

Real-Time Detection of Antenna Tracking Errors for Enhanced Tracking Performance

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Abstract:

In flight test telemetry operations, maintaining reliable communication between airborne platforms and receiving systems critically depends on accurate antenna tracking performance. Under dynamic flight conditions, deviations in azimuth and elevation pointing can lead to significant degradation in received signal strength. The impact of tracking errors on signal performance is often not explicitly quantified, and detection of such errors during flight remains an open challenge. This study presents an analysis framework for evaluating antenna tracking performance and telemetry link reliability using real flight test data. The true line-of-sight (LOS) direction is calculated from geometric coordinate transformations and compared with measured antenna pointing angles to define tracking errors. A gain degradation model maps angular tracking errors to antenna gain losses, while transmitter antenna gain is estimated using a pattern-based body-frame transformation that accounts for airborne antenna placement and platform maneuvers. The framework has been applied to flight test data, where combined analysis of signal level, model residual, and demodulator quality enables root-cause identification of telemetry loss events and supports antenna system configuration decisions for subsequent flight test operations. Consistent results obtained on a second receiving system indicate that the framework can be extended to other receiving antenna configurations.

Key words: *Antenna Tracking, Link Budget, Flight Test Analysis, Orientation-Dependent Gain, Tracking Error Detection*

Introduction

Flight test operations with telemetry rely on continuous and reliable telemetry links between airborne platforms and receiving systems. As the diversity of airborne platforms increases the variety of onboard antenna configurations and receiving system types also grows. Each combination introduces distinct signal propagation and tracking behavior that must be understood to ensure mission success.

Receiving tracking antennas must maintain accurate alignment with the airborne transmitter under highly dynamic flight conditions. Inaccuracies in antenna pointing — caused by tracking delays, control limitations, or mode transitions — can result in significant signal loss and occasional data loss.

Conventional link budget analyses focus on transmitter power, free-space path loss, and nominal antenna gains, but do not account for dynamic platform orientation or receiving system tracking accuracy. The effective gain of an airborne antenna depends strongly on the relative geometry between the platform and the receiving system, which changes continuously during flight and is modulated by platform maneuvers. Similarly, the effective gain of the

receiving antenna is a function of its real-time pointing error with respect to the true LOS direction.

This paper presents an analysis framework that addresses these limitations by combining flight test instrumentation (FTI) data recorded onboard with telemetry measurements from the receiving antenna. The framework is applicable across different platform types and receiving system configurations.

System Overview

The flight test environment comprises multiple airborne platforms and multiple receiving systems operating in the S-band frequency range. Platforms include both fixed-wing aircraft and rotary-wing types, each carrying a telemetry transmitter connected to blade-type antennas [1]. Depending on the platform, antennas may be located on the upper fuselage, lower fuselage, or both, resulting in different radiation coverage characteristics.

Receiving systems vary in antenna aperture and beamwidth, from narrow-beam parabolic dish systems to wider-beam systems. Each system records received signal levels, antenna pointing angles, frame synchronization status, and

receiver quality metrics. The FTI system records platform position, altitude, and attitude angles. FTI and receiving antenna data are acquired by independent systems at different sampling rates and subject to independent timing offsets, requiring explicit time alignment before analysis. The framework has been applied to two ground receiving systems with substantially different gain characteristics. The detailed analysis is presented for one receiving system (RX System #1)

Methodology

The framework processes FTI and receiving system data through five sequential steps: time synchronization, line of sight (LOS) geometry calculation, airborne antenna gain modeling, receiving antenna gain modeling, and link budget estimation with telemetry quality assessment. Tab. 1 lists the key input parameters.

Tab. 1: Key input parameters of the framework.

Parameter	Description
Platform position (lat, lon, alt)	Aircraft geometric coordinates from FTI
Attitude (heading, pitch, roll)	Platform orientation angles from FTI
Receiving antenna position	Receiving system geometric coordinates
Antenna pointing (az, el)	Measured receiving antenna pointing angles
Received signal level	RF power level per channel (dBm)
Telemetry status	Telemetry OK/NOK indicator
Receiver quality metric	Demodulation quality per channel (dB)

Data Acquisition and Time Synchronization

FTI and receiving system data are acquired by independent systems with different sampling rates and hardware latencies. The tracking lag is determined by aligning the calculated and measured antenna azimuth profiles over a defined search range. All receiving antenna measurements are then time-shifted accordingly.

Line-of-Sight Geometry and Tracking Errors

Platform and receiving antenna coordinates are converted to a common Earth-fixed reference frame. The relative position vector is then expressed in a local frame at the receiving antenna, giving the true LOS azimuth, elevation and slant range. Tracking errors are defined as the angular differences between the calculated LOS angles and the time-aligned measured pointing angles.

Airborne Antenna Gain Model

The transmitter antenna gain is estimated from the measured radiation pattern of the airborne blade antenna. The LOS vector is transformed into the body-fixed frame using instantaneous heading, pitch, and roll angles [2]. The onboard antenna installation — upper or lower fuselage — is configured per channel according to the platform's frequency-to-antenna assignment, ensuring the appropriate radiation pattern is applied for each channel. Platform maneuvers continuously modify the body-frame geometry, producing dynamic gain variations captured at each time step.

Receiving Antenna Gain Model

The receiving antenna gain is modeled as a function of the angular pointing error [3]:

$$G_{\text{ant}} = G_{\text{peak}} - 12 \cdot [(\Delta_{\text{Az}}/\text{BW}_{\text{Az}})^2 + (\Delta_{\text{El}}/\text{BW}_{\text{El}})^2] \quad (1)$$

where G_{peak} is the peak antenna gain and BW_{Az} , BW_{El} are the 3 dB beamwidths. The gain is bounded by the side lobe level and transitions to a back-lobe value beyond the back-lobe onset angle. Total system gain additionally incorporates LNA, cabling, and receiver chain contributions.

Link Budget and Telemetry Quality Assessment

The received signal level is estimated as [4]:

$$P_{\text{calc}} = P_{\text{tx}} + G_{\text{tx}} + G_{\text{rx_sys}} + L_{\text{tx}} - \text{FSPL} \quad (2)$$

where P_{tx} is transmitter power, G_{tx} is body-frame transmitter gain, $G_{\text{rx_sys}}$ is total receiver system gain, L_{tx} is line loss, and FSPL is free-space path loss. Telemetry synchronization status and receiver quality metrics are time-aligned and analyzed together with signal estimates and tracking errors.

Signal Level Calculation and Tracking Error Analysis

Fig. 1 presents the five-panel diagnostic plot for RX System #1, CH2 (2363 MHz, lower fuselage antenna). This plot is the primary tool for validating the link budget model on a single channel and for diagnosing the source of any signal-level anomaly.

The inputs to this analysis comprise the FTI-recorded platform position (latitude, longitude, MSL altitude) and attitude (heading, pitch, roll), the receiving antenna-recorded antenna pointing angles, the channel-specific RF level, and the telemetry frame-sync status. The transmit-side gain uses the measured blade antenna pattern; the receive-side gain uses a Gaussian beam approximation [3] with $G_{\text{peak}} = 27$ dB and 3 dB beamwidth of 6° for the system. Time alignment

between the FTI and receiving antenna data streams is established by an automatic lag search that best aligns the geometrically computed LOS azimuth with the measured antenna azimuth.

The diagnostic has two objectives: confirm that the calculated signal level (FSPL combined with transmit gain and receive-system gain) tracks the measured RF level under nominal conditions, and isolate the periods in which the two disagree so that each disagreement can be attributed to a specific cause — out-of-beam pointing, multipath, or unmodeled gain features — and correlated with telemetry loss.

Panel (a) in Fig. 1 overlays measured (blue) and calculated (orange) signal levels with three event-type shadings: red for telemetry loss, purple for large model deviation $|\Delta P| > 10$ dB, and orange for out-of-beam pointing. The two traces track each other closely throughout mission, confirming the validity of the link budget model.

Panel (b) in Fig. 1 shows the residual $\Delta P = \text{Measured} - \text{Calculated}$ as a signed bar plot. Positive bars (green) indicate the measured value exceeds prediction — typically multipath enhancement or constructive reflection — while negative bars (blue) indicate it falls below prediction, typically obstruction, polarization mismatch, or unmodeled pattern features. The residual remains within ± 10 dB across most of the flight, with isolated negative drops to roughly -20 dB late in the mission, coincident with low-elevation geometry.

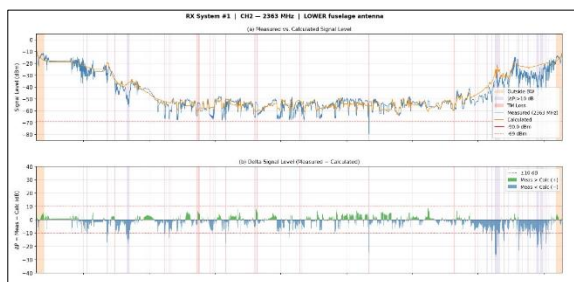


Fig. 1 RX System #1, CH2 (2363 MHz, lower fuselage). (a) Measured vs. calculated. (b) Delta signal. (Red shading: Telemetry loss; purple: $|\Delta P| > 10$ dB; orange: outside $\pm BW/2$.)

Panels (c) and (d) in Fig. 2 display the azimuth and elevation tracking errors against the receiver antenna's $\pm BW/2 = \pm 3.0^\circ$ half-beamwidth limit. These are the indicators of pointing-induced gain loss: an error within the beamwidth produces at most 3 dB of receive-side loss, while an error outside it drops the receive gain rapidly via Eq. (1). The azimuth error remains within $\pm 2^\circ$ throughout most of the flight, well inside the beam. The elevation error is near zero during mission but exceeds the $+3^\circ$ limit at takeoff and

landing — phases in which the platform is at low elevation and the antenna pedestal operates near its limits.

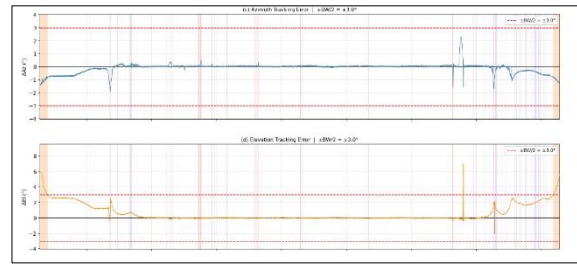


Fig. 2. (c) Azimuth tracking error. (d) Elevation tracking error. (Red shading: Telemetry loss; purple: $|\Delta P| > 10$ dB; orange: outside $\pm BW/2$.)

Panel (e) in Fig. 3 provides the geometric context: relative bearing (the LOS azimuth in the platform body frame) and slant range. The bearing cycles repeatedly between $\pm 180^\circ$, reflecting the flight pattern circling the receiving antenna, while the range varies between approximately 5 km and 80 km. This panel allows any event visible in (a)–(d) to be linked back to a specific mission phase.

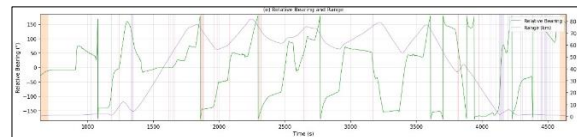


Fig. 3. (e) Bearing and range. (Red shading: Telemetry loss; purple: $|\Delta P| > 10$ dB; orange: outside $\pm BW/2$.)

Telemetry Data Loss Correlation

Fig. 4 and 5 combine the measured-vs.-calculated signal levels for both channels with the corresponding receiver quality metrics.

Panels (a) and (b) in Fig. 4 show the signal traces for CH1 (2205 MHz, upper fuselage) and CH2 (2363 MHz, lower fuselage). Panels (c) and (d) in Fig. 5 show the telemetry quality for the reference CH3 and the active channels CH1 and CH2 respectively. This layout enables direct correlation between RF signal anomalies and demodulator response.

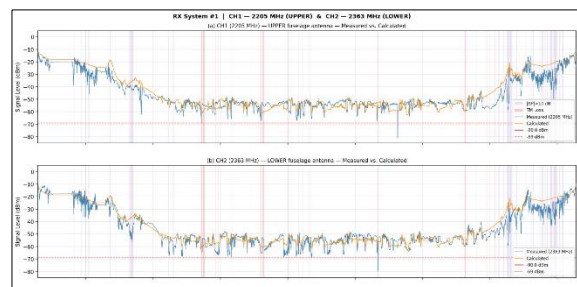


Fig. 4 Signal level and Telemetry quality — RX System #1. (a) CH1 (UPPER, 2205 MHz) measured vs. calculated. (b) CH2 (LOWER, 2363 MHz) measured vs. calculated.

For RX System #1, the recorded telemetry loss (highlighted in red) is concentrated in two temporal clusters during the mission. In every loss interval, the measured signal departs visibly from the calculated curve, the residual exceeds the ± 10 dB threshold, and the receiver quality metric collapses simultaneously. This three-way coincidence — model deviation, signal drop, and quality collapse — confirms tracking-induced gain degradation as the root cause of loss for this receiver.

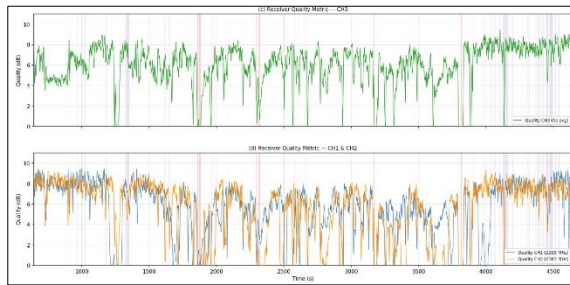


Fig. 5 (c) Receiver quality CH3. (d) Receiver quality CH1 & CH2. Red shading: Telemetry loss; purple: $|\Delta P| > 10$ dB.

Flight Route and Mission Analysis

Beyond the time-domain diagnostics presented, the framework produces an integrated geometric summary that places the measured signal in the geometric context of the mission. The objective of this summary is to identify how the platform's spatial trajectory and orientation interact with the radiation patterns of the airborne antennas and the pointing of the receiving antenna. The analysis is split into three views: the flight route in a local frame (Fig. 6), the LOS angular coverage in the receiving antenna polar frame (Fig. 7), and the body-frame projection of the

receiving system as seen from the platform (Fig. 8). Together these views inform antenna placement and frequency assignment decisions for future platform configurations, identify favorable and unfavorable platform attitudes for telemetry coverage, and provide input data for subsequent flight planning.

Flight Route and Signal Distribution

Fig. 6 shows the flight route plotted in a local frame centered on the receiving antenna, color-coded by measured signal level (red — low, green — high). Concentric range rings at 5 km intervals provide a quick visual scale, and orange diamonds mark the best-per-bin point in each 10 km range bin (computed only beyond the 10 km inner boundary indicated by the red dashed ring, where geometry-driven effects dominate). Purple crosses denote telemetry loss instants. The left panel shows the route as observed via CH1 (upper fuselage); the right panel shows the same route as observed via CH2 (lower fuselage).

For both channels, the signal level is consistently highest in the inner 5–10 km region around the receiving antenna and degrades systematically with increasing range. In the outer western pattern (around 60–70 km, lower-left), where the platform performs the working maneuver, both the locally degraded signal level and the clustering of telemetry-loss markers are observed in the same region. This visualization enables the identification of mission segments and maneuvers where telemetry performance is reduced, supporting flight planning and post-flight assessment.

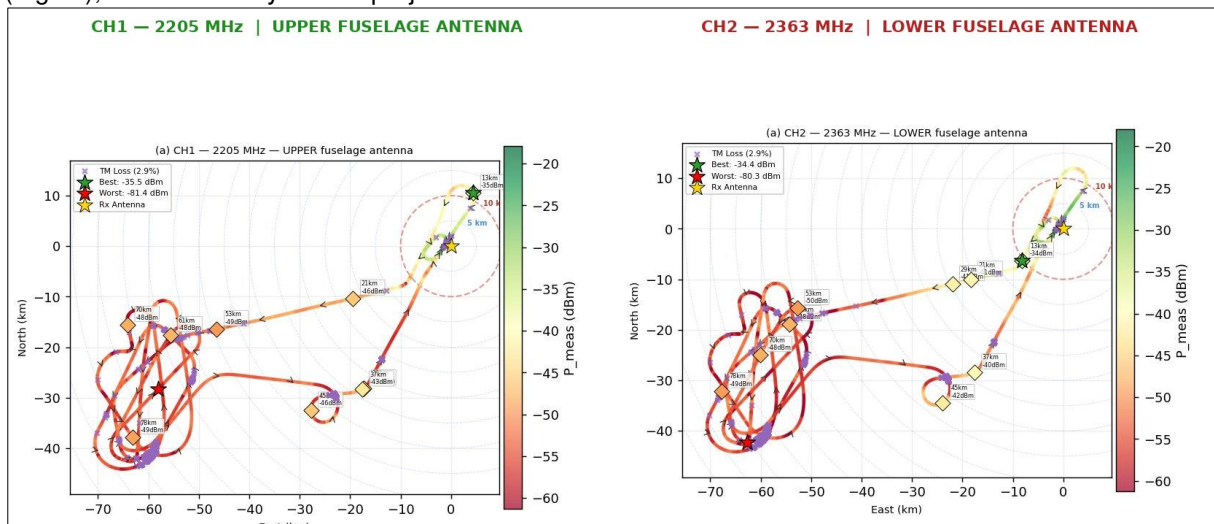


Fig. 6. Flight route — RX System #1. Left: CH1 (upper fuselage). Right: CH2 (lower fuselage). Stars: best/worst instants. Diamonds: best-per-bin (≥ 10 km). Red ring: 10 km boundary. Purple crosses: Telemetry loss.

LOS Angular Coverage

Fig. 7 presents the LOS azimuth and elevation coverage as polar plots in the receiving antenna frame. Panel (b) is a full-circle azimuth polar showing the radial distribution of the LOS over the flight: most of the flight is spent in the western sector relative to the receiving antenna. Panel (c) is a quarter-circle elevation polar showing the elevation angular distribution; the dashed red lines mark the operational elevation envelope (0.1° minimum, 25.3° maximum). Most operational time is spent at below 10° elevation angles where atmospheric multipath, ground reflection, and pedestal tracking limits all contribute to increased model residual variance.

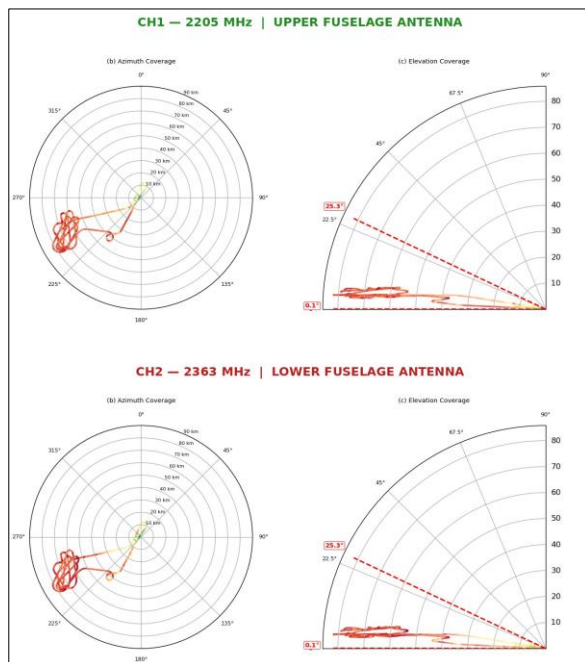


Fig. 7. LOS angular coverage — RX System #1. Top row: CH1 (upper fuselage). Bottom row: CH2 (lower fuselage). (b) Azimuth coverage. (c) Elevation coverage. Red dashed lines: operational elevation envelope.

Body-Frame Antenna Direction Analysis

Fig. 8 shows the body-frame projection of the receiving system: the angular coordinate is the bearing of the receiving antenna as seen from the platform body frame (NOSE = 0° , RIGHT = 90° , TAIL = 180° , LEFT = 270°), and the radial coordinate is the slant range (km). The diamonds mark the best-per-bin points (signal level color-coded) and the red X marks the worst-signal instant. This view is the most informative for antenna selection because it places the receiving antenna in the same reference frame as the airborne antenna pattern.

For CH1 (upper fuselage, left panel), the best-per-bin markers are distributed broadly around the platform with no strong clustering, indicating that the upper antenna achieves favorable

conditions across multiple aspect angles. The worst-signal point (red X) lies in the front-right quadrant, consistent with attitudes in which a banked turn places the upper antenna boresight away from the receiving antenna.

For CH2 (lower fuselage, right panel), the best-per-bin markers cluster heavily in the rear hemisphere (TAIL and TAIL-LEFT), consistent with the lower antenna's downward-looking pattern, which reaches its maximum gain when the platform is between the receiving antenna and the operating area. The worst-signal point falls in the same hemisphere where the platform attitude briefly reduces the effective lower-antenna gain.

The contrast between the two body-frame distributions shows that the upper and lower antenna patterns are largely complementary; the dual-antenna configuration maintains link availability across a wider range of platform attitude than a single-antenna installation could provide.

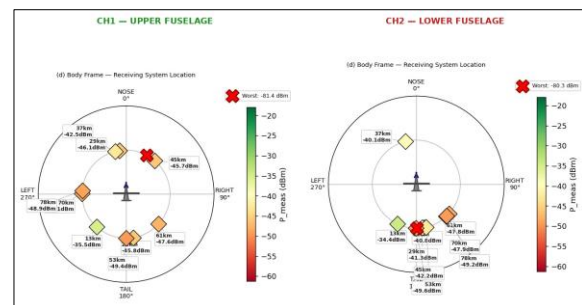


Fig. 8. Body-frame projection of the receiving system — RX System #1. Left: CH1 (upper fuselage). Right: CH2 (lower fuselage). Angular: receiver antenna bearing in body frame (NOSE= 0° , RIGHT= 90° , TAIL= 180° , LEFT= 270°). Radial: slant range (km). Diamonds: best-per-bin. Red X: worst-signal instant.

Conclusion

A framework for assessing antenna tracking performance and telemetry link reliability has been presented and validated on recorded flight test data. The framework integrates time synchronization, LOS geometry, orientation-dependent gain modeling, link budget estimation, and TM quality assessment into a unified pipeline applicable across different platform types and receiving system configurations.

The framework has been applied to S-band flight test data, reproducing measured signal levels with consistent agreement during stable flight phases. Combined analysis of signal level, model residual, and demodulator quality enables reliable root-cause identification for data loss events, and the body-frame orientation analysis confirms the importance of dynamic gain

modeling. In addition, the framework has been tested on data from a second receiving system with different antenna characteristics, producing consistent results.

Future work targets the deployment of this framework as a near-real-time pipeline that detects antenna tracking errors during flight, operating on the live data streams from receiving antenna systems. The proposed correction architecture is illustrated in Fig. 9: the tracking error ΔAz drives a predictive LOS calculation, whose output is fed back to the auto-track system as an antenna command correction. Predictive LOS-based pointing — where commanded antenna angles are derived from geometric prediction rather than reactive tracking — is expected to reduce the tracking lag observed in dynamic flight phases. Extending the framework to all receiving systems used in flight test operations would provide a unified link assessment capability across the diverse antenna configurations encountered in practice.

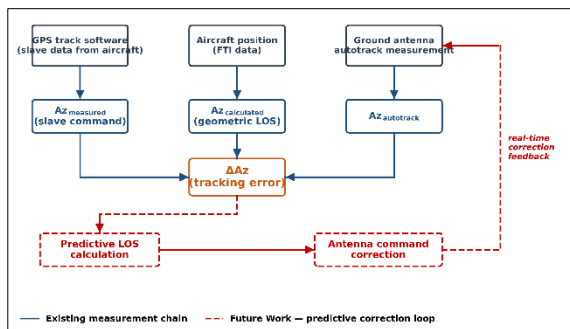


Fig. 9. Real Time Azimuth Correction Workflow.

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