National Aeronautics and Space Administration

Battery Health Quantification for TDRS Spacecraft by Using Signature Discriminability Measurement

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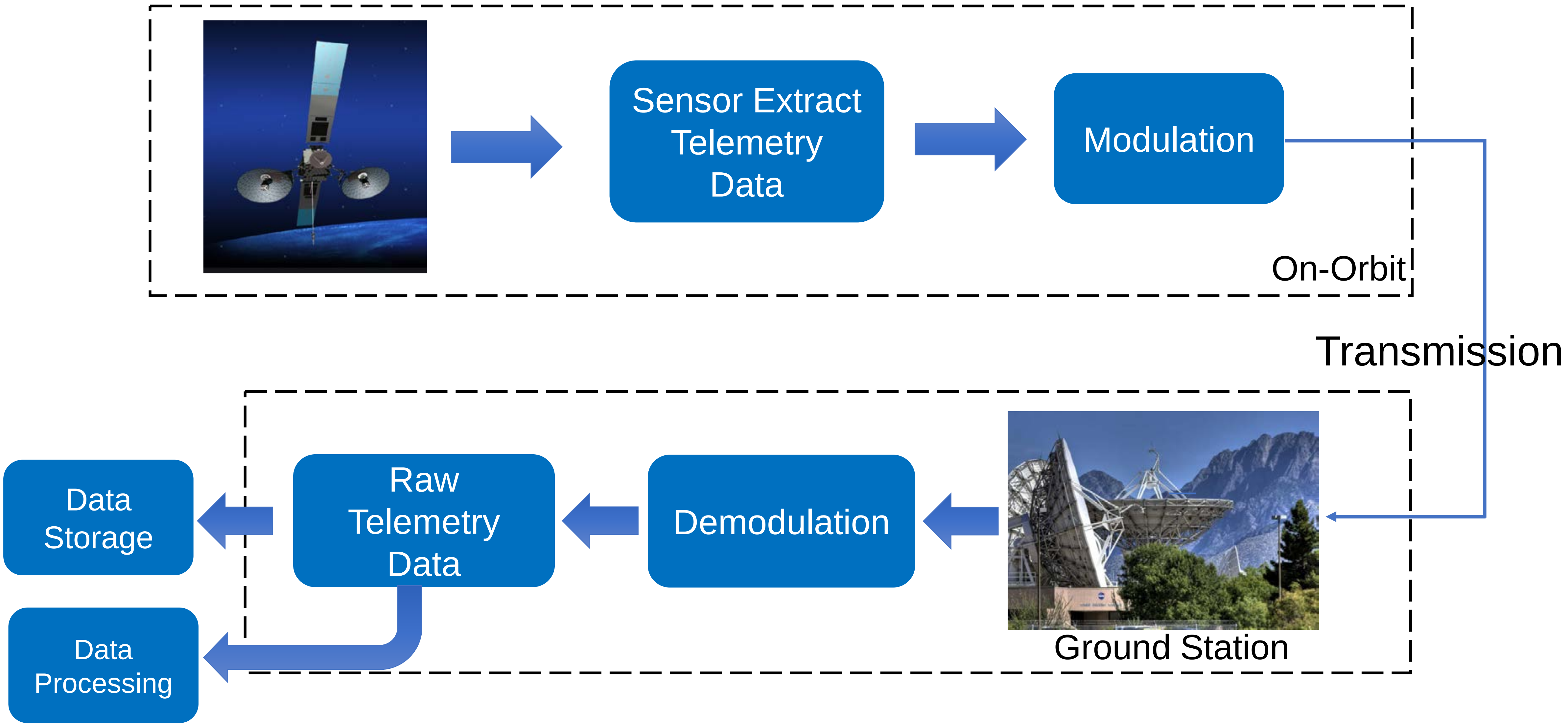
Exploration & SPACE Communications

More than you ever imagined...

Introduction: Tracking and Data Relay Satellites (TDRS)

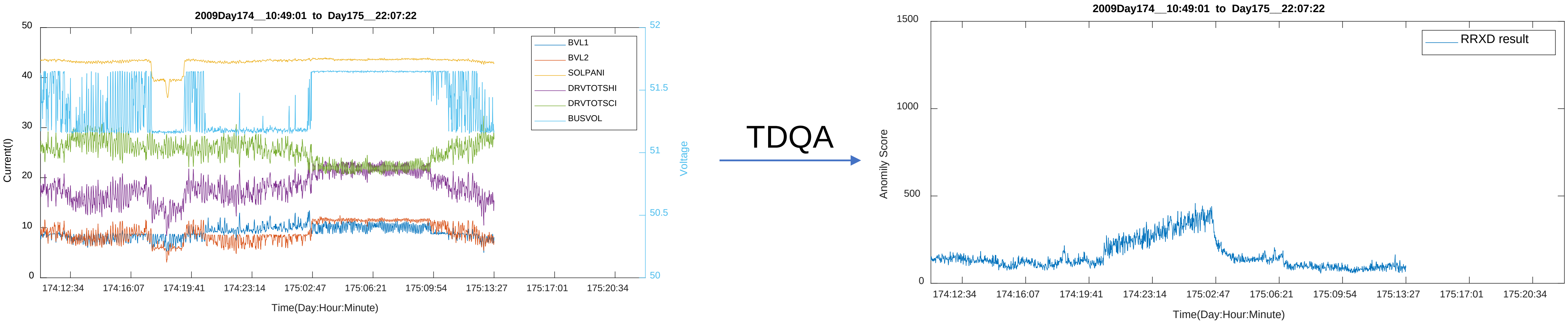
- NASA's Goddard Space Flight Center (GSFC) operates a constellation of ten active geosynchronous Tracking and Data Relay Satellites (TDRS). The primary mission of TDRS constellation is to provide relay communications from low-Earth orbiting spacecraft to the primary ground stations.
- The Space Network project office at GSFC has managed the constellation of spacecraft over the past 30 years.
- This paper presents a new concept of battery analysis called telemetry quality quantification (TQQ) and discusses the progress that has been made in battery performance estimation for the second-generation TDRS spacecraft.
- This activity is important because many of the TDRS fleet of spacecraft have exceeded their on-orbit design lifetime and, therefore, NASA must carefully manage the spacecraft to continue operations while avoiding an end-of-mission scenario that leaves a non-functioning spacecraft in geosynchronous orbit.

Tracking and Data Relay Satellites (TDRS)



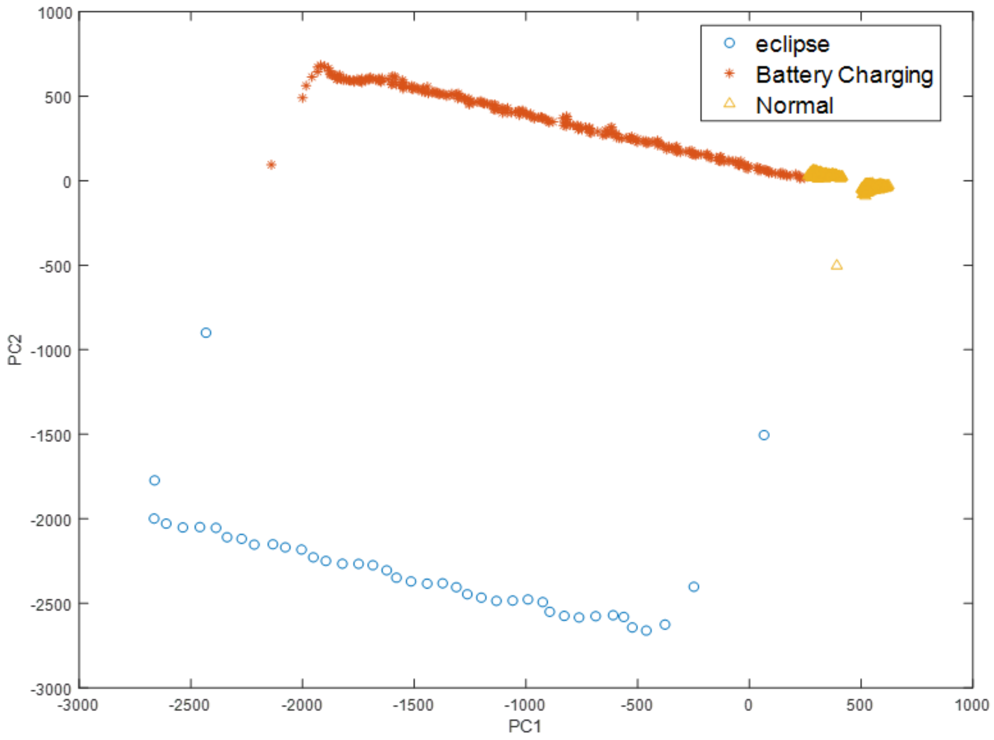
Telemetry Data Quantification Analysis (TDQA)

- TDQA is quite different from traditional analysis currently being used, such as expert model and limit checking.
- TDQA makes use of hundreds of different telemetry parameters to characterize spacecraft's health situation and function of behavior by using quantification algorithm.
- It provides many advantages and benefits that current analysis method cannot. Such as, fast, easy to implement and real time processing.



Application in TDQA

- Application in TDQA
  - Subsystem anomalies detection
  - Spacecraft behavior classification
  - Subsystem anomalies quantification
  - Battery quality quantification
- Advantage of TDQA
  - Fast analyzing
  - Soft decision rather than hard decision
  - Real time processing

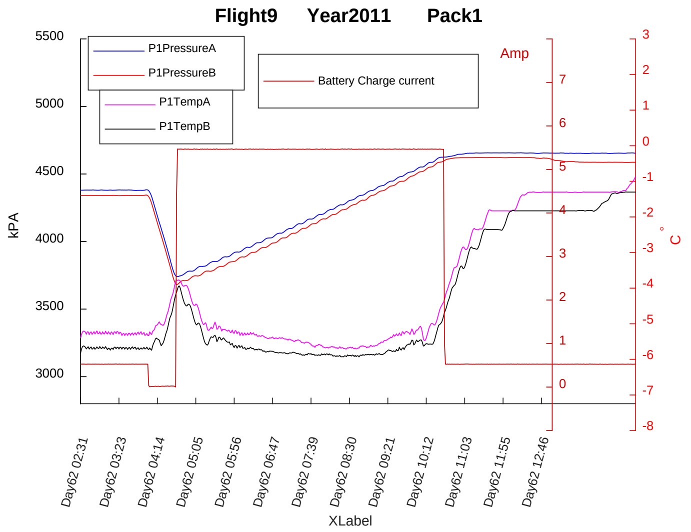


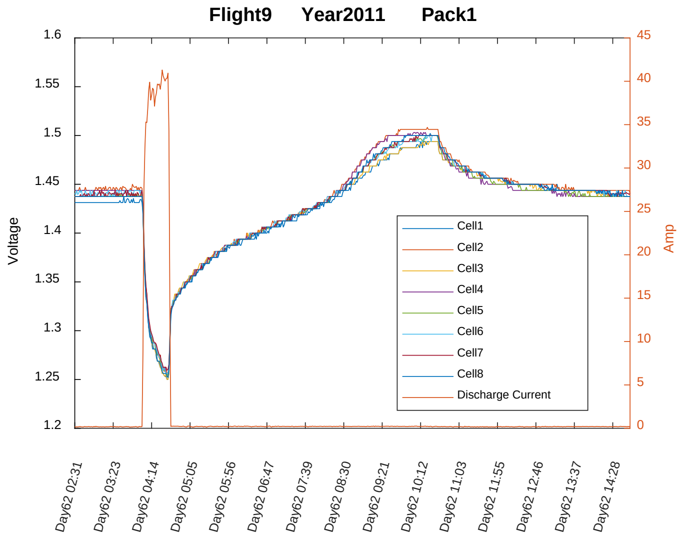
Battery Performance evaluation and discriminability measurement (1)

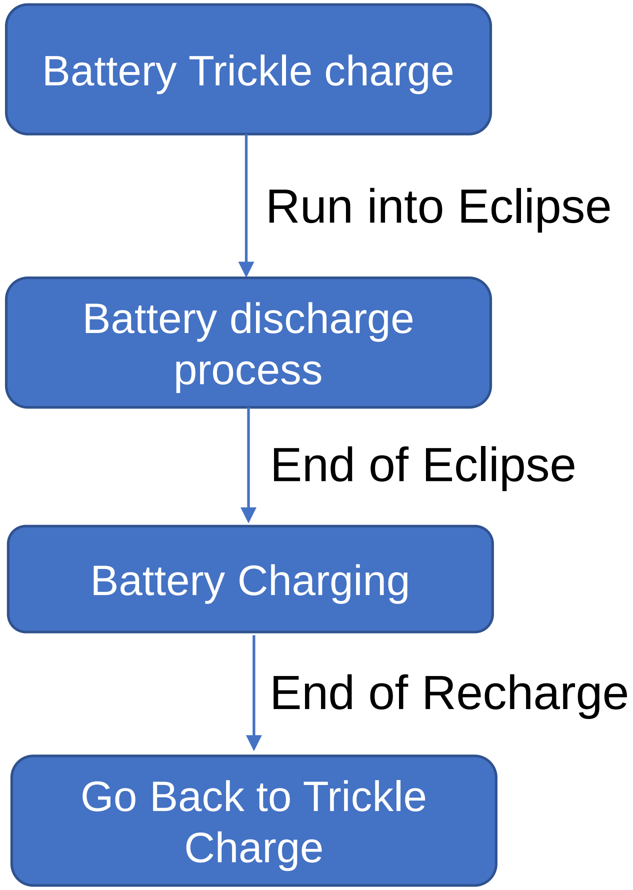
- The second generation of TDRS spacecraft contain a single nickel hydrogen battery consisting of four battery packs with a total of 29 cells with 110 Amp-hour (Ah) total capacity per spacecraft and provide power to the spacecraft during each eclipse and for contingency support.
- In recent years, several battery cells have exhibited divergence indicating cell capacity loss, which can affect the long-term spacecraft reliability.
- The NASA has a great deal of experience with battery reconditioning on the 1st gen satellites NiCad batteries. That design was 3 for 2 redundant allowing one battery to be reconditioned while the other two were available to support the bus.

Example of TDRS Battery during eclipse condition

- Nickel hydrogen battery provide reliable discharge processes during each eclipse season to TDRS spacecraft.
- Battery during discharge and recharge process provide considerable information in regrading to battery performance and remaining cell capacity.
- The analysis of battery performance should be executed by using the telemetry data that battery running discharge or recharge rather than trickle charge.

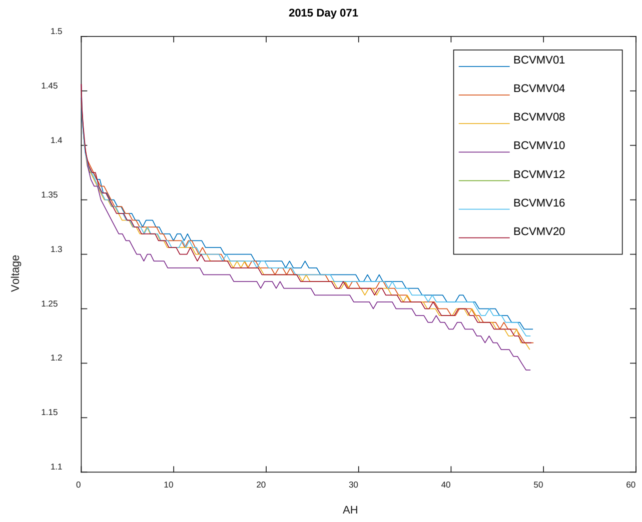


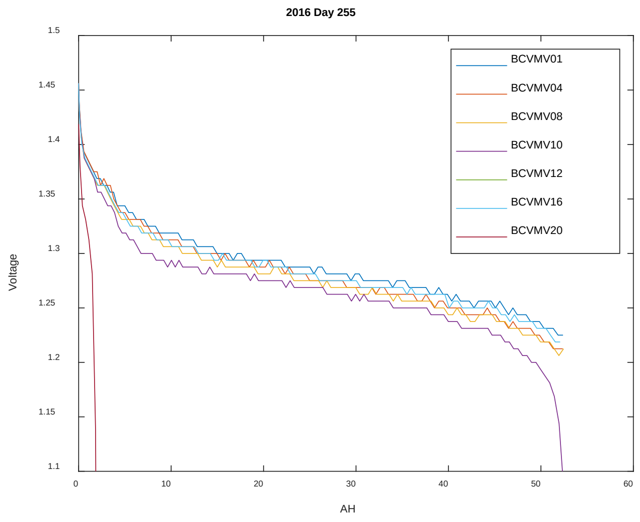


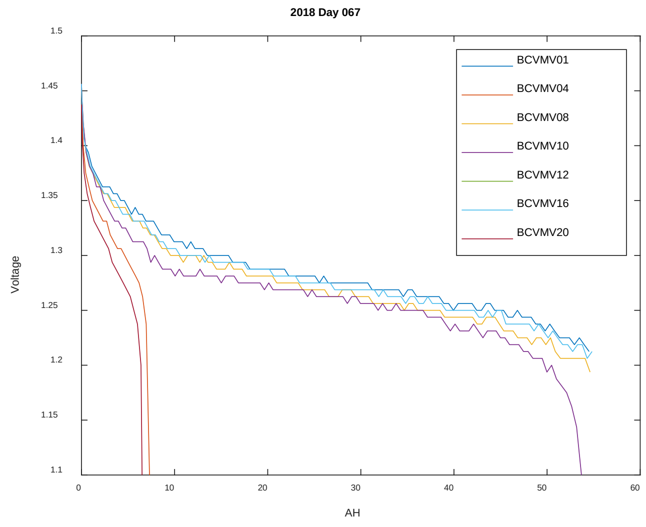


Battery Performance evaluation and discriminability measurement (2)

- One critical issue of TDRS batteries is the challenge of battery cell capacity estimation when the spacecraft is operating on orbit. Since the batteries never fully discharge in each eclipse condition, telemetry can only observed a partial V/Ah curve. Consequently, the current quality of the battery cells is hard to predict until the failure of a cell appears.







Signature Discriminability Measurement (SDM)

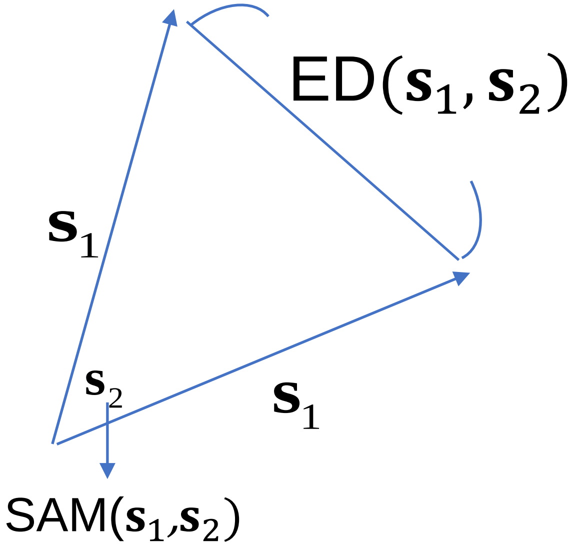
- SDM is primarily based on measuring the divergence between two input signals. This can be significantly useful to compute discriminability between health subsystem signal and failed substance signal.
- Euclidean Distance (ED):

$$\mathbf{s}_1 = (s_{11}, s_{12}, \ldots, s_{1L})^{\mathbf{T}} \qquad \mathbf{s}_2 = (s_{21}, s_{22}, \ldots, s_{2L})^{\mathbf{T}}$$

$$\mathrm{ED}(\mathbf{s}_1, \mathbf{s}_2) = \left\| \mathbf{s}_1 - \mathbf{s}_2 \right\|_2 = \sqrt{\sum_{l=1}^{L} (s_{1l} - s_{2l})^2}$$

- Signature Angle Mapper (SAM):

$$\mathrm{SAM}(\mathbf{s}_1,\mathbf{s}_2)=\cos^{-1}\left(\frac{\langle \mathbf{s}_1, \mathbf{s}_2 \rangle}{\|\mathbf{s}_1\|\|\mathbf{s}_2\|}\right)$$



Geometric illustration for SAM and ED

Signature Discriminability Measurement (SDM)

- Signature Information Divergence (SID) method using relative entropy in information theory to compute discriminability between two signals.

$$p_{1l} = s_{1l} / \sum_{l=1}^{L} s_{1l} \qquad p_{2l} = s_{2l} / \sum_{l=1}^{L} s_{2l}$$

$$D(\mathbf{s}_1 \| \mathbf{s}_2) = \sum_{l=1}^{L} p_{1l} \log(p_{1l} / p_{2l})$$

$$D(\mathbf{s}_2 \| \mathbf{s}_1) = \sum_{l=1}^{L} p_{2l} \log(p_{2l} / p_{1l})$$

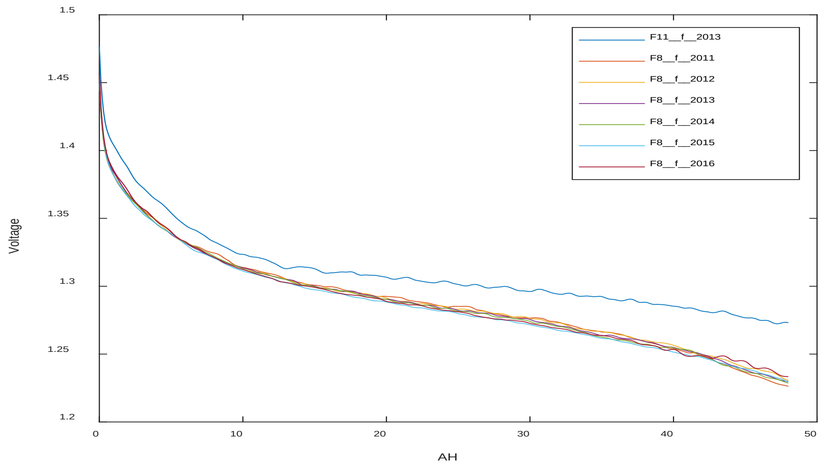
$$\mathrm{SID}(\mathbf{s}_1, \mathbf{s}_2) = D(\mathbf{s}_1 \| \mathbf{s}_2) + D(\mathbf{s}_2 \| \mathbf{s}_1)$$

SDM Battery Cell Performance Analysis

- In this paper, we focus on the V vs Ah curve analysis to estimate the health of the battery cells during battery discharge process.

$$\mathrm{Ah}(t) = \frac{\mathrm{DCHI}(t-1) - \mathrm{DCHI}(t)}{2} \Delta t$$

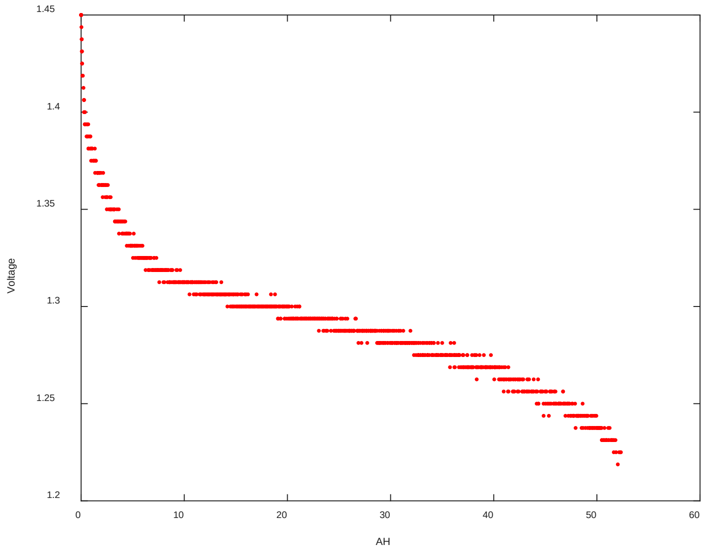
- The healthy cell data that we selected as our reference is extracted from TDRS 11 at the launched year. Even though TDRS 11 from a different generation than TDRS 8-10, the batteries that are installed in both spacecraft are similar and can be used as the reference data.



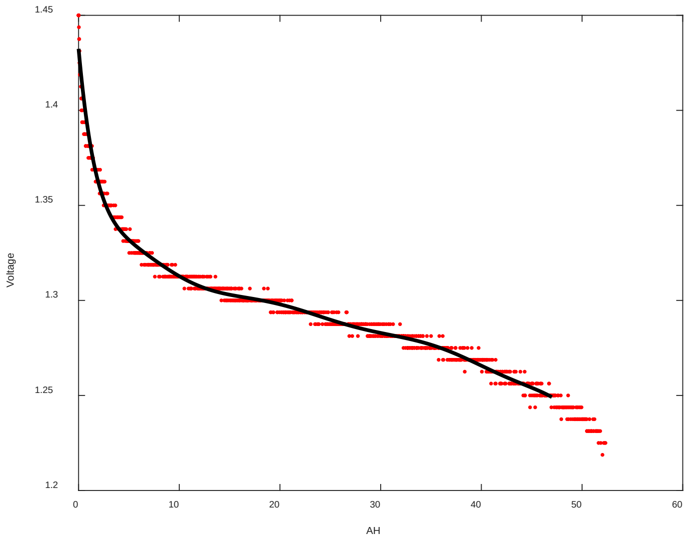
Non-Linear Regression Approach in Estimation of True Cell Signal

- Statistically, linear regression is an approach to modeling the relationship between a scalar response and one or more variables.
- Linear or nonlinear regression function:

$$y = \sum_{i=1}^{N} \alpha_i x_i^{\,c} + \alpha_o \text{ for } c \geq 1$$



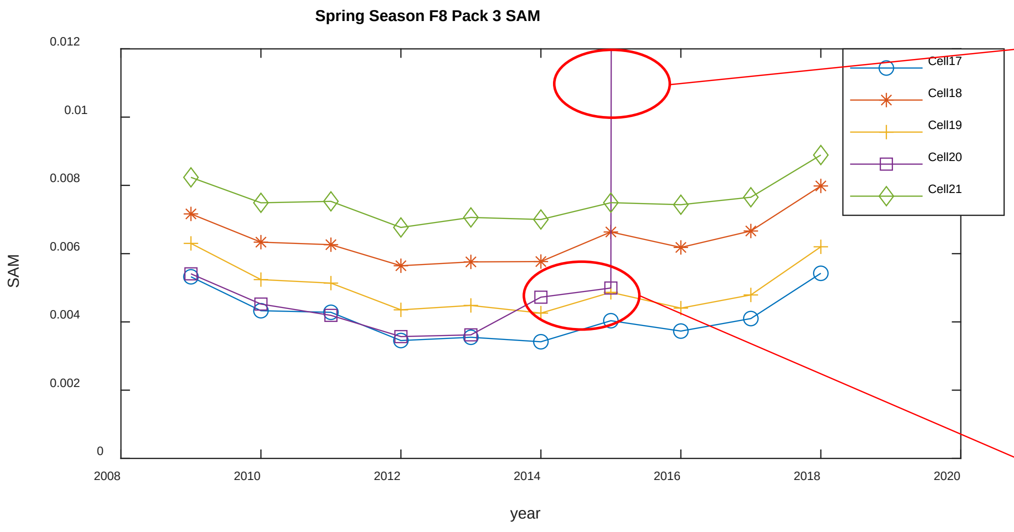
Observed Cell Voltage Data



Estimated Cell Voltage Data

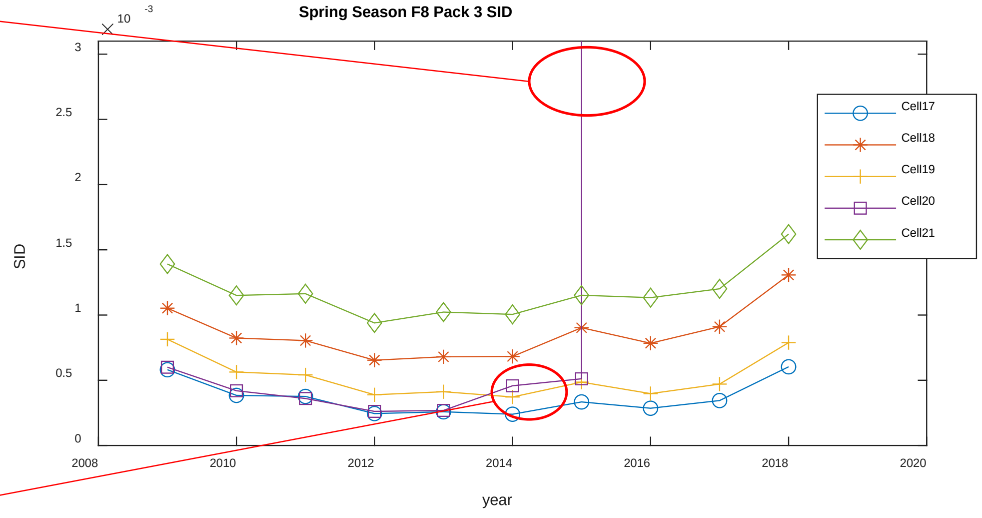
SDM Battery Cell Performance Analysis Results (1)

- SDM applied to quantify current performance of battery cell. The cell with abnormal discriminability when compared to the rest of the cells in same pack indicates the anomalous event. These anomalies could be the failure of a scanner, the leaking of chemical substance or other unknown events.



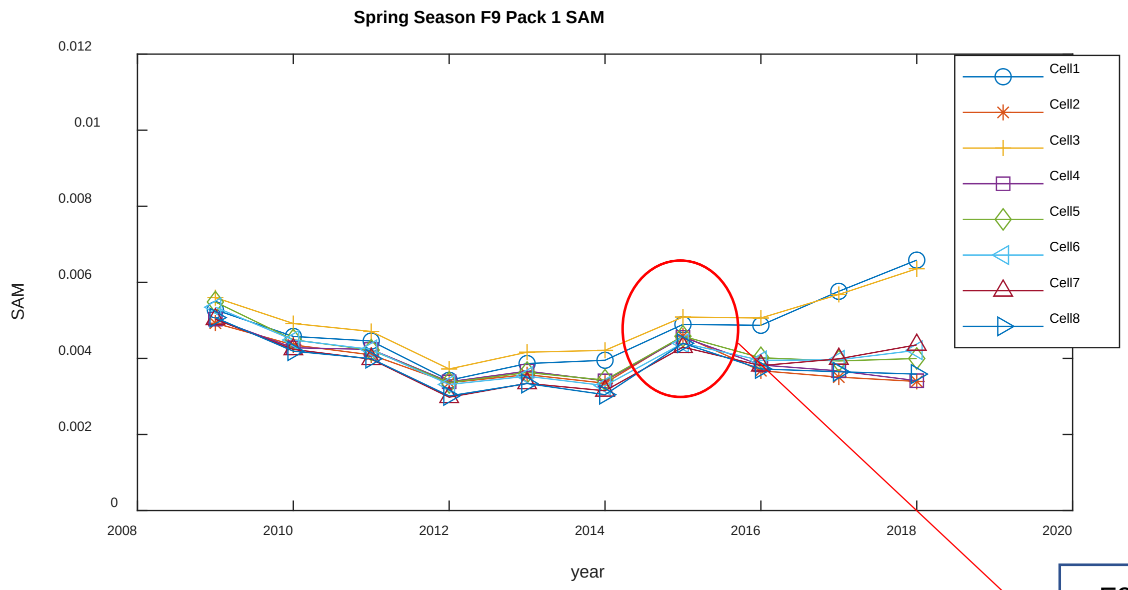
F8 cell 20 failed at fall 2015

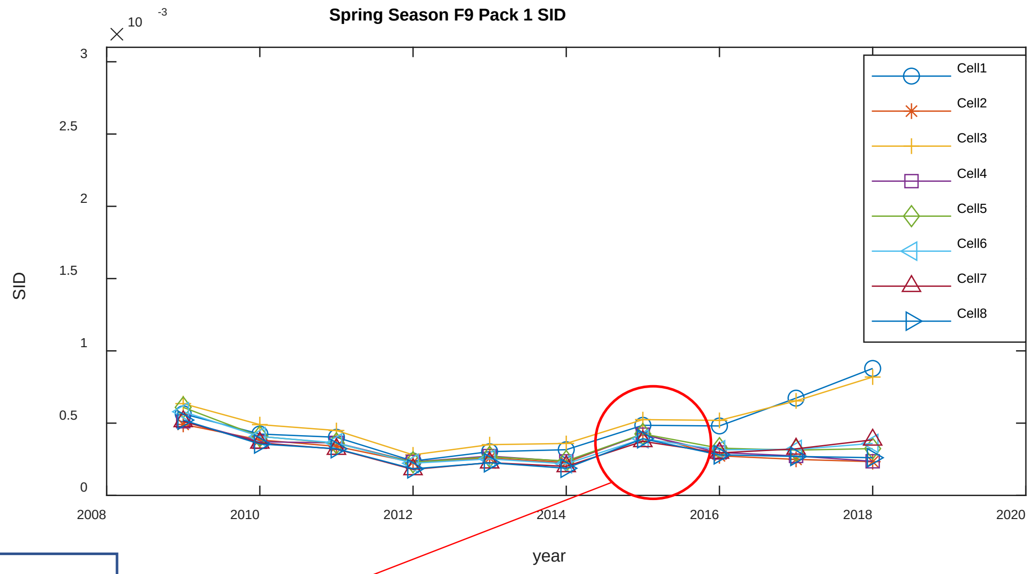
SDM results showing that we can observe some signs of failure since spring 2014



SDM Battery Cell Performance Analysis (2)

- Flight 9 results shows that 2 cells in Pack 1 shows significant divergence from rest of the cells in same pack, which indicate these 2 cells have loss of capacity. Both SAM and SID shown similar results for cell 1 and cell 3.

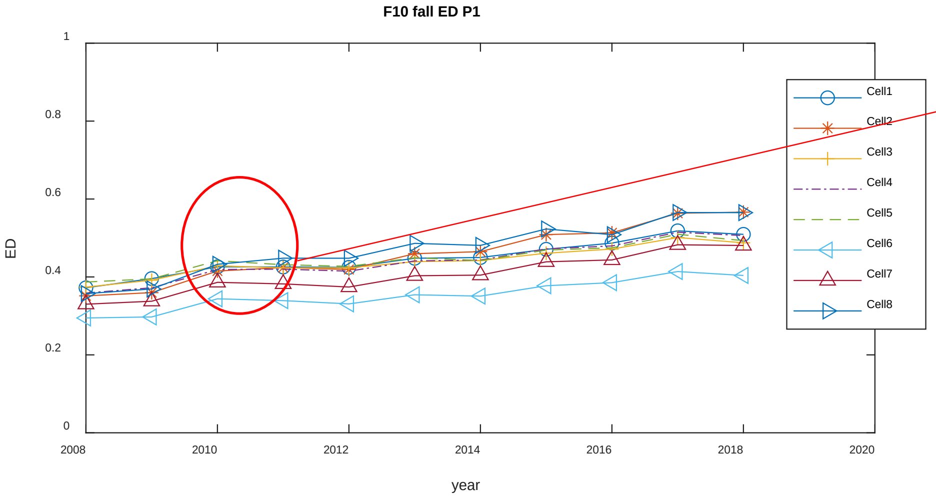




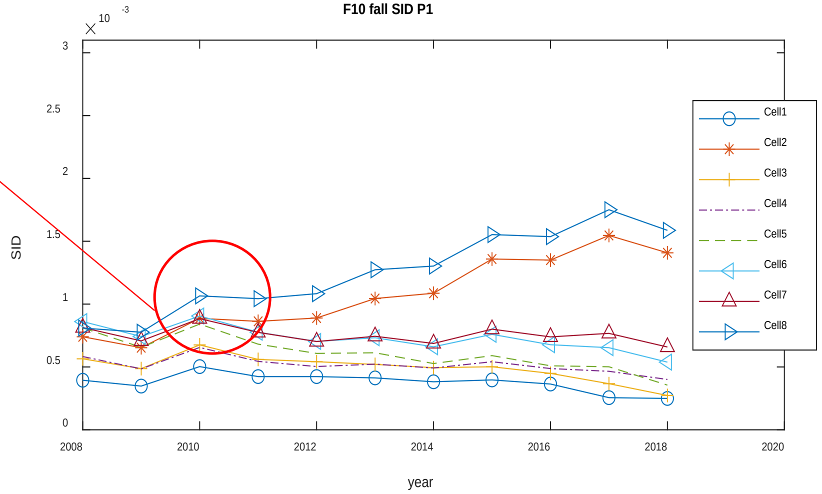
F9 Cell 1 and cell 3 started to diverge from rest cells since 2016. We can say these two cells have potential failure.

SDM Battery Cell Performance Analysis (3)

- Similar examples can also be found in analysis of TDRS 10 data as shown in Figure. Cell 1 and cell 2 in TDRS 10 also diverge from the rest of the cells beginning at 2010. However, these two cells do not seem to become worse as we can see in 2018. Moreover, we can observe that the ED is not as sensitive as SID. This is because ED only considers the distance between two signals and does not take the signal shape into account.



F10 Cell 2 and cell 8 show divergence form other cells since 2010.



Conclusion

- Our experiment indicates that the SDM algorithm can be helpful for managing spacecraft batteries and for quantifying and trending the performance of cells.
- A yearly or monthly trending of the data is an important methodology to analyze the performance of the spacecraft
- By using the SDM algorithm to quantify the performance of each individual spacecraft component, we can easily analyze the spacecraft performance by yearly or monthly trending of the SDM
- Continue develop algorithms for analyzing each subsystems to improve the efficiency in monitoring spacecraft quality.
- Future Work:
  - Reaction wheel anomaly detection and analysis
  - Bus voltage limiter (BVL) anomaly detection and analysis.
  - Thruster anomaly and failure prediction.

Thanks for your attention