

AAS 23-294

# Metric Tracking Data Analysis

Diagnosing Anomalies in Tracking Data for Improved  
Orbit Determination & Ground Station Performance:  
Case Studies from Three Lunar Missions

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# Outline



*SSC Ground Station, Dongarra, Australia*

1. Navigation & OD in Operations
2. MTDA – Objectives, Methods, Outcomes
3. Kalman Filtering in OD
4. Combining KF, Statistics and Graphics
5. Sample results 3 x Lunar Missions
  - Beresheet ;CAPSTONE;KPLO
6. Future Plans
7. Lessons/Conclusions

# Navigation & OD in Operations

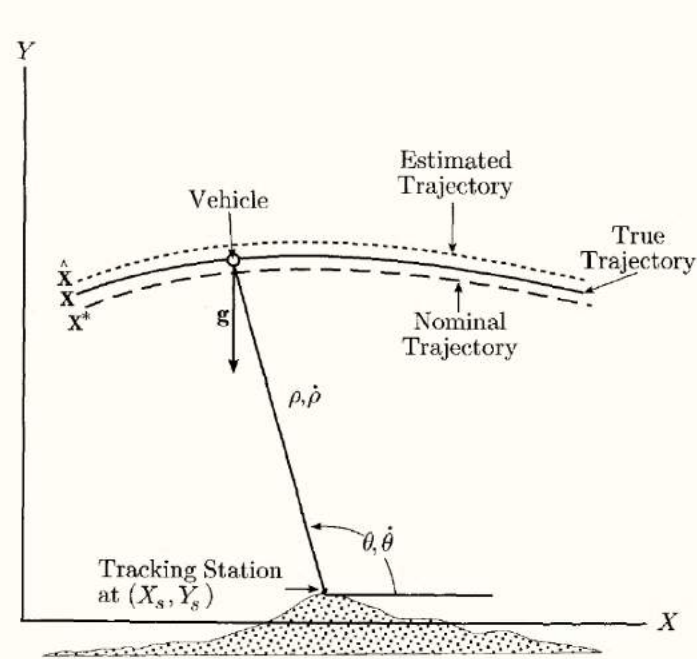


Figure 1.2.1: Uniform gravity field trajectory.

Credit: Tapley et al. *Statistical Orbit Determination*

- ISG + SEE: Combine statistics, graphics with Flight Dynamics
- Enable missions to perform their own quality checks & diagnostics of tracking for accurate orbit determination and navigation
- MTDA: Analytics and software tools for the detection and diagnosis of anomalies in RF tracking data.
- Contribution: Objective, validated feedback on: *OD models & tuning; Ground stations; satellite -in real time*

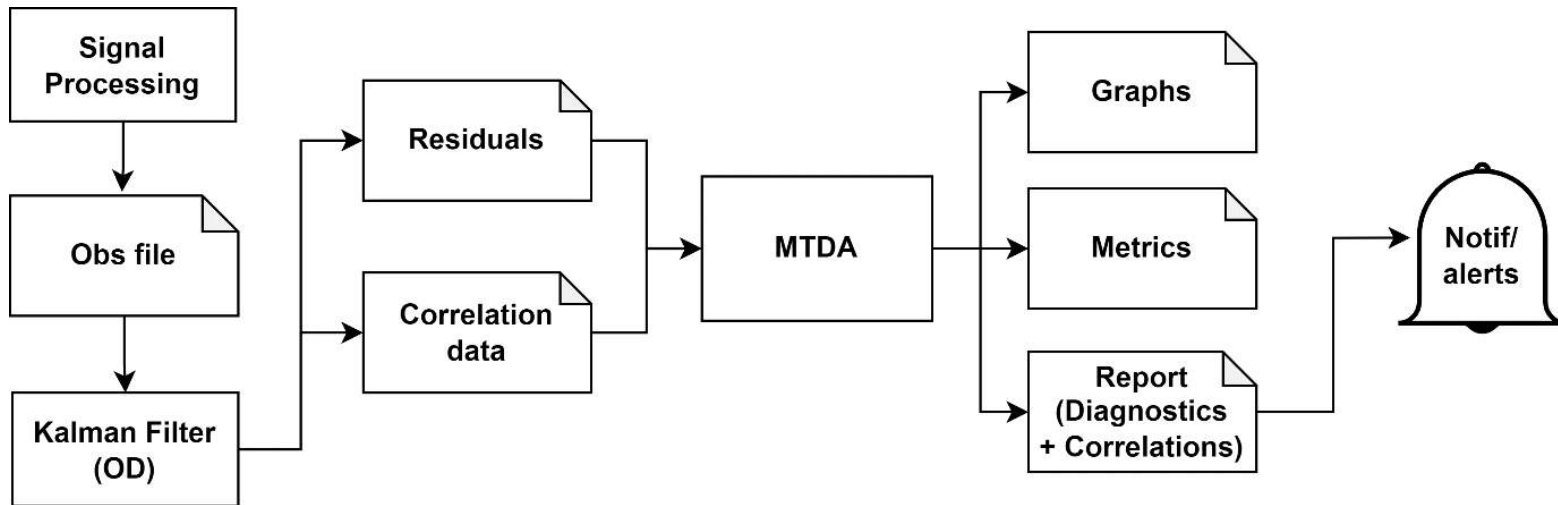
# MTDA Objectives & Outcomes



*Combination of Kalman filter dynamics + Time series analysis + statistical graphics, to **objectively advise**:*

1. **Flight Dynamics I:** Indicate areas of the Kalman filter that are poorly tuned
2. **Flight Dynamics II:** Characterize correlations to improve OD modelling and tuning
3. **Flight Dynamics/Ground stations I:** Detect anomalies in tracking data
4. **Ground stations II:** Tracking data quality; compare to nominal; root-cause of a “bad” pass
5. **Mission owners:** Satellite behavior/anomalies effecting navigation.

# Workflow



# Methodology

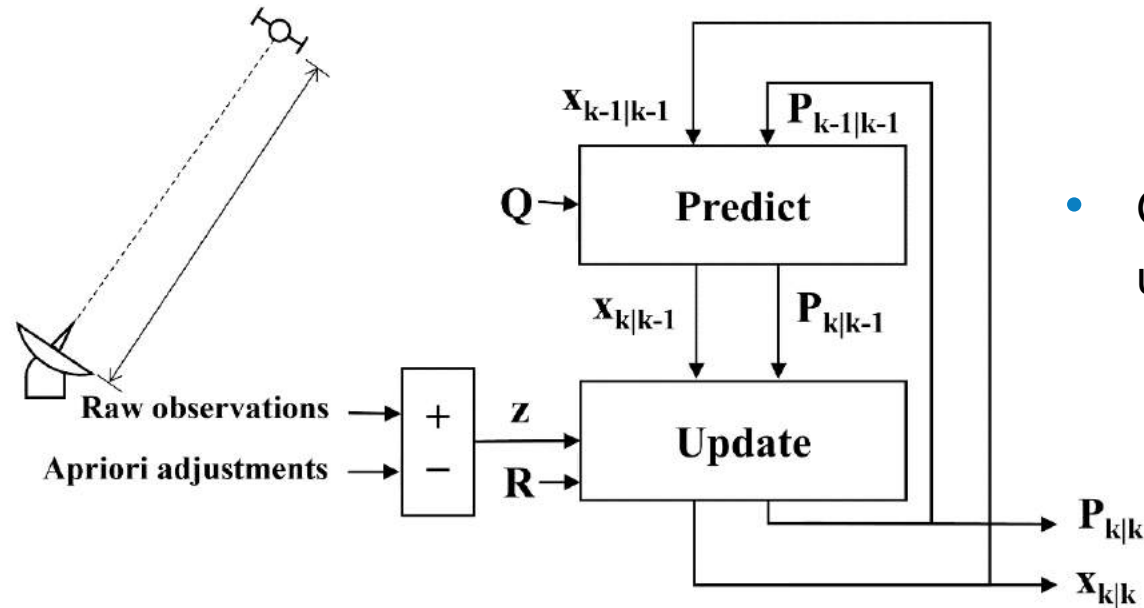


***SSC Ground Station, South Point, Hawaii***

1. Exploratory Data analysis
2. Outlier analysis
3. Correlations / Auto-correlations / ARIMA
4. Regression analysis
5. Time series / Trend analysis
6. Root-cause analysis
7. Moving window/Jump detection
8. White noise + distribution analysis

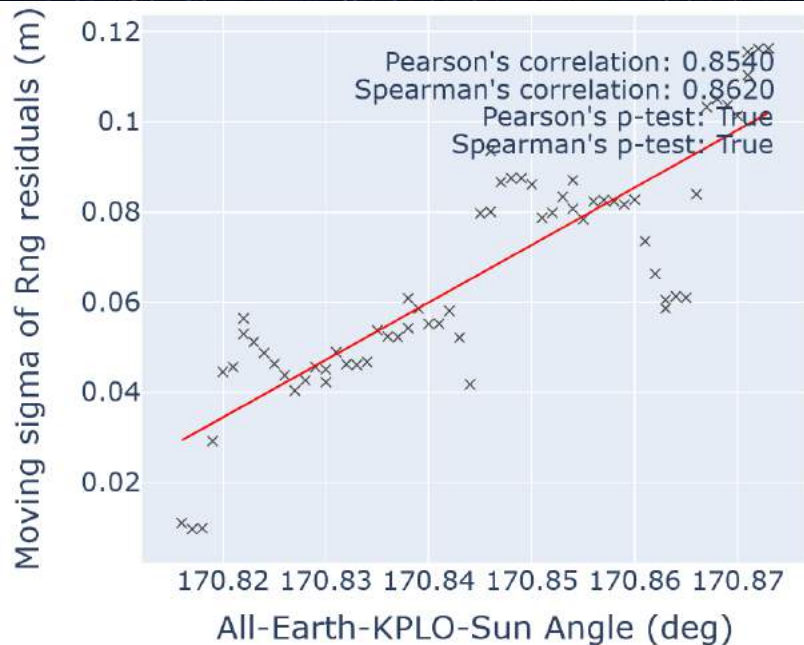
# Kalman Filtering in OD

- State vector ' $\mathbf{x}$ ' contains all parameters to be estimated
  - Spacecraft position/velocity
  - Drag coefficients
  - Receiver biases, etc.
- Ground-station observations are used to update states over time



*Simplified Diagram of KF performing OD*

# Kalman Filtering in OD



Noise of range prefit residuals for KPLO mission

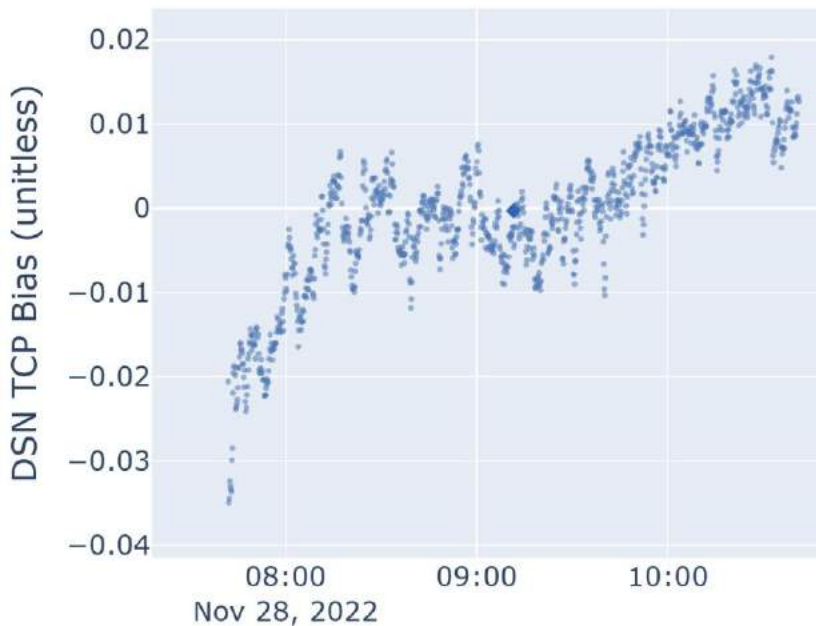
## Prefit residual

- Observed minus Computed (OmC)

$$\tilde{\mathbf{y}}_k = \mathbf{z}_k - \mathbf{H}_k \hat{\mathbf{x}}_{k|k-1}$$

- Zero-mean
- Prefit noise is equivalent to observation noise

# Kalman Filtering in OD



*TCP bias for KPL0 mission*

## Bias

- Estimates slow-moving offsets in observations, such as unknown timing errors in receiver
- Should look 'random' – i.e., no recognisable patterns, not periodic
- Should not be correlated with any other parameters (e.g., elevation, Sun-aspect angle)

# Kalman Filtering in OD



*SSC Ground Station, Santiago, Chile*

## Benefits of Correlation Analysis

- Improve observation noise models
- Exclude observations from noisy regions
- Highlight unknown sources of noise
- Tune process noise of orbital parameters to absorb maneuvers more quickly

# Results

## Beresheet/SEE Flight Dynamics

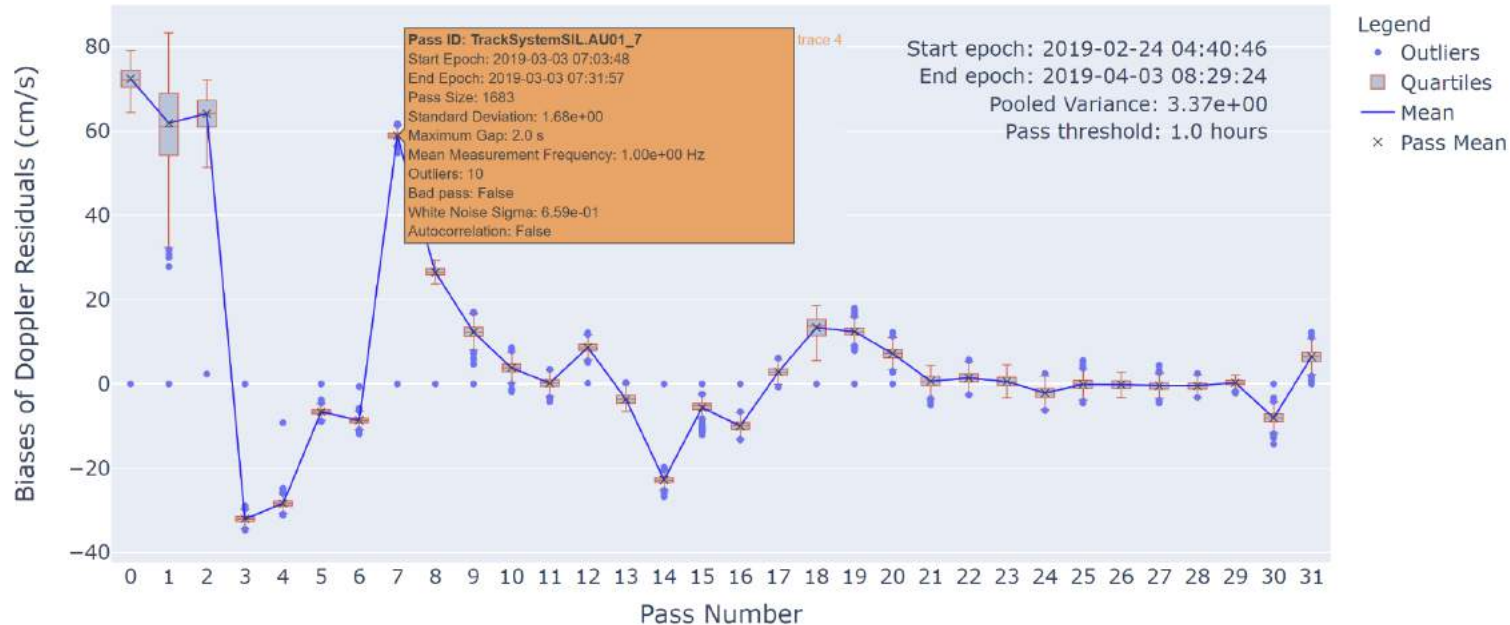


*Beresheet lander on Lunar approach*

# MTDA Tool – Beresheet Residuals

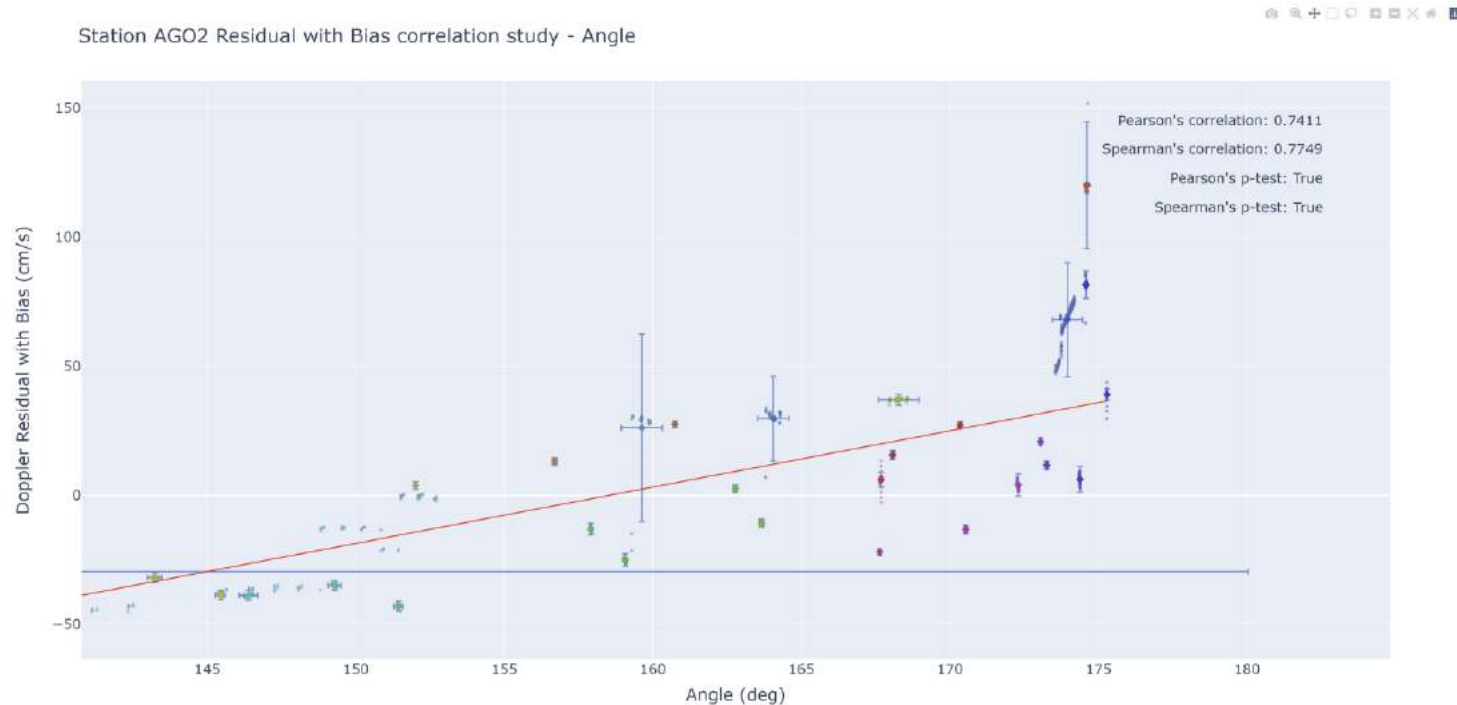


Station AU01, Biases of Doppler Residuals (cm/s) by Pass (Full)



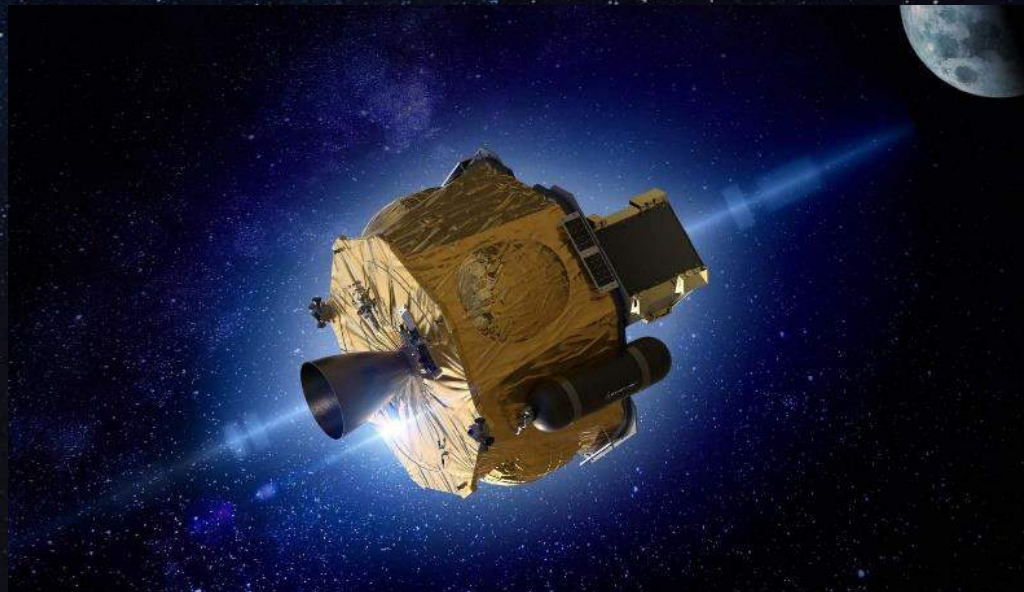
**SSC ground station Dongarra, Australia;** Doppler residual by pass, showing Bias drift in post-fit residuals—caused by attempting to fit an orbit to the rotating spacecraft, with a 60° antenna boresight offset. The orange box shows the intra-pass statistics for pass 7

# MTDA Tool – Beresheet Residuals /Correlation



**Beresheet mission SSC ground station AGO2; Indicating a positive correlation between Doppler Residuals and Sun aspect angle .**

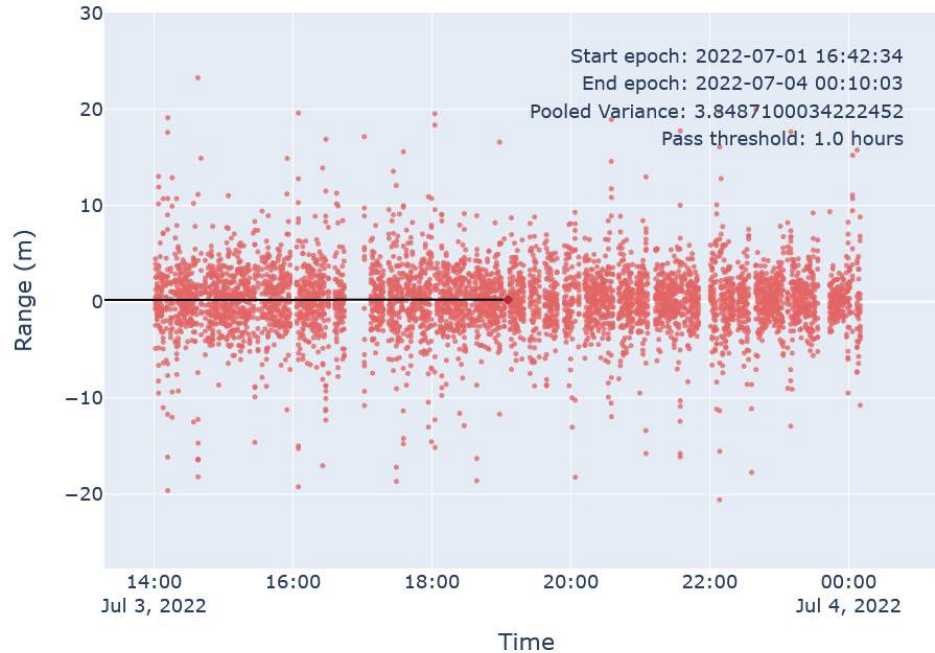
# Results: Rocket Lab / CAPSTONE / SEE Flight Dynamics



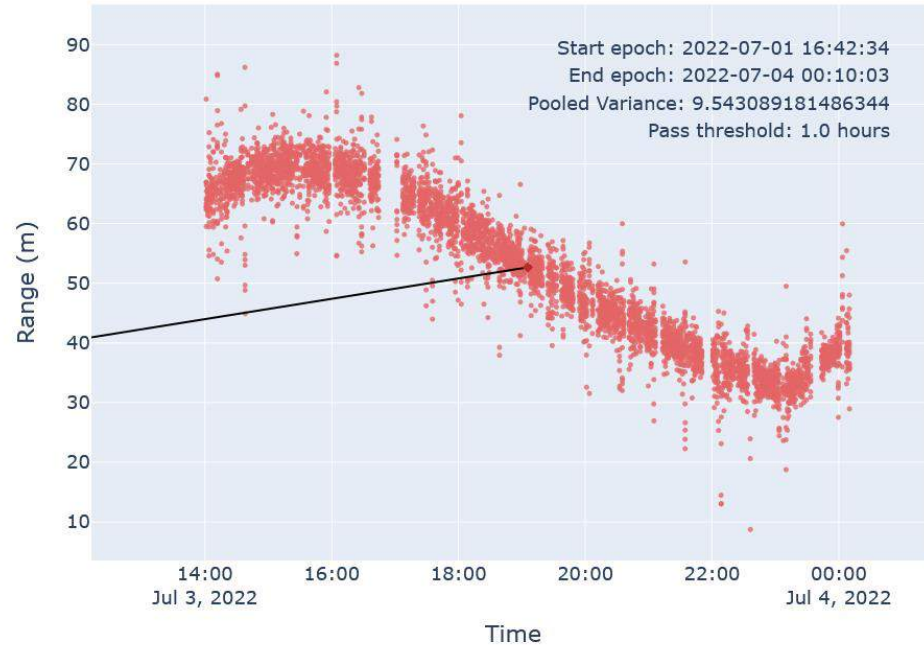
*Rocket Lab's Photon with CAPSTONE*

# Residual vs Time – CLSA04 Pass 3

Station SSC.SSC-CLSA04, Range Pre Fit Residual vs Time



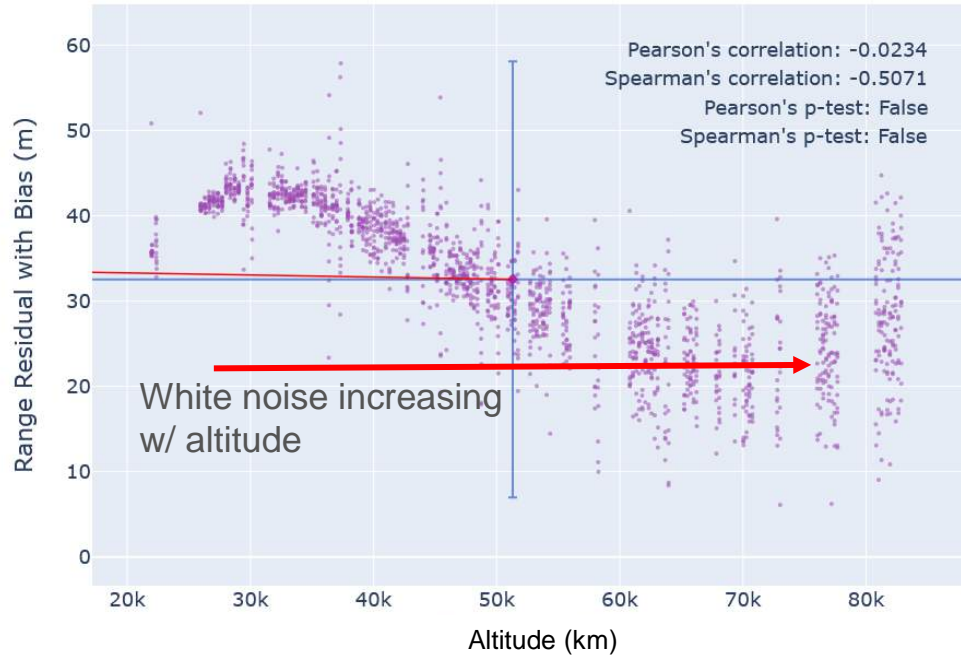
Station SSC.SSC-CLSA04, Range Residual with Bias vs Time



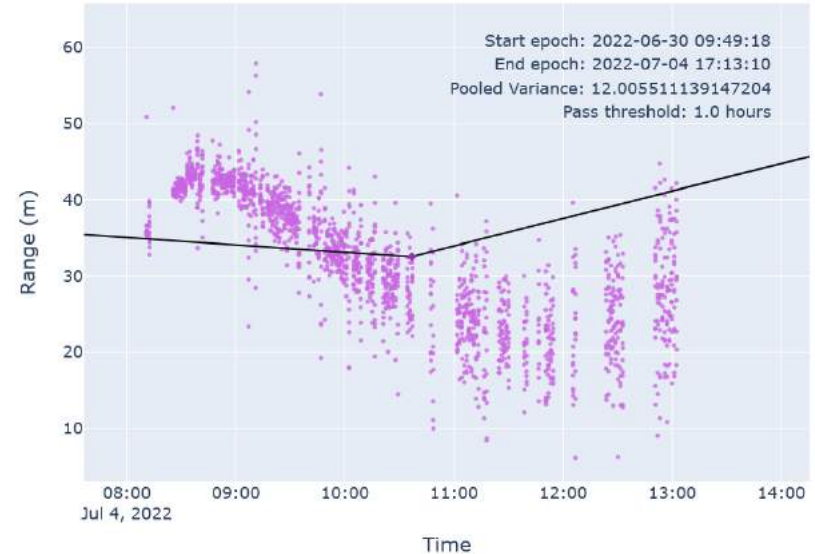
Bias adds on a wave-like trend to residuals

# Raw Range vs Distance from Capstone – SEKI01

Station SSC-SEKI01 Residual with Bias correlation study - Altitude (km)



Station SSC.SSC-SEKI01, Range Residual with Bias vs Time



# Results: KPLO / SEE Flight Dynamics



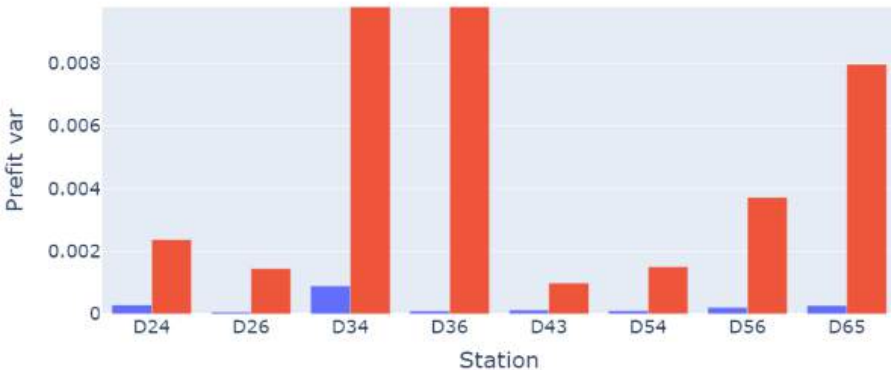
*Rendering of Korean Pathfinder Lunar Orbiter (KPLO)  
Credit: KARI*

# Station Summaries

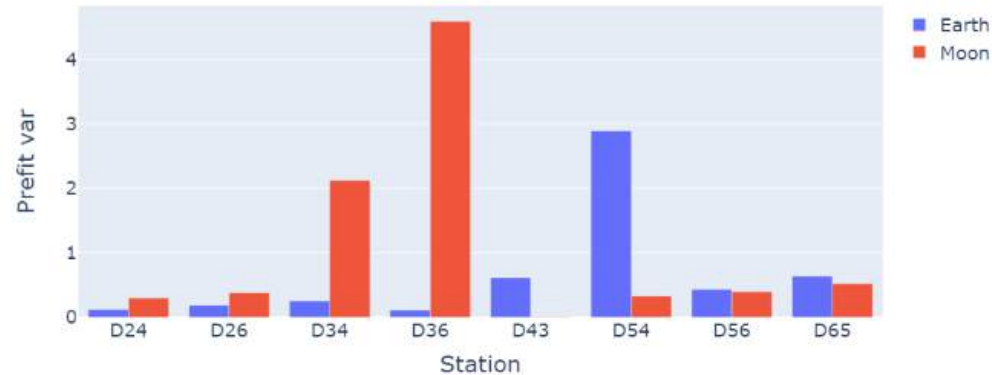
- Comparison of station performance for Earth- and Moon-centred observations, residuals (prefit, prefit with bias, and bias alone).
- Mean and pooled variance is calculated for each station (pooled over all passes).
- *Variances many times higher for Moon-centred observations compared to Earth-centred*

## Prefit residual variance:

TCP



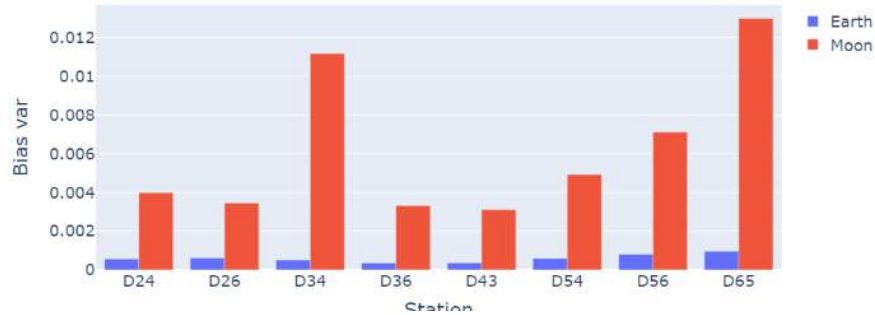
SEQ



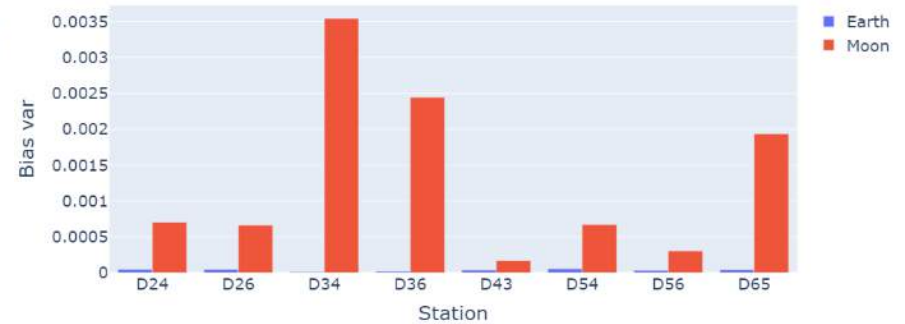
# Station Summaries Continued

## Bias variance:

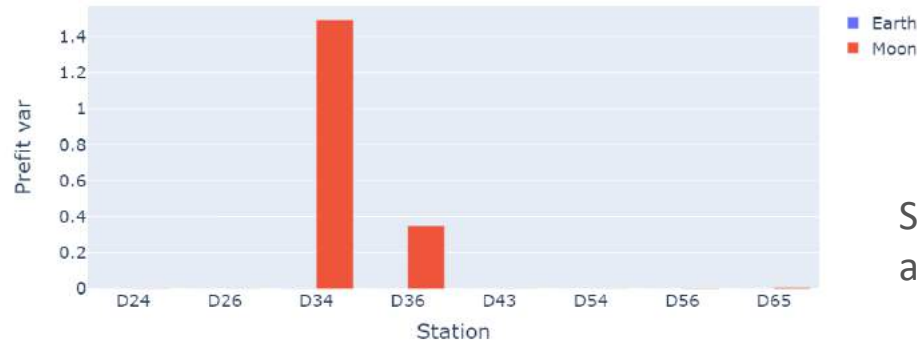
TCP



SEQ



TCP



Stations D34 and D36 show abnormally large variances

# Future Work



- Distribution of noise within a pass - Gaussian or some other distribution
- Extend application of MTDA Toolkit to more pre-launch activities, including certification of a tracking system; inform mission design
- Assist orbit determination analysts in determining the optimal tracking method for OD
- Wider range of missions, interplanetary trajectories, etc.

# Lessons & Conclusions

- Critical that Analytics/Data scientists work closely with Astrodynamics/Flight dynamics
- Statistics can be useful! (in astrodynamics)
- MTDA graphics and statistics allowed the SEE flight dynamics team to improve their OD models
- Statistically rigorous analysis of tracking data and feedback on anomalies
- Automated analysis and easy-to-interpret graphics

# ***THANK YOU!***

## ***Questions?***

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Published Papers at AIAA/AAS/AMOS  
<http://www.industrialsciences.com.au/published-papers/>

# Science or Engineering?

Theodore von Karman:

**“The difference between science and engineering is that science seeks to understand what there is; while engineering seeks to create what never was”**

