Conjunction Assessment Risk Analysis

Conjunction Assessment
Late-Notice High-Interest
Event Investigation:
Space Weather Aspects

D. Pachura, M. D. Hejduk
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Background: Conjunction Assessment

• Conjunction Assessment Risk Analysis (CARA)
  – Evaluates collision risk between two satellites expected to come in close proximity of each other (by calculating probability of collision \(P_c\))
  – Mitigates collision risk, if necessary

• Conjunctions usually identified several days before close approach
  – Risk usually follows more-or-less canonical development paradigm
• However, sometimes risk increases or decreases quite suddenly
  – More insight needed into the circumstances behind such cases
Introduction

• Tasked to analyze short notice events which are generally a result of unexpected, large state changes
• Looked at all reported conjunctions for *ca.* 700 km protected missions from May 2015 though Feb 2016
• Performed an analysis to determine whether there is any correlation between large state changes/late notice event identification and the following factors:
  – Sparse tracking
  – High drag objects
  – Space weather
• Examined specific late notice events identified by missions to try to identify root cause
Broad Investigation of Large State Changes

• Late-notice events usually driven by large changes in primary (protected) object or secondary object state
• Main parameter to represent size of state change is component position difference divided by associated standard deviation ($\varepsilon/\sigma$) from covariance
• Investigation determined actual frequency of large state changes, in both individual and combined states
  – Compared them to theoretically expected frequencies
• Found that large changes ($\varepsilon/\sigma > 3$) in individual object states occur much more frequently than theory dictates
  – Effect less pronounced in radial components and in events with $P_c > 1e-5$
• Found combined state matched much closer to theoretical expectation, especially for radial and cross-track
  – In-track is expected to be the most vulnerable to modeling errors, so not surprising that non-compliance largest in this component
Summary of “Other” Correlation Results

• Pc correlation with large state changes in primary not very strong
• Large state changes in the secondary do correlate to large changes in Pc, but not all that strongly
  – Value of Kendall’s Tau ranged from 0.37 to 0.6
• Sparse tracking for secondary does not correlate with large state errors
• Higher EDR values for secondary do not correlate with larger state errors
Correlations with Solar Activity

• Elevated levels of solar activity can produce an unstable atmosphere whose density is difficult to model
  – More strongly true with geomagnetic storms (Dst, a_p)
  – Can also be observed with EUV (F10, M10, S10, Y10, &c.)

• Different possibilities for essence of the problem
  – Higher solar activity simpliciter
  – Mismatch between predicted and realized solar activity

• Will investigate the former with correlation studies
  – Median F10 and a_p over prediction interval
  – Peak a_p over prediction interval

• Will investigate the latter with case studies
Combined $\epsilon/\sigma$ vs Median $F_{10}$: Any Component $\text{abs}(\epsilon/\sigma) > 3$

### Radial $\epsilon/\sigma$ vs $F_{10}$
- Pearson: -0.045421
- Kendall: -0.010952
- Spearman: -0.01571

### In-Track $\epsilon/\sigma$ vs $F_{10}$
- Pearson: 0.080548
- Kendall: 0.00075321
- Spearman: 0.0022534

### Cross-Track $\epsilon/\sigma$ vs $F_{10}$
- Pearson: -0.081365
- Kendall: -0.071691
- Spearman: -0.10548

### 3 DoF $\chi^2$ vs $F_{10}$
- Pearson: -0.08473
- Kendall: -0.0090947
- Spearman: -0.012218
### Combined $\varepsilon/\sigma$ vs Solar Indices: Tabular Summary

<table>
<thead>
<tr>
<th></th>
<th>Radial</th>
<th>In-Track</th>
<th>Cx-Track</th>
<th>Chi-Sq</th>
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<tr>
<td><strong>Median F10: Kendall</strong></td>
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<tr>
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<td>$\varepsilon/\sigma &gt; 5$</td>
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<td>-0.003</td>
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<td>0.01</td>
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<td><strong>Peak Ap: Kendall</strong></td>
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<tr>
<td>All Data</td>
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<td>-0.04</td>
</tr>
</tbody>
</table>

- Correlations are essentially nonexistent in all areas

**Simple elevated levels of solar activity do not correlate with large changes in relative miss**
Late-Notice HIE Case Studies

- Examined four late-notice events that fell within data investigation period of current study
  - 1 MAY 2015 to 1 FEB 2016

- **Events examined**
  - Terra vs 38192; TCA 24 JUN 2015
  - Aura vs 89477; TCA 29 AUG 2015
  - Terra vs 37131; TCA 19 DEC 2015
  - GPM vs 28685; TCA 5 SEP 2015
    - Determined not to be space weather related

- **Will look at**
  - $\varepsilon/\sigma$ vs time (same as $\Delta$ position to uncertainty plots from daily/HIE report, like at right)
  - $P_c$ vs time (same as from daily/HIE report)
  - $Dst$ and $a_p$; prediction vs actual
    - Segmented by what is available in support of each update
JSpOC uses JBH09
- JB08 + HASDM
- Anemomilos DST prediction

Updated at JSpOC 3x per day

Model Input summary:
- S10, S54 are daily and 54-day S10.7 index for >200 km heating of O by solar chromosphere 28.4-30.4 nm emissions in x10-22 Watts per meter squared per Hertz
- M10, M54 are daily and 54-day M10.7 index for 100-110 km heating of O2 by solar photosphere 160 nm SRC emissions in x10-22 Watts per meter squared per Hertz
- Y10, Y54 are daily and 54-day Y10.7 index for 85-90 km heating of N2, O2, H2O, NO by solar coronal 0.1-0.8 nm and Lya 121 nm emissions in x10-22 Watts per meter squared per Hertz
- F10, F54 are daily and 54-day solar 10.7 cm radio flux in x10-22 Watts per meter squared per Hertz
- \( a_p \) is the 3-hour planetary geomagnetic 2 nT index (00-21 UT)
- Dst is Disturbance Storm Time geomagnetic index in nT
- DTC is delta exospheric temperature correction in units of K
Space Weather Evolution Charts

- Upper left shows Dst; lower left shows $a_p$
- Black line is “issued” (definitive) data
- Colored lines are predicted data
  - Each line begins when a given OD update executed
  - Each line shows predicted values of the geomagnetic index of choice
    - When Dst lines move to small positive value, prediction stops (zeroes in file)
    - When $a_p$ lines move to small negative value, prediction stops (ones in file)
- Dst threshold for solar storm compensation engagement also shown
- Upper right shows $\varepsilon/\sigma$ for each component
  - Miss distance vs combined covariance
- Lower right shows $P_c$ vs time
Case Study #1: Terra vs 38192, TCA 24 JUN 2015

- Predicted and Definitive Dst History
- ε/σ vs Time to TCA
- Predicted and Definitive Ap History
- Pc vs Time to TCA
• About half a day before spike in \(a_p/Dst\) begins
  – Some predicted increased Dst activity, but not of severity actually realized
  – Predictions at very end of storm over-predict Dst
  – Final prediction and shrinking covariance produces Pc drop off

• SWTS indicates conjunction vulnerable to large Pc changes due to density mis-modeling

• Bottom line: missed solar storm and subsequent prediction failures produced late changes
Case Study #2:
Aura vs 89477; TCA 29 AUG 2015
Space Weather Trade-Space Result: Aura vs 89477; 56 Hours to TCA

- Run from update right as spike in $a_p/Dst$ is beginning
  - No predicted spike in relevant ASW space weather file
- Indicates that conjunction vulnerable to large Pc changes due to atmospheric mis-modeling

• Bottom line: space weather predictions missed significant solar storm
  - Most likely cause of late-breaking change in Pc
Case Study #3:
Terra vs 37131; TCA 19 DEC 2015
Space Weather Trade-Space Result: Terra vs 37131; 28 Hours to TCA

- Run from update before 2 OoM change in Pc observed
  - Strange actual behavior in Dst
  - Modest unmodeled increase in Ap
- SWTS indicates that conjunction vulnerable to Pc changes due to atmospheric mis-modeling

- Bottom line: odd space weather behavior, and deviation from predication, probably responsible for modest increase in Pc
Late-Breaking HIEs: Overall Summary

- Large state changes occur more often than theory would indicate
- Do not correlate at global level with any obvious causal condition
  - Light tracking, hard-to-maintain orbits, or generally elevated solar activity
- **Case studies indicate two culprits**
  - Failure of JSpOC space weather predicted indices to predict solar storms
  - Edge cases for general screenings
- **Is there any good news?**
  - No, not really
Solar Storm Response – What are we doing?

- CARA has begun receiving atmospheric model input data from JSpOC
  - Gives CARA analysts insight into what is being modeled
  - CARA analysts can work with outside experts (SWRC) to evaluate reasonableness and likelihood of predicted space weather events
- CARA analysts can use model input information and outside evaluation of predictions to provide more nuanced feedback as to when to expect increased uncertainty and variation due to space weather
  - Additionally, as shown by this study, it is a great help for post-event analysis
- Developing operational ConOps for how and when to apply space weather trade space with model insight
JSpOC Space Weather Information Files: Data Currency

• Three types of data in file
  – “Issued” – definitive values for the solar/geomagnetic index, subjected to full availability of feeder data and consistency tests
  – “Nowcast” – initial observations of values, hand-scaled and not subject to consistency tests
    • Measurements stay in “nowcast” status for typically 24 hours
  – “Predicted” – values are predicted
    • EUV predicted values from 54- and sometimes 108-day autoregression analyses of past data
    • Geomagnetic indices are predicted from observed solar activity earlier in the solar rotation (and thus expected to become georelevant at a given future time)

• Data type timing
  – Issued/Nowcast data used in propagating states from epoch to current time
    • Scaled/debiased with HASDM results
  – Predicted data used in propagating states from current time to TCA
  – Accuracy of predicted data can influence propagated result substantially
Normal Deviates and Chi-squared Variables

- Let $q$ and $r$ be vectors of values that conform to a Gaussian distribution
  - These collection of values are called *normal deviates*

- A normal deviate set can be transformed to a *standard normal deviate* by subtracting the mean and dividing by the standard deviation
  - This produces the so-called $Z$-variables

$$Z_q = \frac{q - \mu_q}{\sigma_q}, \quad Z_r = \frac{q - \mu_r}{\sigma_r}$$

- The sum of the squares of a series of standard normal deviates produces a chi-squared distribution, with the number of degrees of freedom equal to the number of series combined

$$Z_q^2 + Z_r^2 = \chi^2_{dof}$$
Normal Deviates in State Estimation

• In a state estimate, the errors in each component (u, v, and w here) are expected to follow a Gaussian distribution
  – If all systematic errors have been solved for, only random error should remain

• These errors can be standardized to the Z-formulation
  – Mean presumed to be zero (OD should produce unbiased results), so no need for explicit subtraction of mean

\[
Z_u = \frac{u}{\sigma_u}, \quad Z_v = \frac{v}{\sigma_v}, \quad Z_w = \frac{w}{\sigma_w}
\]

• Sum of squares of these standardized errors should follow a chi-squared distribution with three degrees of freedom

\[
Z_u^2 + Z_v^2 + Z_w^2 = \chi^2_{3\text{ dof}}
\]
State Estimation Example Calculation

- Let us presume we have a precision ephemeris, state estimate, and covariance about the state estimate
  - For the present, further presume covariance aligns perfectly with uvw frame (no off-diagonal terms)
- Error vector $\varepsilon$ is position difference between state estimate and precision ephemeris, and covariance consists only of variances along the diagonal
  - Inverse of covariance matrix is straightforward

$$
\varepsilon = \begin{bmatrix} \varepsilon_u \\ \varepsilon_v \\ \varepsilon_w \end{bmatrix}, \quad C = \begin{bmatrix} \sigma_u^2 & 0 & 0 \\ 0 & \sigma_v^2 & 0 \\ 0 & 0 & \sigma_w^2 \end{bmatrix} \quad C^{-1} = \begin{bmatrix} 1/\sigma_u^2 & 0 & 0 \\ 0 & 1/\sigma_v^2 & 0 \\ 0 & 0 & 1/\sigma_w^2 \end{bmatrix}
$$

- Resultant simple formula for chi-squared variables

$$
\varepsilon C^{-1} \varepsilon^T = \frac{\varepsilon_u^2}{\sigma_u^2} + \frac{\varepsilon_v^2}{\sigma_v^2} + \frac{\varepsilon_w^2}{\sigma_w^2} = \chi^2_{\text{dof}}
$$

- Extension to case with off-diagonal terms straightforward
Pearson Correlation Coefficient

- Evaluates the degree of a linear relationship between two variables
- Usually evaluated by the formula \( s \) is sample standard deviation, with range of interesting and often not helpful outcomes

\[
r = \frac{1}{n-1} \sum_{i=1}^{n} \left( \frac{x_i - \bar{x}}{s_x} \right) \left( \frac{y_i - \bar{y}}{s_y} \right)
\]

- Some interpretive guidance via relationship to \( r^2 \) value from linear regression: square of Pearson = regression \( r^2 \)
  - Pearson value of 0.5 would equate to \( r^2 \) of 0.25—not very impressive
- Really would like something that reveals even non-linear correlation
• **Rank correlation test**
  – With two vectors of data X and Y, compares (Xi,Yi) to every other (Xj,Yj)
  – Pair is concordant if, when Xi>Xj, Yi>Yj; discordant if the opposite
  – Parameter is (# concordant pairs - # discordant pairs) / (total pairs)
    • So same range of values (-1 to 1) with same meaning

• **Much more robust test**
  – Will find both linear and nonlinear correlation
  – Computationally expensive [\(\sim O(n^2)\)], but computers are doing the work

• **Tied situations create problems**
  – In present analysis, arises when comparing continuous to discrete distribution
    • *e.g.*, \(\epsilon/\sigma\) to tracking levels (because tracking levels are counting numbers, so can have multiple \(\epsilon/\sigma\) values aligned with same tracking level)
  – Even more computationally expensive modifications to adjust for ties
  – Spot-checked these and saw no difference in computed result
Spearman’s Rho

- Test of monotonicity, computed by summing squares of differences in rank
  - Mapped into same -1 to 1 range of values, with same interpretation

- Computational formula

\[
\rho = 1 - \frac{6 \sum_{i=1}^{n} d_i^2}{n(n^2 - 1)}
\]

- Computationally easier but more vulnerable to outlier data
- Usually larger than Kendall’s tau
- Included here for consistency/contrast

Main factor to consult is Kendall’s Tau
Broad Investigation of Large State Changes

• Determine actual frequency of large state changes, in both individual and combined states
  – Compare to theoretically expected frequencies

• Determine whether broadly correlated with potential/expected causes
  – Low tracking
  – Harder-to-maintain orbits (larger energy dissipation rate)
  – General levels of solar activity (EUV and Joule atmospheric heating)
• Main parameter to represent size of state change is component position difference divided by associated standard deviation ($\varepsilon/\sigma$)
  – Presumption of OD is that errors are normally distributed and unbiased
  – $\varepsilon$ is difference in component position between subsequent state estimates
  – $\sigma$ is square root of associated variance from first state’s covariance
  – Dividing $\varepsilon$ by $\sigma$ creates standardized normal variable ($\mu=0$ because unbiased)
  – Set of these should thus conform to standard normal distribution

• Same method currently used in CARA daily and HIE reports
Large State Changes: Parameterization (2 of 3)

- However . . . This is only true for the “diagonalized” situation, in which covariance axes and coordinate frame axes align
  - Results meaningful only if ellipse closely aligns with coordinate axes
  - Once ellipse rotated, then component errors are correlated
    - Individual component error distributions no longer independent random variables
- How often are covariance error ellipsoids naturally diagonalized?
  - Not terrible assumption for individual satellites (primary, secondary)
  - More tenuous for combined situation (miss distance vs combined covariance)
- Bottom line: $\varepsilon/\sigma$ statistics at the component level must be used with care
  - When plotted against only positive axis, presume $\varepsilon/\sigma$ to be $\text{abs}(\varepsilon/\sigma)$
• **Comparison alternative: Mahalanobis distance**
  
  – If individual component errors normally distributed, then sum of squares of individual ratios ($\varepsilon^2/\sigma^2$) will constitute a 3-DoF $\chi^2$ distribution
  
  – Formulary $\varepsilon C^{-1}\varepsilon^T$ properly considers all correlations and makes the calculation independent of coordinate system
  
  – Approach less frequently encountered, so less intuition built up around result
  
  – But will be supplied and examined along with Gaussian variables
  
  – Can also examine 2-DoF situation for only radial and in-track
    
    • More information on this later
Frequency of Large State Changes: Secondary Objects

Radial

In-Track

Cross-Track

Percentage of Events

$\epsilon/\sigma$

<1

1-2

2-3

3-5

>5

$10^{-2}$

$10^{-1}$

$10^{0}$

$10^{1}$

Percentage of Events

$\epsilon/\sigma$

<1

1-2

2-3

3-5

>5

$10^{-2}$

$10^{-1}$

$10^{0}$

$10^{1}$

Percentage of Events

$\epsilon/\sigma$

<1

1-2

2-3

3-5

>5

$10^{-2}$

$10^{-1}$

$10^{0}$

$10^{1}$

Legend:

- All Updates
- Subset with Event PcMax > 1E-05
- Subset of PcMax with > 1 OoM $\Delta$Pc
- Subset of PcMax with > 2 OoM $\Delta$Pc

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Frequency of Large State Changes: Primary Objects

**Radial**

- Percentage of Events
- $\epsilon/\sigma$
- Categories: $<1$, 1-2, 2-3, 3-5, >5

**In-Track**

- Percentage of Events
- $\epsilon/\sigma$
- Categories: $<1$, 1-2, 2-3, 3-5, >5

**Cross-Track**

- Percentage of Events
- $\epsilon/\sigma$
- Categories: $<1$, 1-2, 2-3, 3-5, >5
Summary of Frequencies: Primary and Secondary Objects

• Data summary
  – Table below reports situation for which $|\varepsilon/\sigma| > 3$

• Commonly-known theoretical “percentages” for univariate Gaussian distribution consider two-tailed results
  – 95.4% for 2-σ distribution considers results from 2.3% to 97.7%
  – 99.7% for 3-σ distribution considers results from 0.15% to 99.85%

• Actual percentages for primaries surprisingly large
  – Very similar for radial component; much larger differences with other two
    • Perhaps a little comfort in this, as radial generally most important component for CA

<table>
<thead>
<tr>
<th></th>
<th>Overall</th>
<th>Event Pc &gt; 1E-05</th>
<th>&gt; 1E-05 &amp; ΔPc &gt; 1 OoM</th>
<th>&gt; 1E-05 &amp; ΔPc &gt; 2 OoM</th>
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<td></td>
<td>Primary</td>
<td>Secondary</td>
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<tr>
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<td>1.57</td>
<td>1.33</td>
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<tr>
<td>In-Track</td>
<td>5.88</td>
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<td>Cross-Track</td>
<td>13.53</td>
<td>7.10</td>
<td>2.64</td>
<td>0.88</td>
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</table>

Overall, prevalence is greater than theory would predict. However, presence in events of significance notably reduced.
Comparison of $\varepsilon/\sigma$ to Theory: Primary and Secondary Objects
Comparison of $\epsilon/\sigma$ to Theory: Interpretation

- Radial behaves reasonably well—better than theory until more extreme part of tails reached
  - Cannot see tail behavior very well in provided plots
- In-track has non-theoretical distribution beyond about $\epsilon/\sigma > 1$
  - As remarked previously, worse for secondaries than for primaries
- Cross-track highly leptokurtic—peaked with very long tails
  - Does not match a Gaussian distribution at all
- In using chi-squared distribution, 2-DoF framework gives more sanguine situation
  - Eliminates effect of large cross-track differences
  - Nonetheless, non-theory outliers dominate performance in the tails
- None of these results sets match the theory particularly well
- Immediate conclusion difficult
  - OD residuals suspected to be leptokurtic
  - Present trend could be extension of this
Combined Situation

STATE-CHANGE FREQUENCY AND COMPARISON TO THEORY
Frequency of Large State Changes: Miss vs Combined Sigma

**Radial**

- Percentage of Events
- $\epsilon/\sigma$ vs. 10^1
- $<1$, 1-2, 2-3, 3-5, >5

**In-Track**

- Percentage of Events
- $\epsilon/\sigma$ vs. 10^1
- $<1$, 1-2, 2-3, 3-5, >5

**Cross-Track**

- Percentage of Events
- $\epsilon/\sigma$ vs. 10^1
- $<1$, 1-2, 2-3, 3-5, >5
Comparison of $\varepsilon/\sigma$ to Theory: Miss Component vs Combined Sigma
Frequency of Large State Changes: Tabular Summary

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<td>2.54</td>
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<td>Cross-Track</td>
<td>13.53</td>
<td>7.10</td>
<td>0.90</td>
<td>2.64</td>
</tr>
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</table>

• Values much closer to theoretical expectation, especially for radial and cross-track
  – In-track is expected to be the most vulnerable to modeling errors, so not surprising that non-compliance largest in this component
Combined $\epsilon/\sigma$ vs Median $F_{10}$: All Data

- Radial $\epsilon/\sigma$ vs $F_{10}$
  - Pearson: $-0.0028185$
  - Kendall: $0.0081204$
  - Spearman: $0.012195$

- In-Track $\epsilon/\sigma$ vs $F_{10}$
  - Pearson: $-0.011297$
  - Kendall: $-0.0096707$
  - Spearman: $-0.01425$

- Cross-Track $\epsilon/\sigma$ vs $F_{10}$
  - Pearson: $0.012868$
  - Kendall: $0.0055951$
  - Spearman: $0.0081742$

- 3 DoF $\chi^2$ vs $F_{10}$
  - Pearson: $0.0034562$
  - Kendall: $0.016049$
  - Spearman: $0.023996$
Combined $\varepsilon/\sigma$ vs Median $F_{10}$: Any Component $\text{abs}(\varepsilon/\sigma) > 5$

**Radial $\varepsilon/\sigma$ vs $F_{10}$**
- Pearson=-0.062121
- Kendall=-0.02537
- Spearman=-0.035908

**In-Track $\varepsilon/\sigma$ vs $F_{10}$**
- Pearson=0.13122
- Kendall=0.048062
- Spearman=0.07194

**Cross-Track $\varepsilon/\sigma$ vs $F_{10}$**
- Pearson=0.11416
- Kendall=0.087877
- Spearman=0.13029

**3 DoF $\chi^2$ vs $F_{10}$**
- Pearson=0.13234
- Kendall=0.047596
- Spearman=0.069937
Issues in Comparison to Theory

• Commonly-known “percentages” for univariate Gaussian distribution consider two-tailed results
  – 95.4% for 2-σ distribution considers results from 2.3% to 97.7%
  – 99.7% for 3-σ distribution considers results from 0.15% to 99.85%

• Potential double-counting of large state changes
  – Subsequent updates analyzed for large state change behavior
  – In a chain of updates, return to normalcy will appear as a second large change
  – Demarcation between one and two events not so easy to define
    (S = small state change; L = large state change)
    • S S L L S S – one or two events?
    • S S S L S S L S S – one or two events?
    • S S S S S S L – one or two events (would it have been counted as two if one more update had been available?)
  – For data-mining simplicity, all large changes counted, with the caveat that reported number might be twice as large as “actual” number
• CARA member of NASA LWS space weather expert panel
  – Dr. Matt Hejduk as CA expert panel representative
  – Dr. Yihua Zheng as GSFC space physics representative, also representing mission interests

• Purpose of panel to recommend NASA research investments to improve prediction and modeling
  – Will issue formal report of recommendations by December, as well as accompanying journal article
  – Will attempt to focus at least part of recommendation to address JSpOC situation

• Hope to leverage report to push state of the art at JSpOC
  – However, from their perspective, a large investment was just made in atmospheric density prediction modeling; need to focus on other items
• Will investigate whether file update frequency can be accelerated
  – Brief JSpOC on these results to show the problems that latencies create
    • See if there are mechanisms to improve efficiencies
  – Use SWTS function to determine whether such intervention is needed
    • Events that are not vulnerable to atmospheric density mismodeling would not require
      out-of-cycle updates
    – Would not have helped cases investigated here, as entire solar storms were missed
• However, probably a fairly long time before there is much improvement with such scenarios