

An Initial Investigation in the Viability of Degraded Modes for Advanced RF Seekers

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Abstract—Existing air-to-air RF seekers do not feature a specified degraded mode. The existence of such a mode would greatly increase the resilience of the radar seeker, reducing the chances to see a mission compromised by either technical failure or deliberate impairment (countermeasures). However, the problem is extremely challenging due to timing aspects as the mission is extremely short.

This paper presents an initial investigation and the results of an initial study to identify, on receive only, the array components most likely to cause faults, to find solutions for increasing resilience and to establish the most promising pathways to reconfiguration. It is an ambitious first step on a technical challenge never investigated before.

Index Terms—air-to-air RF seeker, AESA, degraded mode, fault management, reconfigurability

I. INTRODUCTION

Current air-to-air radio frequency (RF) seekers do not include a specified “degraded mode”. This entails that in the event of a fault, affecting either the antenna or a circuit element, such as an amplifier or a filter, the system is not able to detect the fault and reconfigure in order to compensate errors. Such a function would be interesting as it could reduce the chances to see a mission compromised by technical failure. The problem is very challenging due to timing aspects: the mission is extremely short. It is not within the scope of this paper to deal with real-time aspects or to investigate fault detection and identification. The paper is intended as a proof-of-concept and focuses on a rather narrow goal: impairments are simulated with a statistical approach using the model of a generic RF seeker receiver. The perceived position of a target is then compared to a ground truth reference position. By means of tuning a set of digital step attenuators it is shown that the errors on both the azimuth and the elevation angles can be greatly reduced.

II. GENERAL FRAMEWORK

A. Setup and assumptions

The system under test is an air-to-air seeker which uses a system of four phased sub-arrays, located at the corners of a squared-shape, to compute the angular position of a target in terms of azimuth and elevation. Because this is an initial investigation, the transmitter side of the seeker is assumed ideal.

Figure 1 depicts the position of the phase centers of the four antenna sub-arrays used by the seeker. It is assumed that the spacing between the phase centers is equal to half the wavelength. The receiver module is modeled by four receiver chains, identical to the one shown in Figure 2, based on a super heterodyne architecture. The RF stage of the receiver

(dashed orange lines area in Figure 2) is composed of one antenna sub-array, one circulator, one RF filter to suppress unwanted signals, two cascaded Low Noise Amplifiers (LNA) followed by one Digital Step Attenuator (DSA) to keep the signal at a desired level, and then a phase shifter. The downconversion from RF to Intermediate Frequency (IF) is achieved by an IQ mixer modeled with two 90 degrees hybrids, two scalar mixers and a power splitter. In addition, an IF filter that reduces intermediate spurs due to the frequency shifting, an IF LNA and an analog-to-digital converter (ADC) with a 90 degrees input hybrid complete the IF receiver (solid blue lines area in Figure 2). In this study, only the behavior of analog components is taken into account; the quantification errors of the ADC are not considered.

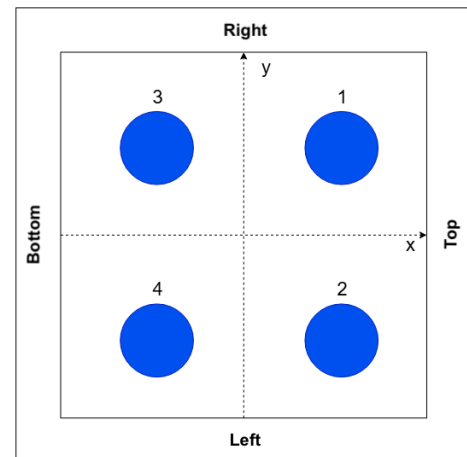


Figure 1: Position of the 4 sub-arrays.

The entire setup is simulated using Matlab and ADS in a joint framework. Matlab is used to model the antenna and perform all the required signal processing to estimate the target angle with a phase monopulse [1]. The receiver chains are implemented in ADS and simulated via harmonic balance analysis. The position of the target is considered fixed throughout the simulations. Results are presented for a target with an elevation of 3° and an azimuth of 2°.

B. Fault Generation and Compensation

Faults on the subarrays are implemented in a binary manner: a faulty subarray is simply turned off. Faults on circuit elements, such as amplifiers, on the other hand, are scalable. This allows us to either treat them deterministically, i.e. the parameters of a circuit element are altered in an abnormal manner, or stochastically. In a stochastic approach, faults are

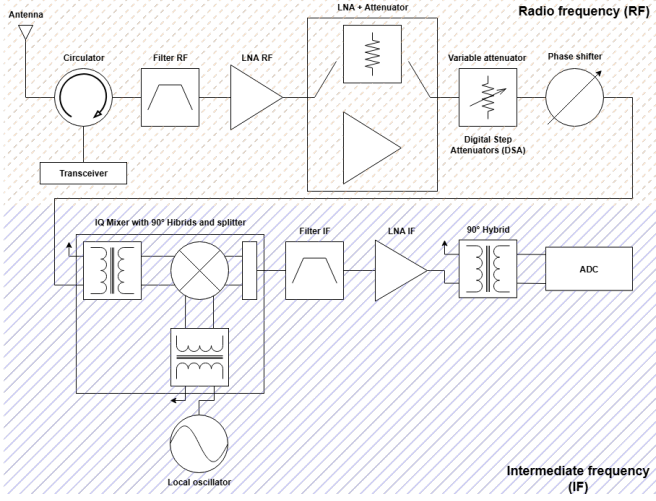


Figure 2: Generic block diagram of a receiver chain. Four such chains are simulated to compute the azimuth and the elevation of the target.

modeled using random variables and account for impairments ranging from small to severe. Table I shows the values used in the simulations presented in this paper. The reference values (without fault) for the gain, noise figure, and input return loss, for the RF amplifier and the IF amplifier, respectively, are listed in column 1. When a fault is present the parameter takes a random value in the intervals listed in column 2. It is important to note that this is a scalable fault analysis rather than a sensitivity analysis, hence the reference value is not part of the interval.

In order to reduce the number of simulations, while retaining a statistically meaningful set, Latin hypercube sampling [2] is used with uniform distributions for the input random variables.

The specific method of fault detection is considered beyond the scope of the paper. At this stage of the investigation the authors simply assume that the presence of faults can be detected and their source can be identified. Modeling faults with the stochastic approach entails a conservative detection scenario in the sense that the quantification of the impairment is not required: simply put, the system needs to “realize” that an amplifier is malfunctioning but does not need to specifically estimate the loss in terms of gain.

Faults are compensated by means of tuning a set of 8-bit digital step attenuators to minimize a predefined error, via a greedy search algorithm. Each attenuator can assume values between 0 and 63, that correspond to attenuation values between 0 dB and 31.5 dB with a step of 0.5 dB.

Table I: Random variables modeling impairments in circuit elements

Variable	Without fault [dB]	With fault [dB]
LNARF_Gain	27	17 – 25
LNARF_NF	1.5	2 – 5.5
LNARF_IRL	-12	-8 – -1
LNAIF_Gain	31	21 – 29
LNAIF_NF	0.9	1.4 – 4.9
LNAIF_IRL	-12	-8 – -1

C. Monopulse principle

The signals received at each monopulse quadrant are modeled as

$$z_k(n) = G_k(n) \cdot e^{j \frac{2\pi f_0}{c} (p_k^T r)} \quad \text{for } k \in \{1, 2, 3, 4\}$$

where f_0 is the carrier frequency, c is the speed of light, $G_k(n)$ is the complex gain of element k at time n , p_k is the vector containing the 3D Cartesian coordinates of the k element and $r = [\sin(\theta) \cos(\phi) \sin(\theta) \sin(\phi) \cos(\theta)]^T$ is the vector that identifies the true target direction in azimuth (ϕ) and elevation (θ).

The receiving array is then subdivided in four quadrants (Up, Down, Right and Left) and the quadrant signals are obtained as the combination of the array element signals as

$$Q_u = z_1 + z_2 \quad (\text{Up})$$

$$Q_d = z_3 + z_4 \quad (\text{Down})$$

$$Q_r = z_1 + z_3 \quad (\text{Right})$$

$$Q_l = z_2 + z_4 \quad (\text{Left})$$

For identical array elements ($G_k(n) = G(n)$) and the monopulse errors

$$\phi_{\text{MP}}(n) = \text{Im} \left\{ \frac{Q_r - Q_l}{Q_r + Q_l} \right\}$$

and

$$\theta_{\text{MP}}(n) = \text{Im} \left\{ \frac{Q_u - Q_d}{Q_u + Q_d} \right\}$$

are found from the quadrant signals and they are used to estimate the target elevation and target azimuth as

$$\Theta_{\text{MP}} = \arcsin \left(\theta_{\text{MP}} \cdot \text{atan} \left(\frac{\lambda}{2\pi d} \right) \right)$$

and

$$\Phi_{\text{MP}} = \left(\frac{\phi_{\text{MP}}}{\sin(\theta_{\text{MP}})} \right) \cdot \frac{\lambda}{2\pi d}$$

where λ is the wavelength $\frac{c}{f}$ and d is the distance between the centers of the subarray. For a faulty element, the gain $G_k(n)$ changes as a function of the n -th fault realisation.

III. RESULTS

A. Example 1

In this example the RF and IF LNAs on sub-array 1 are considered defective. The antennas themselves are fully functional. The approach is deterministic, the fault is assumed to be detected, located and quantified. The system proceeds to compensate by switching the DSAs from nominal mode to degraded mode per Table II. Figure 3 shows the true target position and the perceived target position before and after compensation. The recovery is successful and it is robust in the sense that the DSA configuration is independent of the target position.

Note that all simulations, throughout the paper, were carried-out without thermal noise, since the focus of the paper are errors caused by faults.

Table II: Digital step attenuator values in nominal mode for a trivial compensation

DSA values	Nominal mode	Degraded mode
Sub-array 1	16	16
Sub-array 2	16	29
Sub-array 3	16	29
Sub-array 4	16	29

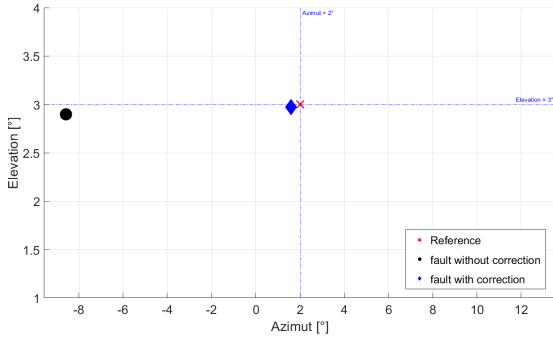


Figure 3: Compensation in a favourable scenario. Real position of the target: red cross; perceived position of the target without compensation: black circle; perceived position of the target with compensation: blue diamond.

B. Example 2

In this second example we consider a much more severe fault scenario. Subarray 2 (lower-right corner) is impaired. Subarray 1 (upper-right corner) is functional, but both the corresponding RF amplifier and the IF amplifier suffer faults. Subarrays 3 and 4 (left-hand side corners) are fully functional. Moreover, we now assume a conservative detection scenario and attempt to blindly compensate a range of potential defects on the amplifiers. Figure 4 shows the impact of the cumulative impairments on the perceived position of the target. The histograms were obtained for a total of 200 samples and smoothed using the kernel density method. Note that the error on the azimuth is particularly large. Tuning the digital shift attenuators (Table III) on all the four branches of the receiver allows a drastic reduction in error as illustrated in Figure 5. Note that, overall, this is a relatively severe impairment, thus the level of error reduction is remarkable.

Table III: Digital step attenuator values in Nominal mode vs. Degraded mode. Note that for this particular example Subarray 2 is completely unresponsive so the value of DSA 2 has no impact.

DSA values	Nominal mode	Degraded mode
Sub-array 1	16	1
Sub-array 2	16	16
Sub-array 3	16	28
Sub-array 4	16	63

Figure 6 allows the data of Figures 4 and 5 to be visualized in a different manner. The red cross represents the real position of the target in the azimuth-elevation plane. The black cloud shows how the considered class of faults, depending on their significance, affect the seeker estimation performance (each point is the result of a simulation for a specific fault). By simply switching the digital step attenuators from the default configuration to compensation-mode, the same faults paint the blue cloud, which is much closer to the true reference position. Because the phase is not compensated, it is expected that the phase monopulse ideal performance is not recovered and that there is a residual bias. Further more, the overall performance of the compensation depends on the position of the target.

IV. CONCLUSION AND FUTURE WORK

The initial results presented in this paper are encouraging. The authors managed to show that, in a simplified scenario, the accuracy of a severely damaged seeker could be restored to a significant extent. This was achieved by simply tuning a set of digital-step attenuators. Subsequent work should primarily focus on considering more complex models of the seeker and improving the reconfiguration strategies by also considering tunable phase shifters.

ACKNOWLEDGMENT

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DATA AVAILABILITY STATEMENT

Data supporting this study cannot be made available due to commercial restrictions.

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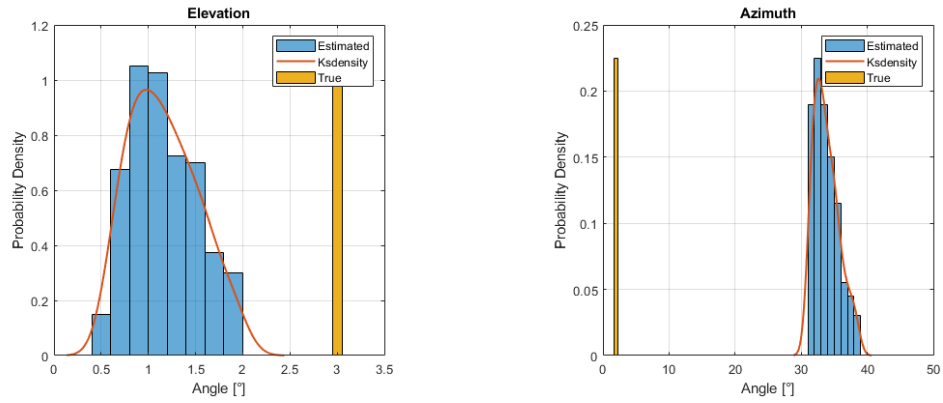


Figure 4: Estimated vs. real target position without compensation. True reference elevation and azimuth in orange. Histogram collecting perceived position for various faults in blue. Probability density function in red computed via kernel density smoothing.

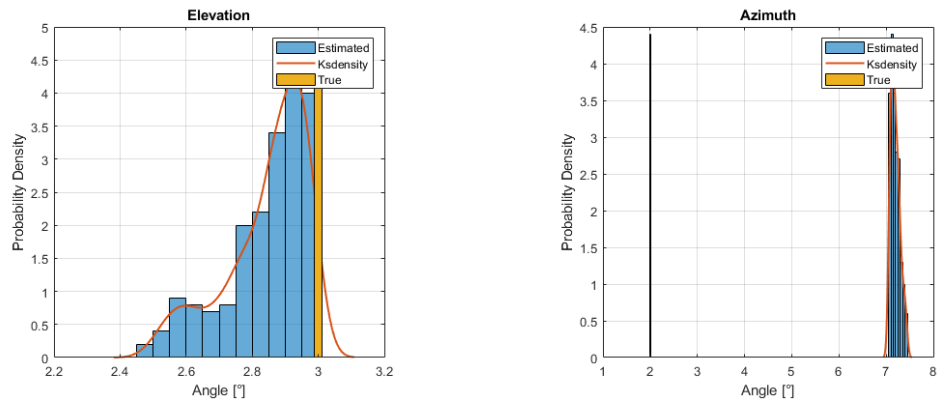


Figure 5: Estimated vs. true target position with compensation. Same convention as in Figure 4.

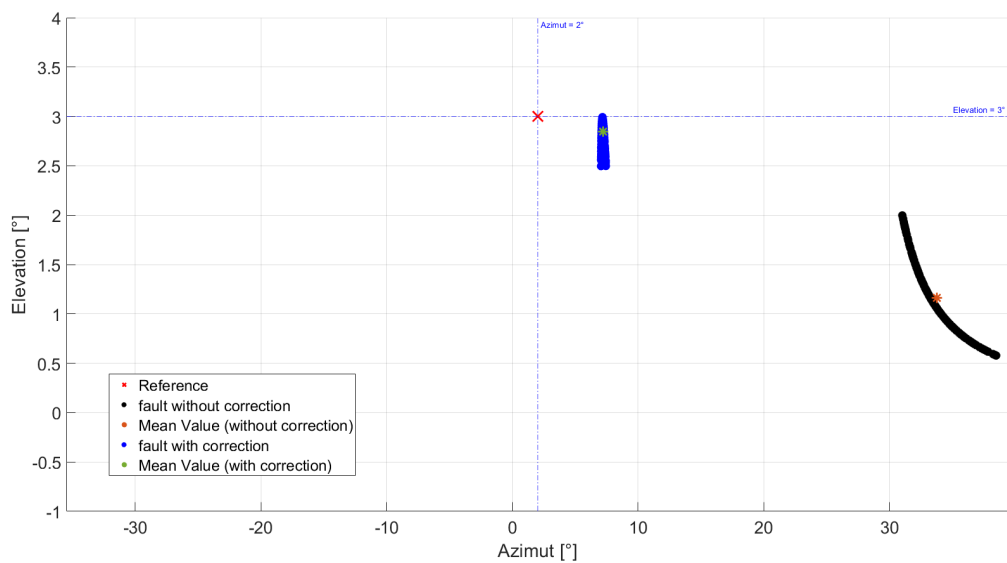


Figure 6: True and estimated position of the target in the elevation vs azimuth plane. The presence of faults causes an error (black cloud) which is compensated to a significant extent by switching in degraded mode (blue cloud).



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