Detecting Satellite Laser Ranging Station Data and Operational Anomalies with Machine Learning Isolation Forests at NASA's CDDIS

Justine Woo (1), Sandra Blevins (1), Benjamin Patrick Michael (2)
1. Science Systems and Applications, Lanham, MD, USA 2. NASA Goddard Space Flight Center, Greenbelt, MD, USA

ABSTRACT

The International Laser Ranging Service (ILRS) is currently composed of 45 active satellite laser ranging (SLR) stations with several more set to join the network over the next several years. Station changes and histories are logged to files, but not always in real time. Sometimes these details are not added until long after changes have been made to the station – on occasion, years later. This in addition to unexpected hardware errors and other system issues that are not immediately detected impact the products generated by analysts. The ILRS Central Bureau (CB) and NASA's Crustal Dynamics Data Information System (CDDIS) have worked to provide tools for station engineers to use. This includes the creation of station plots which contain temperature and pressure information along with LAser GEOdynamic Satellite (LAGEOS) and LAser RElativity Satellite (LARES) tracking information that enable the monitoring of station performance and to determine whether the station has undergone any changes. As next steps, the CDDIS is working to enhance these station performance monitoring tools through machine learning. Isolation forest is an unsupervised machine learning algorithm commonly applied to anomaly detection. In this poster, the CDDIS details the steps taken to track anomalies within SLR station performance using isolation forest with LAGEOS and LARES satellite data.

PROJECT OBJECTIVE

Build a machine learning model to determine if active SLR stations in the ILRS network have experienced a potential hardware or software change. A detection will send an automatic alert when an anomaly is detected in the data providing a reminder for station engineers to review existing station performance monitoring plots and update the station site history logs.

CURRENT STATION MONITORING TOOLS

Currently, plots for each active SLR station in the ILRS network are available on the ILRS website (1, 2). Metrics for station monitoring include the following:

- Meteorological data – used to calculate tropospheric correction, changes in these values may indicate an issue with hardware/software but is prone to false positives due with exceptionally good/bad weather
- LAGEOS plots to detect hardware and software changes or issues (Figure 1 shows a subset)
- 7-Day tracking – provide statistics on weekly performance including the duration and number of NPT collected per pass to visually show where improvements in tracking habits can be changed
- Satellite Data Information – used to gage the overall precision of the system and inform better tracking habits

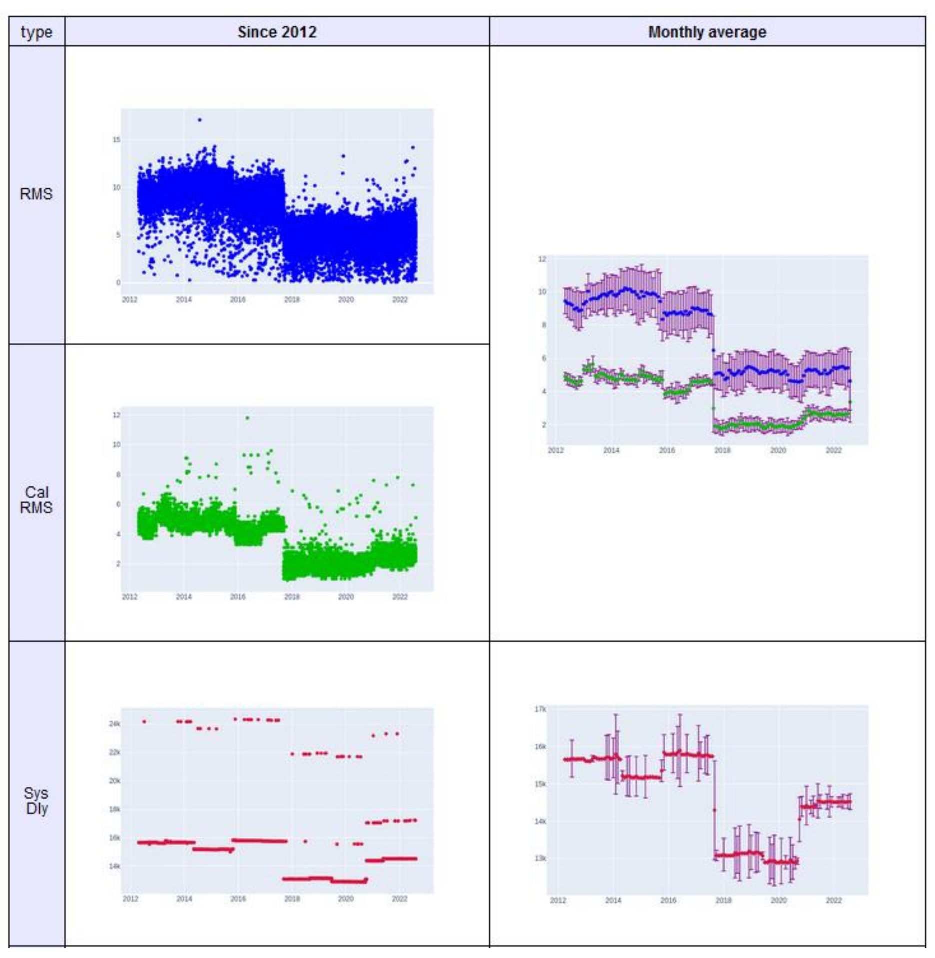

Figure 1: LAGEOS plots for Yarragadee displaying the session RMS, calibration RMS, and the system delay; available on the ILRS website.

ALGORITHM & TRAINING DATA

Isolation forest models were built using data from Yarragadee (Yarragadee) and acted as a starting point to determine if this type of analysis is possible. Yarragadee's data doesn't have a lot of scatter and the station is the highest performer (obtains the most passes) making it easy to work with. LAGEOS and LARES were chosen due to their consistent orbits. After proving viable, the model was applied to Herstmonceux, the second-best performer.

Reviewing historical data (2012/05/01 to 2022/07/19), the Isolation Forest algorithm makes predictions based on data from the past 90-days for the following 7-days. For each of the detections, feature plots are created with the data considered anomalous highlighted (Fig. 3-5 and 7-9).

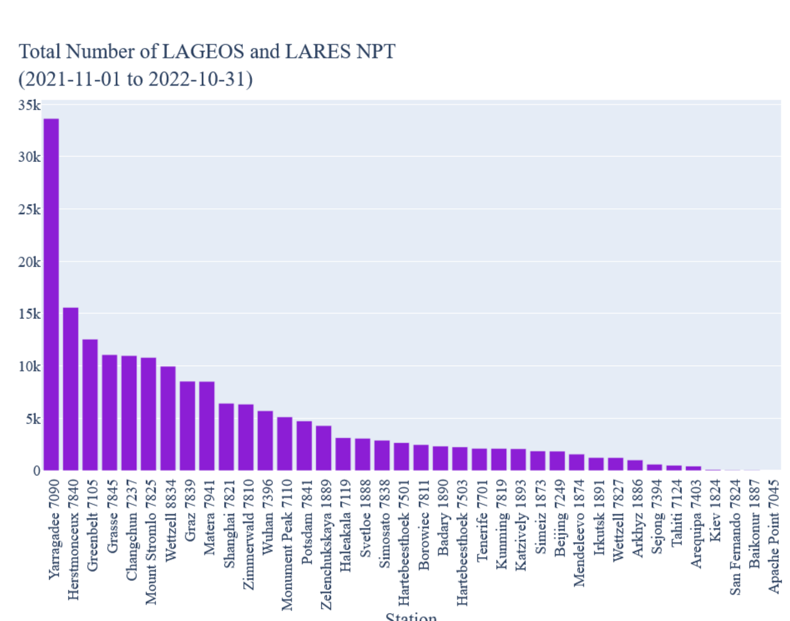

Figure 2: Recent LAGEOS and LARES tracking for the current stations; available on the ILRS website.

FEATURE SELECTION

The following features were selected in collaboration with SLR station engineers for anomaly detection:

- rms40 [ps] = calibration root-mean-square (RMS) of raw system delay
- medianRms40 = median of the calibration RMS
- rmsCalc [ps] = average bin RMS calculated from the range records (11) bin RMS from the mean of raw accepted time-of-flight values minus the trend function
- medianRmsCalc = median of the rmsCalc over the course of a day
- sysDelay [ps] = system delay peak (mean value) of the calibration
- satelliteSIC = satellite identifier

FEATURE JUSTIFICATION & FINDINGS

- The rms40 and the medianRms40 are used in an attempt to balance accuracy with expediency of the alert
- The rms40 rapidly predicts anomalies but has lower accuracy
- The medianRms40 was added to increase accuracy and helps provide a stronger pattern - however, using the median itself led to a delay in days for an anomaly to be detected!
- The medianRmsCalc was used instead of the rmsCalc which was subject to too much natural deviation or noise
- The system delay proved to be the strongest indicator of when a change was made to Yarragadee for a majority of the correct detections
- The satelliteSIC was selected as an unimportant feature but can be used to determine if 3 or 4 satellites can be detected by the model

STATION COMPARISON

Parameter	Legacy Station	Upgraded Station
Operational Year	1979	1982; Major upgrade in 2014
Repetition Rate Laser	10 Hz	1 kHz
Average Number of LAGEOS/LARES Normal Points per Day	14	11
Minimum Number of Passes Required to Form an Estimate	500	100
Number of Untested Days (minimum not met)	50	484

Please note that the ILRS Governing Board's Pass Performance standard only requires 3,500 passes per year with the following as a basis:

- 2 passes per week for each LEO satellite
- 4 passes per week for each LAGEOS satellite
- 2 passes per week for each HEO satellite

Both Yarragadee and Herstmonceux exceed these requirements.

LEGACY STATION – YARRAGADEE

SAMPLE PREDICTION

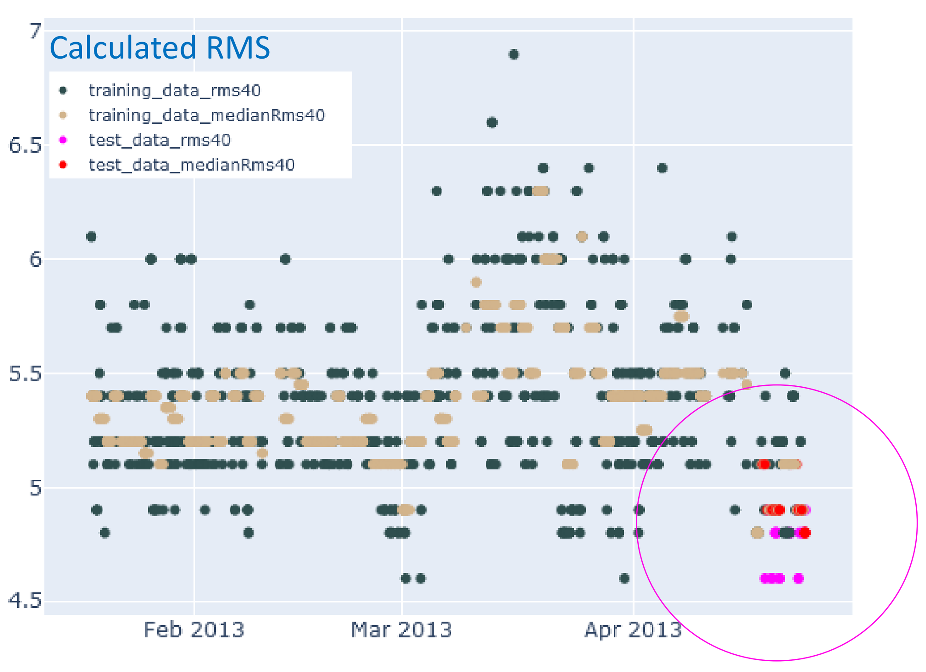

Figure 3: Plot of the Calculated RMS training and test data where an anomaly was detected (circled).

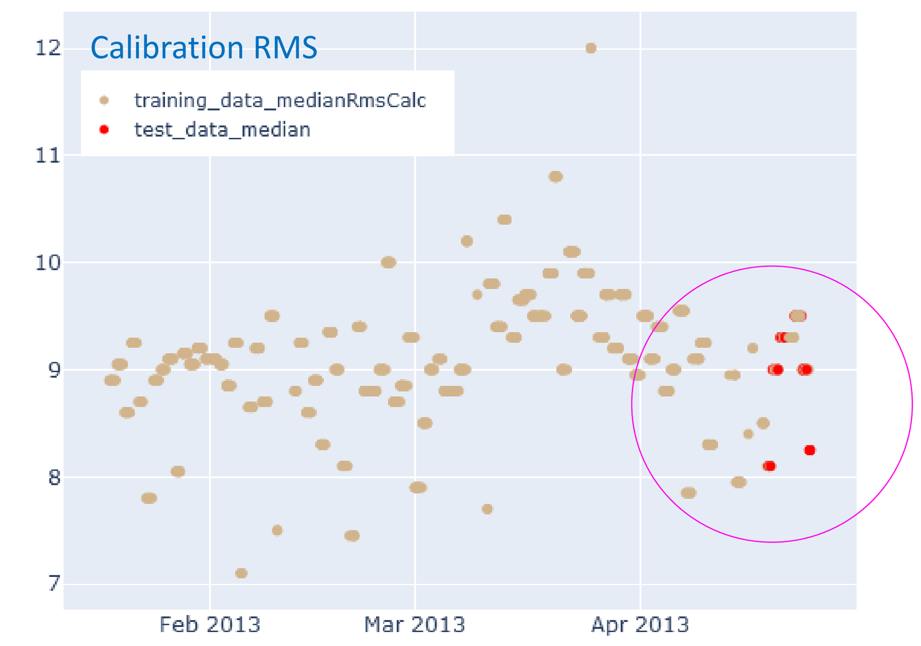

Figure 4: Plot of the Calibration RMS training and test data where an anomaly was detected (circled).

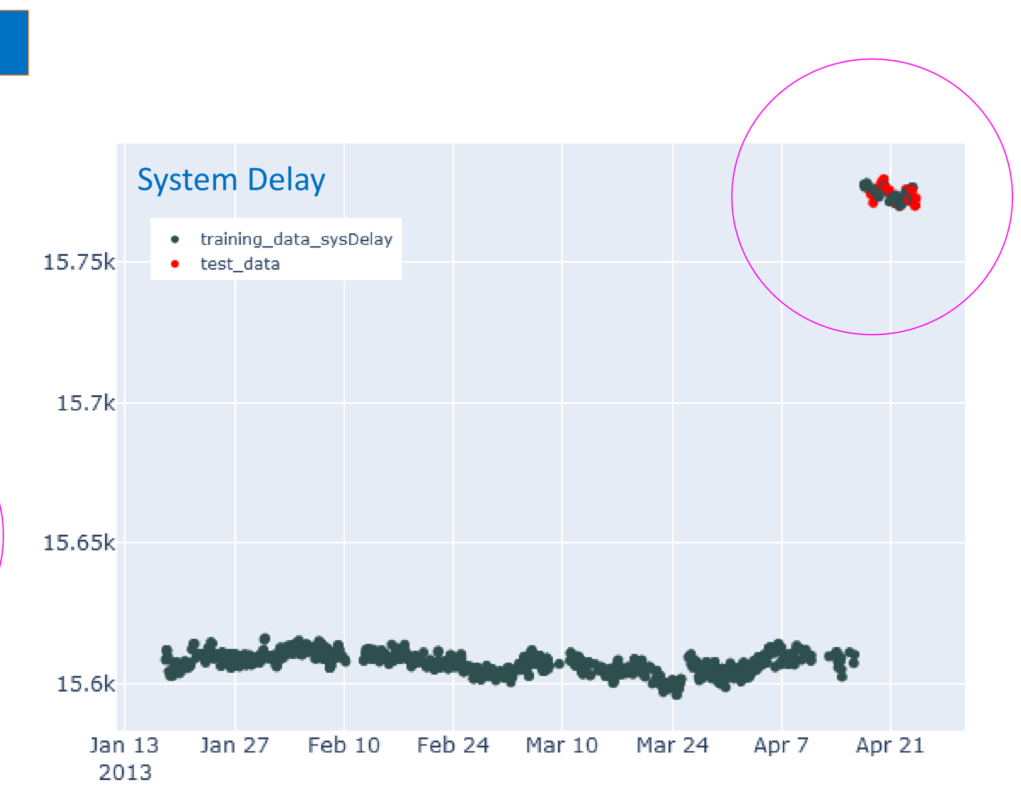

Figure 5: Plot of the System Delay training and test data where an anomaly was detected (circled).

RESULTS

The results for Yarragadee are promising. All the applicable changes were detected by the model. There were a few false-positives that would trigger an alert with only 2 a year.

Prediction accuracies was estimated by checking against station history logs. The results are reported below:

- All records for laser (05) and receiver (06) subsystems where the impact factor is >1 were detected as anomalies
- 271 total anomalies detected (Figure 6)
- 99% of correctly detected anomalies were detected the same day as recorded in the station log
- 55% of detected anomalies were recorded in station logs
- Of the 45% of detected anomalies that were not present in station logs, only 17% would realistically generate an email to alert stations engineers (21 over 10 years). It is possible that station changes were not recorded to the station log. However, of these cases reviewed, this only occurred once.

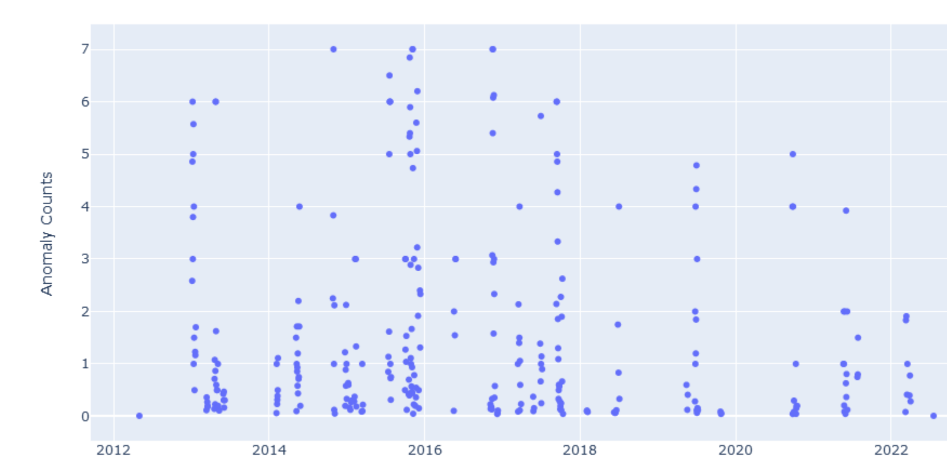

Figure 6: Total anomalies detected with the model plotted against the session datetime.

UPGRADED STATION – HERSTMONCEUX

SAMPLE PREDICTION

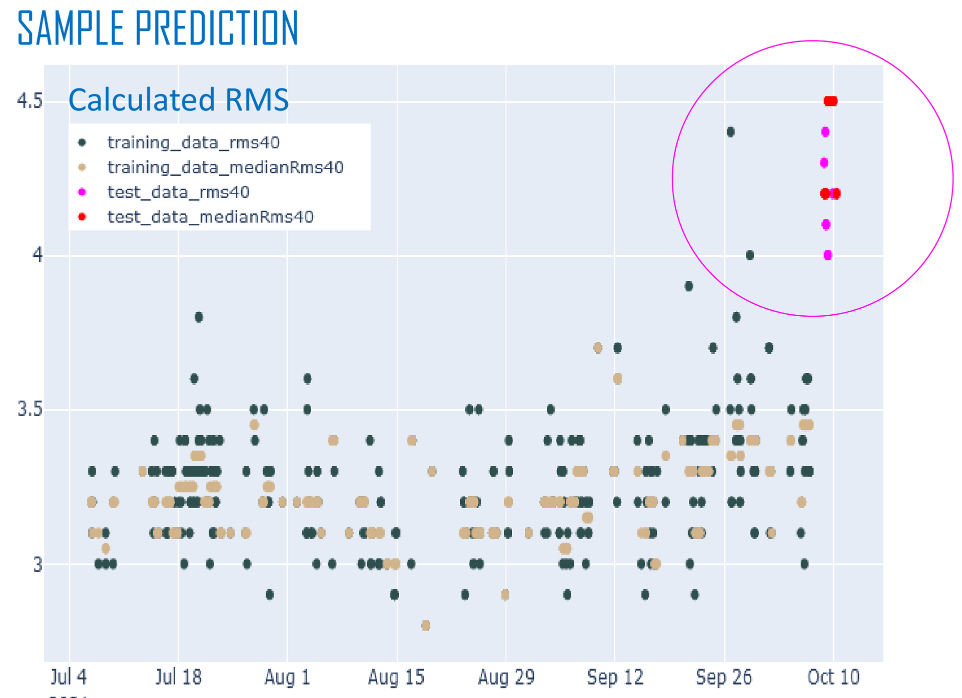

Figure 7: Plot of the Calculated RMS training and test data where an anomaly was detected (circled).

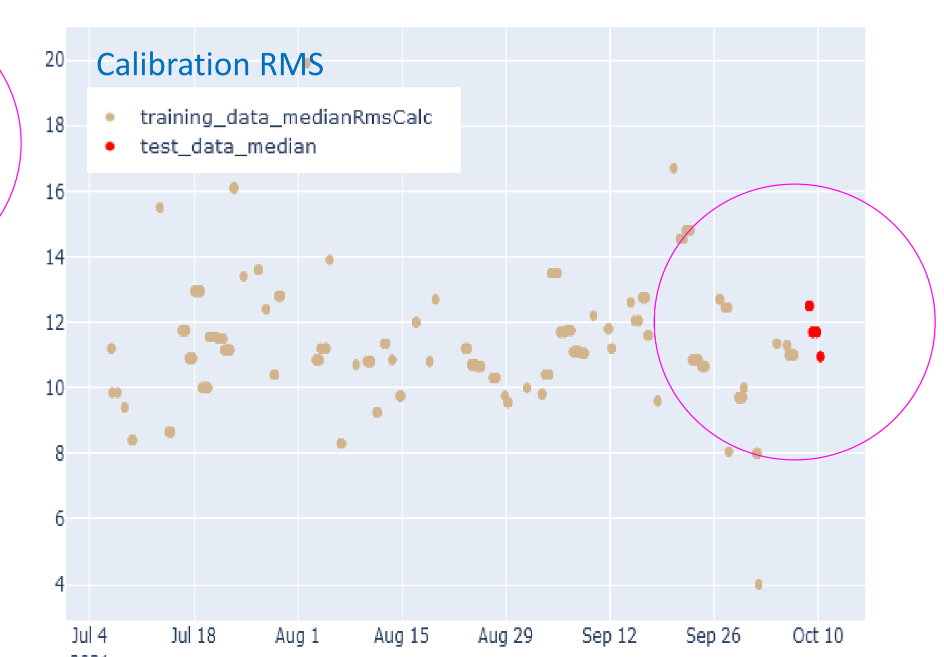

Figure 8: Plot of the Calibration RMS training and test data where an anomaly was detected (circled).

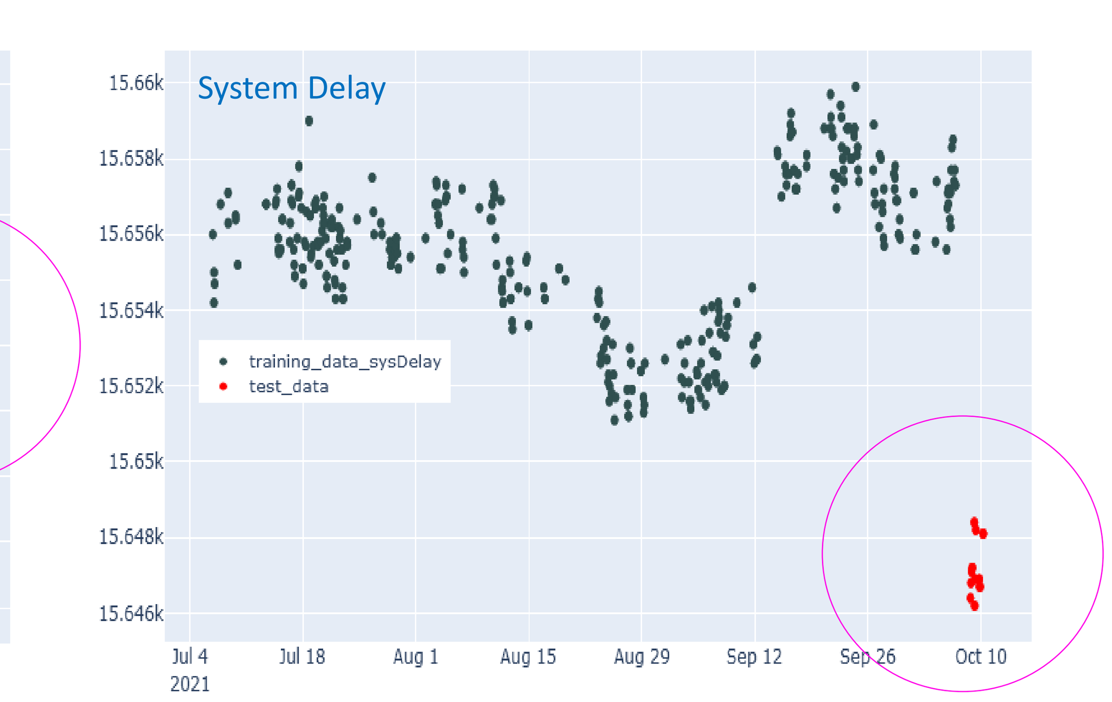

Figure 9: Plot of the System Delay training and test data where an anomaly was detected (circled).

RESULTS

For Herstmonceux, the prediction accuracy cannot be accurately estimated using the station history log because only one record exists where the impact factor is greater than 1 for the 05 and 06 subsystems – this change was correctly detected by our model. The reason there are so few records is because the station corrects the system delay value with every SLR pass delivered and therefore set the impact factor to 1. Station personnel at Herstmonceux reviewed the anomalies detected and determined that a majority looked like correct detections.

To compare against the results for Yarragadee above:

- All records for '05' and '06' subsystems where the impact factor is >1 were detected as anomalies – only one records exists
- 183 total anomalies detected (Figure 10)
- 49% of detected anomalies were recorded in station logs
- Of the 51% of detected anomalies that were not present in station logs, only 21% would realistically generate an email to alert stations engineers (19 over 10 years).

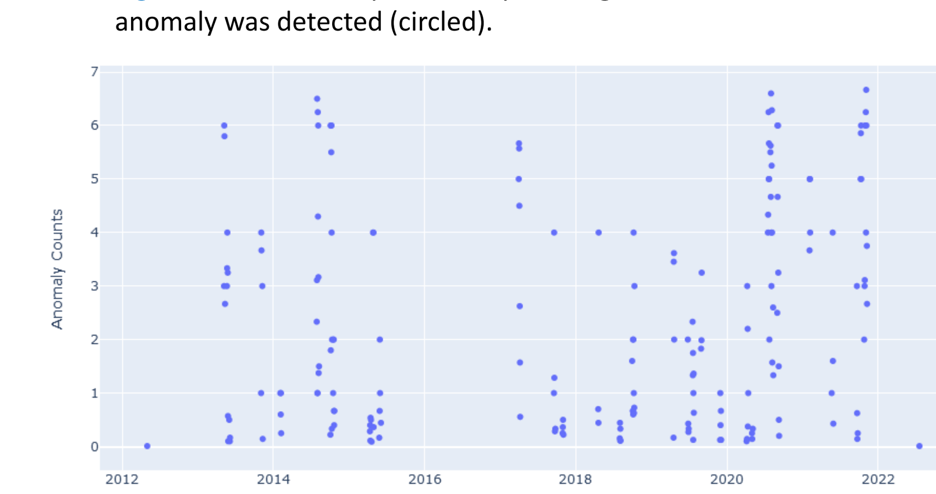

Figure 10: Total anomalies detected with the model plotted against the session datetime.

NEXT STEPS AND FUTURE WORK

Overall, the alert system is viewed as a positive tool even if a couple of false positives are sent a year. This work will be passes onto the NASA SLR Data Operations Center (DOC) beginning next year.

From prototyping, the CDDIS found the following limitations:

- Limits to Model Transferability
  - Models require similar contamination levels
  - There's variation in session availability and hardware components that affect how the model needs to be designed
- Session Availability:
  - In 2022, Herstmonceux had about half of the amount of data Yarragadee tracked for LAGEOS and LARES
  - Unless stations track LAGEOS and LARES daily, it will be difficult to have timely alerts provided
  - Adjustments needed to be made to the model to allow for predictions to be made for Herstmonceux such as lowering the number of required sessions from which a prediction can be made and increasing the percentage of samples used in each base estimator
    - Other attempts such as adding additional satellites and extending the period reviewed, unfortunately, lowered the level of accuracy and increased delays in anomaly detection
- Station Hardware Differences:
  - Stations operating with different repetition rates may find some features more important than others
  - In the future, it may be necessary to group stations by similar hardware components
- When stations experience a change in their system, their tracking may decrease
  - With limited or no data, no predictions can be made

These changes must be investigated before an automated program, which generates models for each station, can be released. For automation, the model weights, durations, and features can be updated based on the percentage of correct detections, setting a maximum for the percentage of false-positive emails that are sent, and comparisons against the site history log where applicable. Additional features that may be useful to apply include RMS50, skew kurtosis, peak-mean, and pressure.

ACKNOWLEDGEMENTS

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REFERENCES

(1) ILRS website: https://ilrs.gsfc.nasa.gov/
(2) ILRS overview of active station plots: https://ilrs.gsfc.nasa.gov/network/stations/active/overview_of_station_plots.html
(3) 2016-2019 ILRS Report: https://ilrs.gsfc.nasa.gov/about/reports/annualrpts/ilrsreport_2016.html