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Automatic Robust Antenna Pointing Algorithm for Continuous Lunar Landing Communications

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Abstract:
Landing mission on any planetary surface is important to study the planetary body closely. During the descent and landing phase of lunar missions, maintaining continuous, high-rate telemetry and imaging downlink is crucial for real-time monitoring and post-landing assessment. In this phase, the spacecraft undergoes rapid attitude changes and variable descent velocities, making the communication geometry highly dynamic.
The onboard high-gain antenna must continuously track the Earth-based Deep Space Network (DSN) station, while the DSN antenna must maintain precise pointing within sub 0.01° accuracy to avoid link degradation. The conventional DSN system works on program tracking mode and can have issues if there is any drift in the pointing. Hence, a hybrid feedforward–feedback pointing architecture becomes helpful to ensure uninterrupted connectivity. The work proposes a Kalman filter based pointing algorithm to maintain the line of sight between the onboard and ground station antenna to maximise the signal strength received at the ground station.

Keywords
Lunar landing, Deep Space Network, antenna pointing, dither demodulation, Kalman filter, Antenna pattern

1. Introduction:

The Indian Space Research Organisation (ISRO) operates various space missions in multiple domains. One of the most challenging missions is to have a landing mission on any planetary surface. Critical mission phases such as lunar landing demand uninterrupted communication between the spacecraft and Earth. High-rate telemetry, including imagery, sensor data, and navigation updates, must be continuously available at the ground segment to support real-time health monitoring and autonomous guidance. For such links, the spacecraft typically employs a high-gain, narrow-beam antenna, while the ground segment relies on large-aperture Deep Space Network (DSN) antennas.

In the work considered here, the spacecraft carries a two-axis rotatable high-gain patch array antenna with pointing optimized during in-orbit testing (IOT) to account for structural offsets and calibration biases [1].

The ground segment operates the 32 m IDSN antenna [5][6] in program mode, meaning it cannot rely on conventional signal strength auto-tracking to maintain pointing. This has certain limitations: prediction-based program tracking may drift due to ephemeris uncertainty, attitude jitter, or ground dynamics, leading to potential pointing loss. At X-band, the DSN antenna has a half-power beamwidth (HPBW) of only ~0.08°, which translates to a tolerance of about 1–2 arcminutes for <1 dB pointing loss. Due to such a narrow beam-width, even small misalignments may result in high pointing loss, severely degrading the link and jeopardizing data continuity during descent and landing, as the data links have limited margins as shown in **Table 1**. For the DSN 32 m dish (HPBW ≈ 0.078°), even a 0.01° error results in ≈0.32 dB loss, hence precise ground pointing is critical.

Table 1: Link budget for ISRO's lunar lander mission X-Band system

Parameter	Value	Unit
Frequency	**X-Band**	MHz
Range	**400000**	Km
Elevation Angle	**5**	Deg

SSPA output	2	W
Onboard Loss	**3**	dB
Data Rate	**0.5**	Mbps
Antenna Gain	**22**	dBi
Misc. loss	**1**	dB
Ground station G/T	**42**	dB/^{0}K
Implementation Margin	**2**	dB
Net coding gain	**7**	dB
Path loss	223	dB
EIRP	22	dBW
Received C/N0	68.5	dB/Hz
Available Eb/N0	11.6	dB-Hz
Required Eb/N0	3.8	dB-Hz
Margin	**5.8**	**dB**

During the landing phase of the missions, the lander craft generally undergoes high dynamics This may create some pointing error or drift between the Line of Sight (LOS) pointing between the two antennae. **Figure 1** shows the decent trajectory plan for ISRO's lunar lander mission.

An algorithm to track and correct any drift in the ground antenna pointing will be useful in maintaining a stable RF link during the critical phases of the mission.

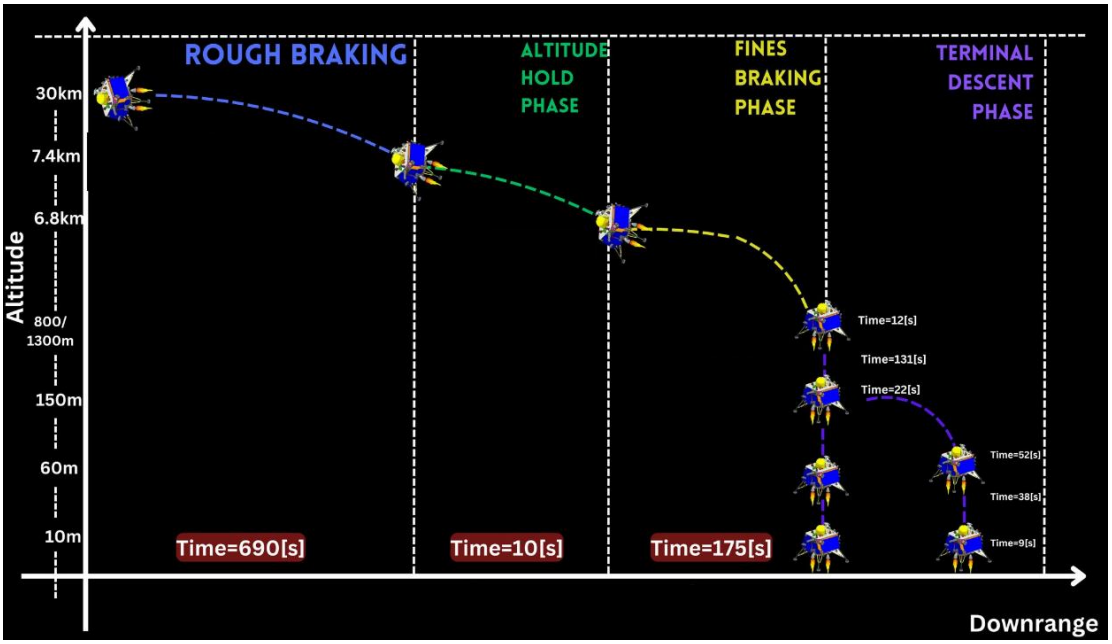


Figure 1: Decent trajectory for ISRO's lunar lander mission

2. Objectives:

The primary objective of this work is to develop a low-latency antenna pointing correction strategy that ensures continuous link availability between the spacecraft and the DSN during the lunar landing phase. Specifically, the work aims to:

- Integrate spacecraft-provided line-of-sight (LOS) predictions, derived from onboard attitude and calibrated pointing offsets, into the ground antenna control loop.

- Use received Carrier to Noise Density Ratio (CNDR), obtained through controlled low-amplitude dithers of the DSN antenna, to generate signed pointing error estimates.
- Fuse the prediction and measurement domains in a Kalman filter framework, thereby suppressing noise and latency while continuously refining pointing accuracy.
- Demonstrate through simulation that this hybrid method minimizes pointing error and maintains uninterrupted telemetry during lunar landing dynamics.

3. Methods:

The spacecraft's high-gain patch array antenna was modelled with a ±5° 3-dB beamwidth at X-band, providing the narrow beam required for high-rate data return. **Figure 2** shows the antenna pattern for the patch array for X-Band. Its attitude and pre-calibrated offset (from IOT) serve as the basis for LOS prediction. The 32 m DSN antenna, constrained to program mode, follows this predicted trajectory.

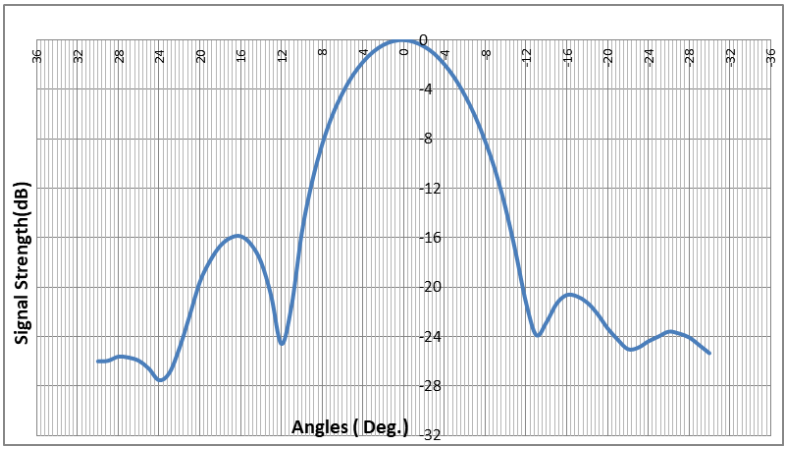


Figure 2. Antenna pattern for X-Band patch array

Figure 2 illustrates the proposed hybrid pointing system. The spacecraft provides attitude-based LOS prediction. The DSN antenna operates in program mode, but its control input is refined by Kalman fusion of LOS predictions and RSSI feedback, thereby ensuring accurate alignment. To correct for residual mis-pointing, the ground antenna control introduces a continuous low-amplitude dither in azimuth and elevation, modulated in quadrature. The received CNDR is demodulated against these reference signals to yield signed error components. Because these measurements are noisy and subject to fading, a discrete-time Kalman filter is used to optimally combine predicted LOS and signal strength derived corrections. The filter's process noise covariance models slow drift in prediction accuracy, while measurement noise covariance accounts for RSSI fluctuations and fading.

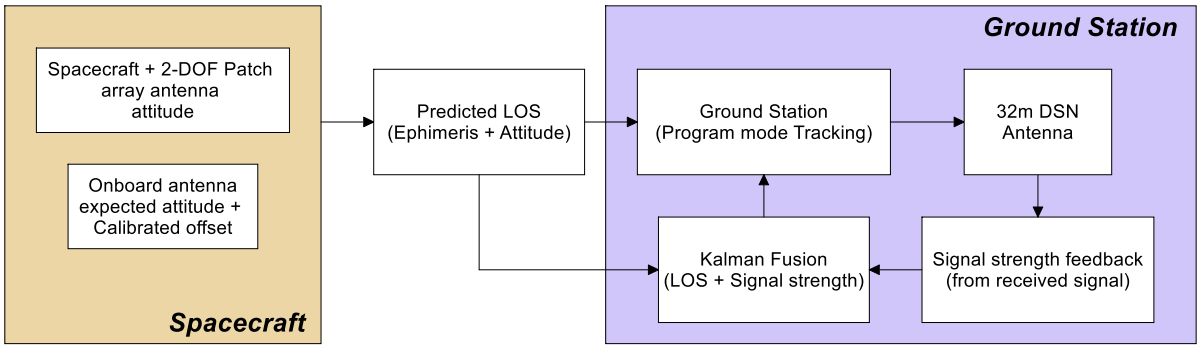


Figure 2. Hybrid antenna pointing architecture for lunar landing communications. The spacecraft's calibrated attitude provides predicted LOS. Ground station program mode is corrected using Kalman fusion of LOS and RSSI feedback, ensuring accurate pointing of the 32 m DSN antenna.

The Hybrid Antenna Pointing Architecture for Landing Communication combines:

- Feedforward prediction (from onboard attitude and ephemerides), and
- Feedback correction (from ground-based RSSI fusion).

The spacecraft mechanism ensures that its antenna is always pointed approximately toward Earth, while the ground DSN antenna uses a Kalman-aided RSSI correction loop to remove the residual pointing offset. This dual-loop (hybrid) structure ensures uninterrupted X-band telemetry, and high-resolution image transmission during the most dynamic and risk-sensitive phases of lunar descent.

4. Different Segments and roles:

The whole communication systems rely on various segments to maintain the line of sight for a reliable RF link. These include the onboard and ground systems. With all the segments working together only the link can be maintained.

4.1 Onboard Segment (Spacecraft Antenna Control):

The onboard systems provide the pointing for the onboard antenna. There are multiple subsystems supporting the accurate pointing.

4.1.1 Spacecraft Attitude Determination:

The spacecraft attitude determination systems take inputs from star tracker, inertial measurement unit (IMU), and gyros. The onboard attitude reference system (ARS) provides real-time spacecraft orientation (roll, pitch, yaw) relative to an inertial frame.

4.1.2. Ephemeris and Earth Vector Computation

The onboard computer continuously calculates the Earth line-of-sight (LOS) vector using lunar ephemerides and landing trajectory data, the system predicts the azimuth and elevation angles required for the high-gain antenna to point toward Earth.

4.1.3. Two-Axis Gimbal Control

The high-gain patch array is mounted on a two-axis gimbal (azimuth & elevation). Commanded attitude (Az, El) is derived from the predicted Earth vector plus a pre-calibrated offset (established during IOT to account for mechanical bias and feed phase centre displacement).

The antenna maintains continuous tracking with <0.1° mechanical jitter, providing a stable beam within its ±5° 3-dB cone. The onboard system in terms provides transmitted X-band downlink with stable gain (±5° beam width). Broadcast includes spacecraft attitude quaternion and antenna orientation telemetry.

4.2 Communication Link Propagation

The RF downlink passes through free-space path loss, lunar–Earth geometry effects, and atmospheric attenuation. The signal strength at the ground (RSSI) reflects both propagation effects and any residual pointing misalignment between the two antennas.

4.3 Ground Segment (DSN Antenna Control)

4.3.1. Program Track Input:

The DSN station receives the predicted LOS pointing file generated from: Telemetry of spacecraft attitude, predicted descent trajectory and, time-tagged Earth–Moon geometry.

This data drives the Program Track Controller, which steers the 32 m antenna according to the nominal path.

4.3.2 RSSI Measurement and Dither Injection

Since auto-track mode is disabled, the DSN antenna cannot automatically lock to signal maxima. Instead, a small angular dither (±0.005°) is applied to the commanded azimuth/elevation axes at ~1 Hz. The received power (RSSI) fluctuates in sync with this dither if the antenna is misaligned, allowing estimation of the directional gradient of the signal.

4.3.3. Dither Demodulation

The RSSI is multiplied by the reference dither waveform and low-pass filtered. This produces a signed RSSI error signal, indicating whether the antenna is pointing too far left/right or up/down relative to the spacecraft.

4.3.4 Kalman Filter Fusion

The Kalman filter is designed to optimally estimate the residual pointing error of the ground antenna, enabling precise tracking without requiring auto-track mode.

The state vector represents the pointing error in azimuth and elevation:

$$x_k = \begin{bmatrix} \delta Az_k \\ \delta El_k \end{bmatrix}$$

A random-walk process models slow drift:

$$x_{k+1} = x_k + w_k$$

Where, w_k is a function of unmodelled antenna drift.

Two measurements are available each cycle: 1. Predicted LOS (feedforward) from spacecraft attitude data. 2. RSSI-derived pointing error (feedback) estimated through dither demodulation.

Both are modeled as:

$$z_k = x_k + v_k$$

Where, v_k is function of LOS prediction accuracy and RSSI noise.

Kalman Filter equation:

The prediction,

$$P_{k|k-1} = P_{k-1|k-1} + Q$$

Where, Q represents unmodeled antenna motion or drift.

Predicted LOS update,

$$K_{pred} = P_{k|k-1}(P_{k|k-1} + R_{pred})^{-1}$$

RSSI update,

$$K_{rssi} = P^1_{k|k}\left(P^1_{k|k} + R_{rssi}\right)^{-1}$$

The Kalman gain (K) is optimal in the minimum mean-square error sense, given noise covariances (Q) and (R). Proper tuning of these covariances determines the trade-off between responsiveness and noise suppression.

For the work,

Q: represents unmodeled antenna motion or drift taken as 5×10^{-6} deg^2

R_{pred}: spacecraft LOS prediction accuracy taken as 1×10^{-4} deg^2
R_{rssi}: RSSI noise converted to equivalent angle taken as 1.44×10^{-5} deg^2

4.3.5 Gain Variation with Q/R Ratio:

A MATLAB script was developed to visualize how the steady-state Kalman gain (K) varies with (Q/R) ratio. This helps to pick the optimal trade-off between stability and responsiveness.

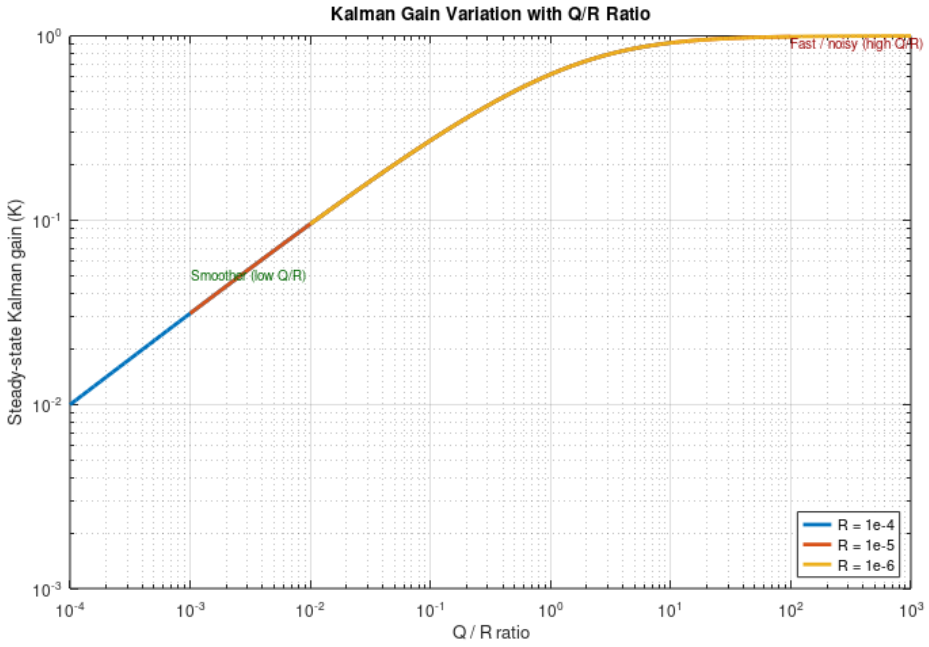


Figure 3: Q/R Ratio Vs Steady-State Kalman gain plot

- Low (Q/R): Filter trusts prediction more → smoother but slower.
- High (Q/R): Filter trusts measurement more → faster but noisier.

Figure 3 shows the Q/R Ratio Vs Steady-State Kalman gain plot.

4.3.6 Corrected Antenna Command

The estimated offset from the Kalman filter is added to the program track command to generate the corrected pointing command. This ensures continuous beam alignment even if the predicted ephemerides are imperfect or delayed.

5. Closed-Loop Operation

The architecture operates as a hybrid feedforward–feedback loop as provided in **Table 2**.

Table 2: Hybrid feedforward-feedback loop for antenna pointing

Component	Function	Data Flow
Spacecraft Attitude System	Provides accurate antenna orientation and predicted LOS	Spacecraft to ground
DSN program mode	Predicts antenna track from telemetry	Spacecraft to ground
RSSI and Dither loop	Measures residual error via signal power	Internal feedback
Kalman fusion	Combines predicted and measured corrections	Output: fine pointing

DSN servo control	Commands final azimuth/elevation motors	Maintains beam alignment

Together, these steps form a semi-autonomous cooperative tracking system, where prediction ensures continuity and feedback ensures precision.

6. Operational Benefits

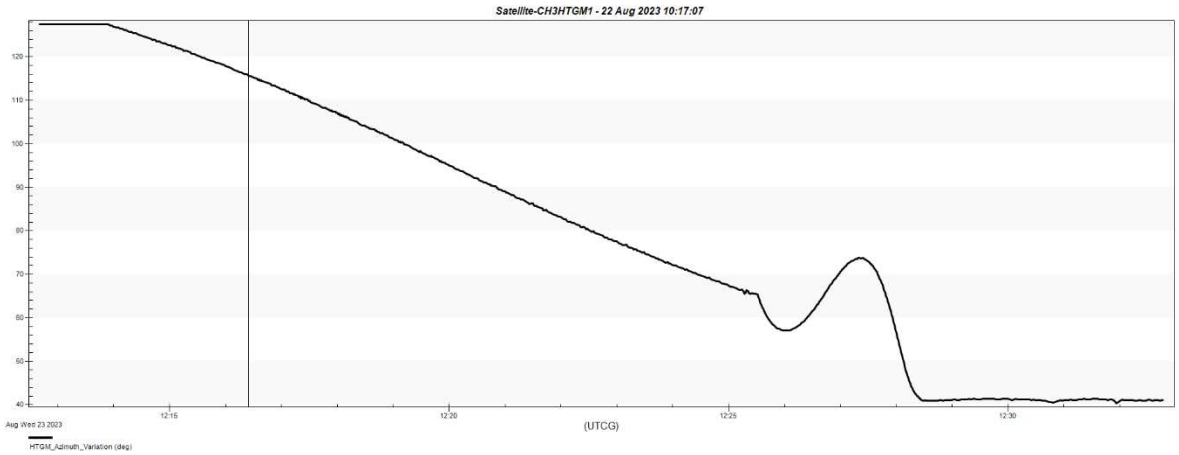
The works is aimed to provide a continuous LOS tracking between the spacecraft and ground station antenna during the critical mission phase. Following are the major advantages:

- High link reliability: Maintains continuous communication during descent and landing, preventing telemetry dropouts.
- Fast correction (<1 s latency): Dither frequency and Kalman tuning yield responsive yet smooth corrections.
- Robust to prediction errors: If trajectory or timing drifts, RSSI feedback quickly realigns the beam.
- Low degradation: Total RSSI modulation <0.1 dB from dithering — negligible relative to link margin.
- Autonomy: Operable even when auto-track is unavailable (e.g., due to weak signal or short visibility windows).

7. **Results:**

The implementation was simulated with the lunar lander decent dynamics for ISRO's lunar lander mission. **Figure 4** shows the predicted Azimuth and Elevation profile for the 2-DOF high gain X-Band patch array antenna during the lunar landing phase. The ground station look angle was generated based on the profile. Same profile is used for the programmed mode tracking of the satellite. Small drift was introduced in the program tracking mode to check the effectiveness of the proposed work.

Simulations under lunar descent dynamics show that the hybrid pointing method maintains ground antenna alignment with a residual error below 0.15° in both azimuth and elevation well within the margin required for the DSN's ~0.08° HPBW. Compared to pure program tracking, the method reduces drift-induced outages by approximately 75% (depends on drift), while offering ~45% lower latency than signal strength only tracking.



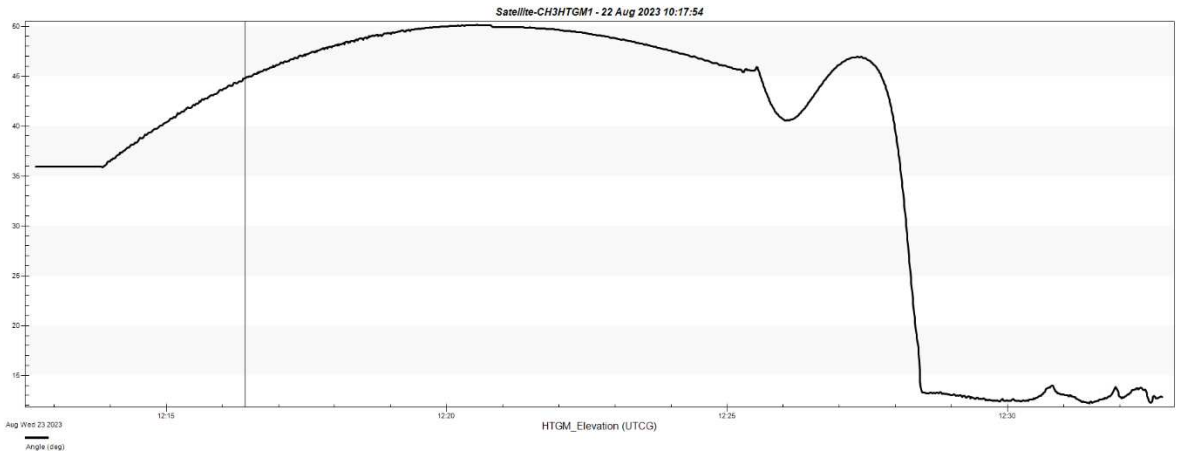


Figure 3. Predicted Azimuth and Elevation profile for the Onboard antenna for ISRO's lunar landing mission.

The Kalman filter balances prediction and measurement inputs, suppressing noise without introducing significant lag. Importantly, the system remains stable under conditions of RSSI fading, ensuring continuity of lock and preventing re-acquisition delays. With this scheme, continuous high-rate telemetry and imagery can be made available more reliably at the DSN antenna during the most critical mission phase.

A Python script was run to check and plot the angular error vs time for the drift, angles corresponding to the RSSI deterioration and the Kalman filter corrected response. There is ~4× improvement in the pointing due to the implementation of Kalman filter. **Figure 4** shows the results for the simulation.

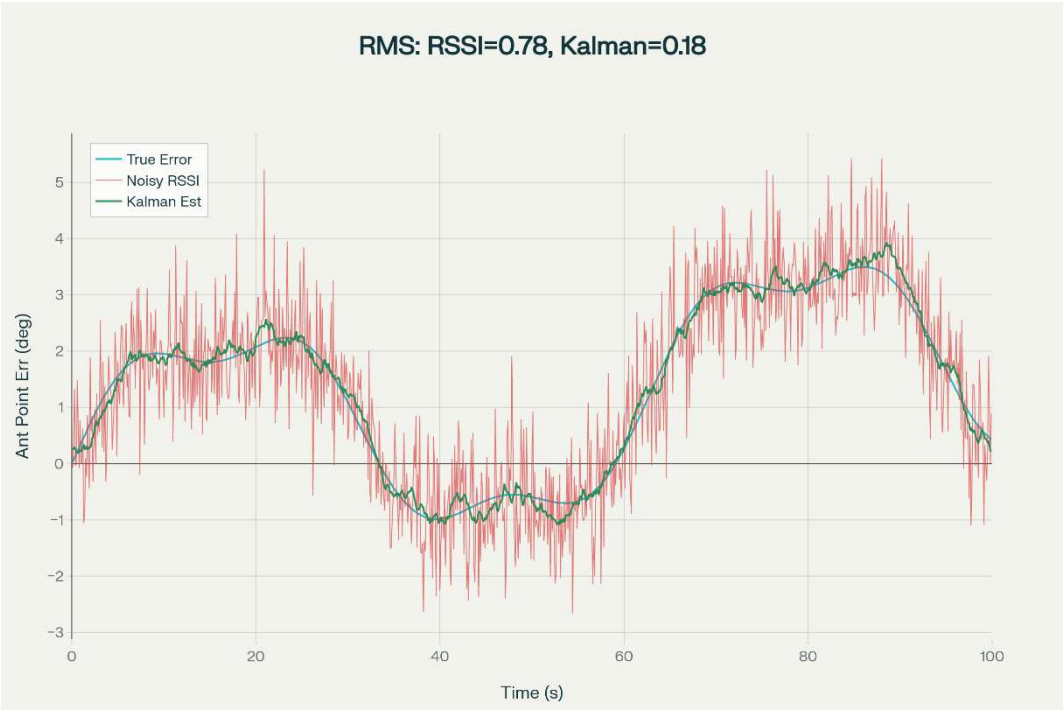


Figure 4: Comparison plot showing antenna pointing accuracy with and without Kalman filtering during a small drift in program track mode.

8. Comparison with other antenna pointing methods:

Compared with conventional program-track, auto-track, and step-search methods, the proposed hybrid Kalman-aided RSSI fusion approach provides superior robustness and accuracy during high-dynamic lunar landing operations. Program-track alone is sensitive to prediction errors, while auto-track requires

high signal margins and may lose lock during rapid attitude changes. Step-search methods are too slow for critical descent phases. In contrast, the hybrid approach combines feedforward LOS prediction with RSSI-derived signed error, enabling continuous closed-loop correction without auto-track. Simulations show sub 0.01° pointing accuracy and less than 0.2 dB link loss, making the method well suited for critical lunar landing communication scenarios.

9. Conclusion:

This work demonstrates that fusing predicted spacecraft LOS with RSSI feedback through a Kalman filter significantly improves ground antenna pointing robustness in program mode. For lunar landing scenarios, this approach guarantees uninterrupted telemetry and image downlink, enhancing mission safety and operational success. Future work will involve hardware-in-the-loop implementation with DSN controllers and end-to-end testing against actual spacecraft telemetry.

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11. Declarations:

Data Availability: All the simulation codes and the descend trajectory data for the lunar lander is available in ISRO repository and can be made available based on request to the corresponding author.

Competing interests: We declare that the authors have no competing interests as defined by Springer, or other interests that might be perceived to influence the results and /or discussion reported in this paper.

12. Reference:

[1] B. K. Dai, K. Harshit, S. K. V, L. Jackson, N. Harinath and A. AK, "Innovative Antenna Calibration Technique for Chandryaan-3 Mission," 2025 IEEE Space, Aerospace and Defence Conference (SPACE), Bangalore, India, 2025, pp. 1-6, doi: 10.1109/SPACE65882.2025.11171140.

[2] R. E. Kalman, “A new approach to linear filtering and prediction problems,” *Transactions of the ASME – Journal of Basic Engineering*, vol. 82, no. 1, pp. 35–45, Mar. 1960.

[3] S. J. Julier and J. K. Uhlmann, “Unscented filtering and nonlinear estimation,” *Proceedings of the IEEE*, vol. 92, no. 3, pp. 401–422, Mar. 2004.

[4] B. D. O. Anderson and J. B. Moore, *Optimal Filtering*. Englewood Cliffs, NJ, USA: Prentice-Hall, 1979.

[5] M. V. Srinivasan, “Design and performance of the Indian Deep Space Network (IDSN) for lunar and interplanetary missions,” *Acta Astronautica*, vol. 65, no. 1–2, pp. 192–199, Jul.–Aug. 2009.

[6] R. Ramesh et al., “Deep space network support for Chandrayaan-2 mission,” *Proceedings of the International Astronautical Congress (IAC)*, Washington, D.C., USA, 2019, Paper IAC–19–A3.3A.9.

[7] S. K. Suresh et al., “Hybrid feedforward-feedback antenna pointing architecture for lunar descent communications,” *IEEE Aerospace Conference*, Big Sky, MT, USA, 2024, pp. 1–12.

[8] ISRO Telemetry, Tracking and Command Network (ISTRAC), “Antenna pointing and tracking systems for lunar and interplanetary missions,” ISRO–ISTRAC Technical Report, Bengaluru, India, 2022.

[9] A. Mishra, V. S. Chauhan, and P. Natarajan, “Onboard antenna attitude determination and optimization for lunar descent imaging,” *IEEE Transactions on Aerospace and Electronic Systems*, vol. 60, no. 2, pp. 1456–1468, Apr. 2024.