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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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To enable spacecraft missions in the task of performing their own quality checks and diagnostics of tracking systems and data for accurate orbit determination and navigation. Industrial Sciences Group (ISG) in collaboration with Space Exploration Engineering (SEE) has developed a set of analytics and software tools for the detection and diagnosis of anomalies in Radiometric tracking data. Metric Tracking Data Analysis (MTDA) combines modern statistical and graphical tools with selected Kalman Filter parameters to perform causal analysis of tracking data anomalies, characterize ground station performance, and pre-process residuals. It also determines correlations between tracking data behaviour and satellite and orbit parameters. We provide case studies from three lunar missions.

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I. INTRODUCTION

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The growth in commercial missions to the Lunar surface and cis-lunar space has implications for the flight dynamics activity in planning and during operations. Such missions typically have smaller budgets than previous government-led missions, and do not typically have a fully dedicated communication network and often have only a small flight dynamics team during operations. Rather, they tend to rely on privately operated ground station networks for communication with the spacecraft. Furthermore, NASA is approaching the commercial ground station market for a Near Space Network to reduce the load on the Deep Space Network for missions covering Earth proximity, GEO to cis-lunar, and cis-lunar to up to 2,000,000 km from Earth, which includes the Sun-Earth Lagrange points 1 and

Many new space organizations are trying new tracking hardware and techniques, both on the ground and in orbit. As a result, accurate orbit determination and navigation will require mission operators to perform their own quality checking, characterization, and diagnostics on tracking data.

To assist smaller budget missions in this task, *The Industrial Sciences Group (ISG)* has been developing a set of analytics and software tools for detecting, diagnosing, and visualizing anomalies in radiometric tracking data, known as Metric Tracking Data Analysis (MTDA). The objective of MTDA is threefold:

1. To report on patterns/anomalies in tracking residuals and characterize correlations with other variables to improve OD modelling and tuning,
2. To characterize spacecraft and ground station performance and tracking data quality, and
3. To report to mission owners on satellite behavior/anomalies affecting navigation.

A key feature of MTDA is to utilize the parameters of Kalman filtering used in orbit determination (OD), such as bias and pre-fit residuals, as performance indicators of orbit determination models, ground station receivers and satellite hardware affecting navigation.

MTDA uses modern statistical and graphical tools, applied to the residuals and Kalman filter parameters, to perform causal analysis of tracking system anomalies, characterize ground station performance, characterize spacecraft tracking hardware, and pre-process residuals as a quality check to assist orbit determination. It also determines correlations between tracking data behavior and satellite and orbit parameters. Correlations can be used for residual bias tuning and quantifying effects that may contribute to anomalous tracking behavior

The use of MTDA in new space missions represents an effective application of statistics into astrodynamics for uncertainty quantification and risk reduction. It is available to a wide range of mission operators, as using the MTDA Toolkit does not require sophisticated statistical knowledge.

The MTDA Toolkit has been used by *Space Exploration Engineering (SEE)* as part of their flight dynamics activities for lunar missions: SpaceIL/Beresheet and the NASA

CAPSTONE/Lunar Photon mission flown by Rocket Lab. These two missions used tracking data obtained by the *Swedish Space Corporation* (SSC). The MTDA Toolkit has also been used recently on the current Korean Pathfinder Lunar Orbiter (KPLO), operated by the *Korea Aerospace Research Institute* (KARI), with tracking performed by the Deep Space Network (DSN), and flight dynamics operations supported by SEE.

II. ORBIT DETERMINATION USING KALMAN FILTERING

To facilitate understanding of MTDA's usage, a simplified overview of orbit determination using Kalman filtering is outlined below and in Figure 1, based on [1].

Firstly, spacecraft observations (such as Doppler and range) are collected through a network of receivers. These observations are initially corrected using known a-priori models (e.g., hydrostatic troposphere delay, observation biases given by data providers, etc.). Then, the prefit-residual y is formed by the equation $y = z - Hx$, where z and x are the observation and state vectors respectively, and H is the observation matrix that transforms from state-space into observation-space. The state vector x contains a list of all parameters to be estimated, such as the spacecraft's position, velocity and solar radiation pressure and drag parameters, as well as other systematic differences that need to be calculated for accurate OD, such as receiver biases.

The Kalman filter then optimally estimates values for each state, given the current observations and state estimates from the previous time step, and the uncertainties of each. Thus, as the spacecraft is tracked over time, the resulting observations are used by the filter to converge the states to their actual values (e.g., the spacecraft's true position, velocity, drag, etc.). There are several aspects of the Kalman filter that must be "tuned" to accurately perform OD – such as process noise, propagation modelling and observation noise modelling. Failure to properly adjust the filter impacts its performance, resulting in inaccurate orbit estimation and unrealistic state uncertainties, which may have follow-on effects on the mission.

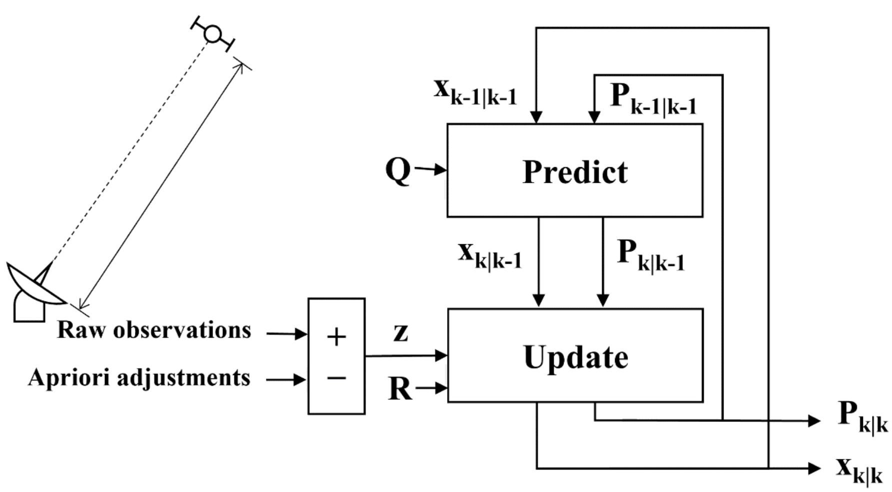

Figure 1. Simplified flowchart of a Kalman filter used for OD.

Figure details:

- $x_{a|b}$ – state vector at time “a” given observations up to time “b.”
- $P_{a|b}$ – covariance matrix of the state vector at time “a” given observations up to time “b.”
- z – observation vector
- Q – process noise matrix
- R – measurement noise matrix

PRIMARY DATA STREAMS

There are three primary data streams that are used in MTDA by default – prefit-residuals, biases, and “raw” residuals. These streams are used by MTDA to indicate areas of the filter that are poorly tuned, or anomalies that require additional investigation.

Prefit-residual

As mentioned in the previous section, the prefit-residual is composed of the difference between the observations and the states in observation-space (i.e., the observation you would expect to observe, given that the state is accurate). The prefit-residual term acts as an “error” signal which the filter seeks to drive to zero by absorbing it into the most appropriate states. Thus, the prefit-residual is expected to have a mean of zero. When the mean is offset from zero in the same direction over many epochs, this typically indicates poorly tuned process noise (too low) as the states are too slow-changing for the filter to absorb.

Noise in the prefit-residual can be used as a proxy for observation noise, as states typically do not contribute significantly to prefit-residual noise. Prefit-residual noise is used by MTDA when identifying regions that produce noisy observations (e.g., in-line with Sun, low elevations, etc.) by correlating noise levels to other parameters (e.g., Sun aspect angle, elevation angle, etc.). Known sources of prefit-residual noise include:

- Low elevations of the spacecraft relative to the station
- Distance to spacecraft (for range observations)
- Low relative velocity (for Doppler observations)
- When the spacecraft is close to in-line or in-line with the Sun relative to the station (small sun aspect angle)
- When the spacecraft exits from behind Moon (due to multipath off the Moon’s surface)
- After maneuvers (not due to observation noise, but rather due to a sudden change in the true orbital parameters).

Noise-correlation analysis assists with improving the performance of the filter in several areas, such as:

- Improving observation noise models
- Excluding observations from noisy regions

- Helping to diagnose source of unexplained noise
- Tuning process noise of orbital parameters to absorb maneuvers more quickly.

Bias

A state called the "bias" is used to capture constant or near-constant unmodelled errors in the observations, such as unknown transponder delay . This is done by giving the state a low process noise, so that it moves slowly over time, and thus absorbs residuals slower than other states.

Biases should look "random", as patterns in a bias term indicate mismodelling. For example, a periodic trend in the bias might indicate that some phenomenon – such as antenna offset on a rotating satellite – has not been modelled correctly.

Biases should also not be significantly correlated to any other parameters or events. For example, a spike in the bias after every maneuver would indicate incorrectly tuned process noise – i.e. the bias absorbs the error too quickly that should correctly be allocated to the orbital states.

III. METHODOLOGY & SOLUTION

The methodologies employed by ISG for MTDA grew out of previous work on characterizing the behavior of Doppler & range residuals using data from the NASA Lunar Reconnaissance Orbiter (LRO) mission, presented previously.[2, 3] The objective was to obtain realistic models and behaviors of residuals to be used as input to mission analysis simulation for the SpaceIL/Beresheet lunar mission of 2019. In this way, MTDA was initially used to inform trajectory design and tracking scheduling in the planning stage.

Residuals of Doppler and Range were used as an indicator of the orbit determination model quality (along with other metrics). The variance and behavior of residuals also indicates signal noise that can be quantified for comparison with expected ground station to spacecraft *white noise.*

The use of realistic tracking data performance improved the validity of the simulation results as it includes detection and characterization of anomalies such as non-random jumps, autocorrelated trends, and outliers. In the newly developed MTDA Toolkit, for use in mission operations, additional features have been added, – including correlation analysis and quantification of the effects of various spacecraft / ground station parameters on tracking data quality. Parameters analyzed for correlation include *altitude, range from station, and Sun aspect angle.*

By performing rigorous identification and classification of "Bad" passes, the analysis in MTDA informs the quality of orbit determination by revealing problems in models through validated statistical graphics. MTDA characterizes ground station results for *white noise within* *and between tracking passes* and compound variance, for comparison with nominal expectations. MTDA performs anomaly detection of residual data and undertakes an objective statistical analysis of data structures to avoid false “apparent” patterns. Finally, the tool provides an independent, validated metric of station performance, useful for station certification.

The statistical methods used in the MTDA toolkit include Exploratory Data Analysis for the determination of outliers, moving average time series to measure noise within a pass, Auto-Regressive Independent Moving Average (ARIMA) techniques to quantify autocorrelation and white noise, and linear regression for correlation between parameters.

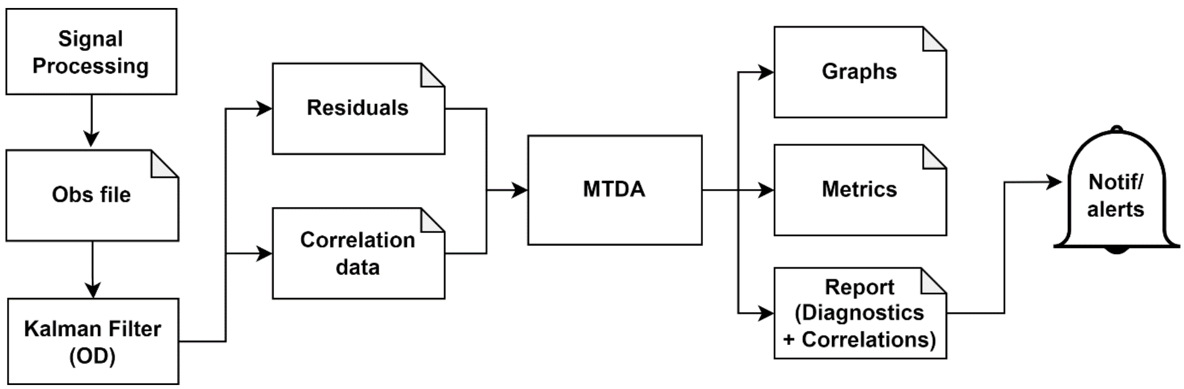

Figure 2. MTDA Workflow

ISG’s MTDA Toolkit starts with residual values of spacecraft observations, such as azimuth and elevation angles, or more commonly Doppler and range observations. Initial pre-processing is performed to analyze tracking data for outliers, quantifying drift in the Bias applied to Orbit Determination, classifying bad passes (with outliers above a certain threshold) and setting a threshold for non-random jumps in residuals. Characterization of performance by the ground station is performed for all stations used in a mission. MTDA quantifies white noise between passes and within a pass and detects non-random trends over time (a wave-like trend for example). This function is particularly useful, as it allows tracking station operators to assess performance between their various ground stations and compare the performance of a single ground station between different missions (see results section below).

For each pass in the residual timeseries the MTDA Toolkit calculates the variation around the mean calculated for the pass, whether it meets the criteria of a “good” or “bad” pass, whether it is showing autocorrelation with previous residuals and quantifies the outliers based on a statistical measure, such as Inter-Quartile Range. The tool is interactive, allowing the user to zoom in on residual analysis of specific pass or time period.

To analyze white noise *within a pass*, the tool uses a moving window to assess 1-σ over time (in much the same way as is used in jump detection). To remove the non-random trends in each pass, the data is fit using ARIMA to extract the pure noise data from the signal, reutilizing the module used to detect anomalous non-random signal behavior. The noise sigma over time is also correlated with other variables such as elevation, range from station, and Sun aspect angle.

MTDA also considers the correlation of the noise **sigma** of residuals (variation of the residuals, as opposed to correlations with the **value** of the residuals) against some correlation term, giving more insight into how correlation terms affect the noise of measurements (in contrast to how correlation terms affect the value of the measurement itself). The intra-pass analysis for white noise uses the previously mentioned white noise tool. It links the curve-fitted white noise time-series with any suggested correlation term, such as satellite range magnitude to station. The *autocorrelator module* in MTDA detects and flags non-random trends for further analysis, thus solving the problem of seeing "apparent structure" in data.[4] The pass-by-pass analysis unique to the toolkit allows for intra-pass statistical analysis of residual behavior to confirm weak points in the tracking process, including correlations between range from station and noise.

The main benefits of MTDA for orbit determination and ground station diagnostics has been to provide a statistically rigorous analysis of tracking data and delivering immediate feedback on tracking anomalies. Limitations on staffing resources in flight dynamics teams, and ground station operations as well as a high cadence of maneuvers planning and executions, mean it is unlikely there will be time and people sufficiently dedicated to the type of statistical analysis described above. Thus, extra time and cost will need to be incurred to perform diagnostic tasks. MTDA seeks to solve this problem by automating the analysis and providing easy-to-interpret graphics.

IV RESULTS

We present sample results of the application of the MTDA Toolkit in collaboration with flight dynamics operations of SEE in three lunar missions: SpaceIL/Beresheet, the NASA CAPSTONE lunar mission flown by Rocket Lab and the Korean Pathfinder Lunar Orbiter (KPLO), operated by the Korea Aerospace Research Institute (KARI). Beresheet and CAPSTONE used tracking data obtained by the *Swedish Space Corporation* (SSC). KPLO had tracking performed by the Deep Space Network (DSN).

Mission 1 – SpaceIL/Beresheet (2019)

SpaceIL's Beresheet spacecraft was the first private mission to the Moon and was undertaken by the fourth country to attempt a soft Lunar landing. On 4 April 2019, Beresheet successfully entered Lunar Orbit, and attempted to land on the Moon on 11 April 2019.[5]

The Swedish Space Corporation (SSC) Satellite Ground Network was used to provide TT&C communication services in support of the SpaceIL Mission. SSC tracked SpaceIL throughout the entire mission, from separation after launch, through Lunar Orbit Insertion (LOI), and until landing. The SSC ground system provided range and Doppler data that SpaceIL used to perform orbit determination.[5]

ISG was contracted directly to SpaceIL to perform statistical analysis of tracking data and simulation in the design phase and operational phase of the mission.[2] In the design phase MTDA's statistical tools were used to characterize ground station performance in terms of quantifying outliers, bad passes, and occurrence of jumps in residual values by using data from a previous mission (NASA's LRO) that used the same ground stations that were to be used by Beresheet.

SEE was contracted to SpaceIL to provide a range of flight dynamics services, including orbit determination during the mission. SEE developed a concept of operations to adapt to the challenges of operational support from the ground stations. The challenges arose mainly from the spacecraft's low gain antennas having a radial separation of 60° between the transmitting antenna and receiving antenna. In addition, the spacecraft was spinning at a nominal rate of 1°/s which caused the periodic outages of TT & C services during each pass.

ISG applied the MTDA Toolkit for tracking data during the mission in collaboration with SEE. SEE used the outputs and analysis provided by the MTDA Toolkit to adjust the orbit determination model and setting of bias values to meet these challenges. The MTDA Toolkit *quantified and gave a visual description of the drift in the bias-fitting residuals* caused by the rotating spacecraft and the antenna offset (see Figure 3 below).

Figures 3 & 4 show an interactive plot including the pass number, start and end of epoch and the number of datapoints for each pass is visible when hovering over their respective boxes. The outliers of each pass are also plotted.

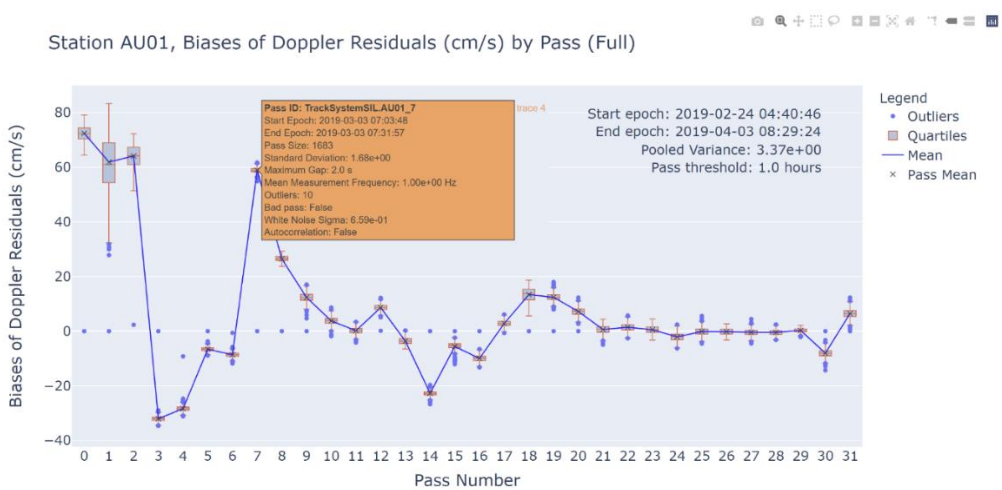

Figure 3. MTDA Graphic: Beresheet mission SSC ground station Dongarra, Australia; Doppler residual by pass, showing Bias drift in post-fit residuals-caused by attempting to fit an orbit to the rotating spacecraft, with a 60° antenna boresight offset. The orange box shows the intra-pass statistics for pass 7 in this example.[3]

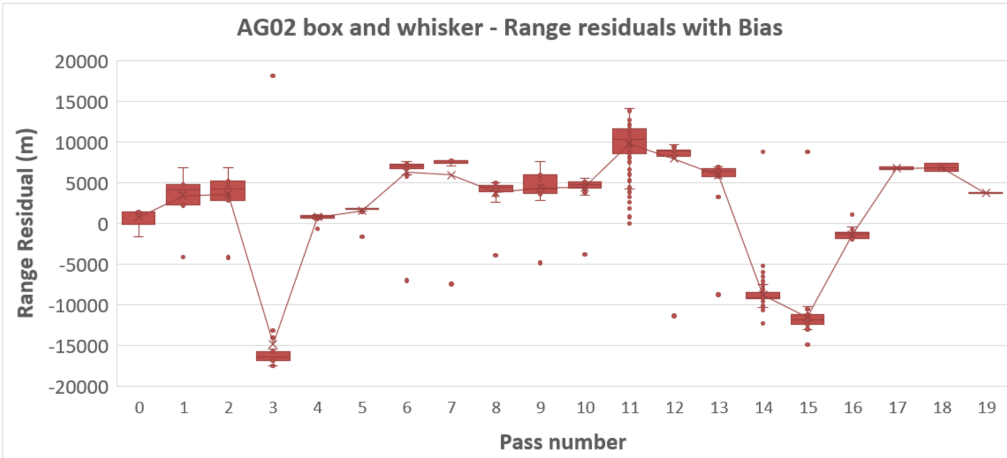

Figure 4. MTDA Graphic: Beresheet mission SSC ground station Dongarra, Australia; Range residual by pass, showing Bias drift in post-fit residuals-caused by attempting to fit an orbit to the rotating spacecraft, with a 60° antenna boresight offset.[3]].

An advantage of the interactive HTML plot is the ability to show additional statistics when hovering over particular passes. An example is shown in Figure 5.

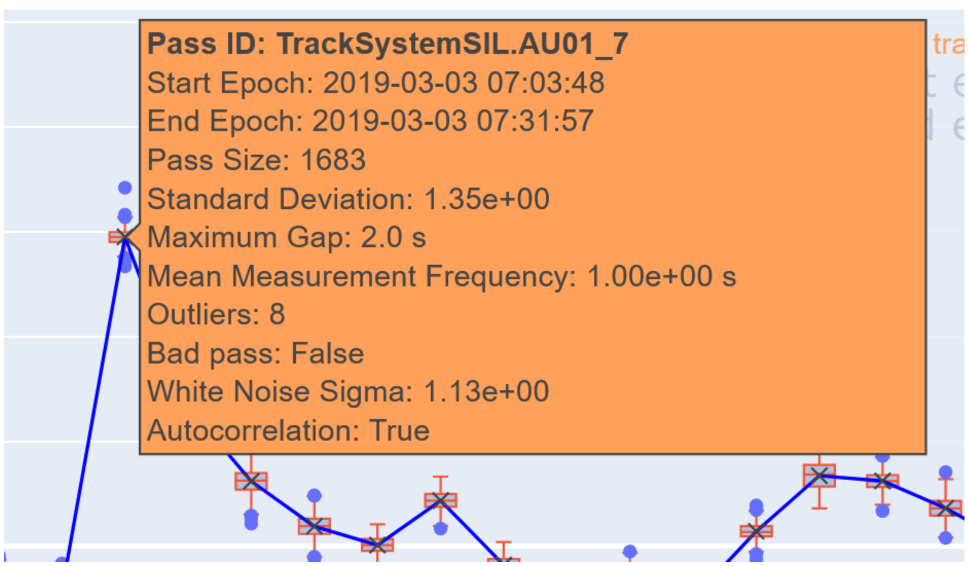

Figure 5. Interactive Hover Overlay Example showing intra-pass statistics.

Another use of the MTDA Toolkit in the Beresheet mission was to find correlations between Doppler and range residuals with *Sun Aspect Angle and range from the station* (see Figure 6 below). The quantification of correlations allows operators to tune residual biases more rapidly and investigate the causes of anomalous behavior that may be a function of the relative station spacecraft geometry.

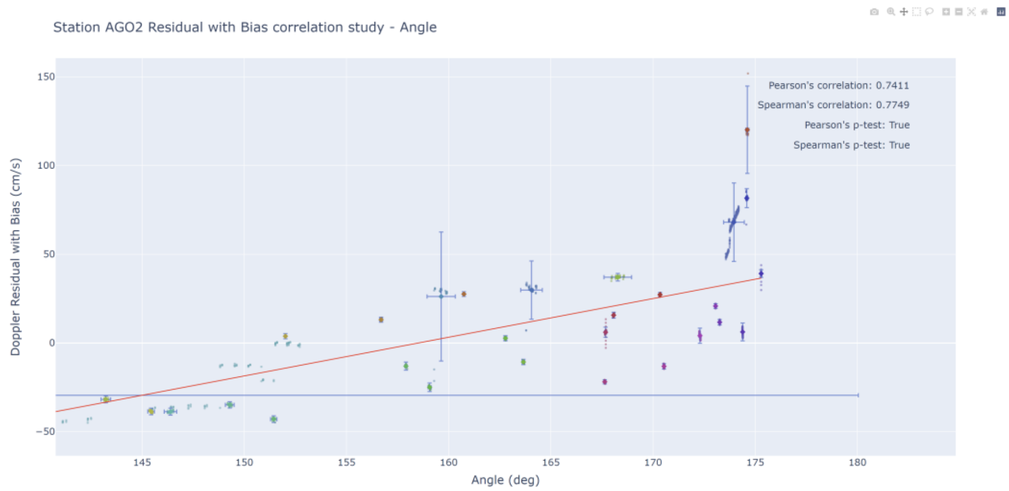

Figure 6. MTDA Graphic: Beresheet mission SSC ground station AGO2; Indicating a positive correlation between Doppler Residuals and Sun aspect angle (grouped by pass and shown in different colors) as validated through Pearson's and Spearman's tests (p-values also shown in top right).

Mission 2 – NASA CAPSTONE/Lunar Photon Flown by Rocket Lab (2022)

The Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE) is a mission funded by the NASA Small Spacecraft Technology Program and was launched in 2022 by Rocket Lab. The Lunar Photon with the CAPSTONE spacecraft was launched into a Low-Earth Orbit, performed several apogee raising maneuvers and the Trans-Lunar Injection (TLI) to place the stack onto a near-escape trajectory, and then released the CAPSTONE spacecraft which traversed a low-energy Ballistic Lunar Transfer (BLT) and was inserted into a Near Rectilinear Halo Orbit (NRHO). CAPSTONE's objectives include demonstrating BLT and NRHO operations to inform fundamental exploration requirements and Gateway planning activities, as well as accelerating the infusion of the Cislunar Autonomous Positioning System (CAPS).[6]

Space Exploration Engineering (SEE) was contracted to Rocket Lab for flight dynamics services for the initial Lunar Photon maneuver sequence. That covered flight dynamics from initial orbit insertion to TLI. ISG collaborated with SEE to apply the MTDA Toolkit to tracking data and residual values during those phases of the mission.

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Major results from applying the MTDA Toolkit to CAPSTONE Doppler and range residuals include detecting distinct trends in range residual data with statistically significant correlations (see Figures 6–8). Correlations between *range residuals and altitude* offer predictive pre-processing options to improve bias tuning and, therefore, Orbit determination. In Figures 6–8, residual behavior was characterized for multiple SSC stations showing differences in performance (white noise and non-random ‘wave-like’ time-series trends).

An important outcome of using the MTDA graphics and statistics was allowing the flight dynamics team at SEE to improve their OD models by modifying the weighting used. One example was to increase residual biases at lower elevations.

The correlation results and graphics can also be used by the ground station operator to correctly diagnose/ identify what is truly a “bad” pass and assist root cause analysis. The correlations graphics guide the “detective” approach to diagnosing anomalies by indicating where to look first, before proceeding to a deeper analysis. Future correlation analysis will include determining if correlations are found between tracking data anomalies and *clock bias on the ground, inaccurate station location and mixing of one-way and two-way Doppler data.*

This application of correlation analysis to tracking anomalies represents an independent and statistically valid way to correctly attribute responsibility for “bad” passes or other anomalous features of tracking data. Figures 7-10 below are outputs from the lunar primary mission data of NASA CAPSTONE from low Earth orbit until TLI.

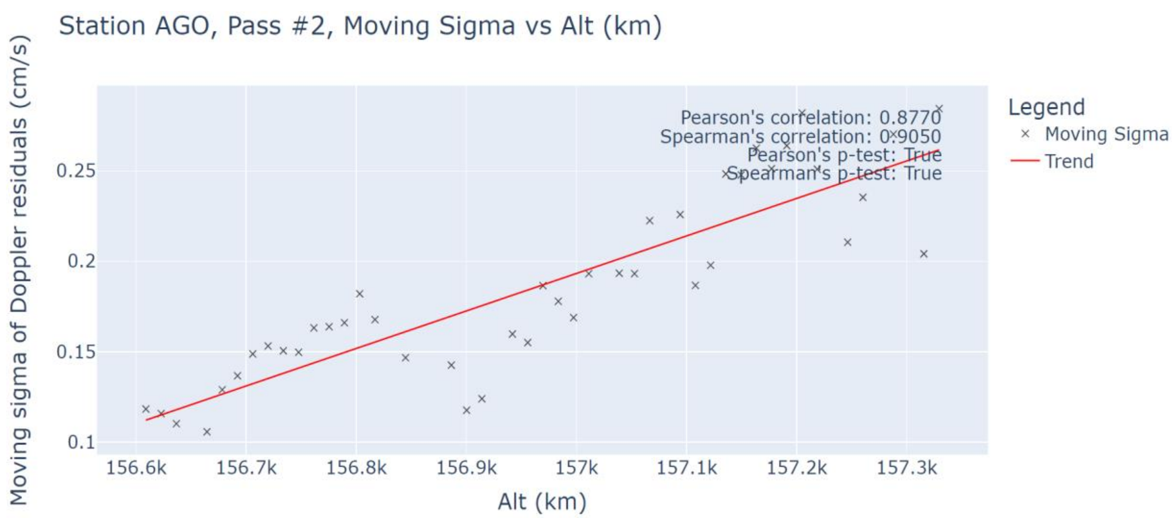


Figure 7. MTDA Graphic (CAPSTONE mission): Correlating moving sigma of Doppler residuals with spacecraft altitude, showing a strong positive correlation between the two variables.

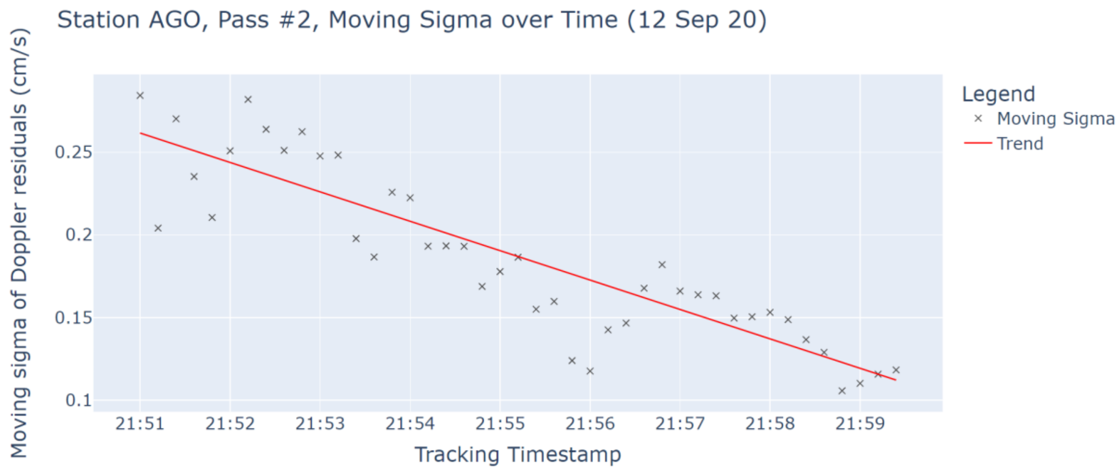


Figure 8. MTDA Graphic (CAPSTONE mission): Correlating moving sigma residuals with data timestamp, showing a decrease in Doppler residual sigma over time.

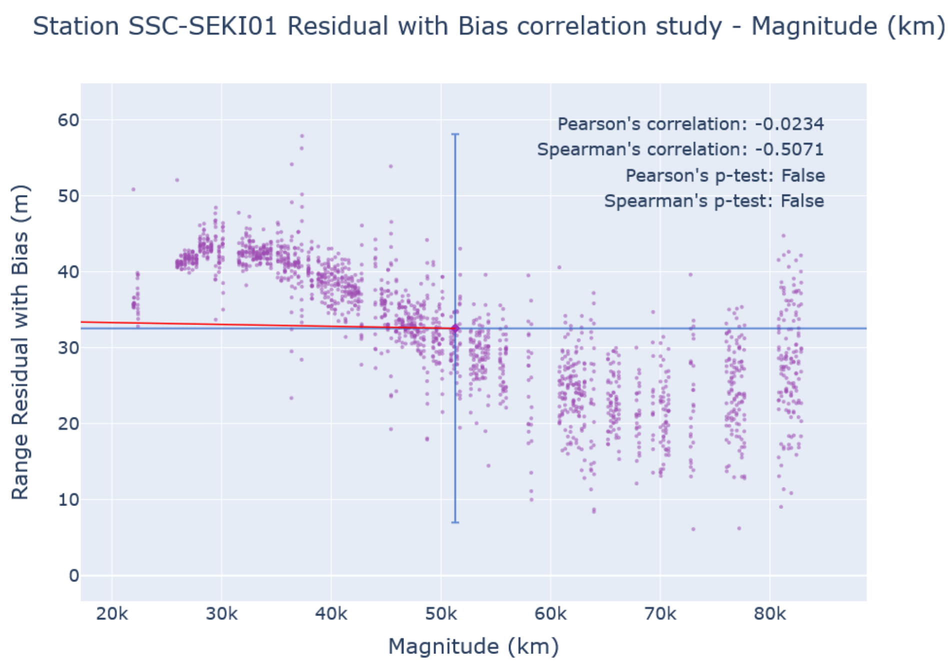


Figure 9. MTDA Graphic (CAPSTONE mission): Range residual vs. distance from CAPSTONE to station

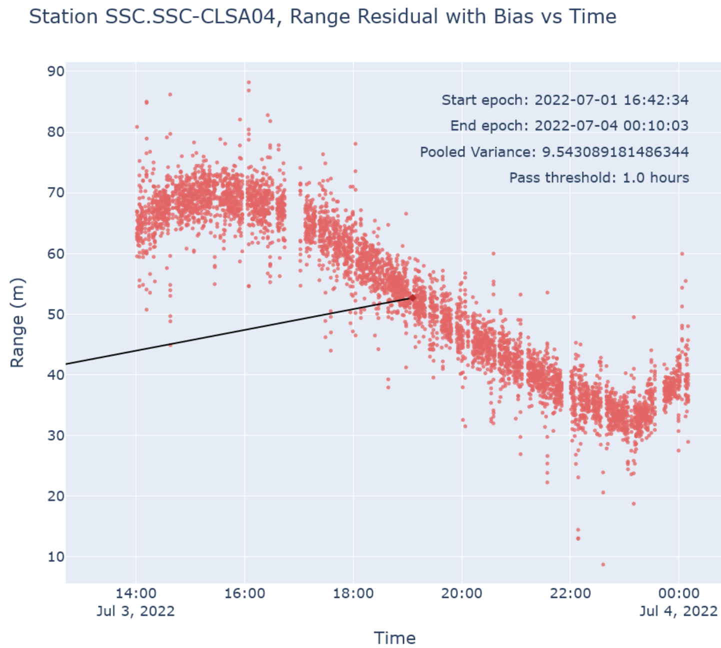


Figure 10. MTDA Graphic (CAPSTONE mission): Range residual vs. time for a single pass, showing a wave with period of approximately 10–11 hours.

MTDA results were aggregated to provide a summary of performance for three of the ground stations used in tracking the CAPSTONE/Lunar Photon mission, over a period of 5 days (see Table 1 below). The results can be used for comparison with nominal or reported station performance. The summary values are determined as a composite of residual behavior for multiple tracking passes. White noise is determined using ARIMA trends fit to prefit (with bias) residual data.

Table 1. CAPSTONE Tracking Station Performance Summaries over a 5 Day Period

Property	**SSC-SEKI01**	**SSC-AUWA01**	**SSC-CLSA04**
Passes	6	5	3
White noise σ (m)	3.72	0.93	2.94
Prefit σ (m)	5.27	1.90	3.85
Prefit + bias σ (m)	12.0	6.57	9.54

Mission 3 – Korean Pathfinder Lunar Orbiter (KPLO) "Danuri" (2023)

The Korea Pathfinder Lunar Orbiter (KPLO), officially named Danuri, is the Korea Aerospace Research Institute's (KARI) first exploratory space mission outside of Earth's orbit. KPLO launched on August 4, 2022 on a Space X Falcon 9 rocket from Cape Canaveral.

KPLO was launched on a ballistic lunar trajectory which reached the Moon in December 2022. After entering a roughly 100-kilometer circular lunar orbit, KPLO will study the Moon for at least one year with its five scientific instruments, starting in January 2023. KPLO used NASA's Deep Space Network (DSN) as the primary TT&C provider during the lunar transfer and early lunar orbit phases of the mission.

Space Exploration Engineering (SEE) was contracted to KARI to assist its team in flight dynamics services for the mission, providing Independent Verification & Validation (IV&V)[9]. That covered flight dynamics from initial orbit insertion, through lunar orbit insertion, and 1 month of lunar orbit commissioning. ISG collaborated with SEE to apply the MTDA Toolkit to tracking data and residual values during the mission.

Kalman filter coordinate systems

A feature of the orbit determination in the mission was the use of two separate Kalman filters – an Earth-centered filter from launch to lunar orbit insertion (LOI) and a Moon-centered filter from 24 hours prior to LOI, through to lunar orbit. MTDA was used to compare the performance of each approach.

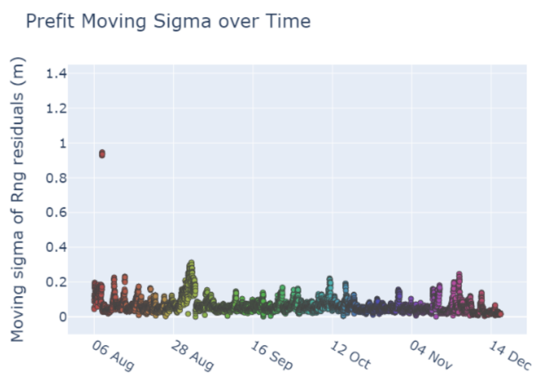
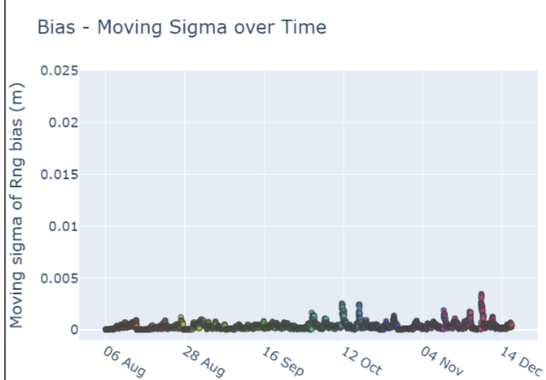
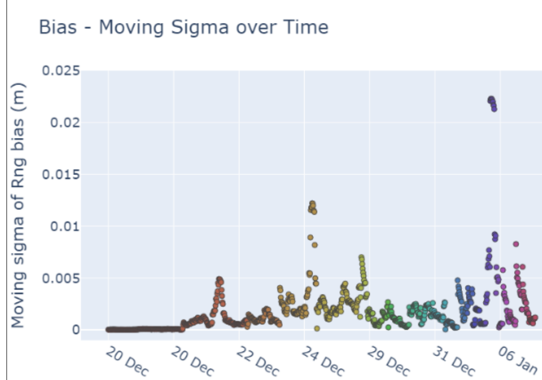
Sigma Type	Earth-centred	Moon-centred
Seq. range (prefit)		
Seq. range (bias)		

Figure 11: Pairs of readings (Earth-centred and Moon-centred) for DSN station D24.

Figure 11 shows prefit and bias plots for both the sequential range and Total Count Phase (TCP) residuals processed within ODTK. ODTK's processing of TCP observations is approximately equivalent to processing Doppler observations. As each pair of plots are set to the same y-axis scaling, we can compare the noise levels in earth-centred Earth- and Moon-centred observations. Moon-centred results and biases from late December show significantly more variation than Earth-centred results. Possible factors affecting the Moon data may be multi-path effects from the Moon's surface, and the order / accuracy of the Moon gravity model used (Grail GL0660B 100 x100 was used for KPLO). Daily momentum off-load (WOL) events were required once KPLO inserted into lunar orbit, which is more than the weekly WOLs during the cislunar phase, and are a contributing factor to the greater data variance.

Effect on navigation of maneuvers and wheel offload events

On the way to the Moon, thrust maneuvers and momentum adjustments using reaction wheels may cause sudden changes in bias and prefect residual values if not modelled correctly. This needs to be quantified to maintain the quality of orbit determination after such events. MTDA was used in the KPLO mission to confirm that there was no significant effect on bias levels during maneuver momentum offload events (see Figure 12 below).

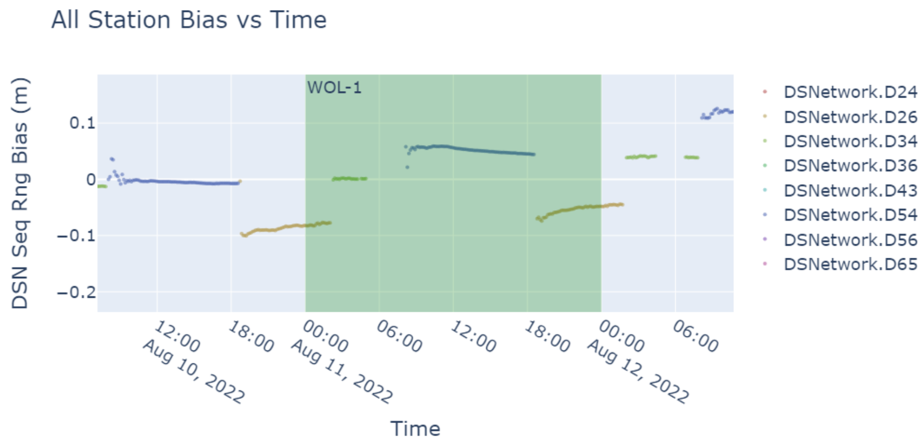


Figure 12: A close-up of a WOL event showing some variation within the daily activity (in the blue series) but notably, this variation does not exceed the noise levels seen outside of the WOL.

Future work includes comparing KPLO maneuver results to other missions that use private ground station networks (e.g. CAPSTONE/Luna Photon and Beresheet). The cross-mission analysis will provide further insight into factors affecting private ground station performance for future missions.

Correlations

We considered measurement of correlations of bias and noise in Doppler and range residuals to physical parameters including elevation angle, Sun-aspect angle, Earth-Moon-satellite angle, and range to station. These results are of use to detect and explain anomalous behavior, as well as confirm expected increases in noise due to explainable physical and geometric parameters (e.g. 180° Sun aspect angle increases noise in residuals).

Figure 13 below shows a general increase in prefit residual (and thus observation) noise at low elevations around 10–20°. This is to be expected, as the observation passes through more atmosphere, meaning that more unmodelled atmospheric effects will affect the observations being made. This is typically handled within the filter by using an elevation-dependent noise model to adjust the observation uncertainty accordingly.

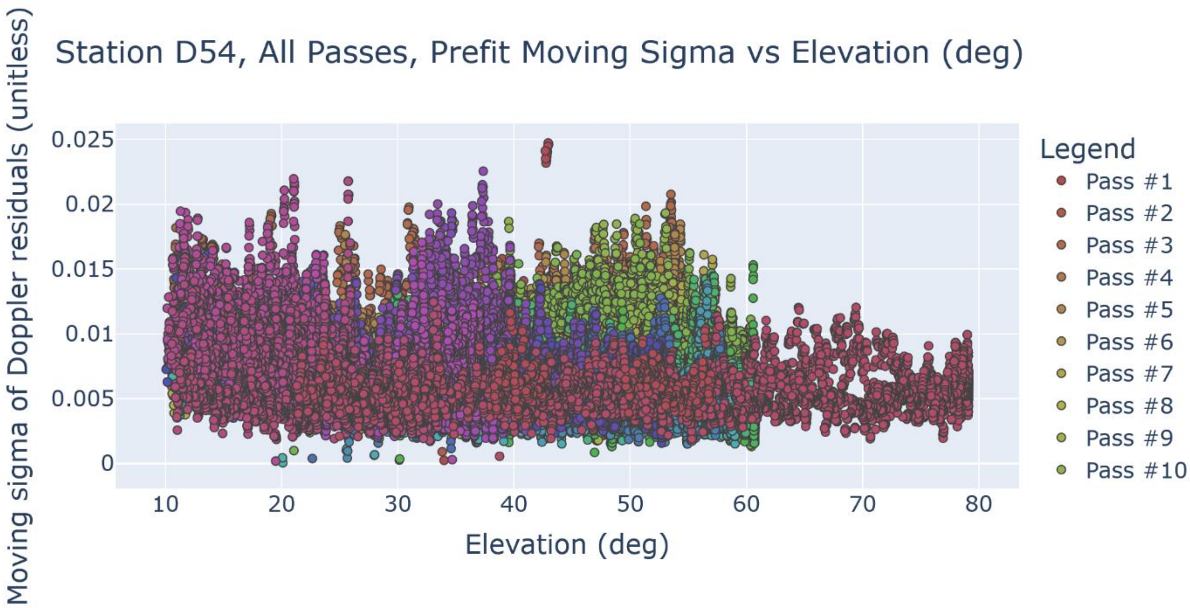


Figure 13: Moving sigma noise of Doppler residuals vs. elevation angle.

Similarly, Figure 14 below shows a sudden increase in noise at a Sun-aspect angle near 180°, due to the radiation from the Sun increasing the noise floor from which observation signals need to be detected. Data from this region is typically excluded so that it does not impact the accuracy of the solution.

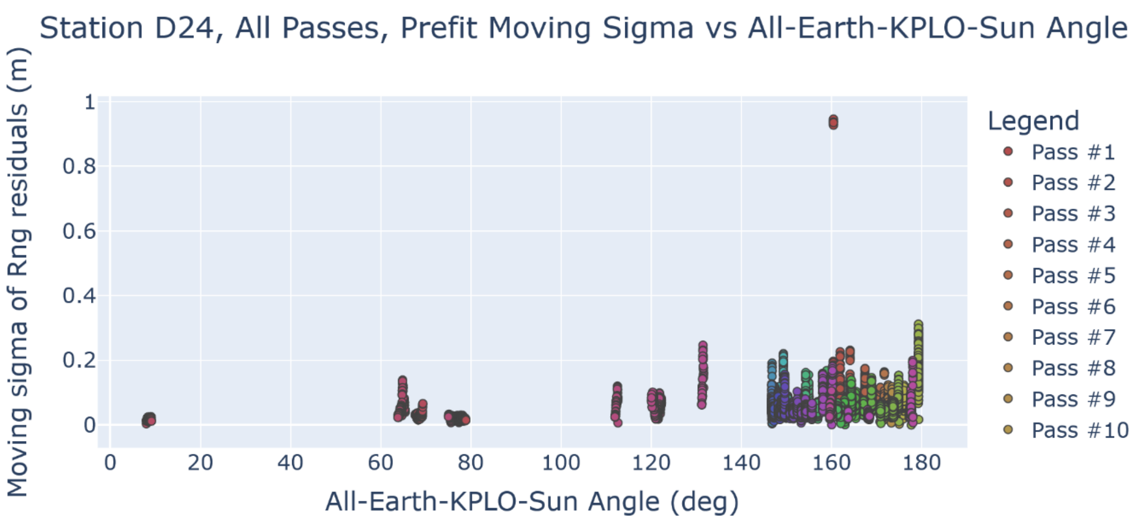


Figure 14: Moving sigma noise of range residuals vs. elevation angle.

ADDITIONAL FEATURES & FURTHER DEVELOPMENT

Further developments of the MTDA Toolkit will focus on areas that provide benefits to mission operations that are difficult to implement for mission owners due to a lack of resources in analytics and statistics. These include **analysis of the distribution** of noise within a pass to determine if it is Gaussian or some other distribution, affecting future modelling and analysis. MTDA can advise on shape and features of distributions within a time series pass-by-pass residual dataset, such as distribution kurtosis. The analysis of correlations will be extended to include correlations of tracking data with spacecraft attitude and antenna angle bore sighting.

ISG also plans to extend the application of the MTDA Toolkit to more pre-launch activities, including certification of a tracking system and to inform mission design by including in simulations the statistical features of *realistic ground station performance*. The aim is to inform mission designers of the effect on tracking of antenna bore sighting, transponder performance, spacecraft rotation and other design parameters that affect tracking performance. Knowledge of these features and sensitivities in the design/planning phase will help mission designers and ground station operators to act accordingly to reduce the occurrence of anomalies, or mitigate them, during the mission. In addition, we propose to use the MTDA Toolkit to assist orbit determination analysts in *determining the optimal tracking method for OD*. For example, deciding between Doppler only, or Doppler and Range . This will be achieved by utilizing the MTDA Toolkit for white noise analysis to assess different tracking methods for minimal residual white noise.

ISG and SEE plan further demonstrations of the MTDA Toolkit in new orbital regimes and interplanetary missions beyond the tools' previous demonstrations on lunar missions. Further development also includes automation of the MTDA Toolkit so it can be better embedded in tracking and flight dynamics software. MTDA is part of ISG's *TRACER* Toolkit (*Tools for Risk Assessment & Uncertainty Quantification*) – a space mission analytics toolkit to reduce uncertainty and risk of complex space missions in LEO, lunar & cis-lunar space. The development of TRACER has been partly funded by the Australian Space Agency.

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