In: 11th European Conference for AeroSpace Sciences (EUCASS 2025), 30 Jun - 4 Jul 2025,
Rome, Italy
https://eucass2025.eu/

# An attitude coordination architecture for communications routing in LEO constellations

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## Abstract

In this work, the challenge of using multiple satellite constellations in LEO for establishing communication links between two ground stations is investigated. Low altitude orbits and limited onboard equipment capabilities, which lead to reduced coverage areas and frequent visibility changes, create a highly dynamic problem. To address typical requirements such as maximising link uptime and/or minimising communication delay, an architecture for optimising the selection of a signal route and attitude control for the involved relay satellites' attitude is presented herein. This architecture is deterministic and can be distributed among all the involved satellites, allowing them to operate individually towards achieving the desired goal.

## 1. Introduction

Satellite constellations have been used since the dawn of space age for communication purposes. This is mainly achieved by placing satellites in orbits suitable for the task, with the typical regime for global coverage being high-altitude Geostationary Earth Orbit (GEO) satellites, as demonstrated by the fleets of long-established operators.[1] However, the cost-to-orbit for payload to GEO is quite higher than the equivalent for Low Earth Orbits (LEO), and modern ventures have favoured these lower altitudes with higher density constellations.[2] The problem that arises when using lower orbits is the reduction of the coverage area, which in turn necessitates the use of more satellite links to form long-range communication networks and careful design of constellations[3,4] in order to facilitate the endgoal , even with modern communication regimes.[5] Due to the nature of the orbital dynamics in these altitudes, the relative position of satellites with ground stations and among themselves constantly shifts. This poses a problem with frequent visibility changes, and for a link to be established between specific endpoints, the signal path among satellites is not constant and must adapt and evolve over time.

In this work, a solution to the problem of path selection for a communications link is presented, which takes into consideration satellite hardware capabilities (equipment position/orientation with respect to the satellite body, field-of-view limitations) as well as the relative positions of every node involved in a communication chain. Other optimization techniques have been proposed based on power consumption,[6] or other aspects[7] and even with reinforcement learning techniques,[8] especially in the case of mega constellations.[9] The approach discussed in this work is purely deterministic, and may be applied to any set of set of satellites spanning possibly more than one constellations, irrespectively of uniformity of hardware capabilities. Given a snapshot of satellite positions, visibility between satellites and ground stations is evaluated with respect to line-of-sight (LOS) obstacles such as the Earth, or other bodies in orbit. This generates a connectivity graph that represents LOS connection capabilities, which of course does not consider the additional problem of dual/concurrent visibility. For every 3-tuple of consecutive nodes in any link, the middle node must be able to reorient in a way that the two extreme nodes of the 3-tuple are concurrently visible to its onboard equipment. The latter problem can be reframed as a geometrical constraint based on the relative positions, and the feasibility of a link segment can thus be determined. Such a link is shown in Fig. 1 between two ground endpoints. If the latter is true, the optimal realignment manoeuvre is obtained by singular value decomposition, and is tracked for the lifetime of the link topology.

The proposed solution takes into consideration the LOS-feasible paths based on satellite positions, which are subsequently filtered to only include the paths that are feasible under dual pointing/concurrent visibility constraints. Evaluation of the possible signal paths allows for further optimisation based on connection requirements, such as

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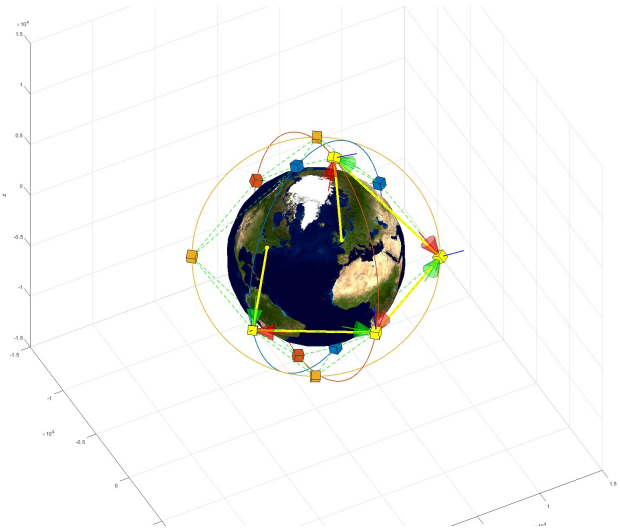


Figure 1: Communication link with two constellatoins

minimisation of delay/lag (using fewer satellite signal hops), or maximisation of uplink time (using fewer/quicker realignments). Based upon the desired criteria, an objective function may be constructed and evaluated whenever an already established path is no longer feasible, and a new one must be selected.

Assuming all satellites already have ephemeris-style data available to them for the orbital parameters of all the involved nodes, a simplified GNC architecture is used where the satellites track the relative targets to form and keep the link up. State feedback control is used to guarantee a maximum error convergence rate, which can be taken into consideration when calculating the total realignment time required for any link topology formation. Simulation results showcase the feasibility of the proposed solution, and the optimization aspect is further exemplified by switching the objective function towards different goals and evaluating resulting link uptimes.

The output of this study is a deterministic GNC architecture that can be distributed among all satellites involved, so that each one can individually calculate the same course of action given a task of establishing a communications link between two ground stations. The only a priori required information is the orbital characteristics of the constellations, and the positions along the orbits for all the satellites. It is assumed in this work that ephemerides-style information is available and common to all satellites, and that all satellites have the compute capability to solve the required optimizations and select the optimal path.

In this paper, the definitions of the system models are presented along with the scenario-specific problems, the candidate solutions are discussed, and a numerical experiment is used to validate the proposed architecture.

## 2. Model and Problem definition

In this section, the assumptions and the models that are used in this work are presented and discussed. Namely, the reference frames, the key quantities, the dynamics models of the system and the relevant AOCS details are presented alongside the formulation of the key challenges addressed in this work.

### 2.1 Attitude and orbital dynamics

Figures 2 and 3 illustrate reference frames used throughout this work, i.e. the Earth Centered Inertial (ECI), the body-mounted (both inertial and fixed) and the Local Vertical Local Horizontal (LVLH) reference frame, respectively. These reference frames will be used to determine relative positions and required reorientations of the satellites involved in the constellation. In this work, the transformations among these reference frames follows the conventions and definitions described in.[10]

### 2.2 Orbital dynamics

In this investigation, we assume a simplified gravitational model which includes only the $J_2$ perturbation **??**, with no other disturbances. Indeed, for the purposes of this study, the effect of the J2 perturbation, i.e. the change of the

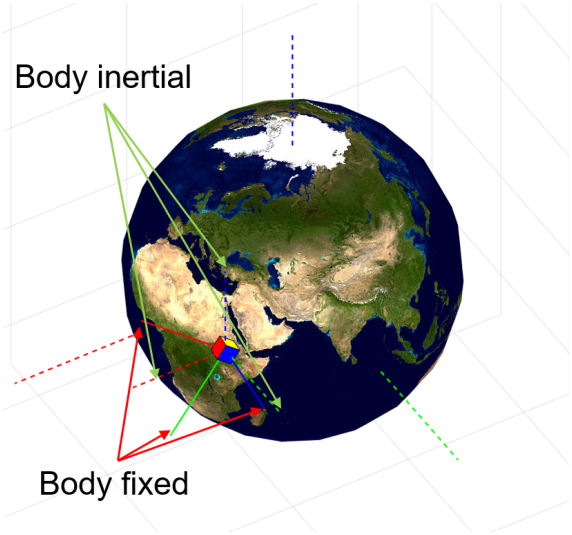



Figure 2: ECI and body frames

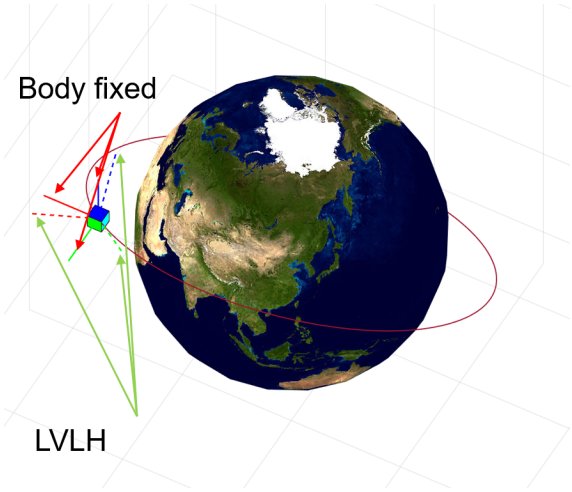



Figure 3: LVLH and body frame

right ascension of the ascending node, has major impact on the satellite constellation geometry compared to any other perturbation operating above 1000 km.[10]

### 2.3 Attitude dynamics

Quaternions are used to represent the body frame rotation of each of the satellites in the constellation with respect to the ECI frame, as follows:

$$q = \begin{bmatrix} q_r & q_x & q_y & q_z \end{bmatrix}^{\mathsf{T}} \tag{1}$$

which together with angular velocity $\bar{\omega}$ can form the state vector $\bar{x} = [q\ \bar{\omega}]^T$. Thus, assuming a rigid body dynamics model, the full-state system dynamics can be written as:

$$\dot{\bar{x}} = \begin{bmatrix} \dot{q} \\ \dot{\bar{\omega}} \end{bmatrix} = \begin{bmatrix} \frac{1}{2} q \otimes q_\omega \\ \mathbf{I}^{-1}\bar{M} - \mathbf{I}^{-1}\left(\bar{\omega} \times \mathbf{I}\bar{\omega}\right) \end{bmatrix} = \begin{bmatrix} \frac{1}{2} q \otimes q_\omega \\ -\mathbf{I}^{-1}\left(\bar{\omega} \times \mathbf{I}\bar{\omega}\right) \end{bmatrix} + \begin{bmatrix} \mathbf{0}_{4x3} \\ \mathbf{I}^{-1} \end{bmatrix} \bar{M} \tag{2}$$

where $\mathbf{I}$ is the inertial tensor of the satellite, $\bar{M}$ the external torque applied to the satellite and $q_\omega = [0 \quad \bar{\omega}^T]^T$. Please also note that the multiplication between quaternions is denoted with $\otimes$.[10]

### 2.4 Communication-link forming

This section discusses the individual problems that need to be addressed in order to achieve the goal of forming a communications link between two ground stations with a satellite relay chain. It is assumed that the satellites involved have on-board communication hardware (i.e., antennae) with either high directivity and thus high gain towards a small region, or lower directivity and gain in a broader direction. In the former case, the antennae lobes are assumed to be steerable by either mechanical means or through beamforming[11],[12] and in the latter case, they are considered to be fixed. In both cases, and for reducing the complexity of the models, the antennae are considered to be able to both transmit and receive a signal through a conical field-of-view (FOV) with an axis that is pointing towards a fixed direction with respect to the main bus of the satellite. In the models considered herein, each satellite may have multiple antennae, with each one having different specifications with respect to orientation and field-of-view width. Such a configuration, with two antennae and their respective FOVs, is depicted in Fig. 4. The axes of the conical FOVs are also depicted, and for simplicity, they are aligned with the $\hat{x}$ and $\hat{y}$ directions of the body frame, marked with red and green lines, respectively.

#### 2.4.1 Line of sight visibility

Given two primary objects (satellites) with positions $\bar{r}_a, \bar{r}_b$, and a number of secondary objects at positions $\bar{r}_i$ with a spherical occlusion zone with radii $R_i$, the line of sight (LOS) visibility is considered as follows:

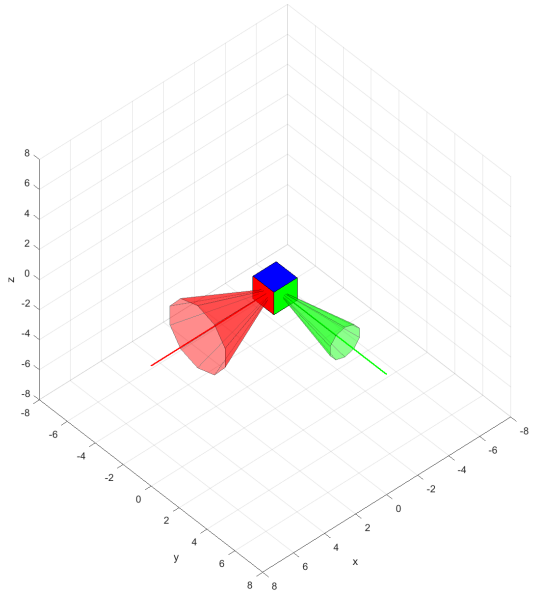



Figure 4: Satellite with two antennae FOV

$$\text{LOS between } \bar{r}_1 \text{ and } \bar{r}_2 \longleftrightarrow \nexists t \in [0,1] \text{ such that } |\bar{r}_a + t(\bar{r}_b - \bar{r}_a) - \bar{r}_i| \leq R_i, \forall i \tag{3}$$

Equation 3 is valid in the case of the Earth as a possible occlusion (with $\bar{r}_i = \bar{r}_e = \mathbf{0}$ and $R_i = R_e = 6.378km$) as well as for any other space-faring sources of occlusions. In this work, only the Earth is considered, but the same principle would apply to additional possible occlusions. The visibility conditions are represented in Fig. 5, where the LOS between the blue and green satellite is blocked while the red satellite can see both the green and blue.

### 2.4.2 Dual pointing

In order for a satellite to be able to establish communications with another satellite or a ground station, one of its antennae needs to have this conical field of view towards a direction such that it encompasses the other communications endpoint. Thus, the dual pointing problem arises for all the satellites in a relay chain, as each one will need to be pointing two antennae towards either two other satellites, or a satellite and a ground station. The feasibility of this

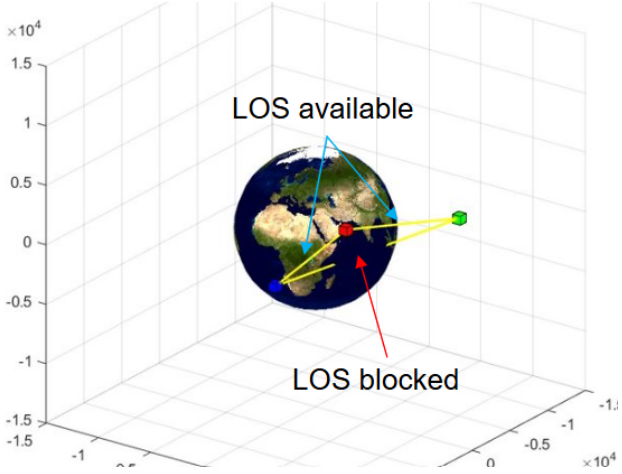



Figure 5: Three satellites, with inter-satellite LOS paths highlighted

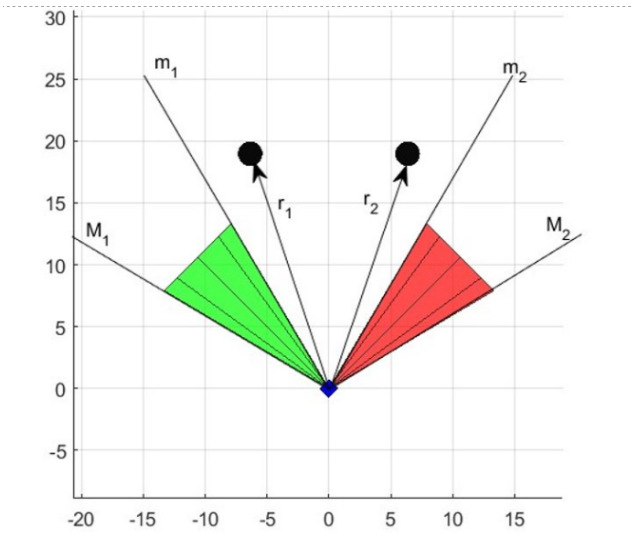



Figure 6: Top-down view of satellite, targets, and antennae FOVs

problem can be examined by geometrical arguments, and in the case of two targets it becomes a 2-dimensional constraint feasibility check as depicted in Fig. 6. In the figure, for simplicity, it is assumed that the main body has already been rotated in a way such that the axes of the FOVs are on the same plane as the one defined by the main body and the two targets, with the axis on the same plane. Based on the geometry of the figure, then, it is easy to deduct that the dual pointing is feasible if and only if the angular distance $\theta$ between the two targets at relative positions $\bar{r}_1$ and $\bar{r}_2$ with respect to the satellite is between the angles $\theta_m$ defined by $\bar{m}_1$ and $\bar{m}_2$, and $\theta_M$ defined by $\bar{M}_1$ and $\bar{M}_2$. In particular, in the example of Fig. 6, concurrent pointing towards both targets is *not* feasible. In case the dual pointing is feasible, then an optimal rotation should be calculated in order to point towards the two targets with both the antennae.

### 2.4.3 Reference attitude generation

The same geometrical arguments presented in Fig. 6 hold in three dimensions as well. The important difference in this case is the dynamics of the system, as discussed in Eq. 2, don't necessarily allow for a "simple" rotation due to the nonlinearities of the system. In order to be able to track two targets, a reference attitude quaternion is needed, and a suitable tracking controller can take over. As per Section 2.4.2, a good reference attitude is one that brings the two targets in the two fields of view of the antennae, as depicted in Figs. 7 and 8.

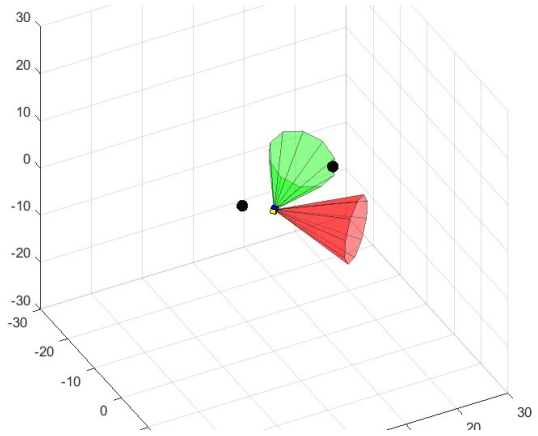



Figure 7: Start of dual pointing realignment

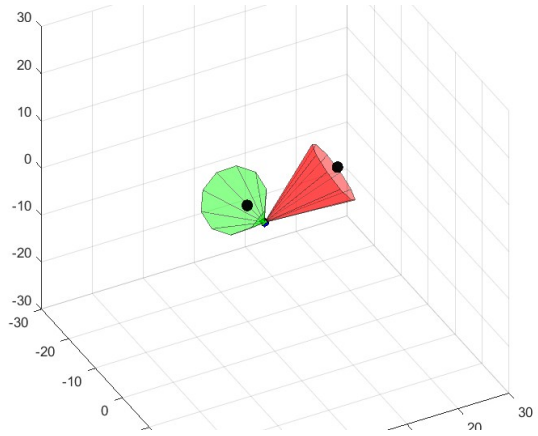



Figure 8: End of dual pointing realignment

Of course, such a realignment manoeuvre must be performed for all the satellites involved in the relay chain, so that they can propagate the signal towards the desired destination.

## 3. Attitude coordination architecture

A high-level overview of the link-forming strategy is depicted in Fig. 9. In order to coordinate the attitude of satellites to establish a link between two ground end points, the first step is to find the feasible signal paths. The first level of constraints is that only satellites within the LOS of each other may form a link segment. After identifying paths with this constraint, the ones that include infeasible (in dual-pointing sense) link relays are discarded. For the ones that include only feasible relays, reference attitude quaternions are generated with the help of singular value decomposition and calculation of the optimal rotation. After having a list of all the paths, with the realignments that are required for each one, an optimization may be introduced where the best one is selected and followed by the satellites.

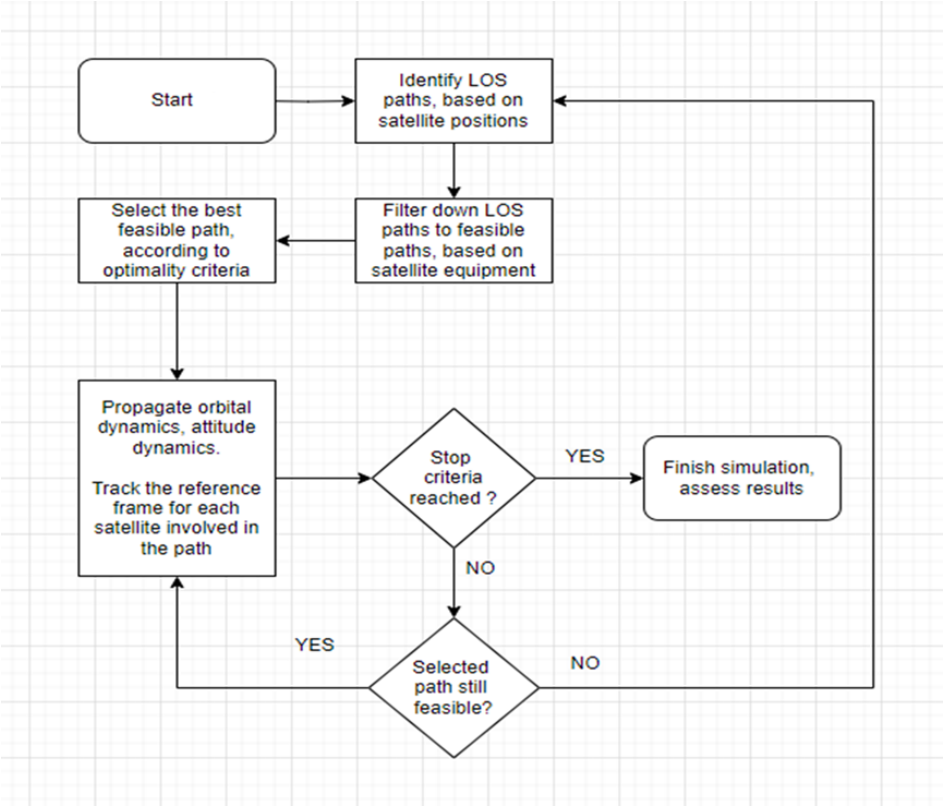



Figure 9: Flowchart of attitude selection process

### 3.1 SVD-based dual-target pointing attitude generation

If geometrical constraints, such as discussed in Section 2.4.2, are satisfied, there must exist a rotation along the direction of the axis perpendicular to the plane, that evenly distributes the angular difference between each antenna's FOV axis and the target position vectors. Representing this rotation as a matrix $\mathbf{A}$, the vectors representing the directions of the FOV axes as a matrix $\mathbf{F}$, and the vectors representing the target positions as $\mathbf{R}$ (all expressed in the same reference frame, e.g. body frame), the problem can be reframed as a minimization problem of a Frobenius norm as follows:

$$\arg\min_{R} ||\mathbf{RF} - \mathbf{T}||_F \tag{4}$$

The Frobenius norm is defined as per:

$$||\mathbf{A} - \mathbf{B}||_F = \sqrt{\sum ||\bar{a}_i - \bar{b}_i||_2^2} \tag{5}$$

and in this case it is applied to normalized vectors as the only constraint is to realign in such a way that target objects are within the FOV of the communications equipment.
This actually reduces the Frobenius norm of the difference of two matrices $\mathbf{A}, \mathbf{B} \in \mathbf{R}^{3x2}$, where each column vector $\bar{v}$ is such that $||\bar{v}|| = 1$, down to:

$$\|\mathbf{A} - \mathbf{B}\|_F^2 = 2\sum(1 - \cos\theta_i) \tag{6}$$

Therefore, the norm is minimized when the dot product of each corresponding set of vectors is maximized. This depends solely on their angular differences $\theta_i$ after applying the rotation. This problem is equivalent to Wahba's problem,[13] and thus admits a solution via Singular Value Decomposition (SVD). Given

$$\mathbf{TF}^T = \mathbf{U\Sigma V}^T \longleftrightarrow \mathbf{R} = \mathbf{UV}^T \tag{7}$$

The matrix $\mathbf{UV}^T$ is always orthogonal given that $\mathbf{U}$ and $\mathbf{V}$ are independently orthogonal (in the case of real matrices), but it may as well represent an invalid rotation (i.e. a reflection). In any case, it holds that $\|\det(\mathbf{UV}^T)\| = 1$ and a simple way to avoid an invalid rotation is to use

$$\tilde{\mathbf{R}} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & \det(\mathbf{UV}^T) \end{bmatrix} \mathbf{UV}^T \tag{8}$$

Equation 8 takes care of the problem of finding the optimal rotation, in the sense of eq 4, that best aligns the vectors representing the antennae FOVs with the desired pointing targets. The approach can be directly implemented in 3D space with 3D vectors as well, and no initial co-planar alignment manoeuvre is needed. With the necessary algebraic manipulations (application of the rotation matrix to current attitude quaternion), this optimal rotation provides for a reference attitude to be tracked by the satellite attitude control system.

### 3.2 Reference tracking

As discussed in the previous subsection, given a snapshot of satellite and target positions, an optimal attitude quaternion can be generated, enabling the satellite to track the targets using its onboard communications equipment. It is assumed that no other information is available to the satellite except for this instantaneous tracking requirement, which is calculated based on orbital data. In this case, a state feedback controller would yield results like the depicted in Fig. 10, if used without angular velocity (i.e., $\bar{\omega}_{ref} = \mathbf{0}$). This is an expected result, since the control law does not have any reference of angular velocity to track, and thus the tracking result is always lagging the reference value.

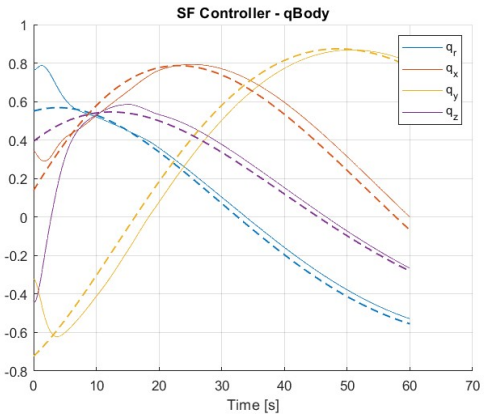



Figure 10: State feedback controller reference quaternion tracking performance

An approach to solve this problem, without any knowledge regarding the targets' orbital status, is to introduce an observer as follows:

$$\begin{aligned} \dot{q} &= \frac{1}{2} q \otimes q_\omega \\ \leftrightarrow q_{n+1} &= q_n + \frac{1}{2} q \otimes q_\omega \delta t \\ \leftrightarrow q_\omega &= q_n^{-1} \otimes \frac{2}{\delta t} (q_{n+1} - q_n) \end{aligned} \tag{9}$$

Equation 9 provides for an instantaneous value of angular velocity for the attitude reference quaternion, between two successive calculations of $q_{ref}$. Given that this angular rate cannot change discontinuously due to the nature of this

problem, a low-pass filter is implemented to smooth out transition between two subsequent values as soon as a new angular rate measurement $\bar{\omega}_c$ is available:

$$\bar{\omega}_{ref}\Big|_{n+1} = \frac{\tau}{\tau + \delta t}\bar{\omega}_{ref}\Big|_{n+1} + \frac{\delta t}{\tau + \delta t}\bar{\omega}_c \tag{10}$$

The results of introducing this angular rate estimation of the desired attitude quaternion $q$ to the state feedback controller are presented in Fig. 11, whereas the actual observer performance is depicted in 12. For these tests, the targets were considered to be satellites with randomized velocities relative to the observer satellite. Starting with an initial $\bar{\omega}_{ref} = \mathbf{0}$, the observer quickly converges to the actual angular rate of the reference quaternion, and thus produces a valid reference signal for attitude tracking.

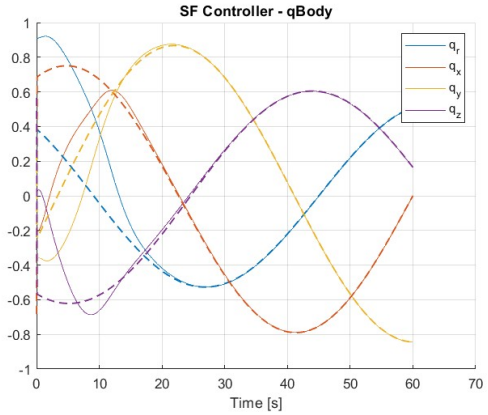



Figure 11: Observer-augmented state feedback controller tracking performance

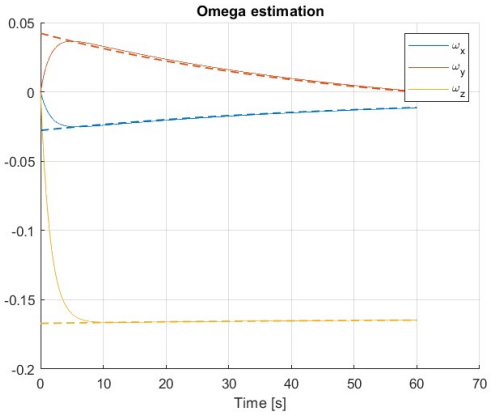



Figure 12: Reference quaternion observer omega estimation

### 3.3 Signal route selection

With the definition of LOS availability as discussed, for each simulation, a dynamic visibility graph (or adjacency matrix) can be constructed to summarize this information. Such a graph is depicted in Fig. 13, for a small number of satellites and two ground stations. The nodes labeled $1, 2$ are the ground stations, and all the rest are satellites. The information contained in this graph would be enough to find the viable signal paths given the constellations' status, however this graph does not take into consideration the dual pointing problem.

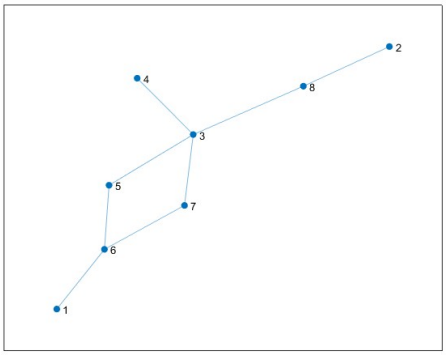


Figure 13: LOS connectivity graph

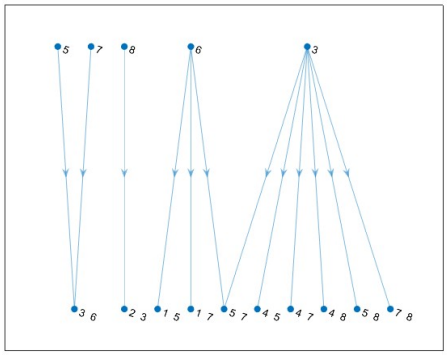


Figure 14: Manoeuvres graph

Instead, the graph of Fig. 13 is deconstructed into a the form represented in Fig. 14. This deconstructed version is yet again a (directed) graph, one that encodes the information of which satellite could be pointed (by LOS availability) towards which pairs of targets, with each such connection represented by an edge. Out of these possible pairs of targets,

Table 1: Satellite constellation data and orbital elements

| Constellation | $\mathbf{N}_{sat}$ | **a [km]** | **i [deg]** | **e** | **Ω [deg]** | **$\omega$ [deg]** |
|---|---|---|---|---|---|---|
| Alpha | 8 | 7200 | 30 | 0.01 | 0 | 0 |
| Bravo | 5 | 7300 | 89 | 0.01 | 0 | 0 |

not all are feasible, as discussed in Section 2.4.2. Therefore, the graph edges are filtered and the infeasible (in a dual pointing sense) connections are discarded.
After the filtering process, the deconstructed graph is split into multiple copies, where in each copy for each single node only one edge pointing to one single pair is kept. This is done for all possible combinations, and from this set of graphs, multiple visibility graphs can be reconstructed where each satellite node has exactly two neighbors. Searching among this set of graphs with any suitable algorithm for paths between nodes $1, 2$ (representing the ground stations) gives all the feasible link routes, based on the original LOS visibility information. A similar approach to this would be to exhaustively find all the paths on the original graph of Fig. 13, and iteratively verify that each connection is feasible, for each found path.
Having obtained, by any means, the sum of the feasible signal paths, in order to select the optimal solution, a cost metric must be associated with each one. In the simplest form, this cost function can be the sum of realignment angles from the current attitude $q_c$ to the required $q_r$ for each satellite that is active in the $i-$th signal path.

$$C_i = \sum \arccos \|Re(q_c^{-1} \otimes q_{r,i})\| \tag{11}$$

A different approach to a metric would be to take into consideration the signal path lifetime, and rate the candidate paths according to the maximum lifetime of their links. This can be obtained through simulation, evaluating the feasibility of a link for a finite time window according to the positions of the satellites involved. Any monotonous function $f$ can be used as a cost function, in this case.

$$\tilde{C}_i = f(T_L), \text{ where } t_1 > t_2 \leftrightarrow f(t_1) < f(t_2) \tag{12}$$

Both of these approaches have been put to the test in this work, and the results based on each of the strategies are presented in Section 4.

## 4. Numerical results

In order to evaluate the proposed methodology, a scenario is simulated. There are two preexisting satellite constellations in LEO, one with an equatorial and one with a polar orbit. Each constellation has 4 satellites, and each satellite is considered to be equipped with identical communication equipment, i.e. two antennae with 30Â° conical FOVs, pointing along the body frame $\hat{x}$ and $\hat{y}$ directions. The goal is to establish a communication link between Cranfield, UK and Sydney, AU and maximize the uptime of the connection. All the satellites are considered to be aware of each other, e.g. by shared ephemeris-type information, and thus individually the methods proposed in Section 2.4 can be independently applied by each one. Given the deterministic nature of the signal route selection process, they will all pick the same optimal route and thus be subsequently able to track the required attitudes.
Based on the constellation orbital elements, a simulation of orbital dynamics for about a full orbital period yields the LOS paths depicted in Fig. 15. It is worth pointing out that given the satellite positions in this setup, there are some time windows for which there is no feasible signal path. Given that the constellations are assumed to not be designed for the purpose, this is to be expected and there is nothing to be done in these no-route cases. By applying the route signal route selection criteria, and tracking as discussed in Sections 2.4.2 and 3.2, the results are as presented in Figs. 16, 17, 18.
In Fig. 16 we observe the link uptime versus simulation time, with the expected drops of connectivity during realignment. It is worth noting that, during the realignment phases, when switching route paths, the uptime percentage is dropping(orange plot) whereas the absolute link uptime in minutes stays constant (blue plot). The overall link uptime percentage is generally increasing throughout the simulation time, and reaches about 70% by the end of sim time.
In Figs. 17 and 18, the tracking performance is shown, with the error spikes corresponding to the phases of topology switching. The proposed control law, in conjunction with the observer as described in Section 3.2, yields good tracking performance, evident by the minimal increase of the error integral after the links have been established, as shown in 18.
Switching to the proposed optimized route selection strategy by evaluating topology lifetime and taking this into consideration, similar results are obtained as depicted in Figs 19, 20, 21.

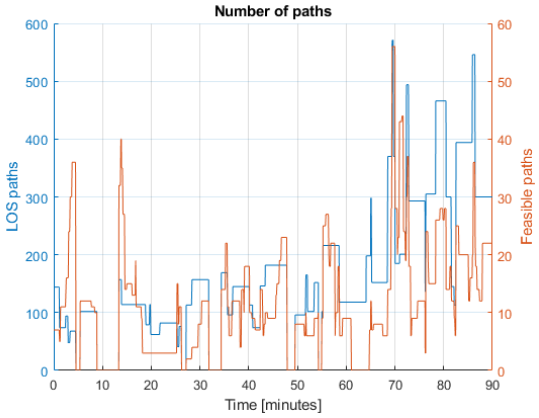



Figure 15: LOS available and feasible paths

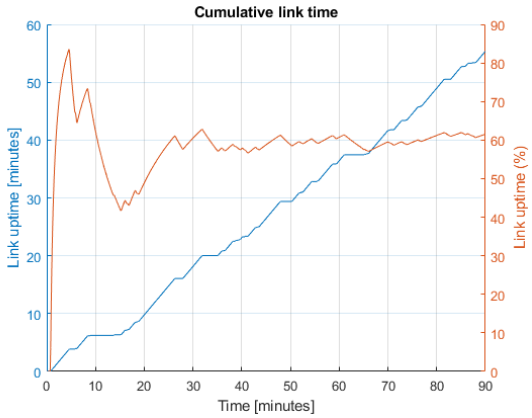



Figure 16: Link uptime (Strategy A)

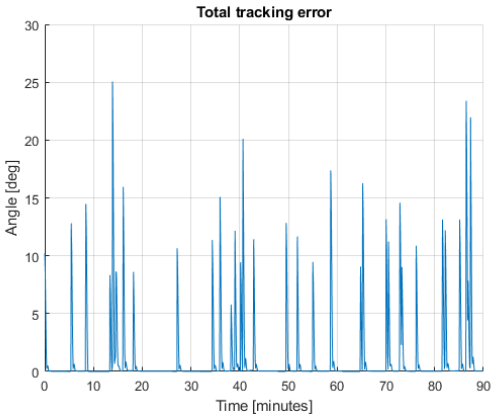



Figure 17: Total tracking error (Strategy A)

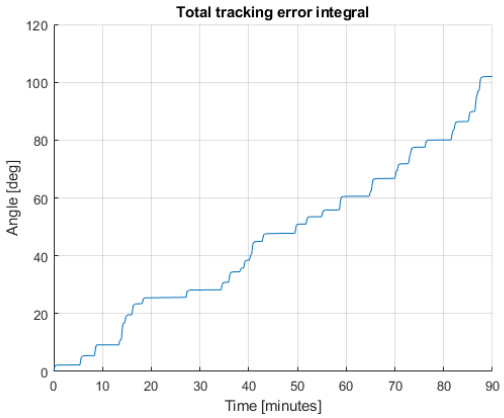



Figure 18: Total tracking error - Integral (Strategy A)

In Fig. 19, an increase in total link uptime is observed, with respect to the previously used link selection strategy. This result is attributed to the fewer link topology changes, due to the optimised selection of signal path. This is also evident in Figs. 20, and 21, with fewer error spikes and the lower overall tracking error integral value.

## 5. Conclusions

This work presented a strategy to establish communication links and coordinate the attitude of satellites orbiting in LEO constellations. In order for the task to be fulfilled, the key challenges of optimizing link routing selection were discussed

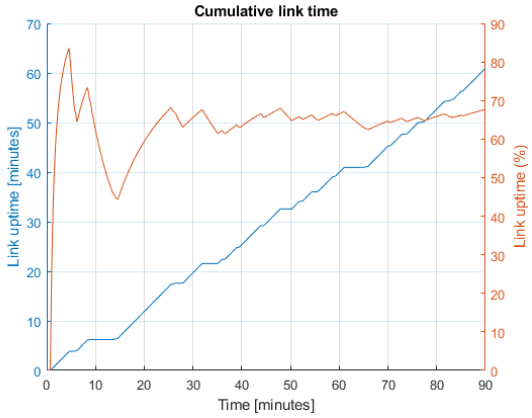



Figure 19: Link uptime (Strategy B)

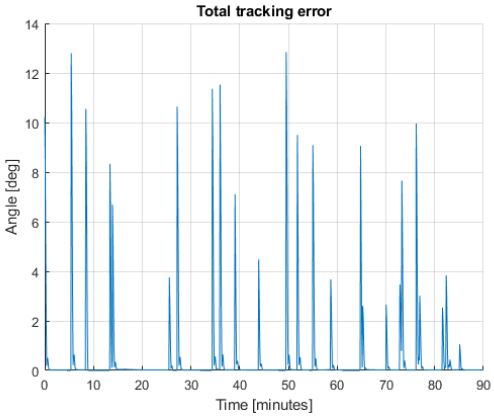



Figure 20: Total tracking error (Strategy B)

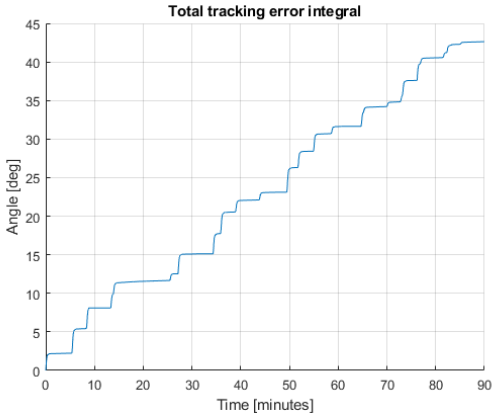



Figure 21: Total tracking error - Integral (Strategy B)

in Sections 2.4.1, 2.4.2, 3.2, highlighting the non-uniqueness of the solutions and the non-predictability of the tracking requirements. The proposed solution, presented in Section 2.4 allowed for successfully establishing time-varying communication links, using multiple inter-satellite links, switching from one path to another following two different optimization strategies. The first one minimises the global realignment manoeuvres among the satellites, and the second one minimises the number of necessary path switches to maximise the uptime of individual links. The proposed solutions have been tested with numerical simulations in section 4, and have proven to be successful. The proposed optimisation via modelling the expected link topology uptime has shown an increase in overall communication uptime, whereas the proposed observer setup has improved tracking performance during link dual tracking.
The simulated scenario was a simplified case, with a low number of satellites involved in the simulation, due to the heavy computational load of the proposed approach. The end-goal would be to have a distributed gnc architecture that would work with mega-constellations, but a refined optimization scheme is required. On the other hand, the proposed strategy can be also useful in cases where pre-existing constellations need to be re-purposed to establish communication links between remote areas on the Earth, with satellites displaced in non-optimised orbits for this specific task. Current work is on transforming this problem into a format that can be solved with integer programming, with promising early results.

## 6. Acknowledgments

This work has been supported by the NATO Science for Peace and Security (SPS) programme, under the grant SPS G6141 - "Federated laboratories for testing formations of responsive satellites".

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# An attitude coordination architecture for communications routing in LEO constellations

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**2025-07-04**
EUCASS
https://doi.org/10.13009/EUCASS2025-707
Platanitis K, Shufflebotham A, Ramavaram HR, et al., (2025) An attitude coordination architecture for communications routing in LEO constellations. In: 11th European Conference for AeroSpace Sciences (EUCASS 2025), 30 Jun - 4 Jul 2025, Rome, Italy

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