VNIR, TIR	Low-Mod	80 x 56m	185	
LANDSAT 5	MSS	MS Imager VNIR, TIR	Low-Mod	80 x 56m	185	
OKEAN-01 series	MSU-S	MS Imager, Red, NIR	Low-Mod	250m	1100	
OKEAN-O	MSU-SK	MS Imager VNIR, TIR	Low-Mod	150 - 820m	620	
IRS-1A	LISS-I	MS Imager VNIR	Low-Mod	72m	148	
IRS-1B	LISS-I	MS Imager VNIR	Low-Mod	72m	148	
IRS-1C	WiFS	Wide Field Sensor Red, NIR	Low-Mod	188m	810	
IRS-P3	WiFS	Wide Field Sensor Red, NIR, SWIR	Low-Mod	188m	770	
IRS-1D	WiFS	Wide Field Sensor Red, NIR	Low-Mod	188m	810	
RESURS O1-3	MSU-SK	MS Imager VNIR, TIR	Low-Mod	170 - 600m	600	
FASAT-B	NAC	Monochromatic Imager Red	Low-Mod	*130 x 97m*	*74 x 55*	
TMSAT	NAC	MS Imager VNIR	Low-Mod	100m	100 x 100	
TUBSAT (DLR)	50mm	Pan Imager	Low-Mod	120	120 x 92	
	16mm	Pan Imager	Low-Mod	370		
OCEANSAT	OCM	MS Imager VNIR	Low-Mod	360 x 236m	1440	
CBERS-1	IRMSS	MS Imager SWIR, TIR	Low-Mod	80 - 120m	120	
		Pan Imager	Low-Mod	80m	120	
	WFI	Wide Field Imager, Red and NIR	Low-Mod	260m	885	
TERRA	MISR	MS Imager VNIR, multi-angle	Low-Mod	275m	360	
	MODIS	MS Imager	Low-Mod	250m-1km	2330	★
TIUNGSAT 1	MSEIS	MS Imager VNIR	Low-Mod	70m	70 x 70	
SAC C	MMRS	MS Imager VNIR, SWIR	Low-Mod	175-350m	360	
	HSC	Pan Imager, High Sensitivity Camera	Low-Mod	300m	700	
BADR B	EIC	Pan Imager	Low-Mod	250m	190 x 140	
MAROC-TUBSAT	EIC	Pan Imager	Low-Mod	250m	190 x 140	
ENVISAT	MERIS	MultiSpectral Imager VNIR	Low-Mod	260m - 1.2km	1150	
AQUA	MODIS	MS Imager	Low-Mod	250m - 1km	2330	★
ADEOS II	GLI	MS imager VNIR, SWIR, MWIR, TIR	Low-Mod	250m - 1km	1600	
IRS-P6	WiFS	Wide Field Sensor Red, NIR	Low-Mod	60m	740	★

Table B.3 Low-Moderate Resolution Satellite Sensors

Low Resolution Missions

Satellite	Instrument	Description	GSD Class	GSD at nadir	Swath (km)	
ASUSAT	Imager	MS Imager VNIR	Low	700m	350 x 250	
GOES 2	VISSR	Geo Spinning Radiometer VIS, TIR	Low	0.9 - 7km		
	VAS	Geo VISSR Atmospheric Sounder	Low	0.9 - 14km		
GOES 8	Imager	MS Imager VIS, MWIR, TIR	Low	1 -8km		
NOAA 9	AVHRR/2	MS Imager VNIR, SWIR, TIR	Low	1.1km - 6km (edge)	>2400	★
NOAA 10	AVHRR	MS Imager VNIR, SWIR, TIR	Low	1.1km - 6km (edge)	>2400	★
NOAA 11	AVHRR/2	MS Imager VNIR, SWIR, TIR	Low	1.1km - 6km (edge)	>2400	★
NOAA 12	AVHRR	MS Imager VNIR, SWIR, TIR	Low	1.1km - 6km (edge)	>2400	★
NOAA 14	AVHRR/2	MS Imager VNIR, SWIR, TIR	Low	1.1km - 6km (edge)	>2400	★
NOAA 15	AVHRR/3	MS Imager VNIR, SWIR, TIR	Low	1.1km	2900	★
NOAA 16	AVHRR/3	MS Imager VNIR, SWIR, TIR	Low	1.1km	2900	★
NOAA 17	AVHRR/3	MS Imager VNIR, SWIR, TIR	Low	1.1km	2900	★
SPOT 4	VGT	MS Imager VNIR, SWIR	Low	1.15km	2200	★
SPOT 5	VGT-2	MS Imager VNIR, SWIR	Low	1km	2200	★
MOS 1A (MOMO 1)	VTIR	MS Imager Green, Red, TIR	Low	900m	1500	
	MSR	Microwave Scanning Radiometer	Low	23 - 32km	320	
OKEAN-01 series	RLSBO	Side-looking Real Aperture Radar	Low	0.7 x 2.8km	450	
(OKEAN 1, OKEAN 2,	RM-08	Microwave Scanning Radiometer	Low	15 x 20km	550	
OKEAN 3, OKEAN 1-7,	MSU-M	MS Imager VNIR	Low	1 x 1.7km	1900	
	MSU-M	MS Imager VNIR	Low	1.5 x 1.8km	2000	
OKEAN-O	RLSBO	Side-looking Real Aperture Radar	Low	1.3 x 2.5km	455 (x2)	
	Delta-2D	Scanning Microwave Radiometer	Low	17 - 120km	1130	
MOS 1B (MOMO 1B)	VTIR	MS Imager Green, Red, TIR	Low	900m	1500	
	MSR	Microwave Scanning Radiometer	Low	23 - 32km	320	
ERS-1	ATSR	Microwave Sounder and Radiometer SWIR, TIR	Low	1km	500	
IRS-P3	MOS	MS Imager VNIR,SWIR	Low	500m - 1.5km	200	
ERS-2	ATSR-2	Microwave Sounder and Radiometer VNIR, SWIF	Low	1km	500	
ADEOS	OCTS	Scanning radiometer VNIR, SWIR, TIR	Low	700m	1400	
	POLDER	Polarisation and Directionality of Earth's Reflecta	Low	6 - 7km	2200	
ORBVIEW 2 (SEASTAR	SeaWiFS	MS imager VNIR	Low	1 - 4km	1500 - 2800	
TRMM	VIRS	MS imager Red, SWIR, TIR	Low	2km	720	
	TMI	Microwave imager	Low	7km	760	
FASAT-B	WAC	Monochromatic Imager NIR	Low	*2.0 x 1.5km*	*1150 x 850*	
TMSAT	WAC	Monochromatic Imager NIR	Low	2.0 x 1.5km	1500 x 1050	
ROCSAT-1	OCI	MS Imager VNIR	Low	800m	700	
UOSAT-12	WAC	Monochromatic Imager NIR	Low	1km	1000 x 1000	
KOMPSAT	OSMI	MS Imager VNIR	Low	1km	800	
TIUNGSAT 1	MEIS	Monochromatic Imager NIR	Low	1.2km	1200 x 1200	
ENVISAT	AATSR	Scanning Radiometer VNIR, SWIR, TIR	Low	1km	500	
ADEOS II	AMSR	Microwave scanning radiometer	Low	5 - 50km	1600	
	POLDER	Polarisation and Directionality of Earth's Reflecta	Low	6 - 7km	2200	

Table B.4 Low Resolution Satellite Sensors

APPENDIX C Spacecraft Configuration Control Summary Table

System	Sub-system	Baseline in Original Proposal	To	Why	Final CDR Solution
Basic Concept		Standard Microsat modification	Enhanced MicroSatellite, based around a stack with other items outside the stack	Volume is not sufficient to house sufficient propulsion and other equipment. Solar array area not sufficient to provide desired performance	Enhanced MicroSatellite, based around a stack with other items outside the stack
		Single Point Failure tolerant			Single Point Failure tolerant
Power	Arrays	GaAs in PicoSat configuration (approx 35W)	Larger arrays than are in the proposal , but same cubic configuration. Array power ~55W (GaAs).	A higher OAP than possible from the 35W fixed panels is required to allow a reasonable payload duty cycle.	Larger arrays than are in the proposal , but same cubic configuration. Array power ~55W (GaAs).
	Battery	Standard microsat, at the bottom of the stack	22 cell (26.4 - 34V) Sloshsat type battery, with SANYO N4000DRL cells, 105.6Whrs	Recent in-orbit failures have raised concern about the SANYO F type 6Ah cell types. The cell type that the power team has most confidence in is the new proposed cell. This is only available at 4Ah. The higher battery voltage allows greater capacity, and also gives a 28V bus which is preferred.	22 cell (26.4 - 34V) Sloshsat type battery, with SANYO N4000DRL cells, 105.6Whrs
	Bus Voltage	Standard Microsat 14V	28V unregulated, 5V regulated	Some systems prefer 14V, some 28V, some don't care. The preference of 28V from the high power TX and the potential high power requirement of the imager are particularly influential. The 28V bus also allows a higher battery capacity with the preferred cells which are otherwise too low in capacity.	28V unregulated, 5V regulated
	Topology	Standard microsat - single BCR	4 BCRs (microtray). SNAP/UoSat-12 Heritage. MPP Tracking	Require 1 BCR per panel because of temp differential (for optimal performance)	4 BCRs (microtray). SNAP/UoSat-12 Heritage. MPP Tracking
		Standard microsat	PCM/PDM (microtray). SNAP/UoSat-12 Heritage	28V power system required	PCM/PDM (microtray). SNAP/UoSat-12 Heritage
Communications	Uplink Rx	S-Band in microtray	9K6 S-Band in Nanotrays (x2) SNAP Heritage	Too many microtrays increase stack height above acceptable level for structural risk. Nanotray heritage means comms equipment is possible to house outside the stack.	9K6 S-Band in Nanotrays (x2) SNAP Heritage
	Uplink Antenna	not specified			S-Band Patch (x4), 2 per receiver
	High Rate Downlink Tx	S-Band in microtray	8Mbps S-Band in Nanotrays (x2). SNAP Heritage	Closest electronics heritage is from SNAP/EOARD work. Also microsat stack would be too high if everything was in microtrays	8Mbps S-Band in Nanotrays (x2). SNAP Heritage
	High Rate Downlink Antenna	Quadrifilar Helix			Quadrifilar Helix
	Low Rate Downlink Tx	none	38K4bps S-Band in Nanotray (x1). SNAP Heritage	Too many microtrays increase stack height above acceptable level for structural risk. Nanotray heritage means comms equipment is possible to house outside the stack.	38K4bps S-Band in Nanotray (x1). SNAP Heritage
	Low Rate Downlink Antenna	none	2x Monopole. SNAP Heritage	similar to SNAP	2x Monopole. SNAP Heritage

System	Sub-system	Baseline in Original Proposal	To	Why	Final CDR Solution
AODCS	Software + Control Mode	Momentum-bias	Gravity Gradient, with momentum bias during imaging. BBQ rest of time.	Reduces wheel use. Reduces risk to mission (probability and impact) of wheel failure.	Gravity Gradient, with momentum bias during imaging. BBQ rest of time.
	Electronics Module	Microsat 14V	MicroSat 28V, with magnetorquer rods rather than PCB coils	To accommodate 28V bus (28V UoSat-12 ADCS to form heritage)	MicroSat 28V, with magnetorquer rods rather than PCB coils
	magnetometers	2x 3 axis magnetometers			2 x UoSat-12 type magnetometers
	sun sensors	4x SSTL sunsensors on EFF	Change of location to SFF, canted mounting position, minor mechanical modifications	Allows cleaner RF surface on EFF, and canting allows better sun-angle geometry.	4x sunsensors, as UoSat-12 but with slight modification, supported on brackets and canted back
	magnetorquers	MicroSat style PCB coils	MTR-10 Magnetorquer rods x 3 (dual)	Save Power, allows greater inertia (bigger spacecraft). SIL design available with limited development/risk	MTR-10 Magnetorquer rods x 3 (dual)
	reaction wheels	x 2 Tsinghua type wheels (both y-wheels)	Modified Tsinghua wheels - greater inertia and 28V supply (one z wheel and one y-wheel)	Spacecraft is larger than Tsinghua. 28V supply available. See FMECA for wheel orientation.	Modified Tsinghua wheels - greater inertia and 28V supply (one z wheel and one y-wheel)
	GG Boom	none	Standard SSTL/Weitzmann Gravity Gradient Boom (note, though..first time for SSTL manufacture of this)	Reduces wheel use. Reduces risk to mission (probability and impact) of wheel failure.	Standard SSTL/Weitzmann Gravity Gradient Boom (note, though..first time for SSTL manufacture of this)
		none	Boom controller, based on UoSat-12 controller	Boom controller needed due to addition of GG Boom to ADCS solution.	Boom controller, based on UoSat-12 controller
	Orbit determination (Hardware)	SSTL GPS			SGR-10 model (PROBA, UoSat-12), Microtray (uses half a tray)
		GPS Antennas			2 x SSTL GPS Patch (UoSat-12)
	Orbit determination (Software)	not specified	On-board GPS orbit propagator (UoSat-12 heritage) with NORAD TLE propagator as a back-up	GPS propagator allows more accurate position knowledge than NORAD propagator whilst allowing intermittent GPS use.	On-board GPS orbit propagator (UoSat-12 heritage) with NORAD TLE propagator as a back-up
	Propulsion system				see separate table below

Propulsion	Concept	Microtray based in the stack, thrusters in centre of a solar panel	Based outside the stack. Thruster level with SFF, in centre of panel edge	Cannot fit inside the stack, and keep the stack to a reasonable height. CoG will be approximately at the SFF due to presence of GG boom.	Based outside the stack. Thruster level with SFF, in centre of panel edge
	Tanks	not specified			2.5 litre Polyflex tanks (x2) with 'foam' in the inside.
	Thrusters	not specified (x 4)	single thruster, resistojet	Single thruster minimises system complexity. Propulsion not critical for Alsat as a stand-alone mission. Within the DMC, propulsion redundancy is expected to be achieved at a spacecraft level. Resistojet/heaters provide expected enhanced DeltaV performance with minimal risk.	single thruster, resistojet
	Propellant	not specified			Butane
	Isolation Valve	not specified			SNAP Heritage, Polyflex
	Fill/drain valve	not specified			SNAP Heritage, Polyflex
	Pressure Transducer	not specified			SNAP Heritage, Polyflex
	Control Electronics	not specified, but probably within the microtray	nanotray situated next to propulsion system, SNAP heritage	SNAP heritage, nanotray use minimises stack size and eases AIT/sub-system testing	nanotray situated next to propulsion system, SNAP heritage

System	Sub-system	Baseline in Original Proposal	To	Why	Final CDR Solution
Structure	Structure	Microsat (PicoSat)	Enhanced MicroSat	Standard MicroSat Volume is not sufficient to house sufficient propulsion and other equipment. Solar array area not sufficient to provide desired performance	Enhanced MicroSat
OBDH	TT&C	Centralised	Distributed TTC	The majority of systems are derived from heritage systems that already have CAN nodes. The use of CAN nodes on remaining modules allows the omission of the TTC module.	Distributed TTC
	OBC (Primary)	386 microtray	386 microtray with FPGA changes	A review of recent FPGA radiation and obsolesence issues resulted in a recommendation to change FPGAs	OBC386
	OBC (secondary)	386-SSDR0 or 1	OBC186	386 is not capable of performing SSDR task, hence will not have 386 SSDRs available. Other SSDRs are new developments. 186 considered safest solution.	OBC186
	SSDR	386 SSDR (x2) (2 microtrays)	PowerPC SSDR (x2), each in 1/2 microtray (sharing same microtray)	386 not capable of data storage >128Mbytes, downlink data rates of 8Mbps, or receiving high data rates from imager	PowerPC SSDR (x2), each in 1/2 microtray (sharing same microtray)
	3rd back up SSDR	none	SA1100 SSDR in half a microtray (share tray with GPS). Based on SNAP OBC. 128Mbytes storage, data rate as high as possible up to 8Mbps.	PowerPC SSDR is a new development and is flying a new processor without flight heritage, in a mission critical single point failure position.	SA1100 SSDR in half a microtray (share tray with GPS). Based on SNAP OBC. 128Mbytes storage, data rate as high as possible up to 8Mbps.
IMAGER	Optics	Tsinghua - 2 lenses	Six Tsinghua lenses (150mm), one for each CCD	Multispectral 600km swath not possible with system in proposal without custom sensor (prohibitive cost). Six lenses and CCDs is considered the least risk option.	Six Tsinghua lenses (150mm), one for each CCD
	Detectors	linear CCDs (x2)	linear CCDs (x6)	Multispectral 600km swath not possible with system in proposal without custom sensor (prohibitive cost)	linear CCDs (x6)
	Electronics	Tsinghua style small bespoke box at top of stack/on Earth Platform	microtray, but Tsinghua circuitry/components re-use where possible	more camera detectors needs more camera electronics. Desirable to physically decouple from lenses and detectors for thermal reasons.	microtray, but Tsinghua circuitry/components re-use where possible

Table C.1 Satellite Configuration Control Summary Table

APPENDIX D Assumed Launch Injection Error Probabilities

The following tables present the 3-sigma launch injection errors as provided by their respective launch agencies during the project.

It is interesting to note that the inclination error for COSMOS is not quoted as being symmetrical (i.e. the same probability gives a higher negative error in inclination than a positive one). This fact was confirmed with the launch agency, although the physical explanation as to why this is the case was not supplied.

Example Launch Injection Errors		COSMOS	Updated (16-01-2002)	
target altitude	686	km		
semimajor axis	-15	15	km	
eccentricity	2.00E-03	no units	28.26	km
orbital period	-20	20	s	
inclination	-0.066666667	0.033333	deg	

Table D.1 Assumed COSMOS Launch Injection Accuracies (3-sigma)

Example Launch Injection Errors		DNEPR (updated 17-01-2002)		
target altitude	650	km		
altitude error	6	km		
degrading by 7-10% per extra separation				
eccentricity (not defined)		no units		km
inclination	-0.04	0.04	°	
RAAN (not defined)		°		minutes

Table D.2 Assumed DNEPR Launch Injection Accuracies (3-sigma)

APPENDIX E Launch Injection Error Analysis

The approach taken for analysis of injection errors was to compare the orbit correction capability of the spacecraft, (based on an estimate of propulsion system performance) with the probability of injection errors in terms of altitude and inclination.

The altitude and inclination were the main parameters of interest for several reasons. The altitude was of primary importance due to the need to match the orbit periods of the different spacecraft and hence allow constellation phasing. The altitude and inclination were also important due to the sensitivity of the long-term orbit LTAN profile to these factors. It is important that the inclinations of the DMC spacecraft are similar in order to avoid the orbit planes drifting too far apart due to an LTAN drift, otherwise the satellite ground tracks can become less well placed. It is also important for each spacecraft to keep the LTAN within a desirable range to maintain good imaging illumination conditions, spacecraft power generation and thermal environment. Orbit eccentricity was of secondary interest, as nominal 3-sigma eccentricity errors were acceptable to the mission, and in any case, any altitude correction could also be used to reduce orbit eccentricity by choosing to fire at the correct point in the orbit. The option to directly correct an error in launch LTAN was not considered due to the inefficiency of such a manoeuvre (only a negligible LTAN change would be achieved using the entire spacecraft propellant supply). The 3-sigma quoted LTAN injection errors would also be well within the acceptable bounds for the mission and would not need correcting. However, the long-term LTAN profile is important and relatively controllable via altitude and inclination selection.

After consideration of expected propulsion system performance and nominal mission requirements for constellation management, 7.3m/s was taken as the available propellant for injection error correction.

Figure E.1 illustrates the correction capability for different combinations of inclination and semi-major axis error with various amounts of propellant. Although 7.3m/s was taken as the nominal DeltaV available for correction, mission trade-offs could be made in the event of an extremely bad error which might require more than 7.3m/s for correction.

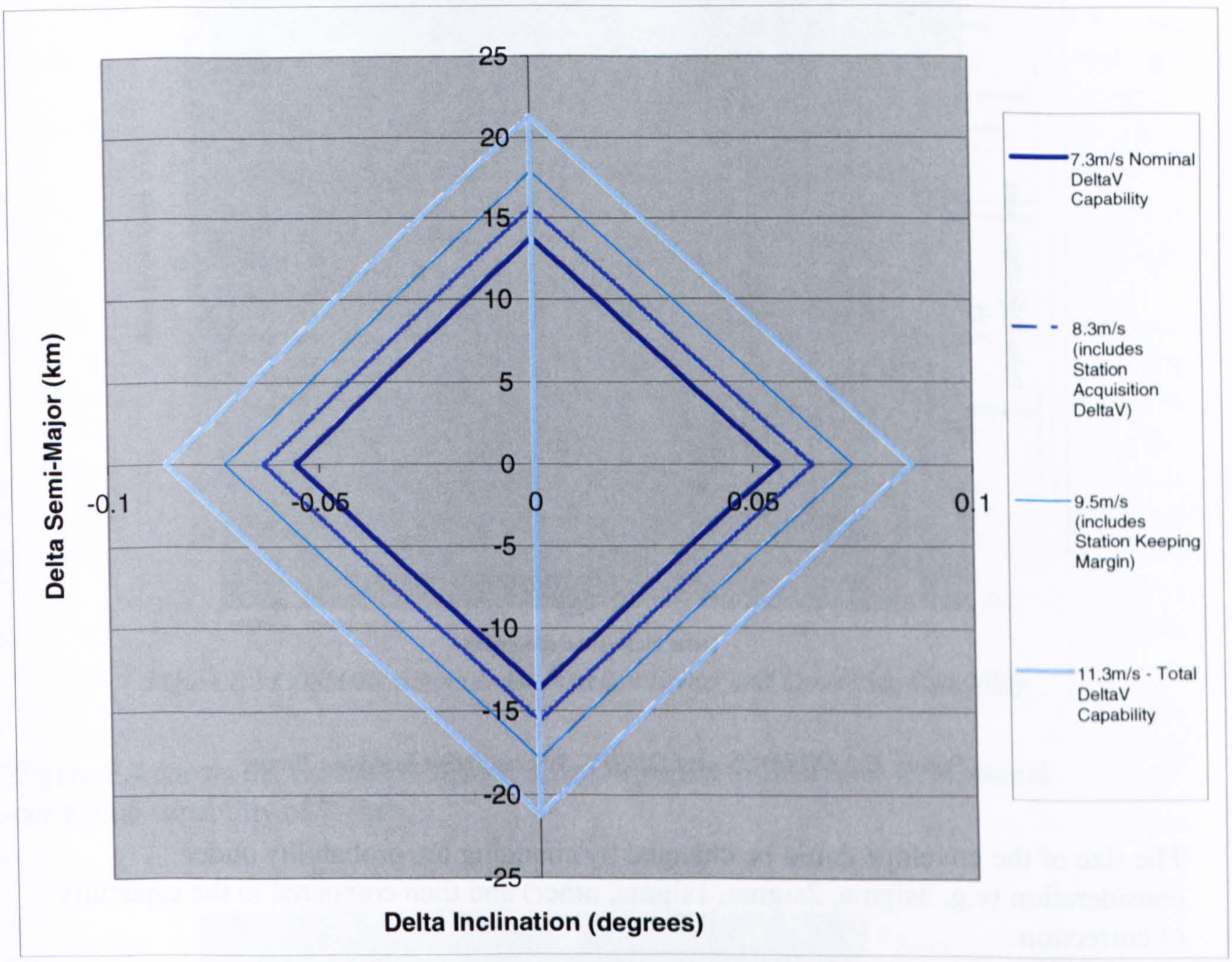

Figure E.1 DMC Orbit Injection Correction Capability

An envelope of 3sigma errors was calculated for both DNEPR and COSMOS launch vehicles, based on quoted values for semi-major axis and inclination, as shown in Figure E.2.

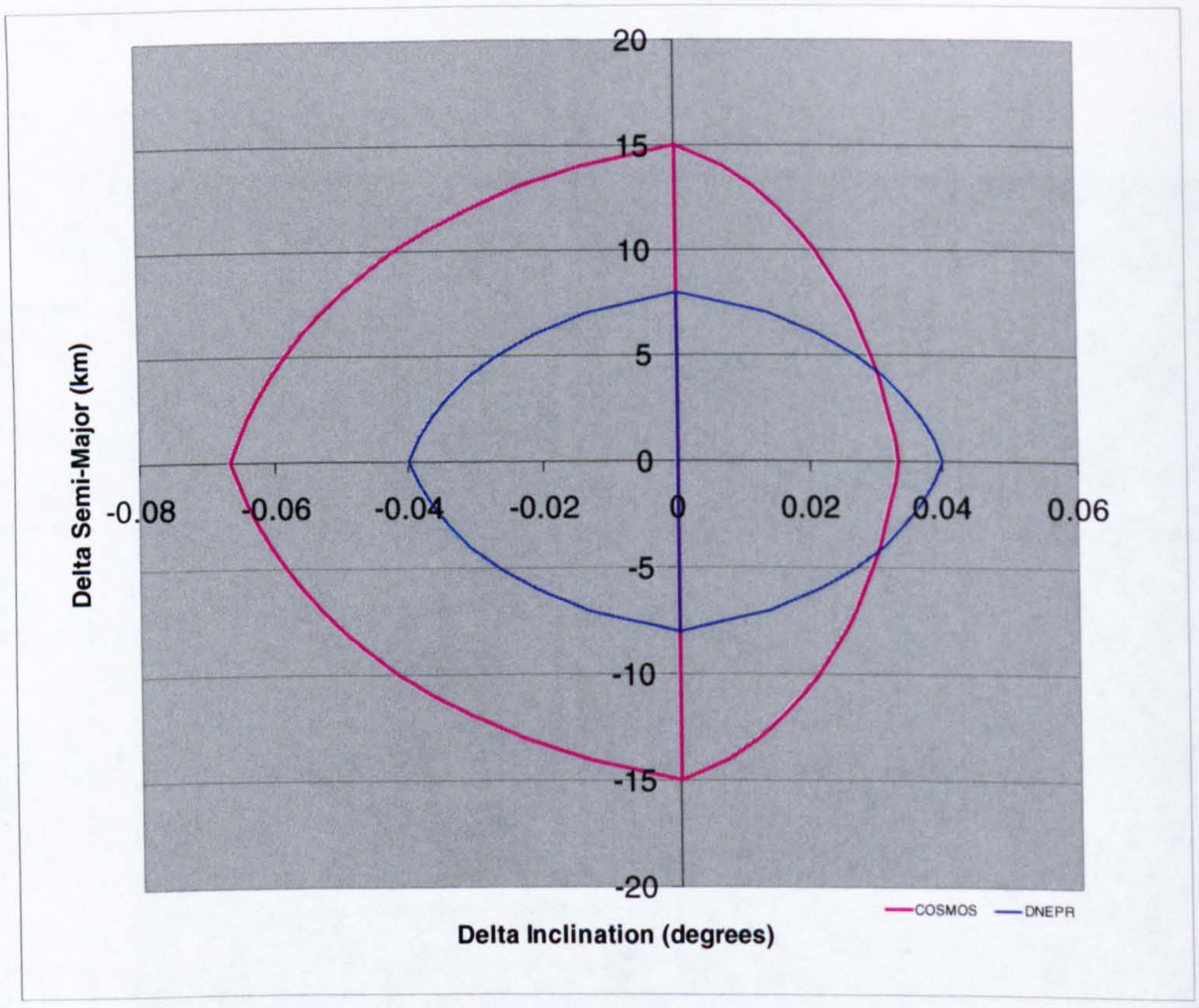

Figure E.2 COSMOS and DNEPR 3sigma Orbit Injection Errors

The size of the envelope could be changed by changing the probability under consideration (e.g. 3sigma, 2sigma, 1sigma, other) and then compared to the capability of correction.

As COSMOS was the final selected launch vehicle this is shown for COSMOS below. COSMOS 3sigma errors can be seen against correction capability in Figure E.3 below. It can be seen that they do not fit within the nominal allowed correction capability.

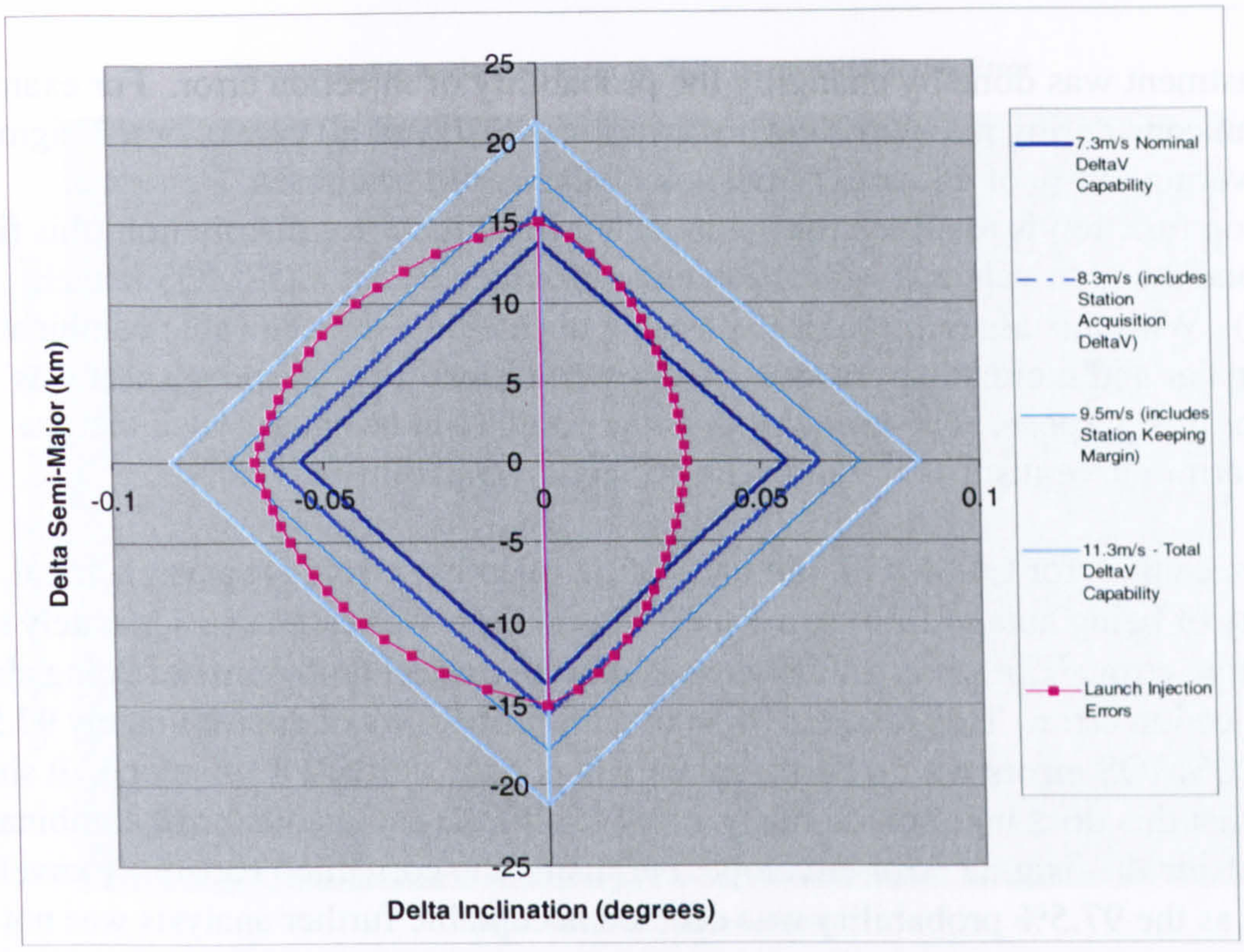

Figure E.3 COSMOS 3sigma Orbit Injection Errors and Correction Capability

Figure E.4 shows the COSMOS launch errors adjusted to fit within the nominal correction capability of 7.3m/s.

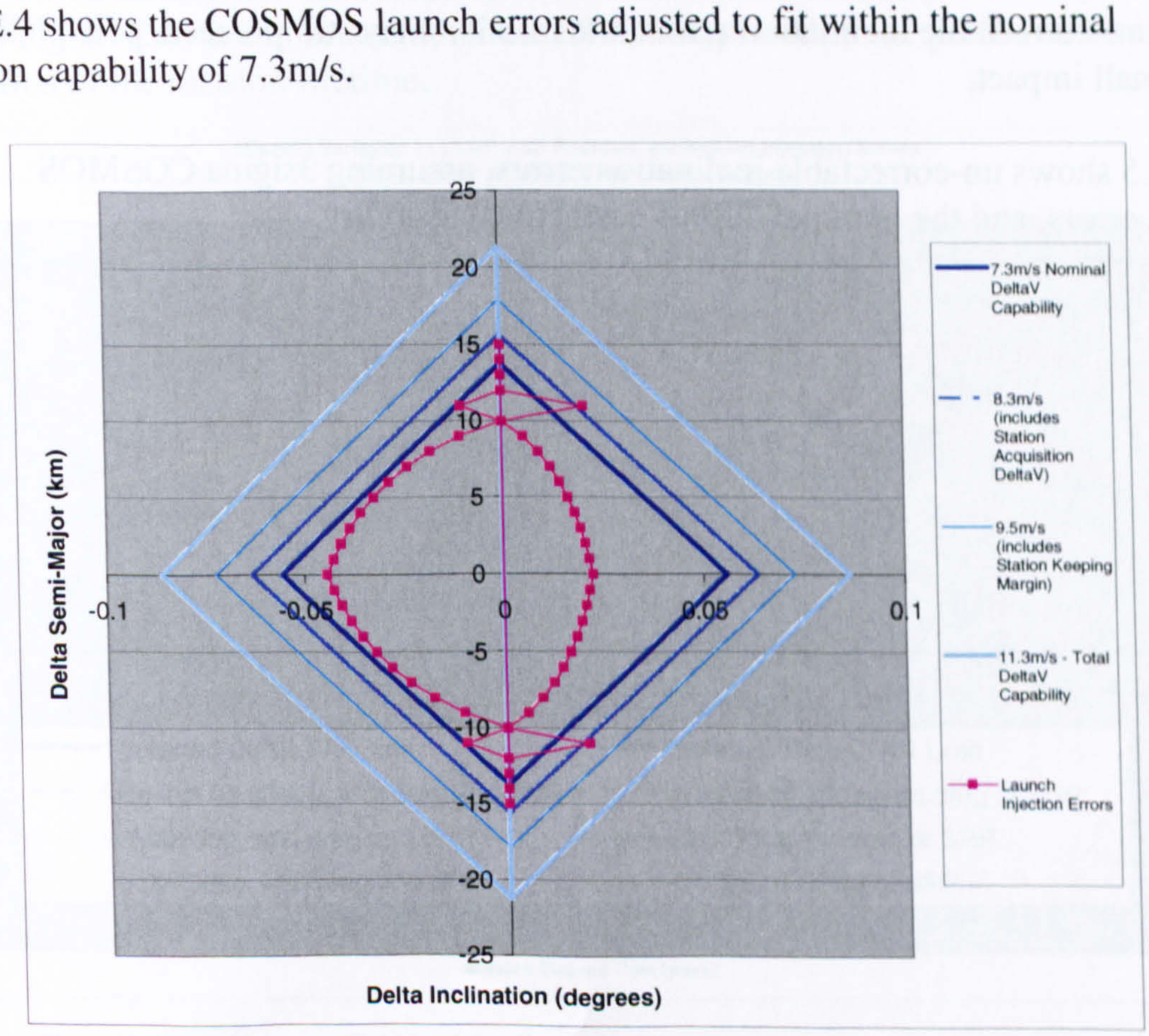

Figure E.4 COSMOS Orbit Injection Errors within Nominal Correction Capability

This adjustment was done by changing the probability of injection error. For example, rather than considering a 3-sigma error (covering ~99.7% of all cases), or a 2-sigma error (covering ~95% of all cases) a bespoke value could be chosen. A normal distribution function is assumed for the launcher injection error distribution (this fits the 2 sigma and 3-sigma values for injection error provided by the COSMOS launch authority). With this assumption, it is possible to calculate the allowable combinations of semi-major and inclination errors for any given probability. A spreadsheet was created for this purpose. The probability value could then be chosen such that the injection error curve just fitted within the correction capability envelope.

It can be seen that, for COSMOS, the inclination injection errors are asymmetrical. The probability of being able to fully correct a positive error, was estimated separately to that of a negative error. The mean value was taken as an overall probability of being able to correct injection error. This resulted in an overall probability of approximately 97.5% that the COSMOS errors would be completely inside the correction envelope. It should be noted that this does not include many cases of altitude-inclination error combination that lie outside the 3sigma error envelope, but inside the correction capability envelope. However, as the 97.5% probability was deemed acceptable further analysis was not undertaken.

Due to the phasing requirement of the mission, semi-major axis correction would be given priority over inclination correction. It should be noted however, that even in the event of un-correctable inclination errors, the mission may still proceed, potentially with only a small impact.

Figure E.5 shows un-correctable inclination errors, assuming 3sigma COSMOS injection errors, and the nominal 7.3m/s correction capability.

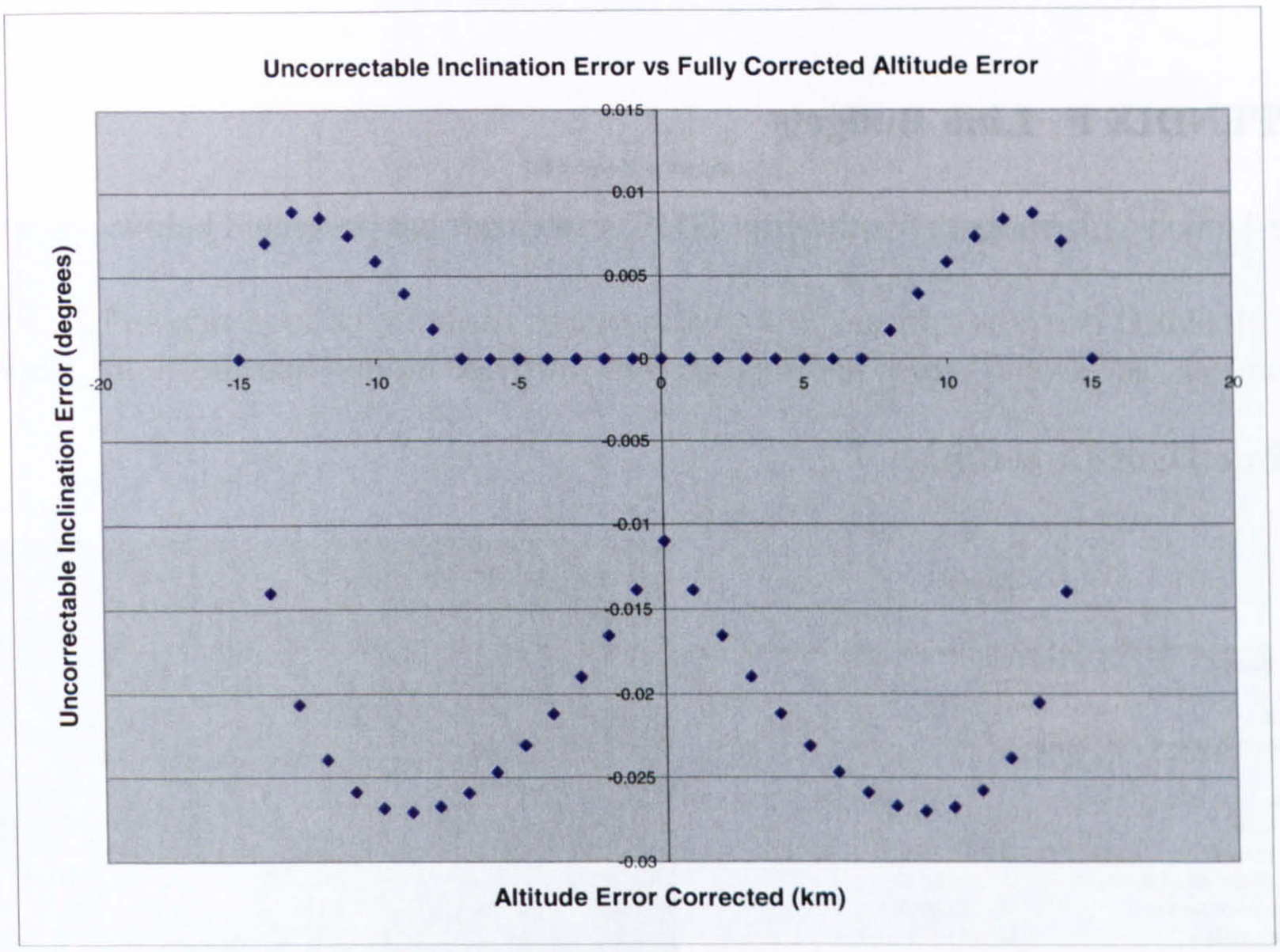

***Figure E.5 Uncorrectable Inclination Errors,* (assuming COSMOS 3sigma Injection Errors)**

The effect of such residual inclination errors on the mission LTAN profile is illustrated below in Figure E.6. It can be seen that the LTAN stays within the preferred limits for the duration of the mission lifetime.

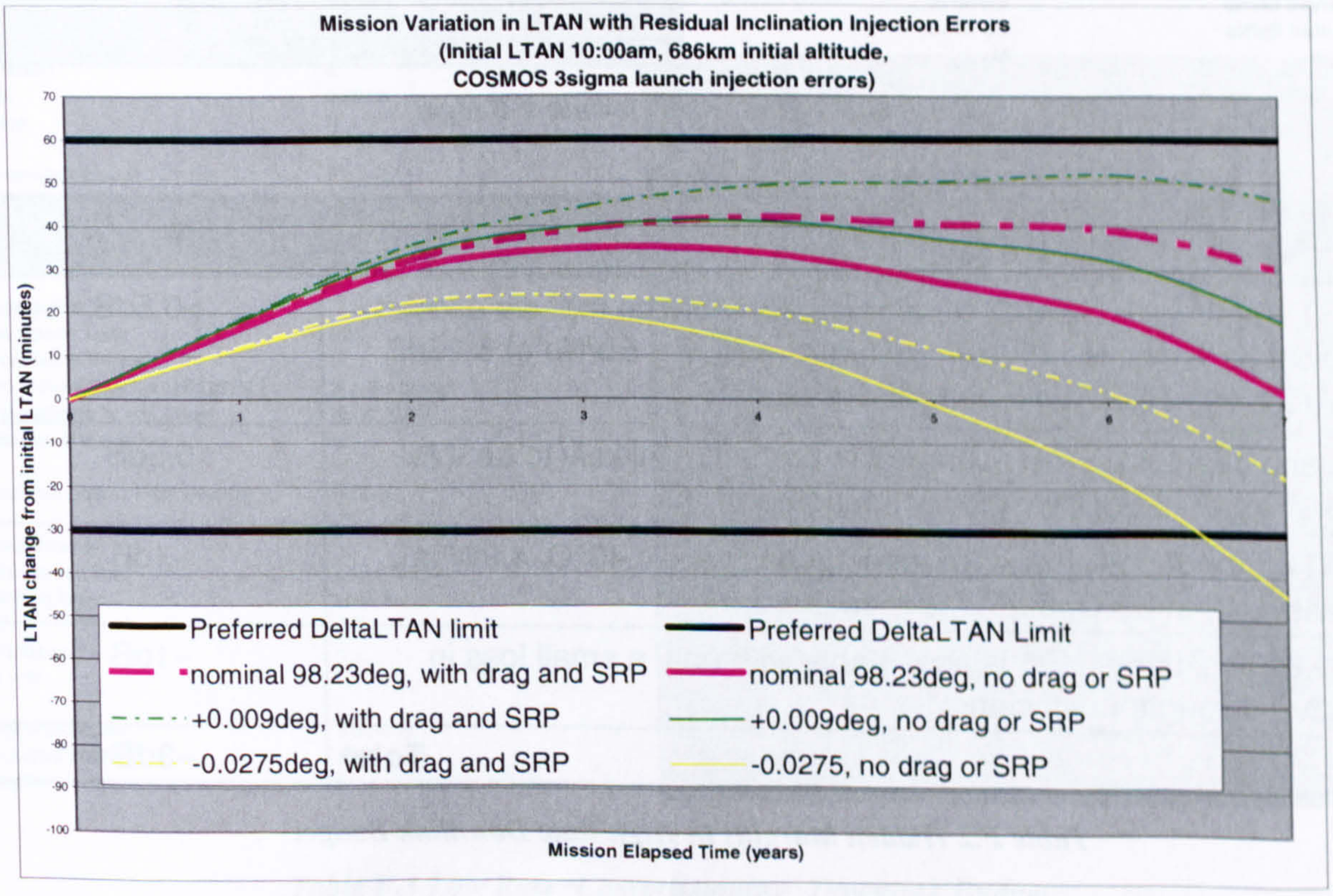

Figure E.6 LTAN drift due to Residual Inclination Errors, (assuming COSMOS 3-sigma errors)

APPENDIX F Link Budgets

The Pre-launch link budgets for the first DMC spacecraft are presented below.

As the calculated margins appear quite low in places for both the high rate and the low rate downlink, additional tables are presented to illustrate hidden margins in the system.

High Rate Data Downlink

			5	10	20	40	60	83	89	
Elevation	El		64.09	62.77	58.04	43.76	26.84	6.32	0.90	degrees
Nadir	gamma		2531.25	2124.80	1557.55	1002.14	779.69	690.65	686.09	km
Range	R									
Transmitter Power	Pt		6.33	6.33	6.33	6.33	6.33	6.33	6.33	dBW (RMS)
Feeder loss	Fl		1.70	1.70	1.70	1.70	1.70	1.70	1.70	dB
Antenna Gain	Gt		0.40	0.52	0.67	0.11	-3.27	-7.78	-8.17	dBi
Equivalent Isotropic Radiated Power	EIRP	+	5.03	5.15	5.31	4.74	1.36	-3.14	-3.54	dBW
Propagation										
Free Space Loss	FSL	-	167.56	166.04	163.34	159.51	157.33	156.28	156.22	dB
Ionospheric losses	Li	-	0.00	0.00	0.00	0.00	0.00	0.00	0.00	dB
Rain fades (99.9% availability)	dLi (3-sigma)		0.01	0.01	0.00	0.00	0.00	0.00	0.00	dB
Tropospheric scintillation	dLt (3 sigma)	-	0.87	0.48	0.27	0.15	0.12	0.10	0.10	dB
Gaseous Attenuation	Lt		0.60	0.30	0.10	0.09	0.07	0.06	0.06	dB
Received Power Flux Density	PFDrx		-134.03	-132.39	-129.54	-126.27	-127.47	-130.92	-131.26	dBW/m²
			-164.10	-162.46	-159.61	-156.34	-157.54	-161.00	-161.33	dBW/m²/4kHz
Groundstation										
Polarisation loss	Lpol (max)	-	1.00	1.00	1.00	1.00	1.00	1.00	1.00	dB
Pointing loss	Lpoint	-	0.08	0.08	0.08	0.08	0.08	0.08	0.08	dB
G/T	G/T	+	12.61	13.52	13.63	13.71	13.73	13.74	13.74	dB
Bolzmann	k	-	-228.60	-228.60	-228.60	-228.60	-228.60	-228.60	-228.60	dB(J/K)
Bit rate	Rb	-	69.11	69.11	69.11	69.11	69.11	69.11	69.11	dBbps
Received Eb/No	Eb/No rx	=	7.02	10.27	13.64	17.12	15.99	12.58	12.24	dB
Required Eb/No	Eb/No req		6.00	6.00	6.00	6.00	6.00	6.00	6.00	dB
Margin	M		**1.02**	**4.27**	**7.64**	**11.12**	**9.99**	**6.58**	**6.24**	**dB**

Table F.1 High Rate Downlink Budget

Description	Hidden Margin
HRTX tests with CDM-600 demodulator indicate that we exceed typical performance (5.5dB), actually requiring Eb/No of 5.25dB only for 10^{-6} BER. Link budget uses 6dB.	>0.5dB
Polarisation loss. 1dB assumed in budget. Unlikely to be this worst case. 0.5dB is typically assumed.	0.5dB
HRTX output power of 4.3W used in budget. At 40°C, 4.9W is measured, at 30°C, 5.25W is measured.	~1dB
10^{-6} BER is used. 10^{-5} is acceptable with only a small loss in packet throughput efficiency.	~1dB
Total	**~3dB**

Table F.2 Hidden Margins in High Rate Downlink Budget

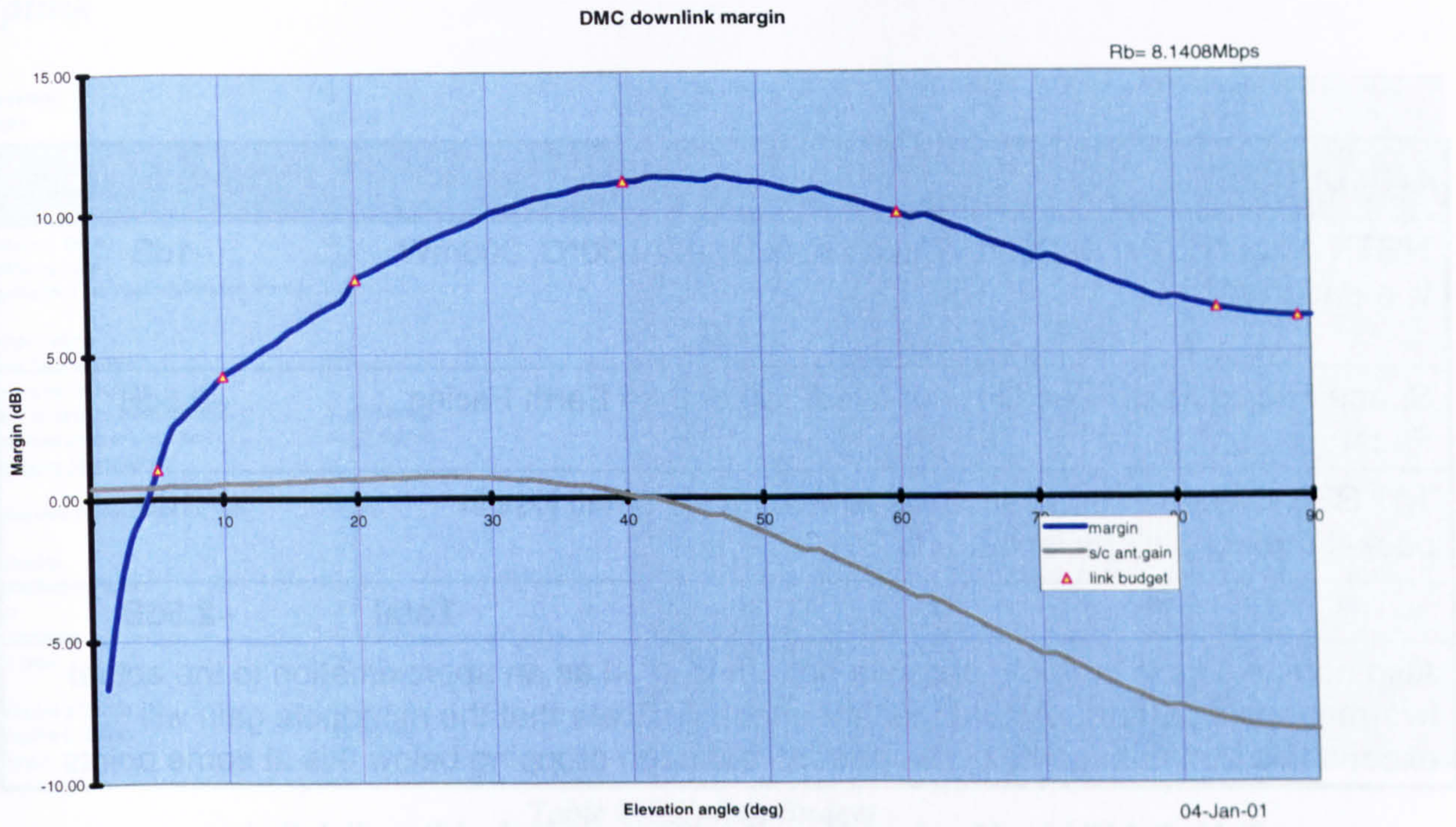

Figure F.1 High Rate Downlink Budget

Low Rate, Commissioning Downlink

			5	10	20	40	60	83	89	
Elevation	El		64.09	62.77	58.04	43.76	26.84	6.32	0.90	degrees
Nadir	gamma		2531.25	2124.80	1557.55	1002.14	779.69	690.65	686.09	km
Range	R									
Transmitter Power	Pt		-6.02	-6.02	-6.02	-6.02	-6.02	-6.02	-6.02	dBW (RMS)
Feeder loss	Fl		4.40	4.40	4.40	4.40	4.40	4.40	4.40	dB
Antenna Gain	Gt		1.54	1.49	1.28	0.34	-1.58	-7.81	-28.00	dBi
Equivalent Isotropic Radiated Power	EIRP	+	-8.88	-8.93	-9.14	-10.08	-12.00	-18.23	-38.42	dBW
Propagation										
Free Space Loss	FSL	-	167.56	166.04	163.34	159.51	157.33	156.28	156.22	dB
Ionospheric losses	Li	-	0.00	0.00	0.00	0.00	0.00	0.00	0.00	dB
Rain fades (99.9% availability)	dLi (3-sigma)		0.01	0.01	0.00	0.00	0.00	0.00	0.00	dB
Tropospheric scintillation	dLt (3 sigma)	-	0.87	0.10	0.10	0.10	0.10	0.10	0.10	dB
Gaseous Attenuation	Lt		0.60	0.30	0.10	0.09	0.07	0.06	0.06	dB
Received Power Flux Density	PFDrx		-147.94	-146.47	-143.98	-141.09	-140.83	-146.01	-166.14	dBW/m²
			-157.77	-156.29	-153.80	-150.92	-150.66	-155.83	-175.96	dBW/m²/4kHz
Groundstation										
Polarisation loss	Lpol (max)	-	3.00	3.00	3.00	3.00	3.00	3.00	3.00	dB
Pointing loss	Lpoint	-	0.08	0.08	0.08	0.08	0.08	0.08	0.08	dB
G/T	G/T	+	12.61	13.52	13.63	13.71	13.73	13.74	13.74	dB
Bolzmann	k	-	-228.60	-228.60	-228.60	-228.60	-228.60	-228.60	-228.60	dB(J/K)
Bit rate	Rb	-	45.84	45.84	45.84	45.84	45.84	45.84	45.84	dBbps
Received Eb/No	Eb/No rx	=	14.37	17.82	20.62	23.61	23.90	18.76	-1.38	dB
Required Eb/No	Eb/No req		11.25	11.25	11.25	11.25	11.25	11.25	11.25	dB
Margin	M		**3.12**	**6.57**	**9.37**	**12.36**	**12.65**	**7.51**	**-12.63**	**dB**

Table F.3 Low Rate 'Commissioning' Downlink Budget

Description	Hidden Margin
HRTX output power of 250mW used in budget. At 30°C, 300mW is measured.	~1dB
Space Facing Facet Feed loss is used, rather than Earth Facing Facet	~0.5dB
10^{-6} BER is used. 10^{-5} is acceptable with only a small loss in packet throughput efficiency.	~1dB
Total	**~2.5dB**
Also note, a simple cardioid antenna pattern is used as an approximation to the actual two-monopole pattern. Actual measurements indicate that the monopole gain will exceed this for the majority of the pattern, although dropping below this at some points	

Table F.4 Hidden Margins in Low Rate 'Commissioning' Downlink Budget

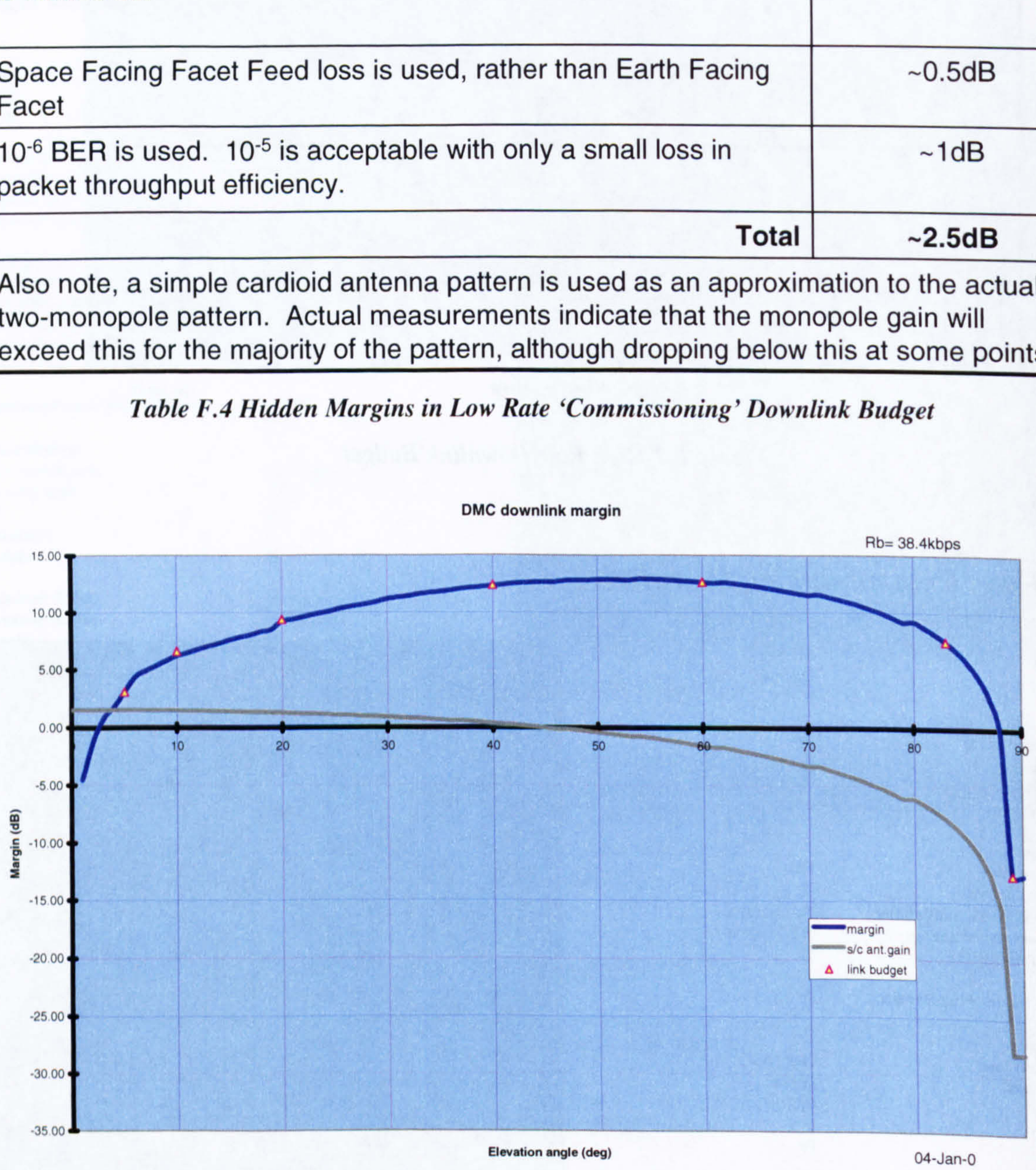

Figure F.2 Low Rate 'Commissioning' Downlink Budget

Uplink

			5	10	25	40	60	83	89	
Elevation	El		64.09	62.77	54.91	43.76	26.84	6.32	0.90	degrees
Nadir	gamma		2531.25	2124.80	1364.93	1002.14	779.69	690.65	686.09	degrees
Range	R									km
Transmitter Power	Pt		10.00	10.00	10.00	10.00	10.00	10.00	10.00	dBW (RMS)
Feeder loss	Fl		0.60	0.60	0.60	0.60	0.60	0.60	0.60	dB
Antenna Gain	Gt		35.00	35.00	35.00	35.00	35.00	35.00	35.00	dBi
Pointing loss	Lpt		0.06	0.06	0.06	0.06	0.06	0.06	0.06	
Equivalent Isotropic Radiated Power	EIRP	+	44.40	44.40	44.40	44.40	44.40	44.40	44.40	dBW
Propagation										
Free Space Loss	FSL	-	166.75	165.23	161.39	158.70	156.52	155.47	155.41	dB
Ionospheric losses	Li	-	0.00	0.00	0.00	0.00	0.00	0.00	0.00	dB
Rain fades (% availability)	dLi (3-sigma)		0.00	0.00	0.00	0.00	0.00	0.00	0.00	dB
Tropospheric scintillation	dLt (3 sigma)	-	0.89	0.50	0.28	0.16	0.13	0.11	0.11	dB
Gaseous Attenuation	Lt		0.60	0.30	0.10	0.09	0.07	0.06	0.06	dB
Received Power Flux Density	PFDrx		-94.66	-93.14	-89.30	-86.62	-84.44	-83.38	-83.32	dBW/m²
Satellite										
Polarisation loss	Lpol	-	1.00	1.00	1.00	1.00	1.00	1.00	1.00	dB
G/T	G/T	+	-37.37	-37.17	-36.10	-35.15	-34.25	-33.81	-33.79	dB
Bolzmann	k	-	-228.60	-228.60	-228.60	-228.60	-228.60	-228.60	-228.60	dB(J/K)
Bit rate	Rb	-	39.82	39.82	39.82	39.82	39.82	39.82	39.82	dBbps
Received Eb/No	Eb/No rx	=	26.56	28.97	34.31	38.08	41.20	42.72	42.81	dB
Required Eb/No	Eb/No req		15.58	15.58	15.58	15.58	15.58	15.58	15.58	dB
Margin	M		**10.98**	**13.39**	**18.73**	**22.50**	**25.62**	**27.14**	**27.22**	**dB**

Table F.5 Uplink Budget

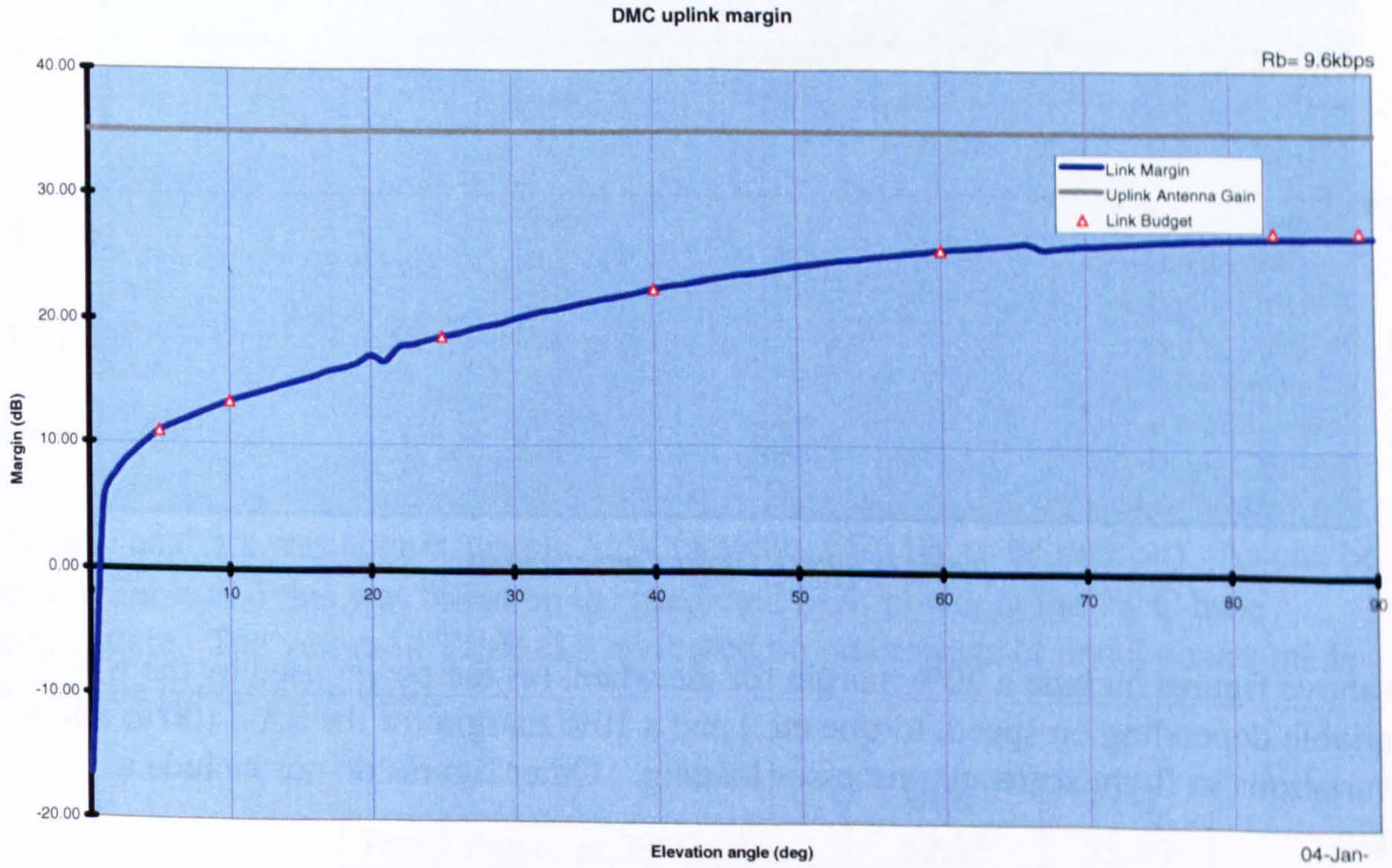

Figure F.3 Uplink Budget

APPENDIX G Power Budget

The pre-launch power budget figures for the first DMC spacecraft are given below.

Peak Power Consumptions

		Switch	Switch Efficiency	Peak Power inc. margin
Bus				
Power system		Fused	0.995	1.95
ADCS module (All)		Bipolar	0.95	1.10
Multiplexor		FET	0.98	0.00
sunsensors-1, 2, 3, 4		FET	0.98	0.00
MAG-0		FET	0.98	0.00
MAG-1		FET	0.98	0.00
Magnetorquer 1, 2, 3		FET	0.98	2.10
Wheel-1		FET	0.98	1.71
Wheel-2		FET	0.98	1.71
Boom Controller		FET	0.98	0.21
OBC 386		FET	0.98	5.24
OBC 186		Bipolar	0.95	1.66
RX-1	S-band	Fused	0.995	1.49
RX-2	S-band	Fused	0.995	1.49
LRTX - Downlink TT&C	S-Band	FET	0.98	5.57
Payloads				
HRTX-1	S-band	FET	0.98	41.14
HRTX-2	S-band	FET	0.98	41.14
GPS		FET	0.98	5.71
SSDR-0 (standby)		FET	0.98	6.64
SSDR-0 (active)		FET	0.98	8.92
SSDR-1 (standby)		FET	0.98	6.64
SSDR-1 (active)		FET	0.98	8.92
Camera Bank 1		FET	0.98	12.86
Camera Bank 2		FET	0.98	12.86
SA1100 (standby)		FET	0.98	4.40
SA1100 (active)		FET	0.98	4.40

Table G.1 Peak Power Consumptions

The above figures include a 20% margin for the wheel (as the power used by the wheel is variable depending on speed, torque etc.) and a 10% margin for the SA-1100 to allow for variations in flight software processor loading. Other figures do not include a margin.

The propulsion system peak power consumption predictions are as shown in Table G.2.

Note that the switch efficiencies are included in the calculation of the peak power in the table above.

	Switch	Switch Efficiency	Peak Power inc. margin
Propulsion			
Controller CAN and Temp Sensors	FET	0.98	0.30
Pressure Transducer	FET	0.98	0.20
Heater 1	FET	0.98	5.14
Heater 2	FET	0.98	15.43
Heater 3	FET	0.98	15.43
Isolation Valve (Opening)	FET	0.98	12.00
Isolation Valve (Hold)	FET	0.98	0.91
Thruster Valve (Opening)	FET	0.98	12.00
Thruster Valve (Hold)	FET	0.98	0.91

Table G.2 Propulsion System Peak Power Consumptions

Battery

The battery capacity was measured to be slightly above the 4Ah nameplate capacity. However, it is recommended that the nameplate capacity of 4Ah be used in calculating the battery capacity and Depth of Discharge expected in different scenarios.

The battery voltage varies from 26.4V to 34V. The battery voltage when discharging will be approximately 26.4V.

Hence the battery capacity to be used when considering Depth of Discharge is 4Ah x 26.4V = 105.6Wh.

The recommended Depth of Discharge for a 5 year lifetime, i.e. assuming approximately 25-30000 cycles, is 15%.

The Battery Return Loss factor to be assumed is 15%.

Solar Panels

The solar panel power (specified at a 28°C base temperature) assumed for operations scenario analysis was approximately 55W (actually 55.65W to be precise). As can be seen in Table G.3 this was based on the predicted EOL power at the 28°C base temperature. The values in Table G.3 are based on predictions of panel power made before the panels were built.

	BOL	**EOL**
Panel Power at 28°C (W)	57.36	55.65
Panel Power at –40°C (W)	65.07	63.20
Panel Power at +80°C (W)	51.38	49.79

Table G.3 Estimated Variation in Panel Power with Temperature at BOL and EOL

Actual solar panel powers were very similar to predictions. It should be noted that during panel manufacture it was decided to populate the +Y panel with the most efficient cells, giving a very slightly higher power from this panel. This is because the +Y panel receives most solar illumination in the nominal imaging operational mode.

Power System Efficiencies

The power system efficiency predictions, pre-launch, are as described in the following sub-sections.

PCM

As a result of measurements on the first DMC flight model build a PCM efficiency (i.e. producing the 5V power supply) of 75% should be used. It should be noted however, that this is actually quite a conservative value, and depending on the current drawn from the system the efficiency may well exceed this.

PDM

Switch/fuse efficiencies are already included in the figures presented in Table G.1 and Table G.2. The efficiencies assumed are:

FET	98%
Bipolar	95%
Fused	99.5%

BCR

A BCR efficiency of 88% is recommended, although the efficiency may well exceed 90% much of the time. Hence this is a conservative assumption.

APPENDIX H Acronyms and Definitions

ADCS	Attitude Determination and Control System
AIT	Assembly, Integration and Test
AODCS	Attitude and Orbit Determination and Control System
AVHRR	Advanced Very High Resolution Radiometer
BBQ	Barbeque
BCR	Battery Charge Regulator
BER	Bit Error Rate
BOL	Beginning of Life
BPSK	Binary Phase Shift Keying
BRF	Battery Return Factor
CAN	Control Area Network
CCD	Charged Coupled Device
CDR	Critical Design Review
CEO	Chief Executive Officer
CEOS	Committee on Earth Observation Satellites
CNES	Centre Nationale des Etudes Spatiales
CoG	Centre of Gravity
COTS	Commercial Off The Shelf
DC	Direct Current
DEM	Digital Elevation Model
DMC	Disaster Monitoring Constellation
DMSG	Disaster Management Support Group
DoD	Depth of Discharge
DRAM	Dynamic Random Access Memory
dV	DeltaV
EC	European Commission
EDAC	Error Detection and Correction
EFF	Earth Facing Facet
EIRP	Equivalent Isotropic Radiated Power
EMC	ElectroMagnetic Compatibility
EO	Earth Observation
EOL	End of Life
ESA	European Space Agency
ETM	Enhanced Thematic Mapper
FET	Field Effect Transistor
FOV	Field of View
FPGA	Field Programmable Gate Array
FRR	Flight Readiness Review
FSL	Free Space Loss
G	Green
Geo	Geostationary
GG	Gravity Gradient
GIS	Geographical Information System
GMES	Global Monitoring for Environment and Security

GPS	Global Positioning System
GSD	Ground Sampling Distance
HQ	Headquarters
HR	Human Resource
HRG	High Resolution Geometric
HRTX	High Rate Transmitter
IDDR	International Decade for Natural Disaster Reduction
IF	Intermediate Frequency
IGRF	International Geomagnetic Reference Field
IR	Infra Red
KHTT	Know How and Technology Transfer
LARST	Local Application of Remote Sensing Techniques
LEO	Low Earth Orbit
LEOP	Launch and Early Operations Phase
LNA	Low Noise Amplifier
LOP	Long-term Orbit Propagator
LRTX	Low Rate Transmitter
LTAN	Local Time of Ascending Node
LVDS	Low Voltage Differential Signal
MAG	Magnetometer
MARS	Monitoring Agriculture using Remote Sensing
MBA	Master of Business Administration
MBTI	Myers Briggs Type Indicator
MDR	Mission Definition Review
MIR	Mid Infra Red
Mono	Monochromatic
MPP	Maximum Power Point
MS	Multi-Spectral
MTQ	Magnetorquer
MWIR	Medium Wave Infra Red
NASA	National Aeronautics and Space Administration
NDVI	Normalised Difference Vegetation Index
NGO	Non-Governmental Organisation
NIR	Near Infra-Red
NOAA	National Oceanic and Atmospheric Administration
NORAD	North American Aerospace Defence Command
OAP	Orbit Average Power
OBC	On-Board Computer
OBDH	On-Board Data Handling
Pan	Panchromatic
PCB	Printed Circuit Board
PCM	Power Conditioning Module
PDM	Power Distribution Module
PDR	Preliminary Design Review
PEST	Politics, Environment, Social, Technical
PFSD	Power Flux Spectral Density
PSU	Power Supply Unit

PUV	Perceived User Value
QFH	Quadrifilar Helix
QPSK	Quadrature Phase Shift Keying
R	Red
RAAN	Right Ascension of Ascending Node
RF	Radio Frequency
RMS	Root Mean Square
RW	Reaction Wheel
RX	Receiver
SAR	Synthetic Aperture Radar
SC	Spacecraft
SFF	Space Facing Facet
SNAP	Surrey Nanosatellite Applications Program
SNR	Signal to Noise Ratio
SRAM	Static Random Access Memory
SRP	Solar Radiation Pressure
SS	Sun Sensor
SSDR	Solid State Data Recorder
SSTL	Surrey Satellite Technology Limited
STK	Satellite Tool Kit
SWIR	Short Wave Infra Red
SWOT	Strengths, Weaknesses, Opportunities and Threats
TIR	Thermal Infra Red
TLE	Two Line Elements
TM	Thematic Mapper
TTC	Telemetry and Telecommand
TTL	Transistor Transistor Logic
TX	Transmitter
UN	United Nations
USGS	United States Geological Survey
VGT	Vegetation
VNIR	Visible and Near Infra Red
w/o	without

Wavelength Terminologies

In this document a number of terms are used to describe different imaging wavelengths. The definition of wavelength boundaries for different terms can differ from document to document. The meaning of these terms as used in this document is defined in Table H.1 below.

					Approximate Wavelength Range, μm
Optical	VISNIR, or VNIR		Visible	Visible	0.4 - 0.7
		Reflected IR	NIR	Near Infra-Red	0.7 - 1.3
			SWIR	Short-Wave Infra-Red	1.3 – 3
			MIR, or MWIR	Mid, or Mid-Wave Infra-Red	3 – 5
			TIR	Thermal Infra-Red	8 – 14

Table H.1 Wavelength Terminologies Used in This Document

Whilst the two columns on the left hand side are simply terms used for convenience in this document, the general guidance for the definitions given in the four columns on the right hand side comes from the Remote Sensing tutorial website [122] provided by the Canadian Centre for Remote Sensing. However, several definitions are slightly modified. These are:

Thermal Infra-Red and Mid Wave Infra-Red.

The CCSR website suggests that the Thermal Infra-Red region runs from 3μm to 15μm. It also goes on to explain that, due to atmospheric absorption, thermal sensing is normally limited to two specific regions - 3 to 5 μm and 8 to 14 μm. In order to distinguish between the two regions in this document the term Thermal Infra-Red is adopted for the 8-14μm region only. The term Mid, or Mid-Wave Infra-Red is adopted in this document for the region of 3 - 5μm. This is also consistent with terminology used in other references which describe the BIRD sensor operating in the 3.4 - 4.2 μm band as discussed in Chapter 5.

Short Wave Infra-Red

No specific numerical range is defined on the CCSR website for the SWIR region, although a useful graphic is provided that illustrates the SWIR range starting near the top of the NIR range and extending almost to the end of the Reflected IR range. The CCSR definition of mid-IR extends exactly from the top of the NIR to the end of the Reflected IR range, and is hence very close to the CCSR defined SWIR range. Hence, to allow the use of the term MIR for the 3-5μm region as described above, the SWIR range is defined in this document as 1.3 – 3μm.