MSL Telecom Ops Automation

Ryan Mukai
Jet Propulsion Laboratory, California Institute of Technology
337 Section Seminar
05/24/2018

Overview

- Introduction and Background
- Overview of MSL Telecom Ops
- Original Daily Process
- Current Automated Process
- Automated anomaly recognition
- Extensions of Automation
- Future Directions

Introduction to MSL Telecom Ops

- Daily Telecom Ops process has the following goals
  - Verify that the spacecraft is communicative
  - Verify the health of Telecom hardware components
  - Verify performance of Telecom subsystem
  - Investigate any signs of hardware problems and improper performance
- Support overall operations
  - Generate performance predicts
  - Evaluate performance versus predicts
  - Evaluate performance and health on a long-term basis

Key Items to Evaluate

- States of Telecom Subsystem
  - Normal execution of CBM windows
  - Normal function of CBM software
- Key Hardware Components
  - Electra Lite Transponder (prime ELT-A – UHF communications)
  - Small Deep Space Transponder (SDST – X-Band)
  - Solid State Power Amplifier (SSPA – X-Band)
  - X-Band Waveguide Transfer Switch
  - UHF Coaxial Transfer Switch
  - X-Band HGA and RLGA
  - UHF antenna

Data Evaluated Every Day

- Telecom Event Records (EVRs)
  - All FATAL EVRs
  - All WARNING_HI and WARNING_LO EVRs involving Telecom subsystem
    - Most warning EVRs are caused by known, harmless idiosyncrasies
- Telecom engineering, housekeeping, and accountability (EH&A) data
- Comm Behavior Manager (CBM) state telemetry
- UHF Data Volumes
- DSN data (MON-0158)

UHF Evaluation

- ELT health
  - ELT temperature channels
  - ELT baseplate temperature
  - ELT RF radiated power when radiating
  - ELT power supply voltage
  - Note: There is no input current channel and there is no power consumption channel for the ELT
  - ELT heartbeat and 1553 bus monitor status
- ELT performance
  - UHF data volume
  - Received signal level (RSL)
  - ADR performance

X-Band Evaluation

- Spacecraft side: SDST
  - Uplink signal power and SNR
  - Uplink receiver static phase error (RX SPE)
  - Power supply voltage, power supply input current, power consumption
  - Output RF power (actually measure SSPA input RF power)
  - Baseplate, voltage controlled oscillator (VCO), and auxiliary oscillator (AUX OSC) temperatures
- Spacecraft side: SSPA
  - Input current
  - Bias voltages (-7 volt line, ALC voltage)
  - AD590 temperature, PRT temperature, baseplate temperature
- DSN side: MON-0158
  - Carrier to noise ratio (dB-Hz), carrier signal power (dBm), system noise temperature (K), Dopper residual (Hz), and symbol SNR (dB) for direct-to-Earth cases

Evaluating States and EVRs

- Check for unexpected spacecraft or CBM state
  - If spacecraft state is SURFACE_STANDBY (safe mode) instead of SURFACE_NOMINAL (normal operations)
  - If CBM state is either SFP_WINDOWS or HAIL_WAKEUP (two types of safe mode) instead of MODE_NORMAL (normal operations)
  - ELT health monitor channels for health status
- EVRs
  - Any FATAL EVR, regardless of subsystem (learn cause of safe mode if we enter safe mode)
  - Any WARNING_HI or WARNING_LO involving Telecom subsystem (i.e. from “cbm”, “uhft”, “sdst”, or other Telecom-related software modules)
  - Idiosyncrasy EVRS
    - Some Telecom warnings can be ignored and are dispositioned as idiosyncrasies

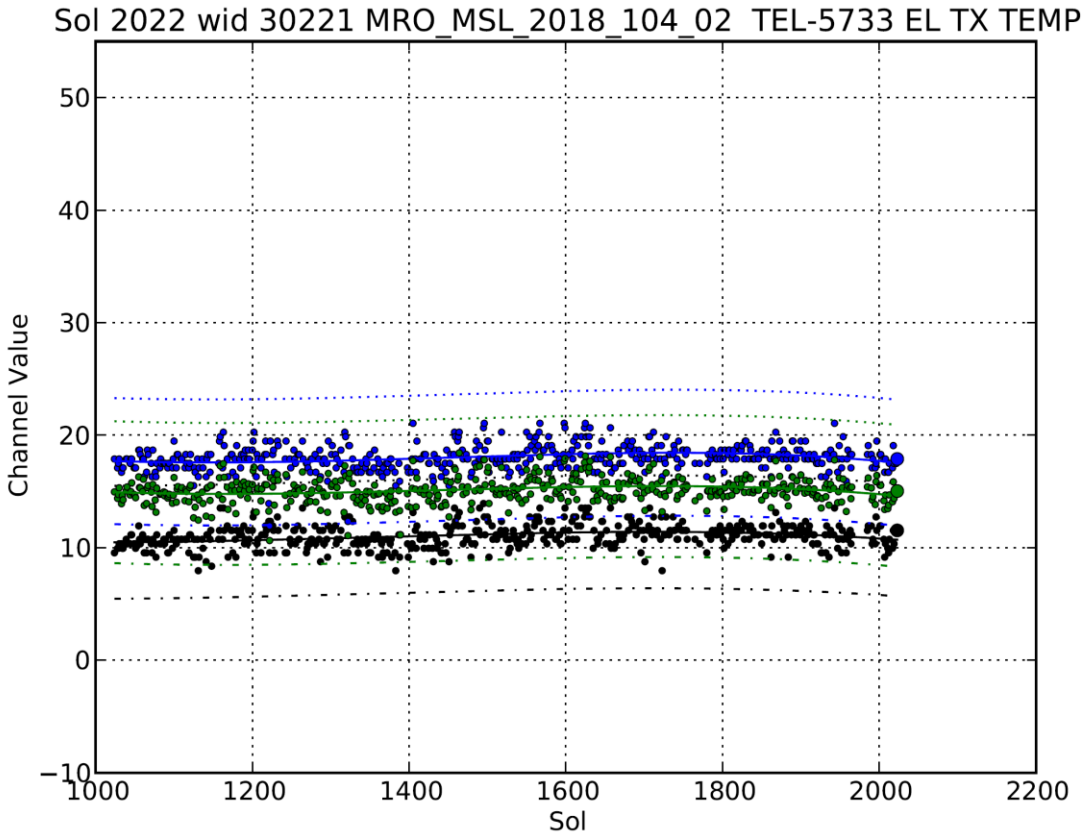
Automation and State Evaluation

- Automated reporting system performs simple checks
  - All unexpected spacecraft/CBM states are flagged for review
  - All FATAL EVRs and all Telecom warnings flagged for review
    - However, we have logic that automatically dispositions WARNING EVRs for:
      - TELECOM-0100: SDST busy bit idiosyncrasy
      - TELECOM-0208: SDST warning and downlink underflow EVRs caused by high CPU load on the rover during parameter operations (does not actually involve SDST or any other Telecom hardware – this is a rover software issue)
      - TELECOM-0213: Lock count overflow EVRs from MTIF when SDST power state changes
    - The idiosyncrasy EVRs are automatically tracked in a database and are regularly trended to look for increases in their frequency
  - Missing UHF relay data – if no data from expected UHF relay pass comes in then trigger a warning

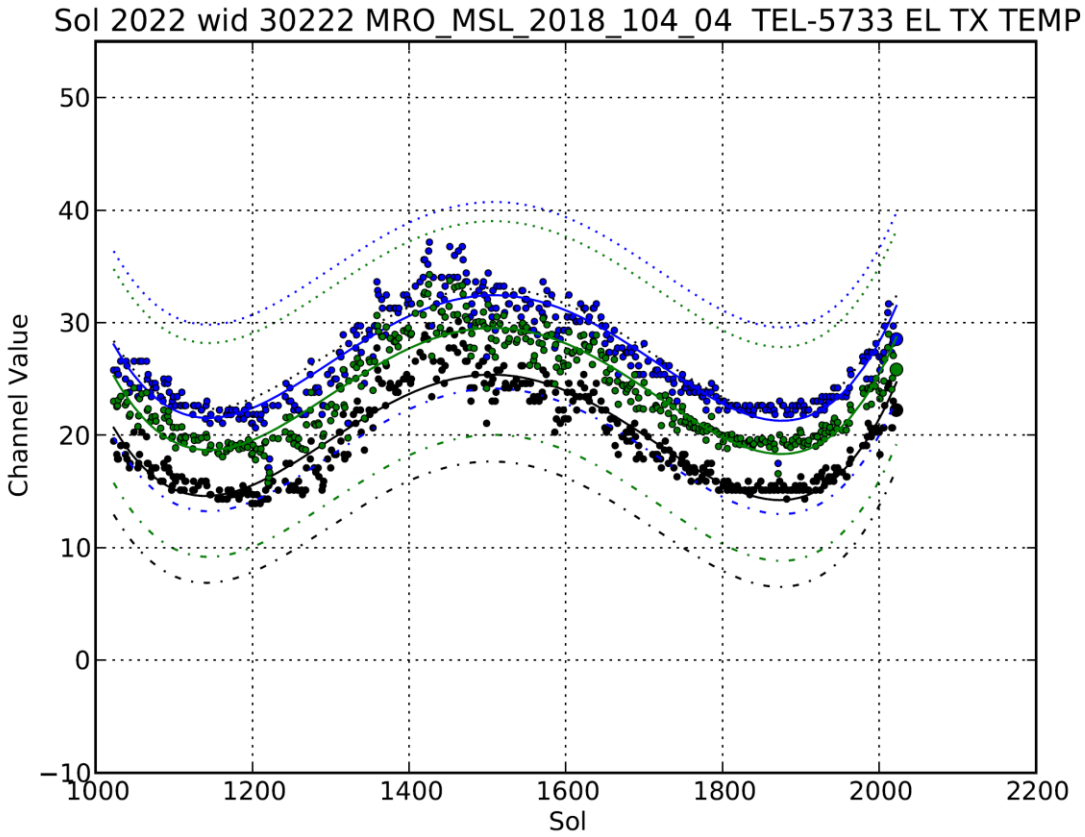
Evaluating EH&A data

- Simple checks for violations of health and safety thresholds
  - Temperatures, voltages, currents, power levels violating safety limits
- Automated trending checks for trend violation
  - Even if a current, voltage, or temperature is well within safety limits, it will be flagged with a notice flag if it is statistically out-of-trend
  - This is intended to allow “soft” anomalies to be brought to Telecom’s attention for review
  - Over each Sol (for UHF, over each window), we trend the minimum, maximum, and mean of each quantity
  - Quantities that are significantly out-of-trend can signify a health issue, even if they are well within safety limits!

Example: MRO morning UHF passes ELT-A Transmitter Temperature



Example: MRO afternoon passes ELT Transmitter Temperature



Evaluating EH&A Data

- Even if the minimum, maximum, and mean are well within statistical trend and well within safety limits, there may still be a problem with EH&A data
  - It is also important to evaluate how an EH&A quantity (i.e. temperature, voltage, etc.) evolves over time
  - This evaluation focuses on the time domain shape of the data
- Evaluating shapes
  - This is not a white noise process – it has a definite time-domain structure
  - Since it is not a white noise process, the “typical shape” can be described

Principal Components Analysis

- Take multiple vectors of time domain data
  - $\{\mathbf{x}_1 \quad \ldots \quad \mathbf{x}_n\}$
- Get mean and autocovariance matrix
  - $\mu = \frac{1}{n}\sum_{k=1}^{n} \mathbf{x}_k$
  - $\Lambda = \frac{1}{n-1}\sum_{k=1}^{n}(\mathbf{x}_k - \mu)(\mathbf{x}_k - \mu)^T$
- Get eigenvalues $\{\lambda_k\}$ and eigenvectors $\{\mathbf{e}_k\}$ of autocovariance matrix
  - Eigenvalues are real-valued and non-negative
  - Obtain them in non-increasing order: $\lambda_1 \geq \lambda_2 \geq \ldots \geq \lambda_n$
  - For an autocovariance matrix, we can always get an orthonormal eigenvector set $\{\mathbf{e}_k\}$ that we use as a basis vector set

Principal Components Analysis

- Given an incoming time vector of EH&A data **x** we can expand it using the eigenvector basis
  - $\mathbf{x} = \frac{1}{n}\sum_{k=1}^{n} c_k \mathbf{e}_k$
  - Important: $\|\mathbf{x}\|^2 = \sum_{k=1}^{n} x_k^2 = \sum_{k=1}^{n} c_k^2$ because this is simply a change of vector basis and expansion on a different set of orthogonal axes in n-dimensional vector space
- Given that $\lambda_1 \geq \lambda_2 \geq \ldots \geq \lambda_n$ we expect most of the energy to be in the early coefficients and much less energy in the later ones
  - For a typical time domain shape:
  - $\frac{\|\mathbf{c}\|^2}{\|\mathbf{x}\|^2} = \frac{\sum_{k=1}^{d} c_k^2}{\sum_{k=1}^{n} c_k^2}$ climbs very rapidly as a function of "d", which is the order of the PCA expansion. It is equal to unity for d = n.
  - But it will climb close to unity for d << n if the shape of the data is "typical"
  - If it is far below a threshold (i.e. 80% or 90%) for a "lower order" d, then too much energy is being projected outside of the "typical" d-dimensional subspace where most energy resides
  - That implies the shape is ABNORMAL

PCA

- Additionally, the d-dimensional vector $\mathbf{c} = \begin{bmatrix} c_1 \\ \vdots \\ c_d \end{bmatrix}$ can be modeled as a vector random process
- For many, but not all, cases, it can be modeled as a Gaussian vector random process with the following probability density function (pdf):
  - $\frac{\exp\left(-\frac{(\mathbf{c}-\mu_c)\Lambda_c^{-1}(\mathbf{c}-\mu_c)^T}{2}\right)}{\sqrt{\det(2\pi\Lambda_c)}}$
  - Here, Λ_c is the covariance matrix for d-dimensional vector $\mathbf{c}$ and μ_c is the mean

Log Likelihood

- The logarithm of the vector Gaussian pdf is:
  - $(\mathbf{c} - \mu_c)\Lambda_c^{-1}(\mathbf{c} - \mu_c)^T$ + C
  - Where constant C results from the logarithm of constant terms in the vector Gaussian pdf
- Log likelihoods that are so low as to be out of range signify that the vector **c** is out-of-family
  - This can be true even if the explained variance fraction $\frac{\|\mathbf{c}\|^2}{\|\mathbf{x}\|^2}$ is within normal range because we may have our energy concentrated in the proper d-dimensional subspace but our expansion vector can be in the wrong part of that subspace
- But in practice, for most EH&A channels, the explained variance fraction catches anomalies – it is unusual to see a good explained variance with vector **c** in the wrong part of the subspace

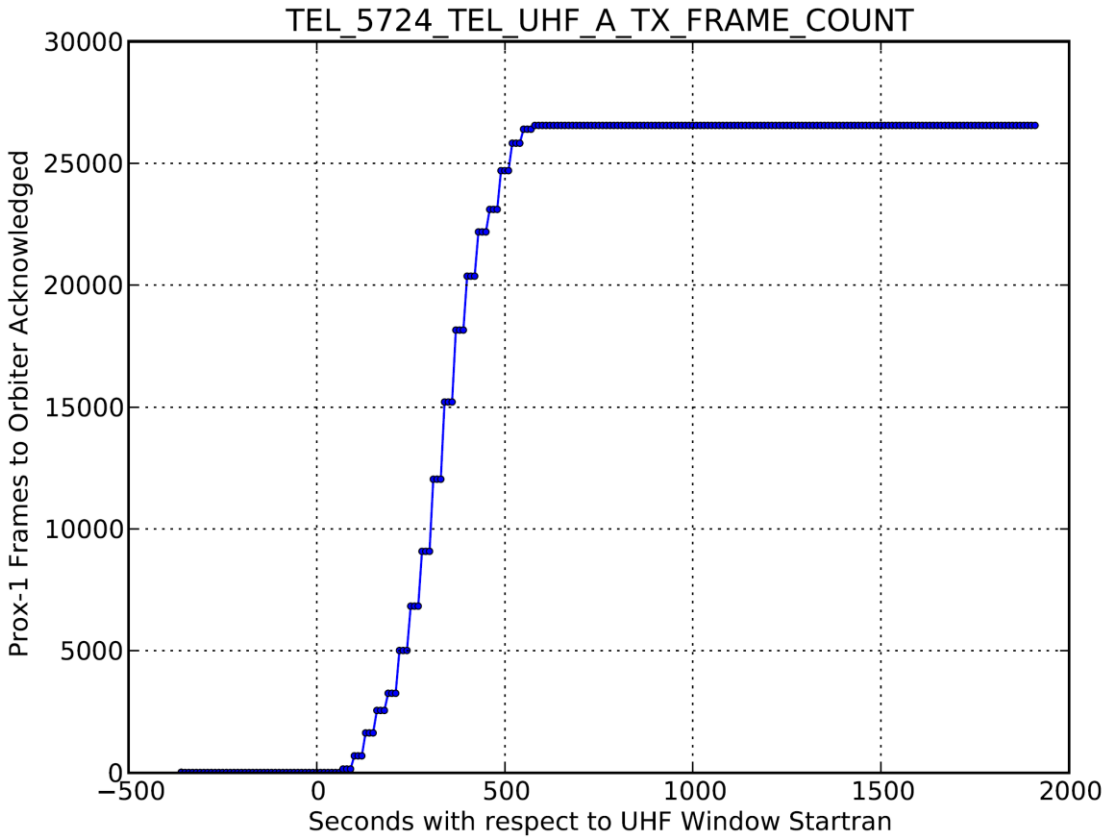
Summary for Shape Analysis

- The PCA check can be used to verify the shape of data as follows:
  - Verify that the data are contained (mostly) within a specified d-dimensional vector space spanned by $\{\boldsymbol{e}_1 \quad \dots \quad \boldsymbol{e}_d\}$
    - This is, in practice, the most critical check since most shape anomalies have the effect of pushing us well outside of the d-dimensional subspace and causing the fraction of explained variance to plummet
  - Verifying that the d-dimensional expansion vector **c** does not have an extremely low log likelihood (i.e. below the 2nd percentile or below an empirical threshold based on previous data)

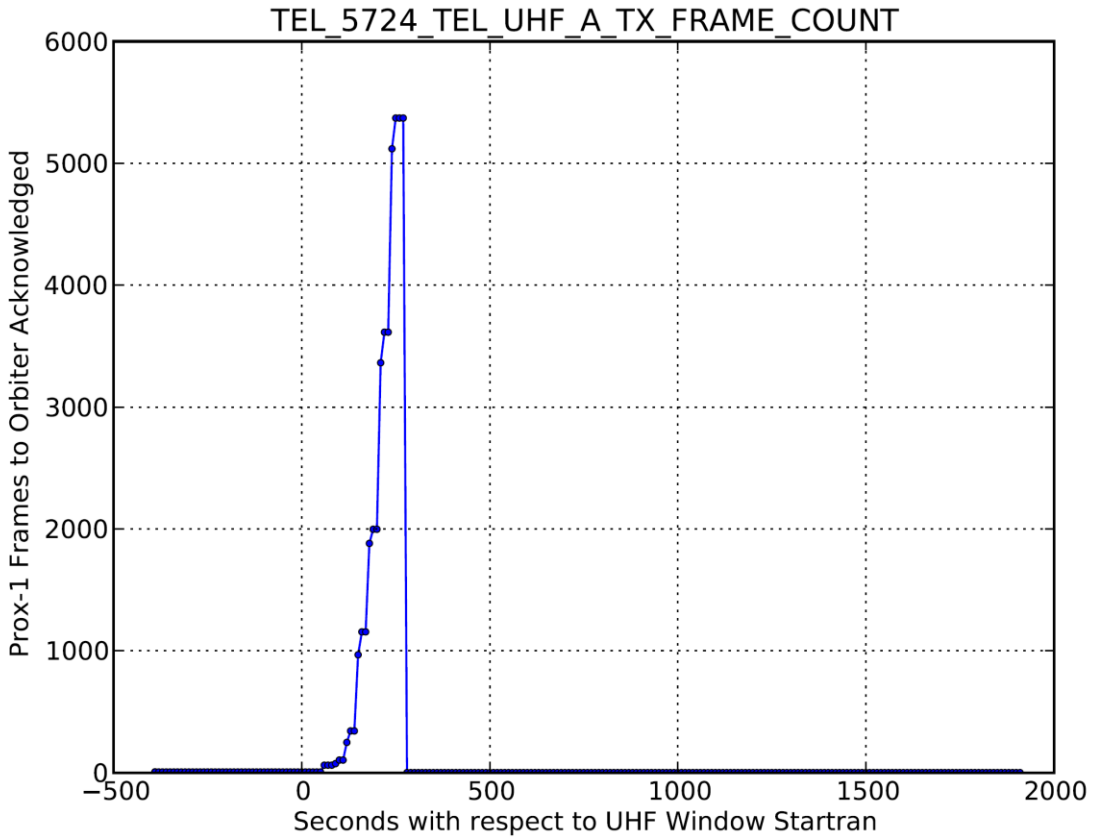
Example 1: Electra Reset Anomaly

- When unexpected ELT-A resets occur, telemetry channels often misbehave.
- TEL-5724: This is a count of the number of acknowledgements received from the orbiter
  - During ELT-A resets, this channel resets to zero, sometimes (but not always) spiking up sharply before resetting.
  - Normally, this has an almost “S” shape (particularly with MRO and ADR), climbing to a peak value and stopping there
  - It should not return to 0 unless radio resets

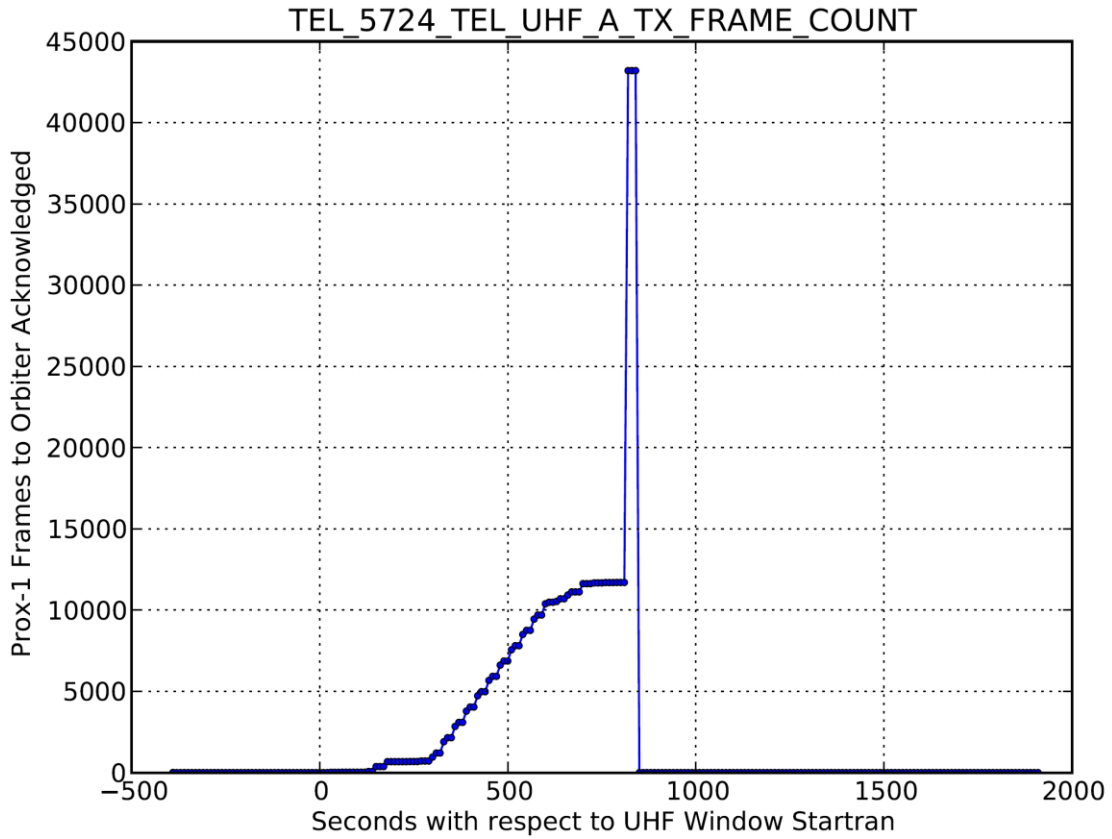
Normal TEL-5724 Time Evolution



TEL-5724 with ELT-A Reset Sol 1673



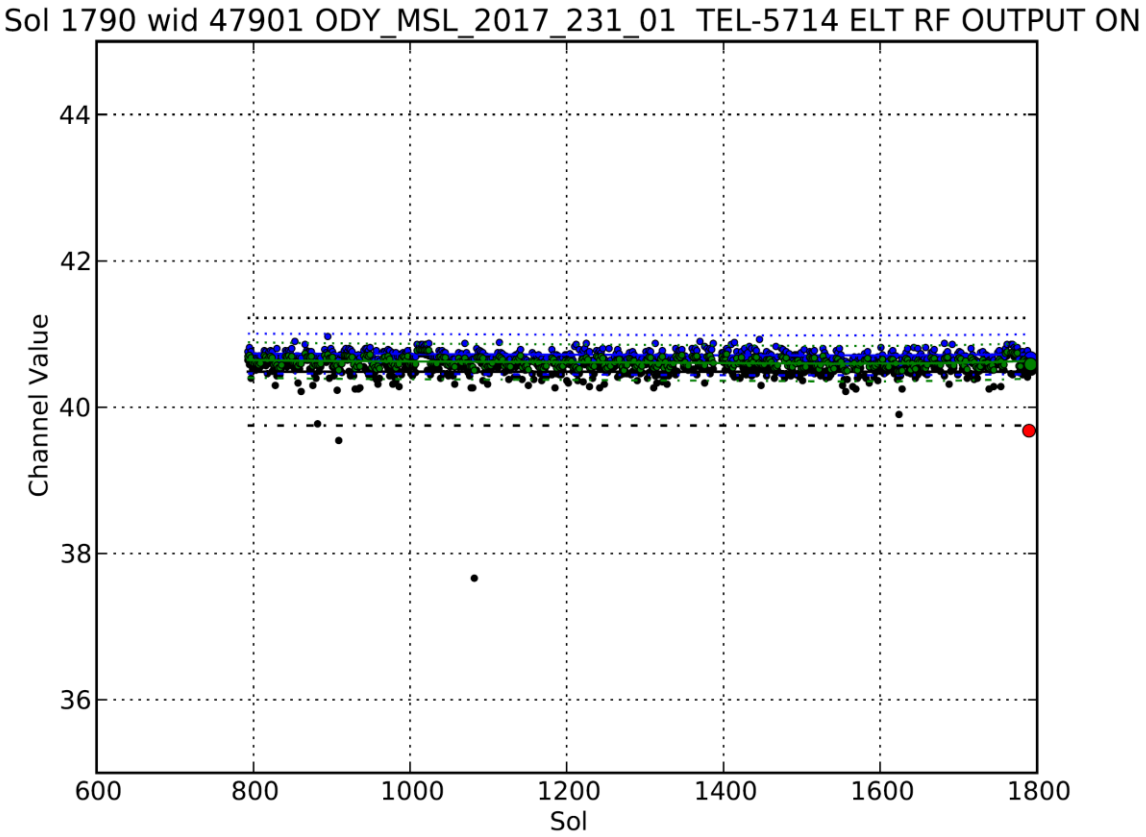
TEL-5724 with ELT-A Reset Sol 1959



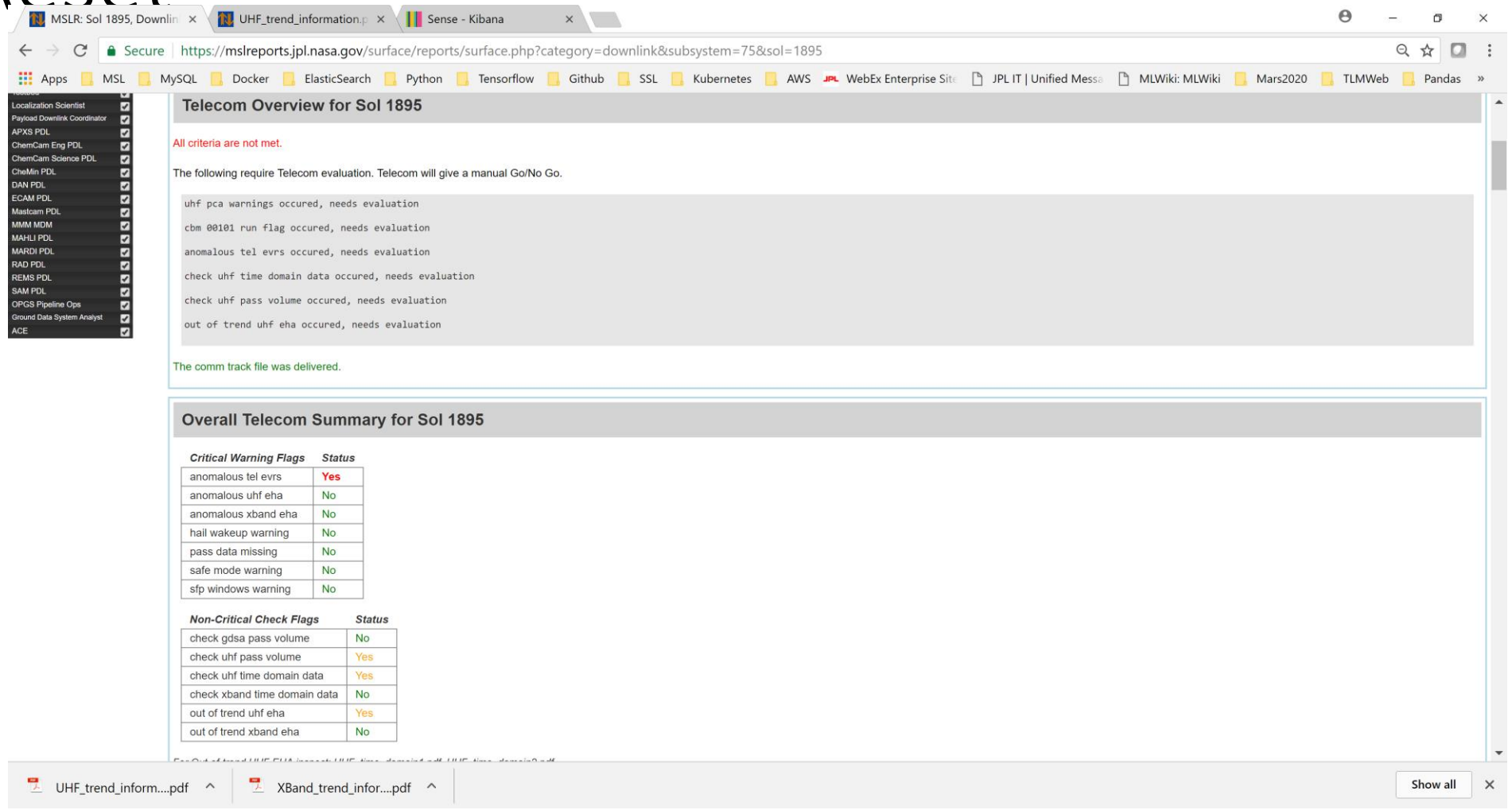
Example 2: Out-of-Trend EH&A

- This is an example of data out-of-trend
  - Out-of-trend minimum ELT-A RF output power in dBm on Sol 1790
  - This turned out to be a minor outlier
  - Even more significant outliers had occurred in the past
  - Automation only scans current Sol for outliers – only current Sol outlier shown in red with historical outliers not highlighted in red
- The average and maximum RF output power for Sol 1790 were well within trend
- As the minimum outlier is not the worst ever and the problem has not repeated again, this is a harmless outlier data point
  - But this does illustrate how the system brings outliers to the user's attention

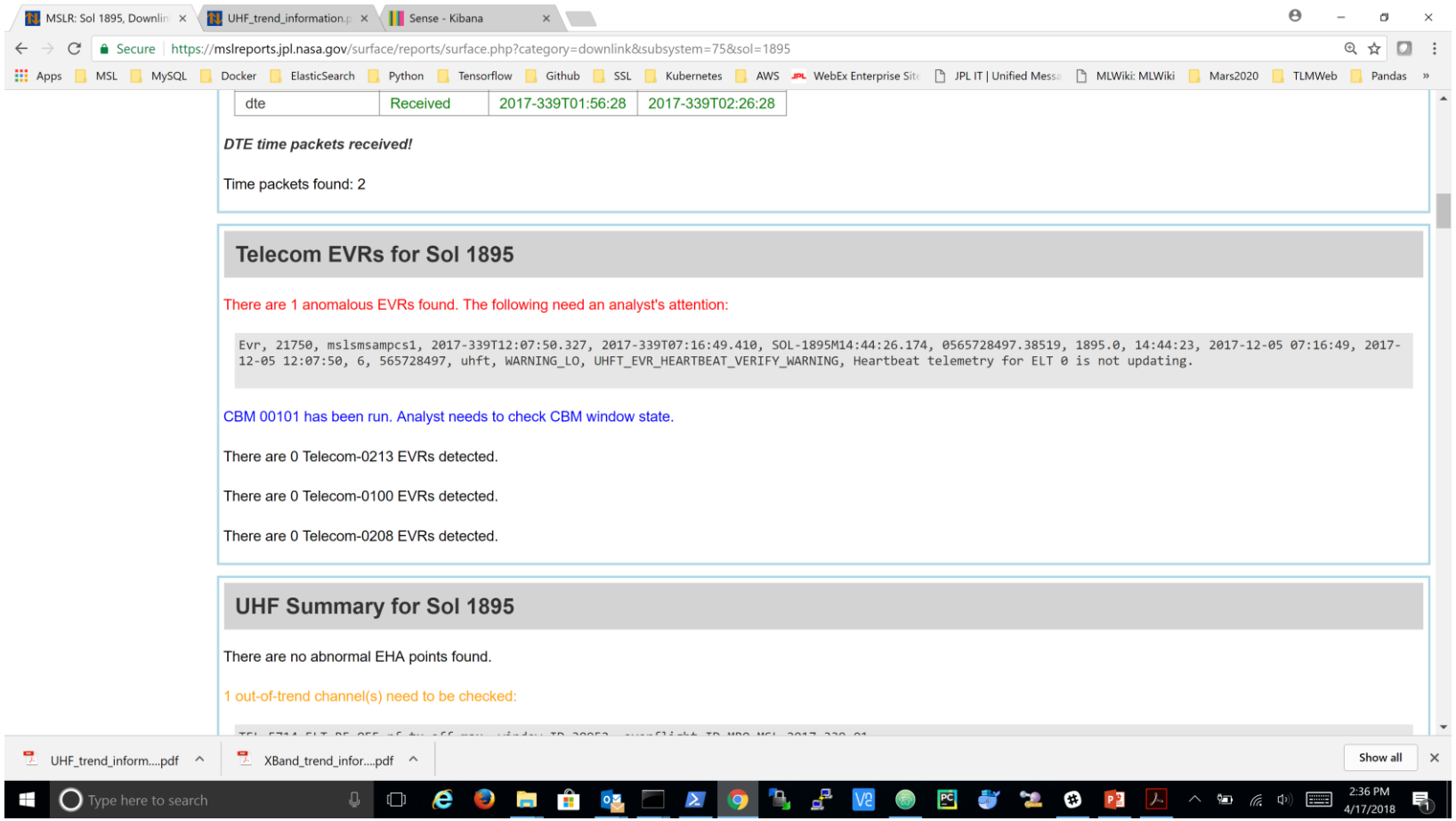
Sol 1790 Minimum RF Output (UHF)



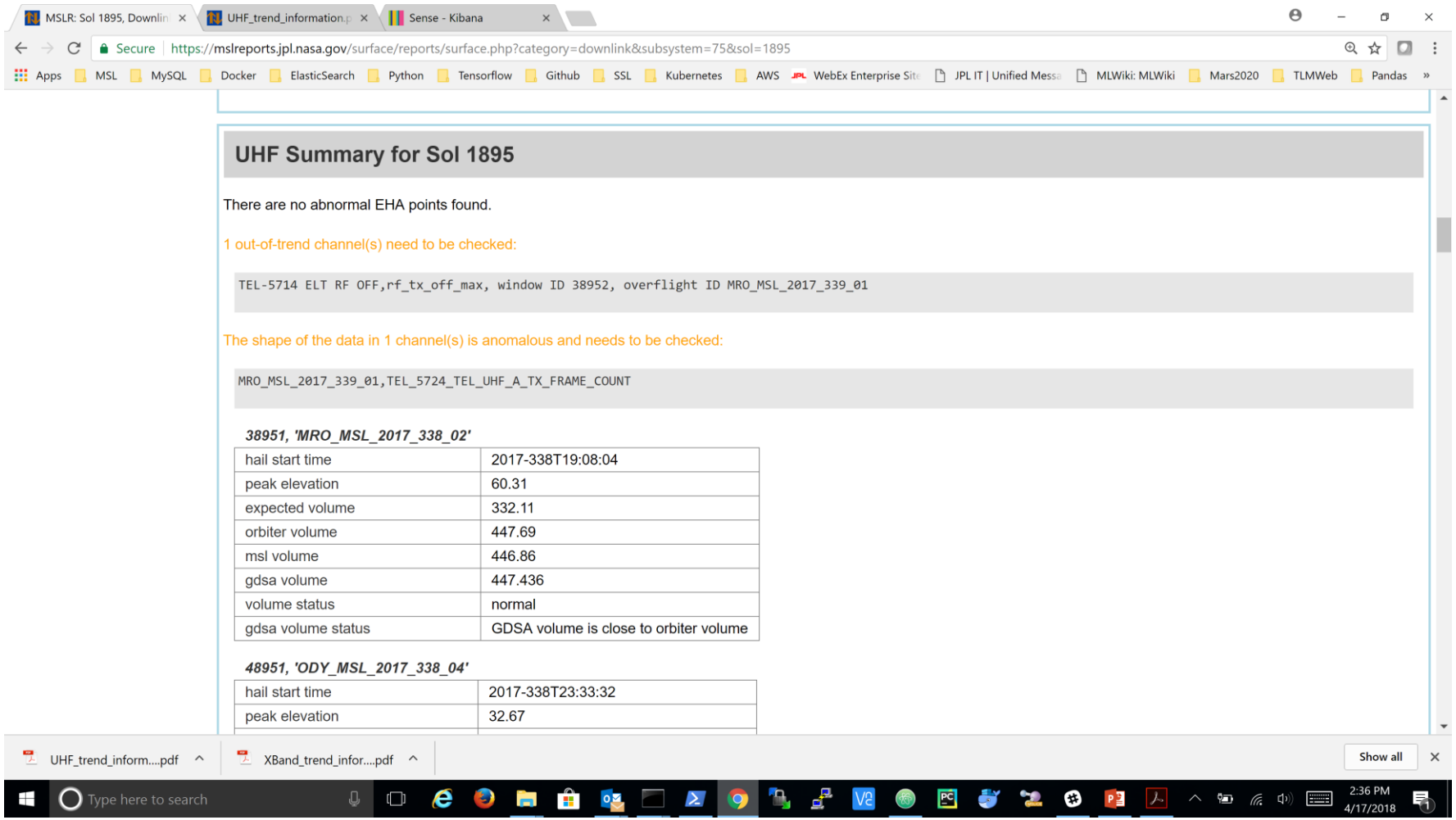
Reporting Example: Sol 1895 UHF Reset



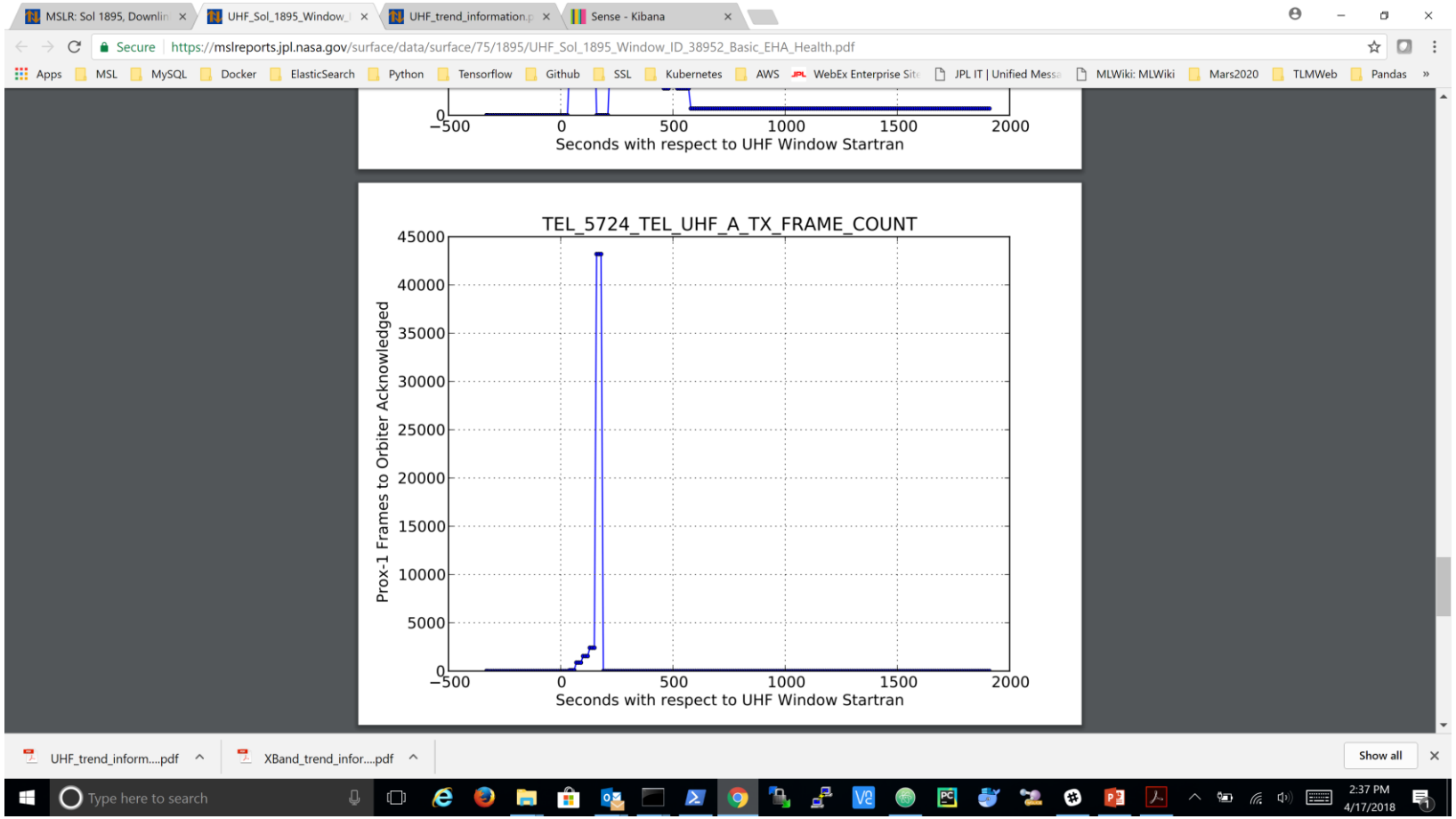
Sol 1895 UHF Reset



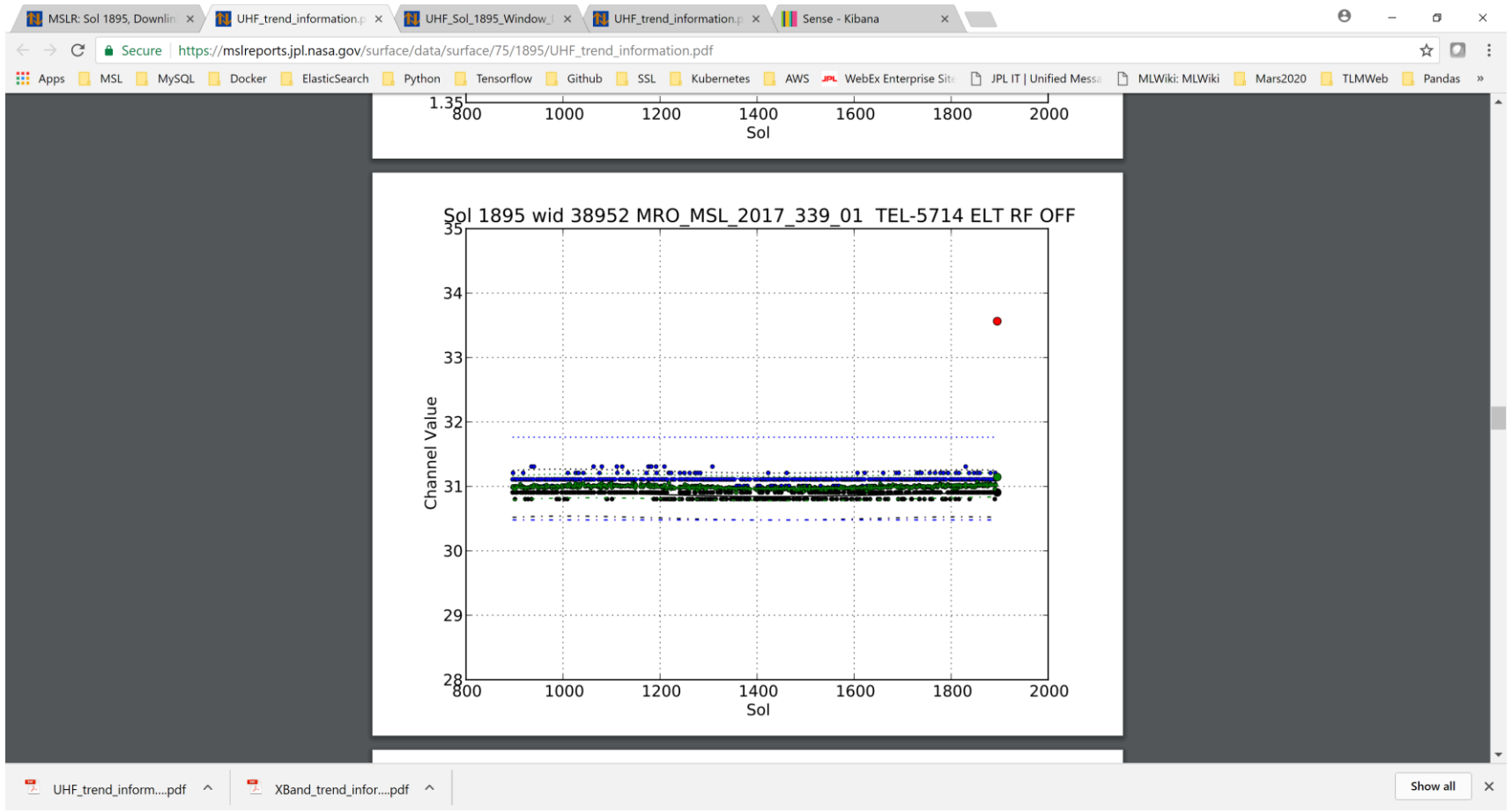
Sol 1895 Continued



Sol 1895 TEL-5724 Shape Anomaly



Sol 1895 Trend Anomaly due to Invalid EH&A



Automation Summary

- Automation enables us to reliably detect anomalous data that often goes unnoticed by humans
  - Humans sometimes fail to notice data that are out-of-trend or that evolve abnormally over time due to the need to assess results from tens of channels in a short period of time
- Workload during a shift reduced from 4-5 hours to just 30 minutes per shift
  - Human operators can focus on unusual data and items requiring their attention
  - Eliminates much repetitive labor and reduces human error
- Data are stored for trending and automatically trended
  - This is a major enabler even for manual analysis by humans as discussed next

Finding Anomalies in Data

- Some anomalies that were present throughout the mission went unnoticed for years under the manual ops process
- Since the automated system gathers and stores data in a MySQL database, it is possible to study these data to identify unusual trends and anomalous patterns
- A key example is the connection between terrain and UHF relay performance

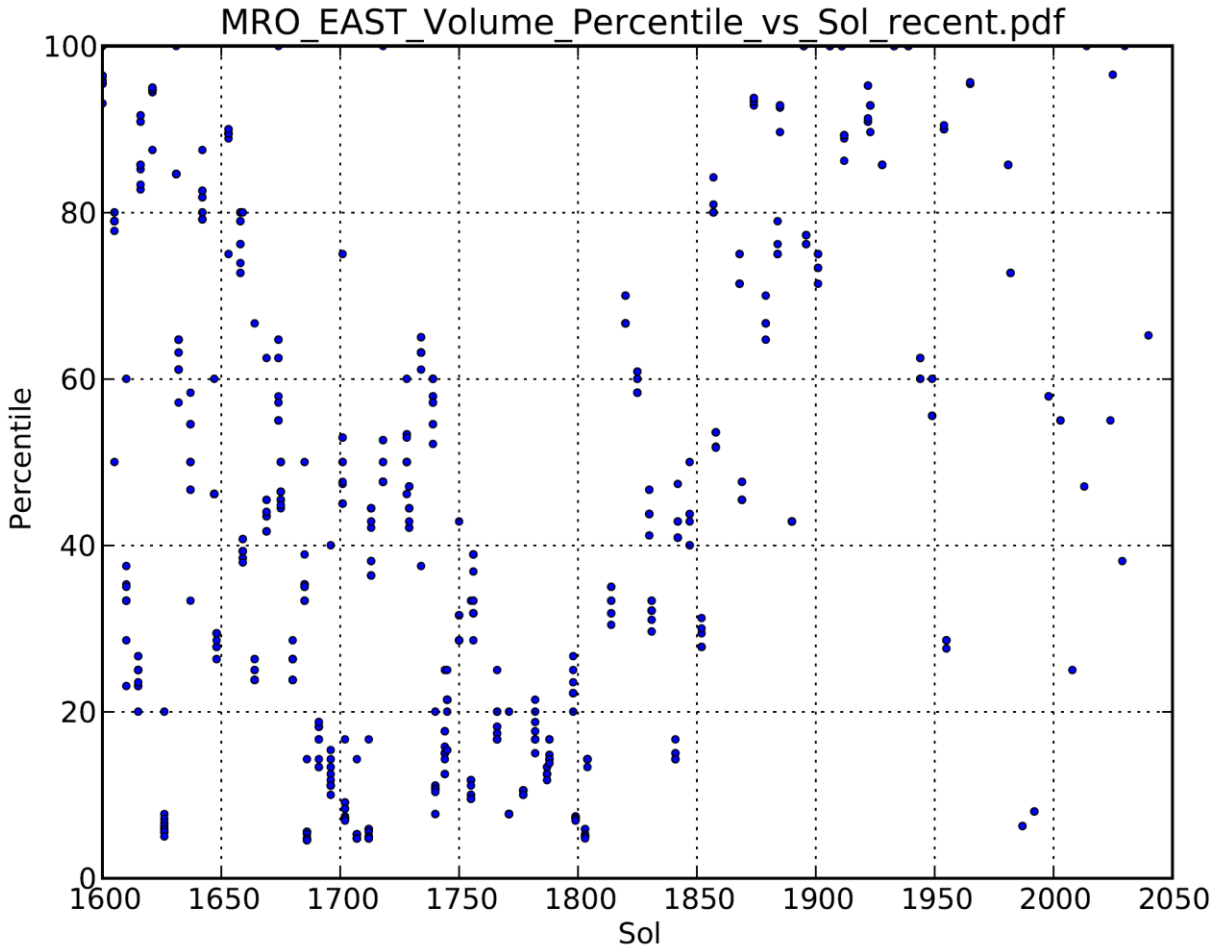
UHF Volume and Terrain

- MRO UHF relay passes exhibit a relationship between return volume and maximum pass elevation
  - High peak elevation occurs at low slant range and in favorable parts of the UHF antenna pattern
  - This leads to higher adaptive data rate (ADR) performance and, thus, higher data volume
- Relay volume thus typical rises with higher peak pass elevation as seen from the rover
- However, relay volumes for peak elevation >= 50 degrees took a significant impact from Sols 1600 to 1800

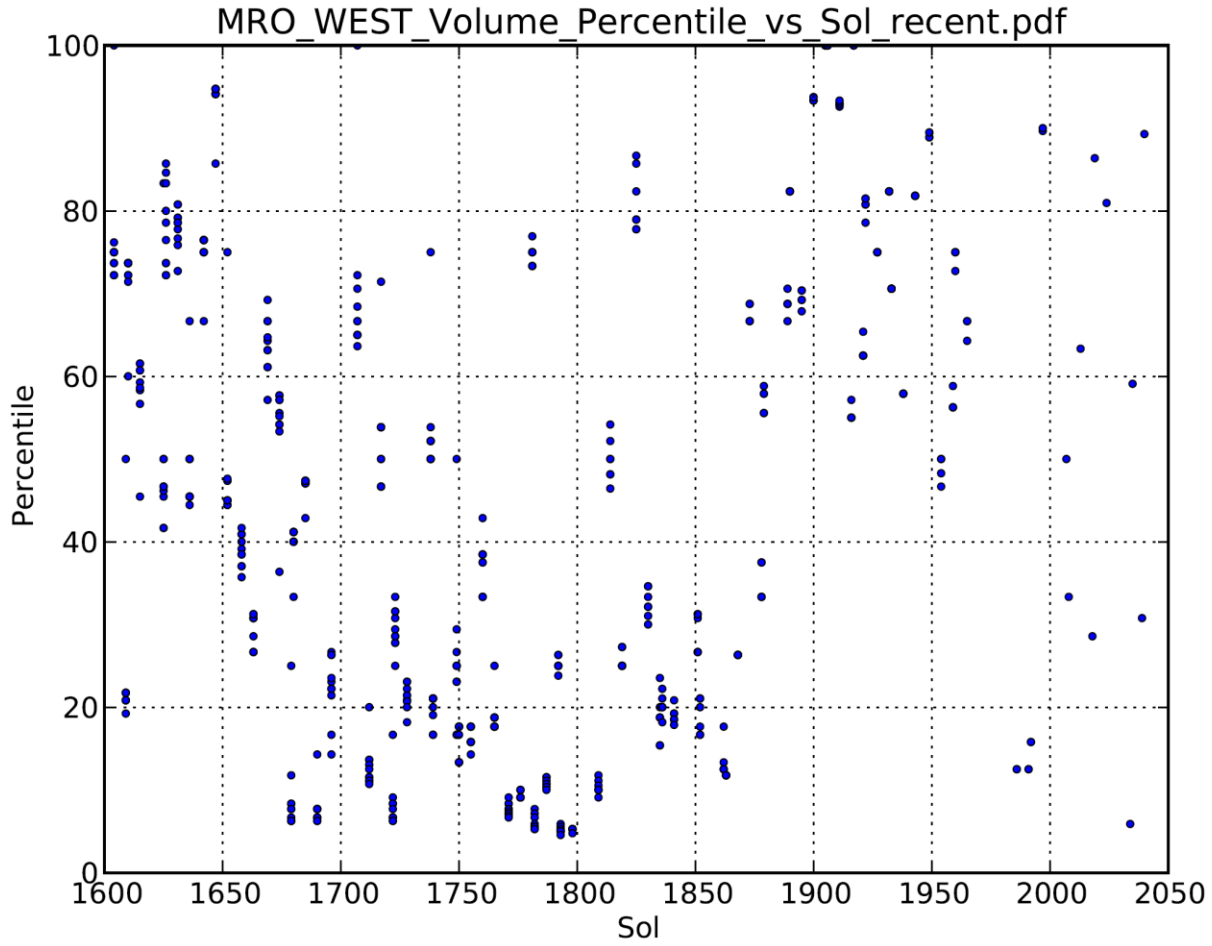
Statistical Performance Decline

- Telecom ranks UHF volume performance using percentiles
  - For a given peak elevation bin and a given pass geometry, passes within the group defined by these geometric parameters can be ranked by percentiles
    - The worst pass would be 0^{th} percentile and the best would be 100^{th}.
  - This permits meaningful comparisons between passes in differing elevation bins.
    - For example, a 300 Mbit pass is very good at a low elevation but is lackluster at a high elevation
- From Sols 1600 to 1800, performance of higher elevation (>= 50 deg peak elevation) passes had been declining severely

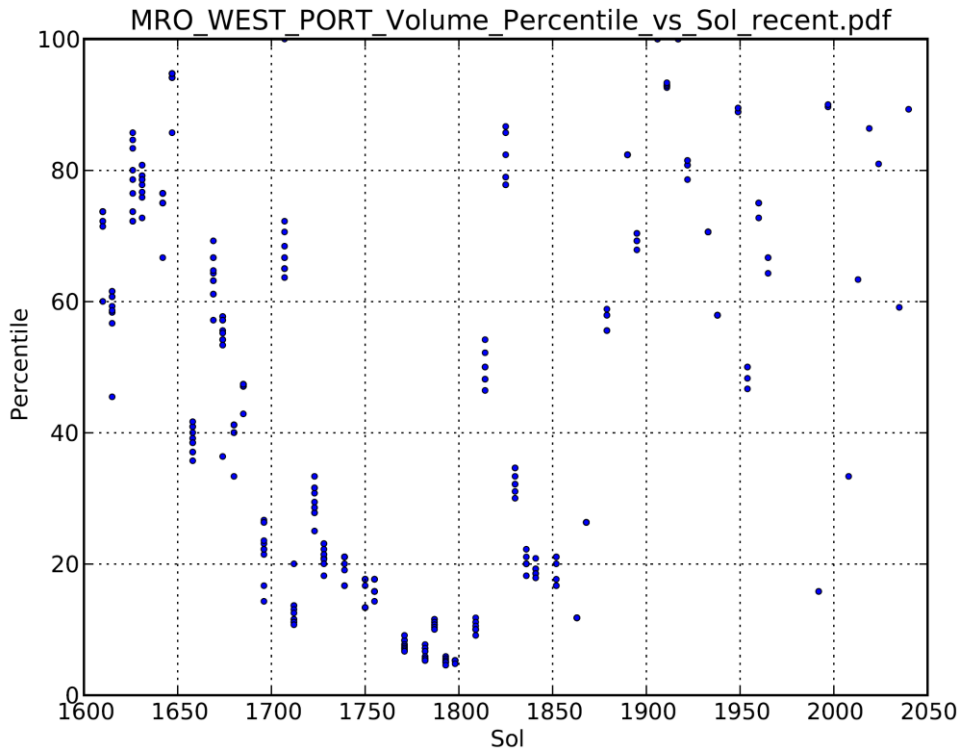
MRO High Elevation Percentile Performance

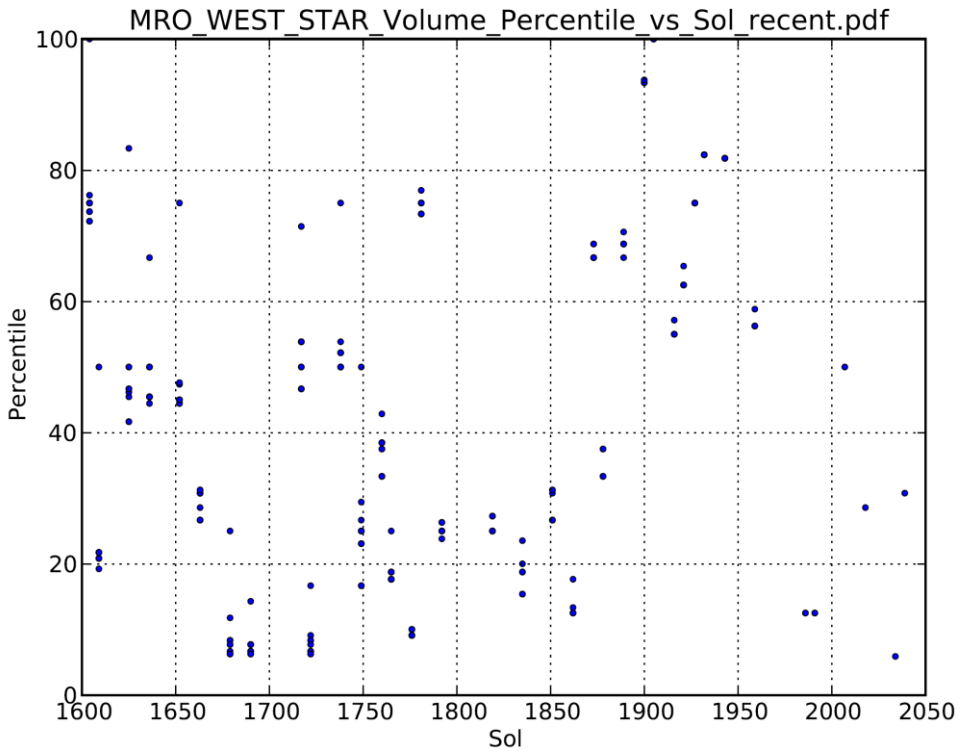


MRO High Elevation Percentile Performance

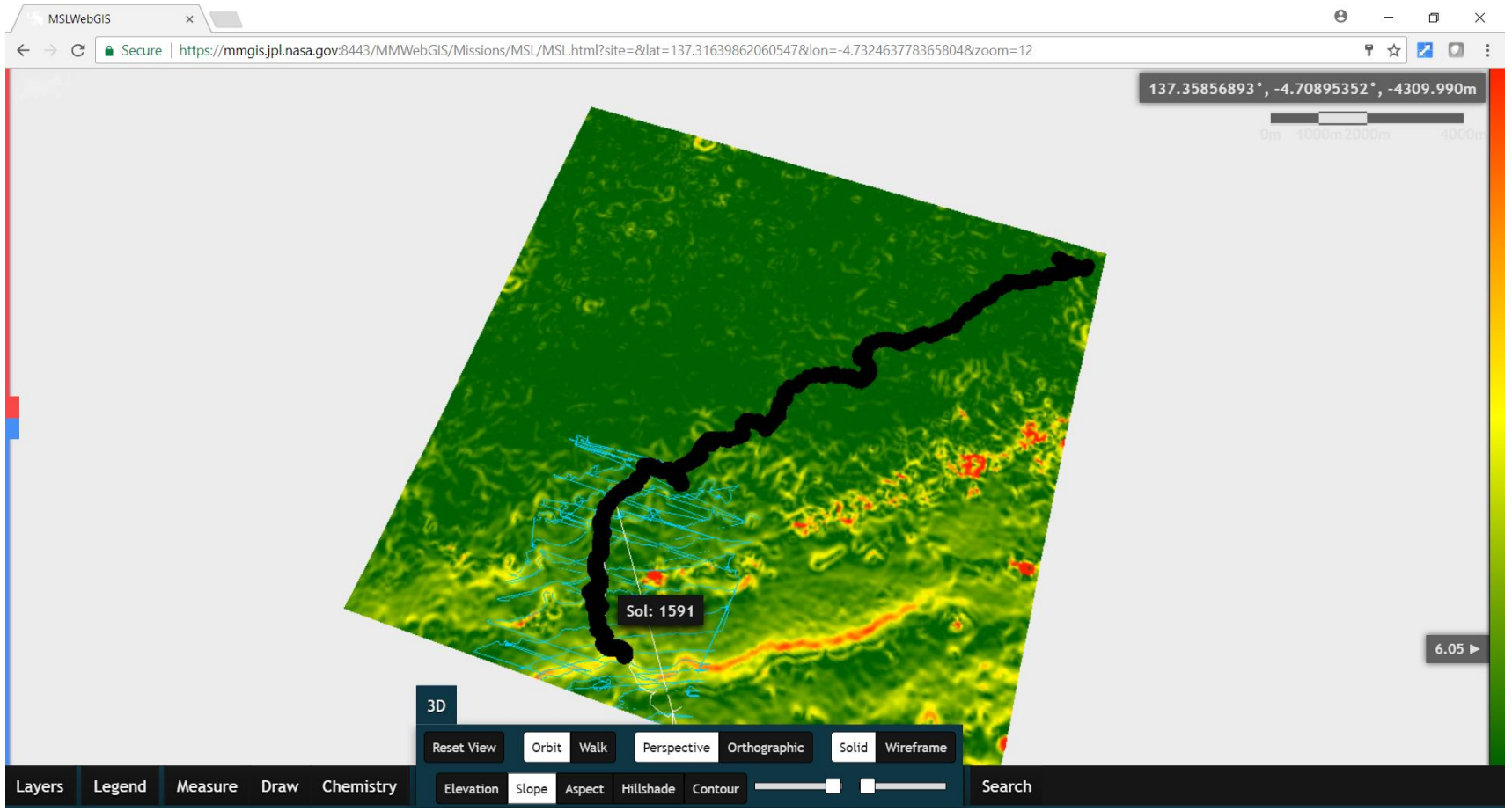


MRO West High Elevation Details

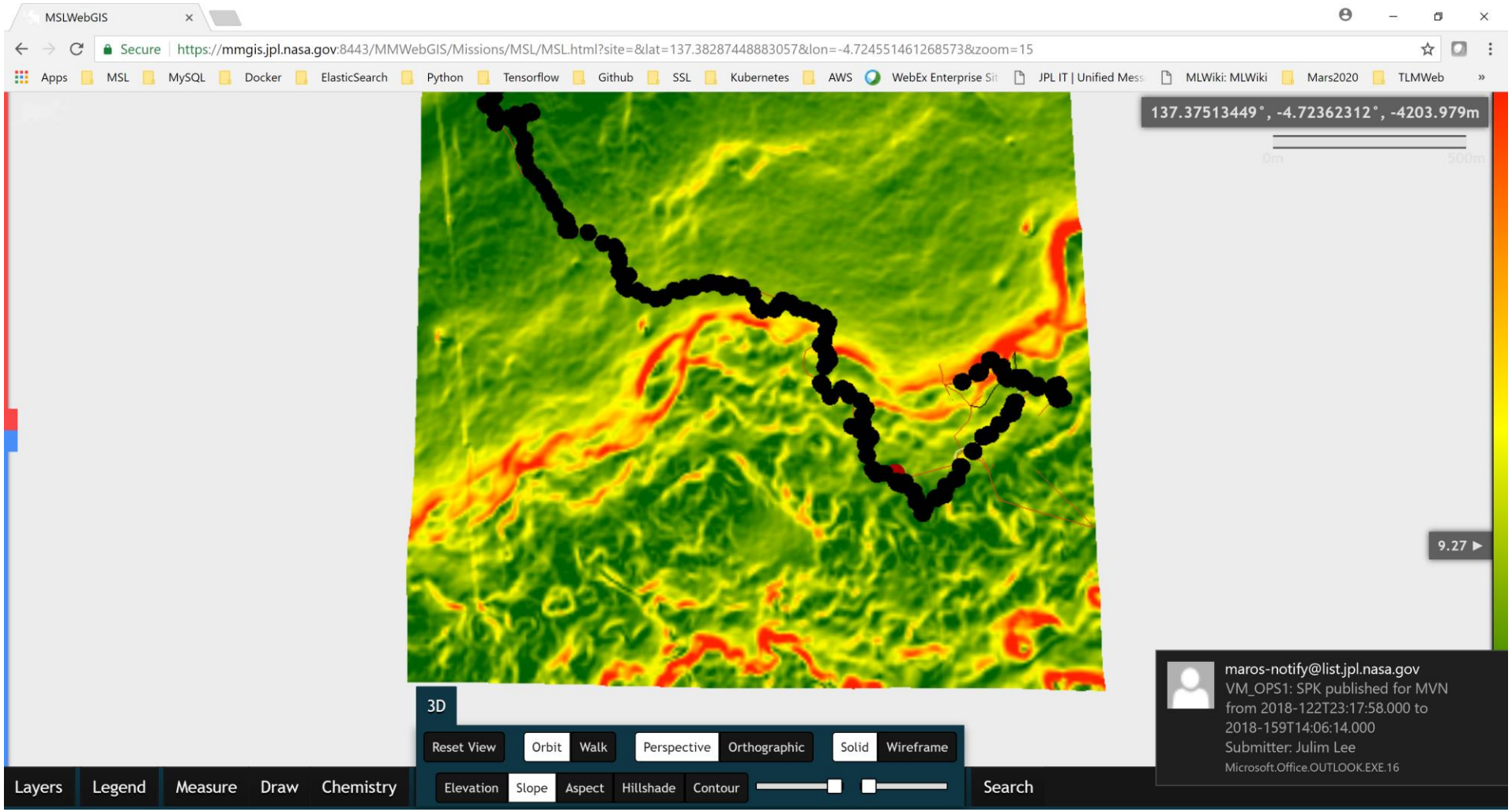




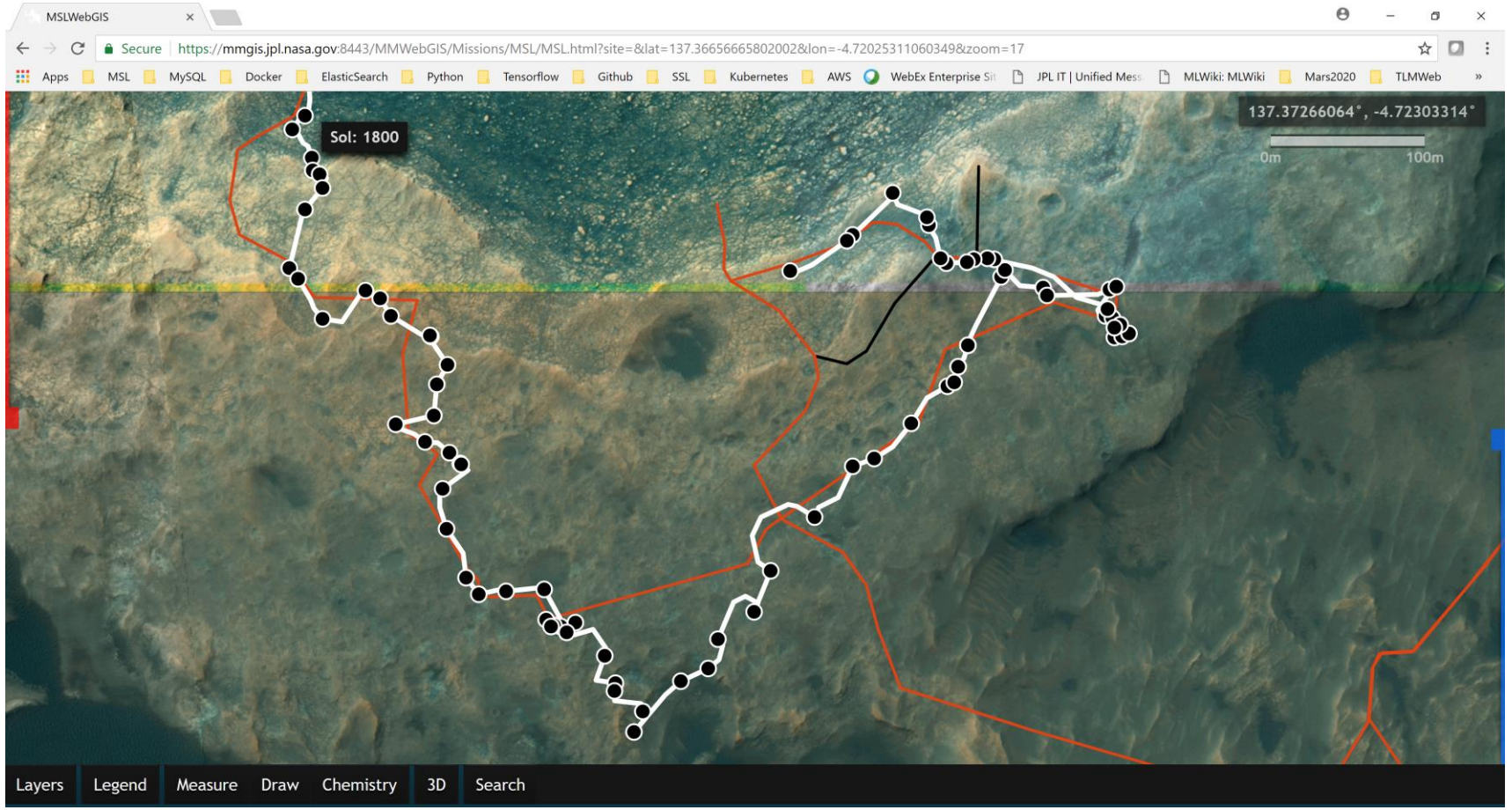
Surface Mission Terrain Overview



Sols 1800 through 2038



Key Locations



Notes on Volume

- Sols 1600 to 1800
  - Approaching Vera Rubin ridge
  - Marked by a steady but severe reduction in UHF return volume performance
- Sols 1800 to 1950
  - On top of Vera Rubin ridge and heading toward the southeast
  - Marked by a steady and substantial climb in performance
  - At the southernmost part of the route, highest elevation on the ridge to date, we reached very high performance percentiles
- Sols 1950 to 2039
  - Drove northeast
  - Marked by a reduction in elevation and a corresponding reduction in data volume performance percentiles

Trending Percentiles and Terrain

- Plots of percentiles, generated using data stored in MySQL, has enabled us to recognize the connection between terrain and performance
  - Even the difference between west port and west starboard passes helps us understand the strong geometric nature of UHF performance
- Combining this with terrain maps has allowed us to understand why we are seeing long-term changes in overall volume performance
- Importantly, this has enabled us to warn the project of likely volume performance issues in the future
  - Coming down from Vera Rubin ridge
  - Heading into the foothills of Mt. Sharp

Future Directions in Algorithms

- There are several key future directions for this work
  - Expansion to analyze multiple channels simultaneously
    - Can be done in the context of existing PCA-based shape anomaly detection
    - Anomalies sometimes involve changes in the correlation between related channels
    - For example, two temperature channels that should follow each other closely may suddenly become uncorrelated – this would signify a issue requiring human review and possible intervention
  - Alternate methods of discovering anomalies in data shape
    - Autoencoder neural networks are a highly promising direction
    - Dictionary learning is another possible direction
  - Improvements to existing PCA shape detection
    - Certain cases call for mixture Gaussian to model PCA expansion coefficients

Future Directions in Applications

- Presently exploring possible applications to test data
- Human test conductors routinely look for out-of-range EH&A data (i.e. temperatures, voltages, pressures)
- Tests carried out under similar conditions can also be grouped into families of related tests
- Statistical analysis of families can yield typical equipment operating patterns
  - Deviations from typical patterns should be flagged for additional human scrutiny

Summary

- In tests and in the real world, Telecom automation enables
  - Reliable detection of anomalous conditions
    - Reliably catches issues that human console personnel have often missed
  - Automated trending and analysis of data
    - Reduces console workload from 4-5 hours per day to about 30 minutes per day
    - Writes much of the report for the operator – operator reviews anomalous data and adds comments to report
  - Automated detection of out-of-trend data
    - Deviations of minimum, maximum, and mean are detected and flagged even when data are within the official safety limits if they are out-of-family
  - Automated detection of unusual time-domain data

Acknowledgements

- We thank Dr. Mazen Shihabi for inviting us to present this work and Dr. Zaid Towfic for his ideas about future multi-channel analysis and other methods of identifying shape anomalies.
- The MSL project is gratefully acknowledged for its support of automation development efforts