Late-Notice HIE Investigation

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Purpose

- **Provide a response to MOWG action item 1410-01:**
  - **Analyze close approaches which have required mission team action on short notice. Determine why the approaches were identified later in the process than most other events.**

- **Method:**
  - **Performed an analysis to determine whether there is any correlation between late notice event identification and space weather, sparse tracking, or high drag objects,which would allow preventive action to be taken**
  - **Examined specific late notice events identified by missions as problematic to try to identify root cause and attempt to relate them to the correlation analysis**

Agenda

- **Frequency/correlation of large state changes**
  - Individual states of primary and secondary objects
    - Overall frequency of ε/σ and comparison to theoretical frequencies
    - Pc vs primary and secondary ε/σ size
    - Secondary ε/σ vs tracking level and vs energy dissipation rate (EDR)
  - Combined states: component miss distances vs combined covariance
    - Overall frequency of ε/σ and comparison to theoretical frequencies
    - Pc vs ε/σ size; ε/σ vs tracking levels, EDR
    - ε/σ vs F10, average Ap, and peak Ap
  - Preliminary conclusions
- **Case studies of four late-notice events**
- **Overall conclusions and way forward**

Dataset to Analyze

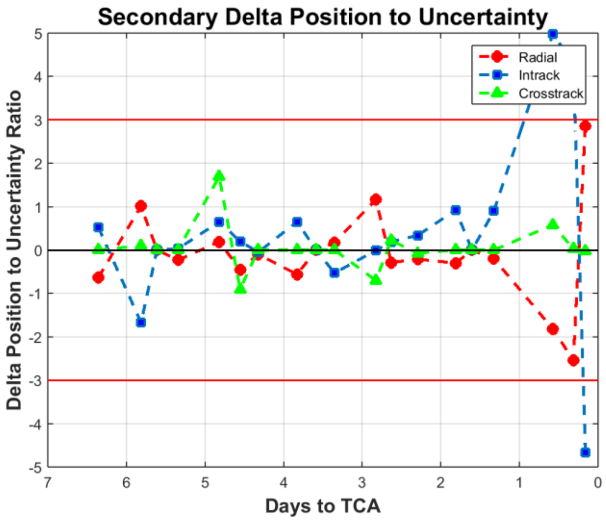
- **All reported conjunctions for *ca.* 700 km defended missions**
  - Landsat-7, Terra, EO-1, Aqua, Aura, CloudSat, CALIPSO, GCOM-W1, Landsat-8, OCO-2, SMAP
- **Data interval from 1 MAY 2015 to 1 FEB 2016**
  - New Dynamic Consider Parameter (DCP) functionality installed on ASW on May 1, 2016, so covariance realism purported to be much improved
- **All CDM updates examined within every event (not just initial identification)**

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)

Large State Changes: Parameterization (1 of 3)

- **Main parameter to represent size of state change is component position difference divided by associated standard deviation (ε/σ)**
  - Presumption of OD is that errors are normally distributed and unbiased
  - ε is difference in component position between subsequent state estimates
  - σ is square root of associated variance from first state's covariance
  - Dividing ε by σ creates standardized normal variable (μ=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: ε/σ statistics at the component level must be used with care**
  - When plotted against only positive axis, presume ε/σ to be abs(ε/σ)

Large State Changes: Parameterization (3 of 3)

- **Comparison alternative: Mahalanobis distance**
  - If individual component errors normally distributed, then sum of squares of individual ratios (ε^2/σ^2) will constitute a 3-DoF χ^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

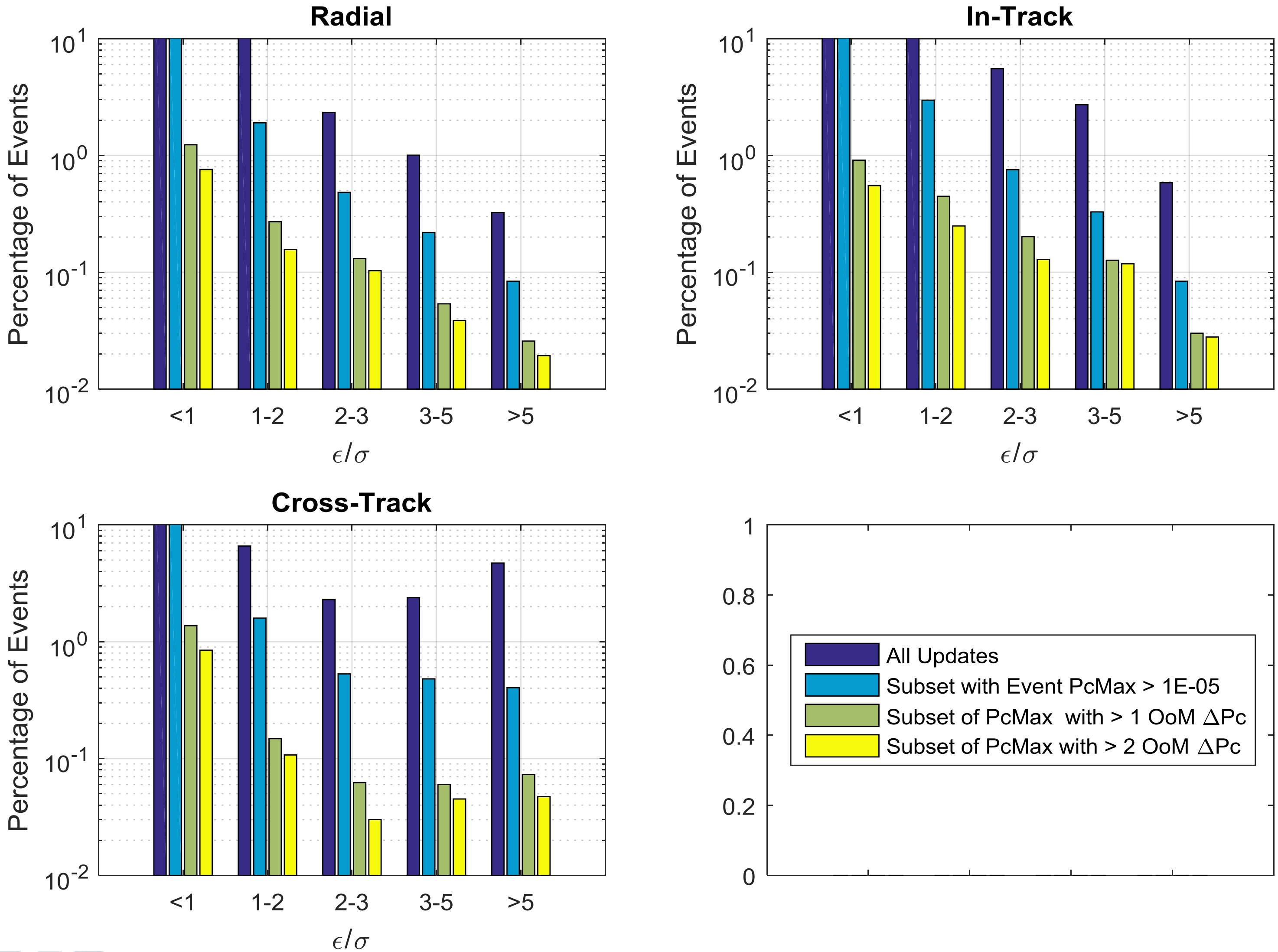
Issues in Comparison to Theory

- **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

Primary and Secondary Treated Individually

STATE-CHANGE FREQUENCY AND COMPARISON TO THEORY

Frequency of Large State Changes: Secondary Objects



Secondary Large State Changes: 3-σ Comparison to Theory

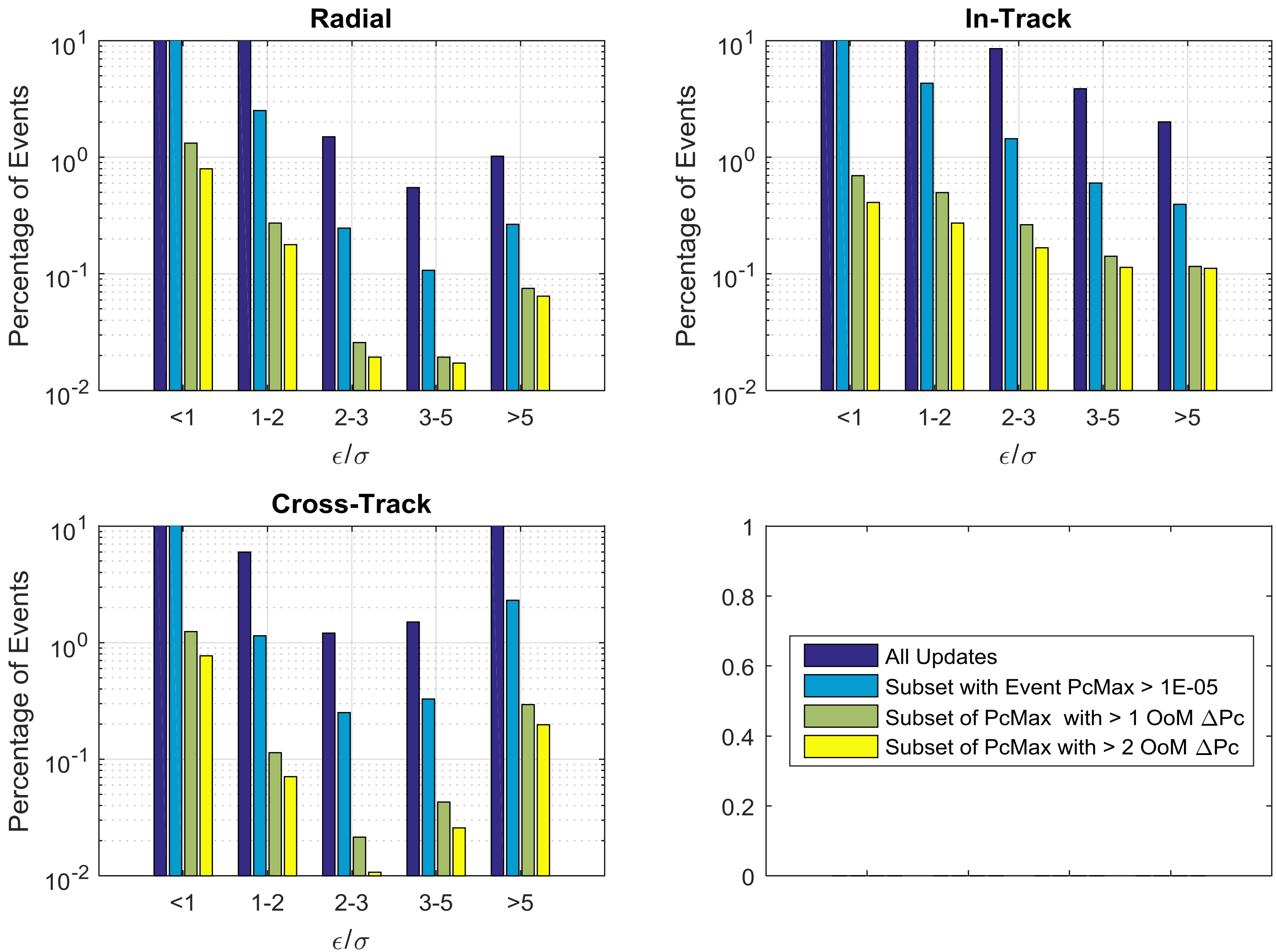
- **Radial frequency a little more than twice theoretical prediction**
  - 1.3% of updates > 3-σ change
  - If all events were double-counted, then would expect 0.6%--have a little more than double this
- **In-track frequency greater than theory**
  - ~3.3%; greater than theory by perhaps factor of five
  - Component most heavily affected by expected modeling errors
- **Cross-track component performs surprisingly badly**
  - ~7.0% of updates; substantially greater than theory
  - Can be largely attributed to very small sigma values
    - Will be addressed in more depth later
- **How often do these matter?**
  - If occur nearly always for low-Pc events, then perhaps not much

Secondary Large State Changes: Frequency in Situations that Matter

- **Change > 3σ and max Pc for event > 1E-05**
  - Radial = 0.3%, in-track = 0.4%, cross-track = 0.9%
- **Change > 3σ, max Pc for event > 1E-05, and Pc change after "large" change > 1 order of magnitude**
  - Radial = 0.07%, in-track = 0.13%, cross-track = 0.15%
- **Change > 3σ, max Pc for event > 1E-05, and Pc change after "large" change > 2 orders of magnitude**
  - Radial = 0.05%, in-track = 0.12%, cross-track = 0.09%
- **Percentages perhaps as much as double "real" values**
- **Sampling is not large enough to allow robust comparison to theory at the 3σ level**

**Overall, prevalence is greater than theory would predict.
However, presence in events of significance notably reduced**

Frequency of Large State Changes: Primary Objects

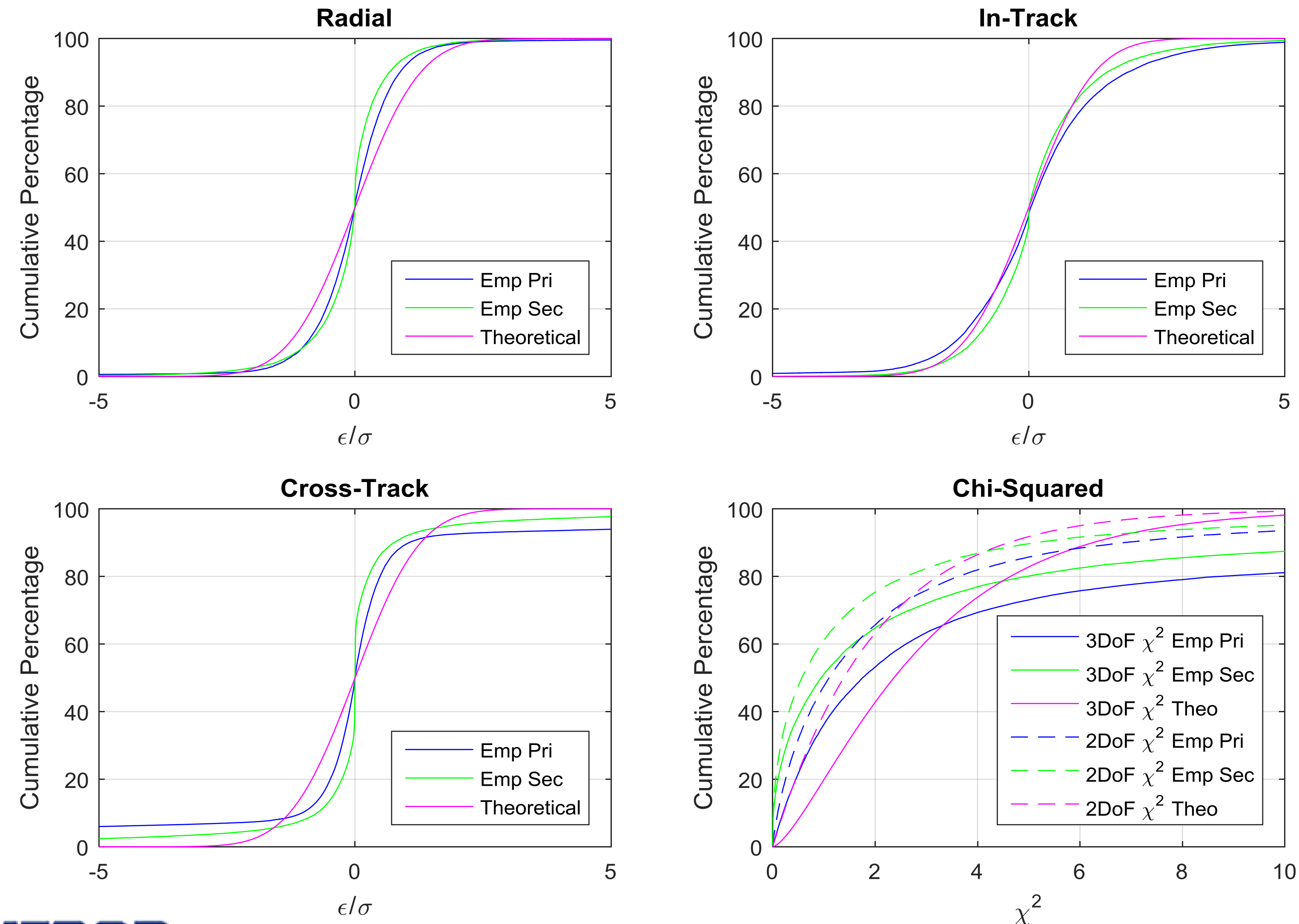


Summary of Frequencies: Primary and Secondary Objects

- **Data summary**
  - Table below reports situation for which abs(ε/σ) > 3
  - Performance tabulated for all events, events with Pc > 1E-05, and additionally with both one and two orders-of-magnitude (OoM) change in Pc value after large update
- **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

	Percent of Events in which abs(ε/σ) exceeds 3							
	Overall		Event Pc > 1E-05		> 1E-05 & ΔPc > 1 OoM		> 1E-05 & ΔPc > 2 OoM	
	Primary	Secondary	Primary	Secondary	Primary	Secondary	Primary	Secondary
Radial	1.57	1.33	0.37	0.30	0.09	0.08	0.08	0.06
In-Track	5.88	3.31	1.00	0.41	0.26	0.16	0.23	0.15
Cross-Track	13.53	7.10	2.64	0.88	0.34	0.13	0.22	0.09

Comparison of ε/σ to Theory: Primary and Secondary Objects



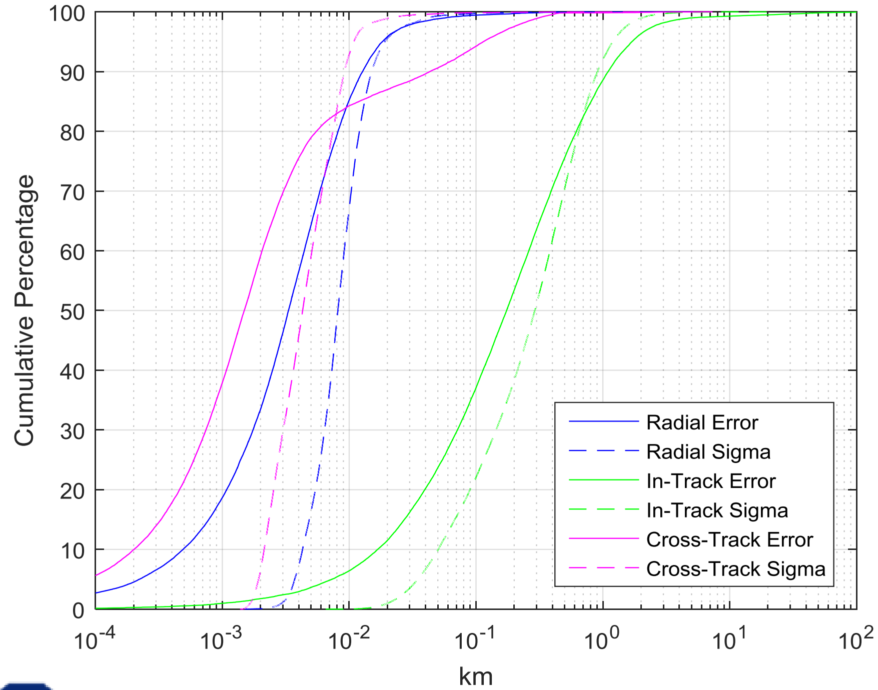
Comparison of ε/σ to Theory: Interpretation

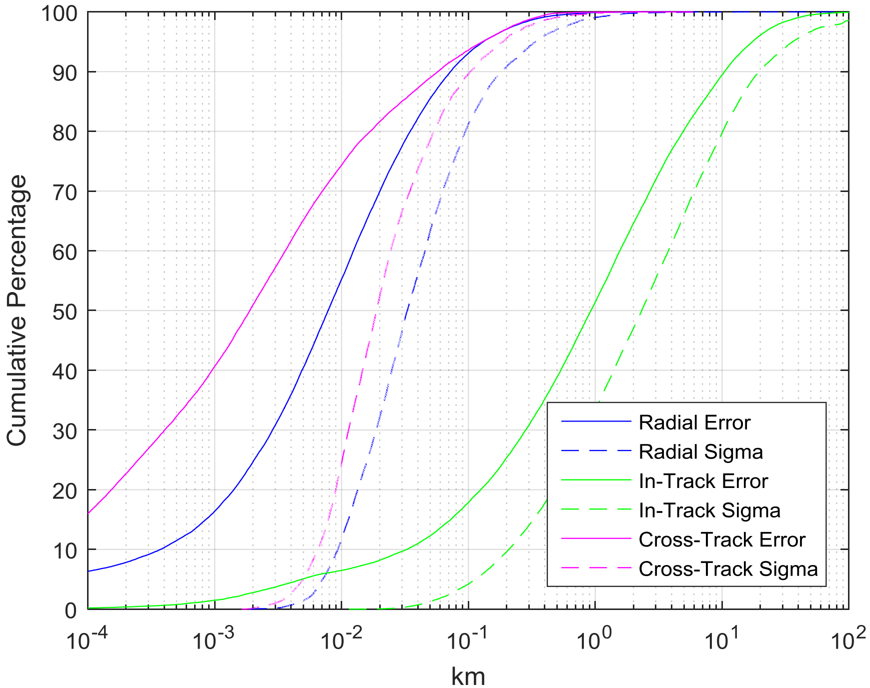
- **Radial behaves reasonably well—better than theory until more extreme part of tails reached**
  - Cannot see tail behavior very well in provided plots
- **In-track has non-theoretical distribution beyond about ε/σ > 1**
  - As remarked previously, worse for secondaries than for primaries
- **Cross-track 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

Error and Sigma CDFs by Component: Primary (left) and Secondary (right)

- **Theory-vs-praxis spread largest for cross-track**
- **Cross-over for cross-track and in-track for primary results**
  - Sigmas coming out of OD probably not large enough; probably could use some kind of adjustment

Cross-track performance due to unreasonably small sigmas





Primary and Secondary Treated Individually

CORRELATION INVESTIGATIONS

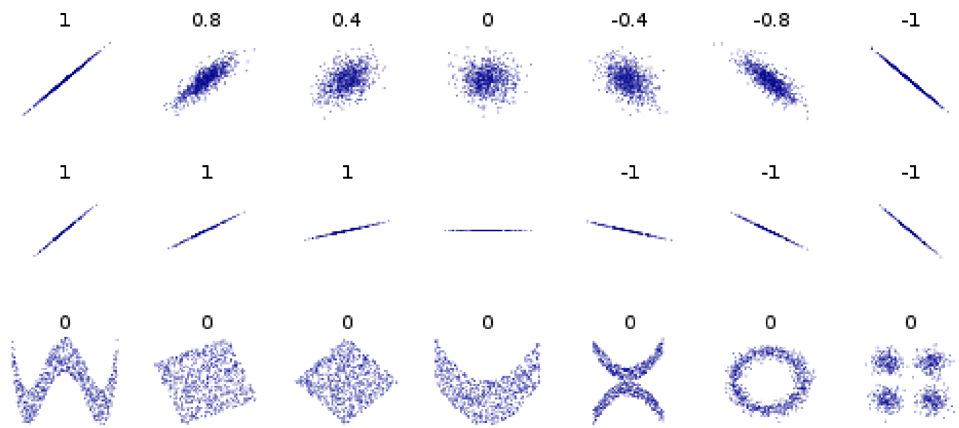
Correlation Indices

- **Correlation tests indicate the degree to which two variables are correlated**
  - Range of values is -1 to 1
  - 1 indicates perfect correlation;
    -1 indicates perfect inverse correlation;
    0 indicates no correlation
- **Three correlation indices in general use**
  - Pearson correlation coefficient: tests for linear correlation
    - What most people learn in statistics class
    - Evaluates how well two datasets exhibit a linear relationship
  - Kendall's tau and Spearman's rho: test for rank correlation
    - Much less frequently taught but more powerful
    - Evaluate how well two datasets move in the same (or opposite) directions
- **All three used in present analysis to examine data correlations**

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**

Kendall's Tau

- **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 [~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.,* ε/σ to tracking levels (because tracking levels are counting numbers, so can have multiple ε/σ 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

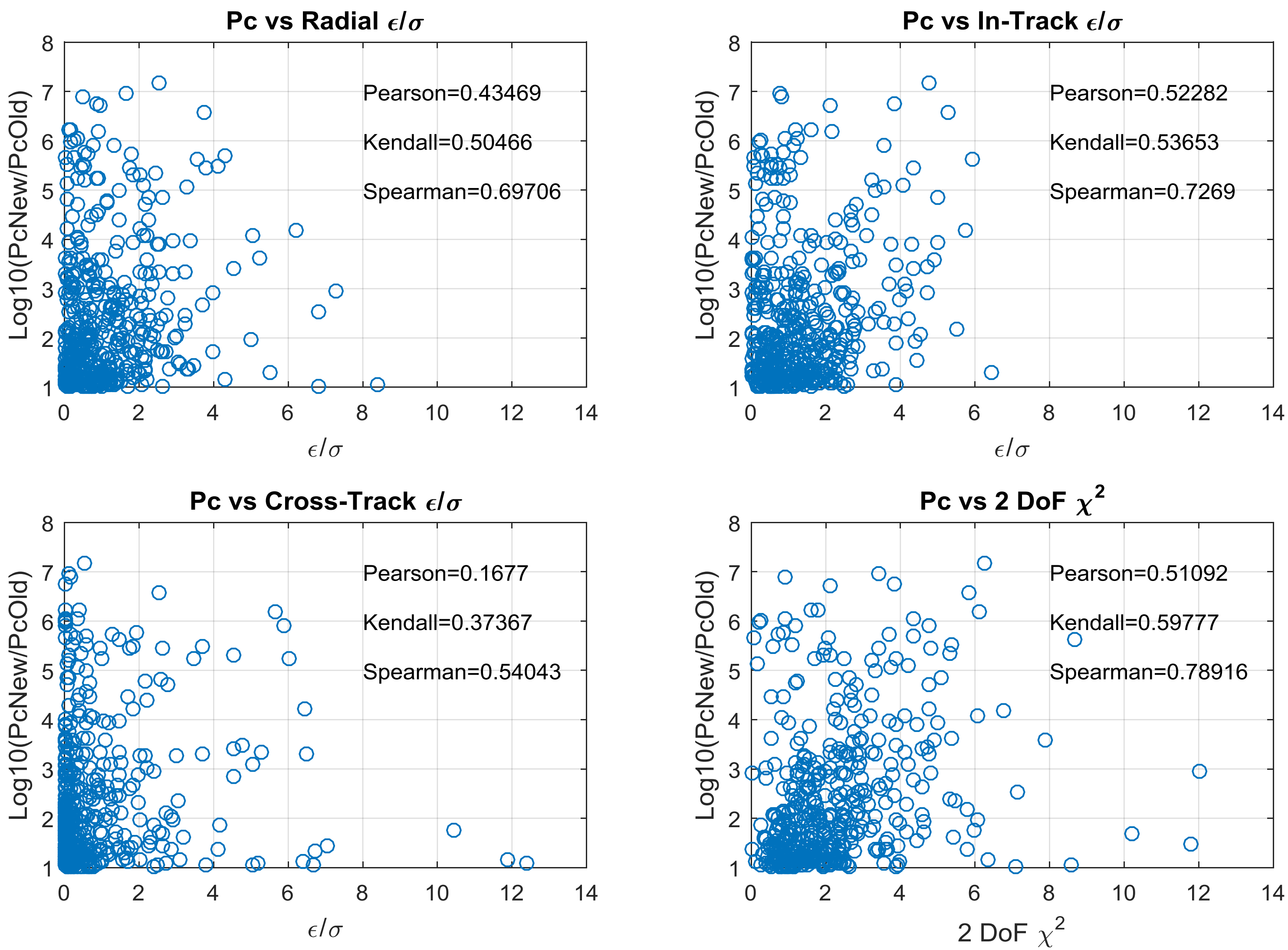
- **Test of monotonicity, computed by summing squares of differences in rank**
  - Mapped into same -1 to 1 range of values, with same interpretation
- **Computational formula**

$$\rho = 1 - \frac{6\sum_{i=1}^{n} d_i^2}{n\left(n^2 - 1\right)}$$

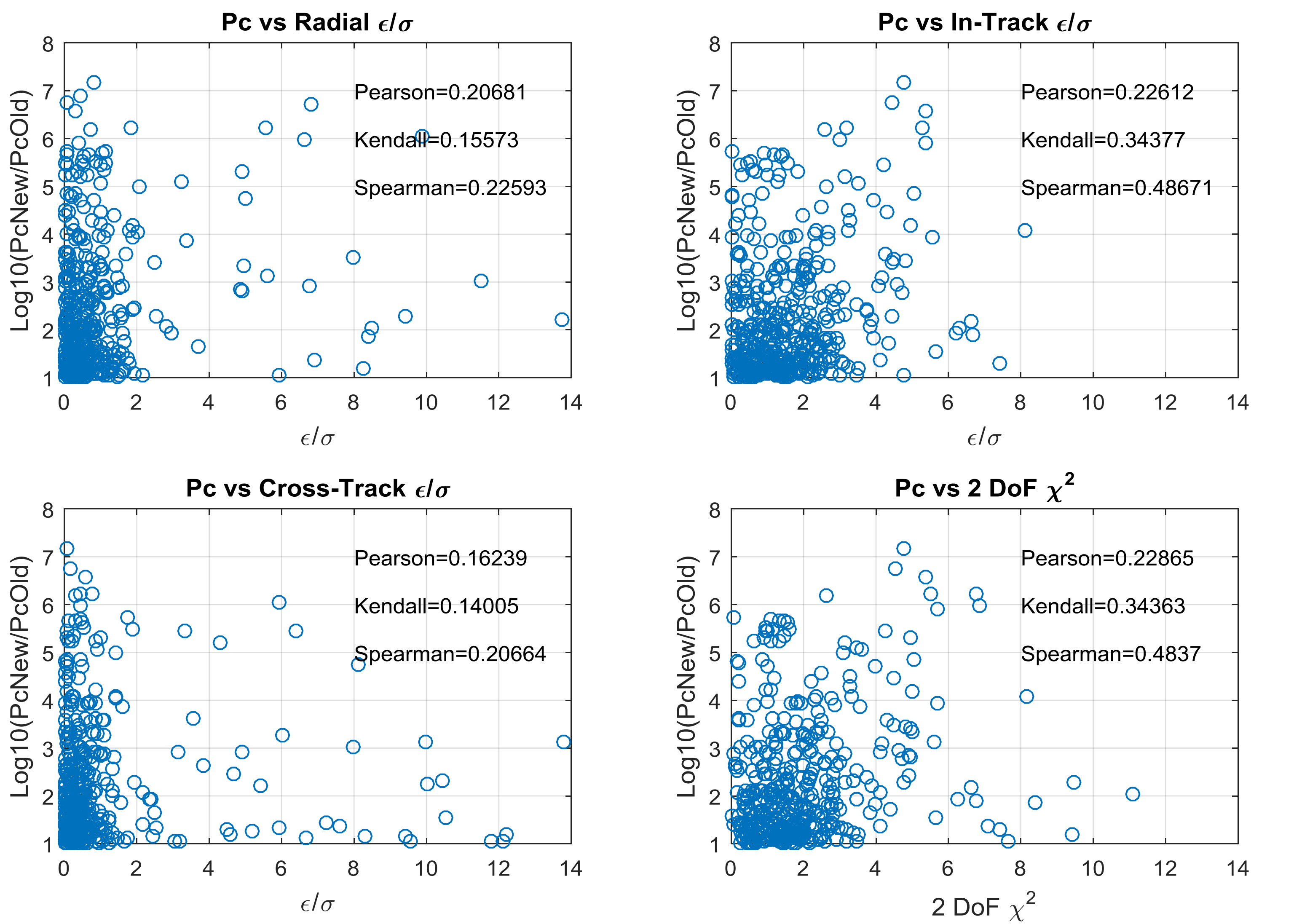
- **Computationally easier but more vulnerable to outlier data**
- **Usually larger than Kendall's tau**
- **Included here for consistency/contrast**

Main factor to consult is Kendall's Tau

Positive Change in Pc vs Secondary ε/σ



Positive Change in Pc vs Primary ε/σ



Positive Pc change vs ε/σ: Summary

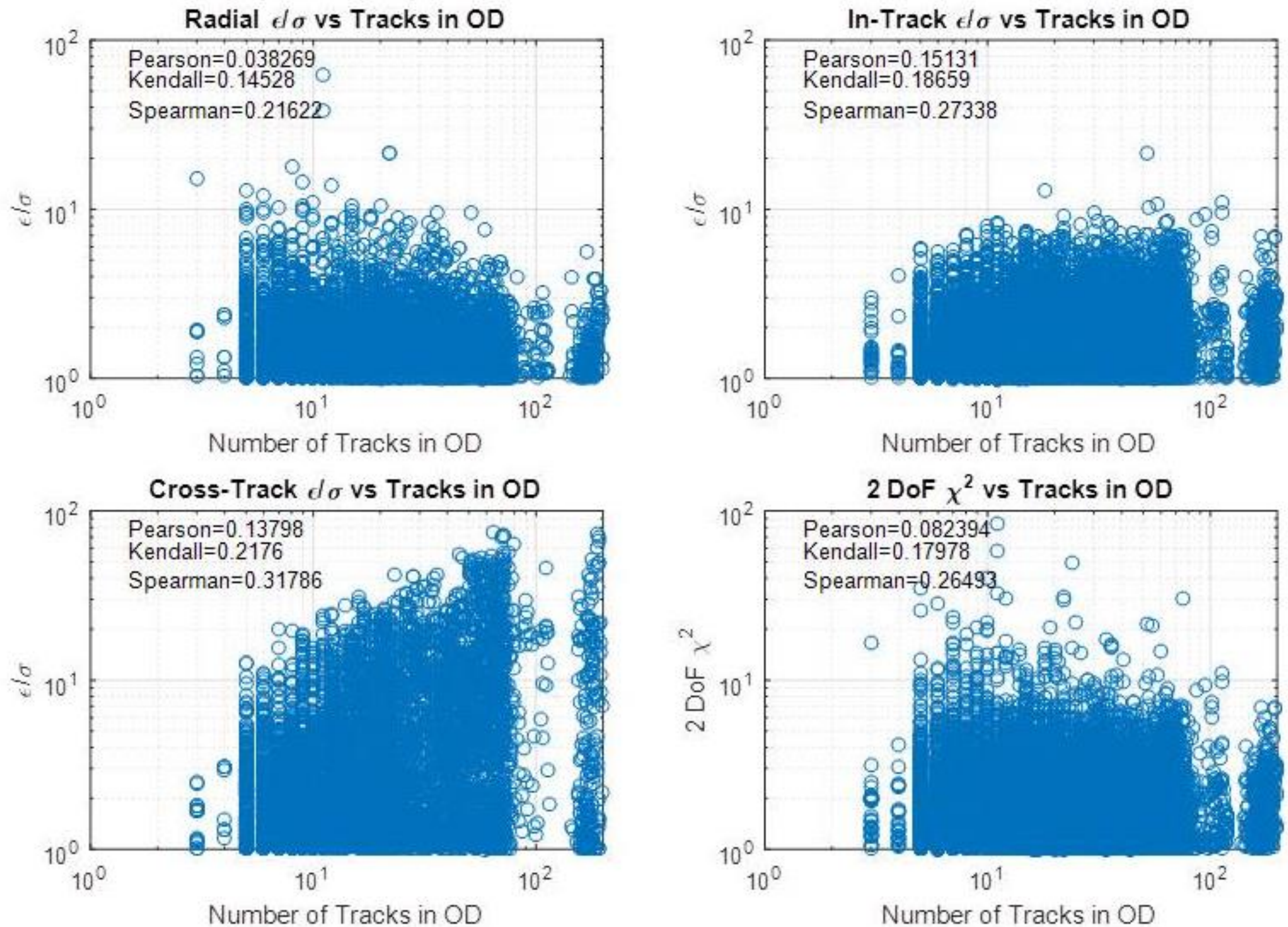
- **Summary table (Kendall's Tau):**

	Radial	In-Track	Cx-Track	Chi-Sq
Primary	0.15	0.34	0.14	0.34
Secondary	0.50	0.54	0.37	0.60

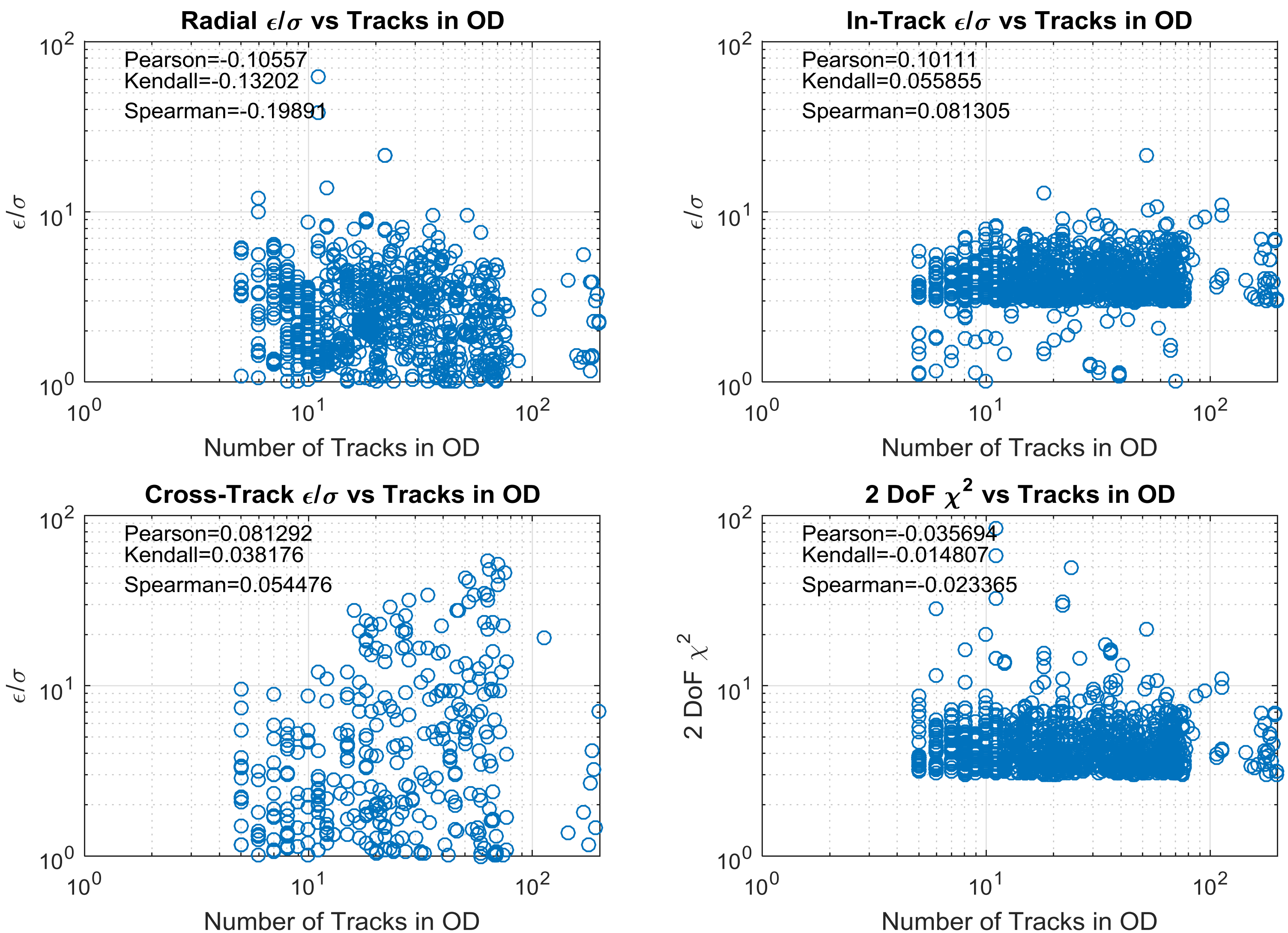
- **Pc correlation with large state changes in primary not very strong**
- **Pc correlation with large state changes in secondary of some significance, but still not overwhelming**

Large state changes in the secondary do correlate to large changes in Pc, but not all that strongly

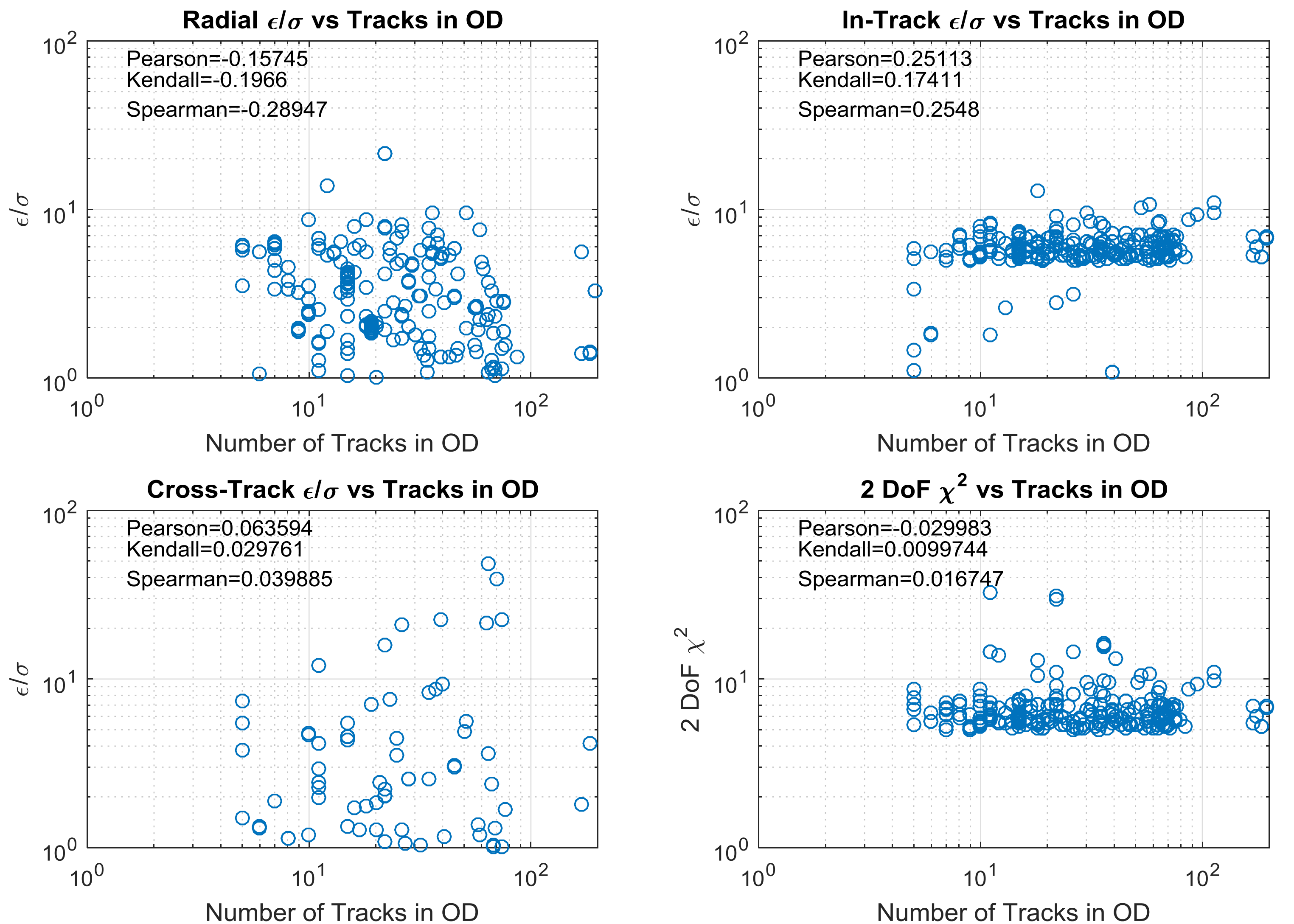
ε/σ vs # of Tracks in Secondary OD: All Data



ε/σ vs # of Tracks in Secondary OD: Radial or In-Track abs(ε/σ) > 3



ε/σ vs # of Tracks in Secondary OD: Radial or In-Track abs(ε/σ) > 5



ε/σ vs # of Tracks in Secondary OD: Interpretation

- **Correlations low, even for high-change events**
- **More tellingly, should produce inverse correlation but instead see positive correlation**
- **Difficult to conclude that unexpectedly large errors are associated with light tracking**

Sparse tracking for secondary does not correlate with large state errors

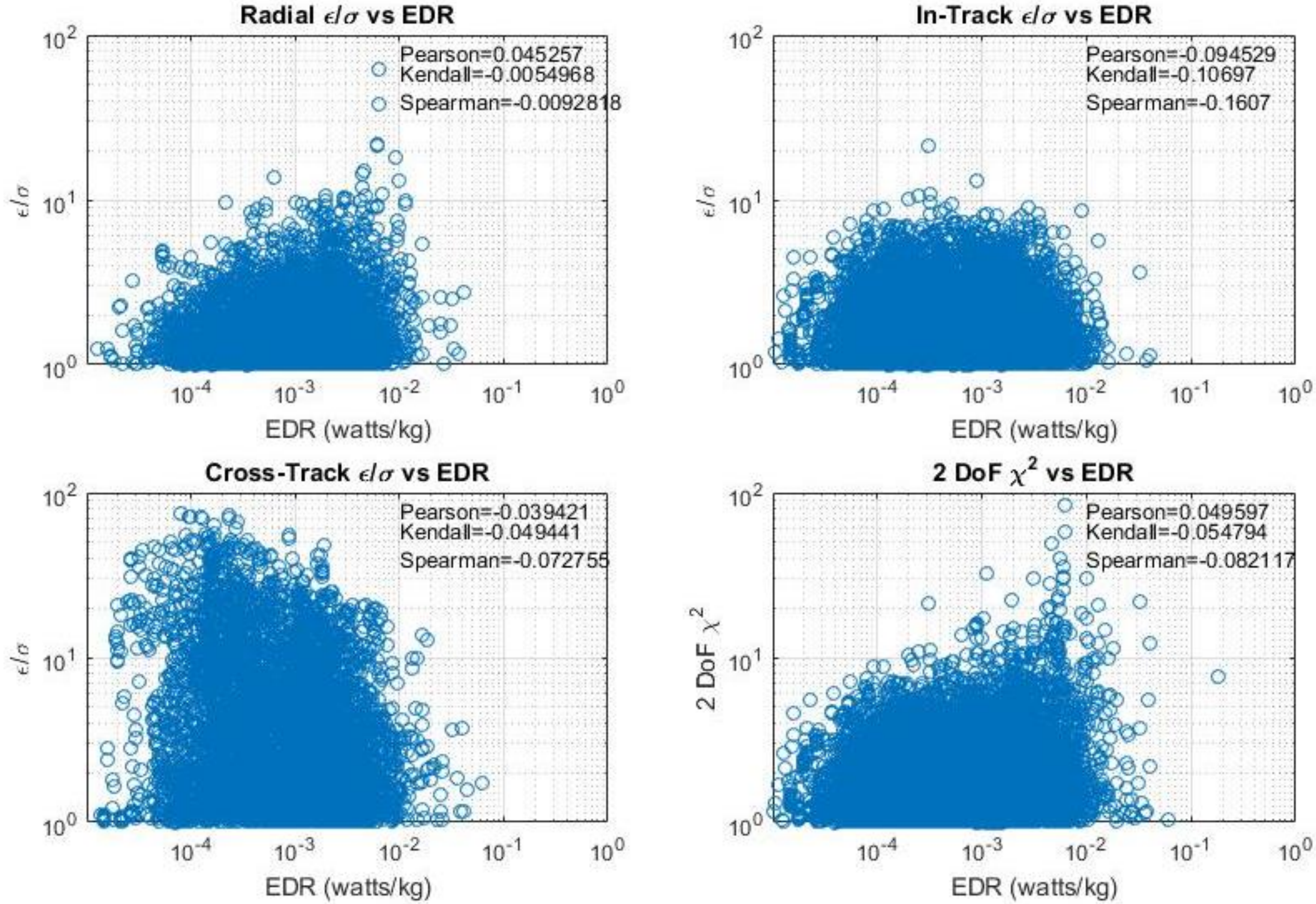
Energy Dissipation Rate

- **In 2001 study, Omitron investigated single-value representation of effect of atmospheric drag**
- **Proposed concept of the energy dissipation rate (EDR)**
  - Dot product of inertial drag acceleration vector and inertial velocity vector

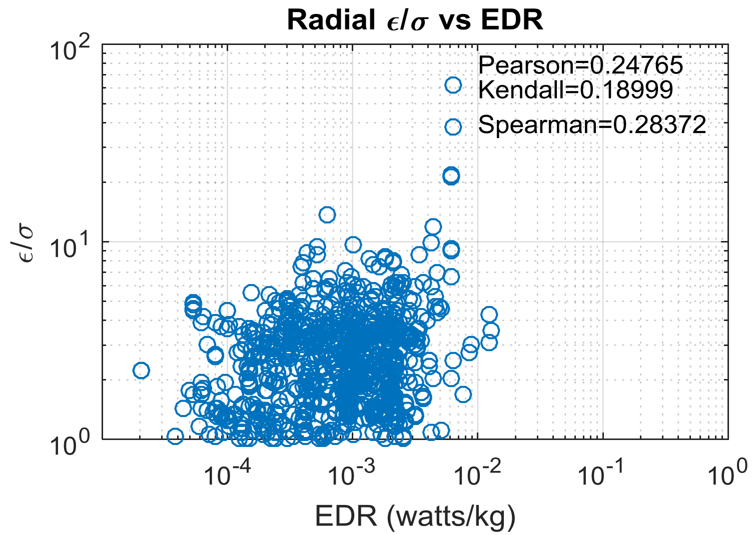
$$EDR(t) = -\vec{A}_D \bullet \vec{V}$$

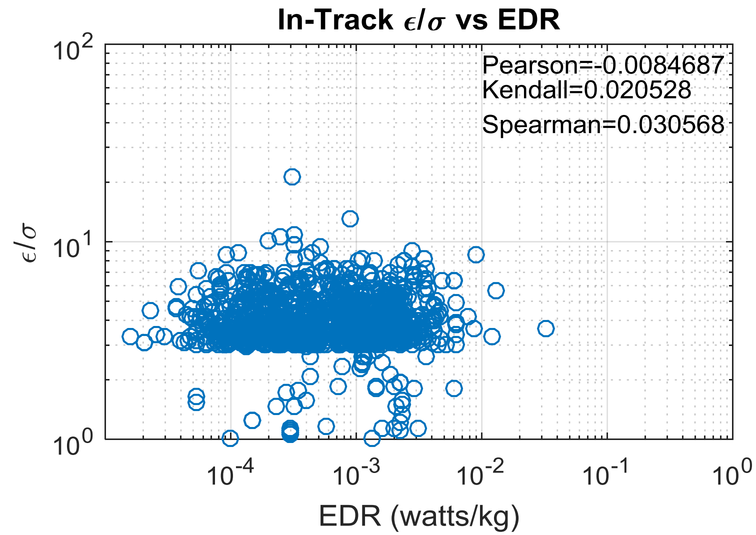
  - Units of watts per kilogram
  - Represents amount of energy being removed from the orbit
  - Occasionally amount of energy being added to orbit, such as by solar wind
- **EDR can serve as single-value encapsulation of ballistic coefficient and atmospheric density**

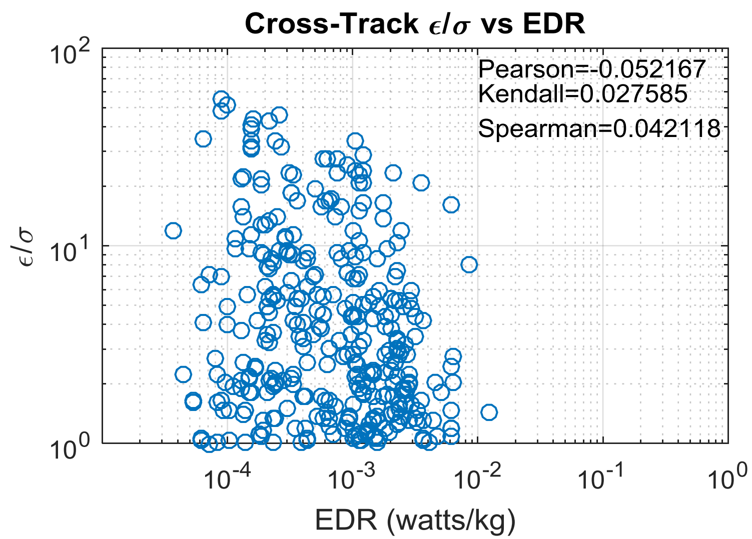
ε/σ vs EDR of Secondary: All Data

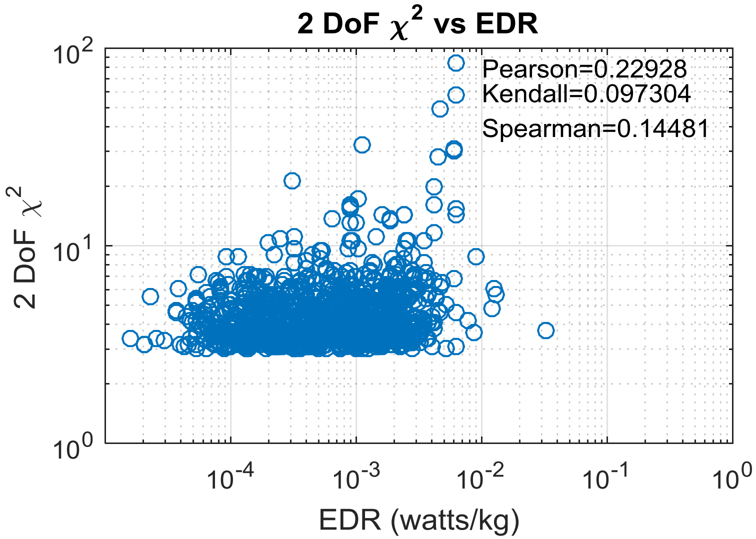


ε/σ vs EDR of Secondary : Radial or In-Track abs(ε/σ) > 3

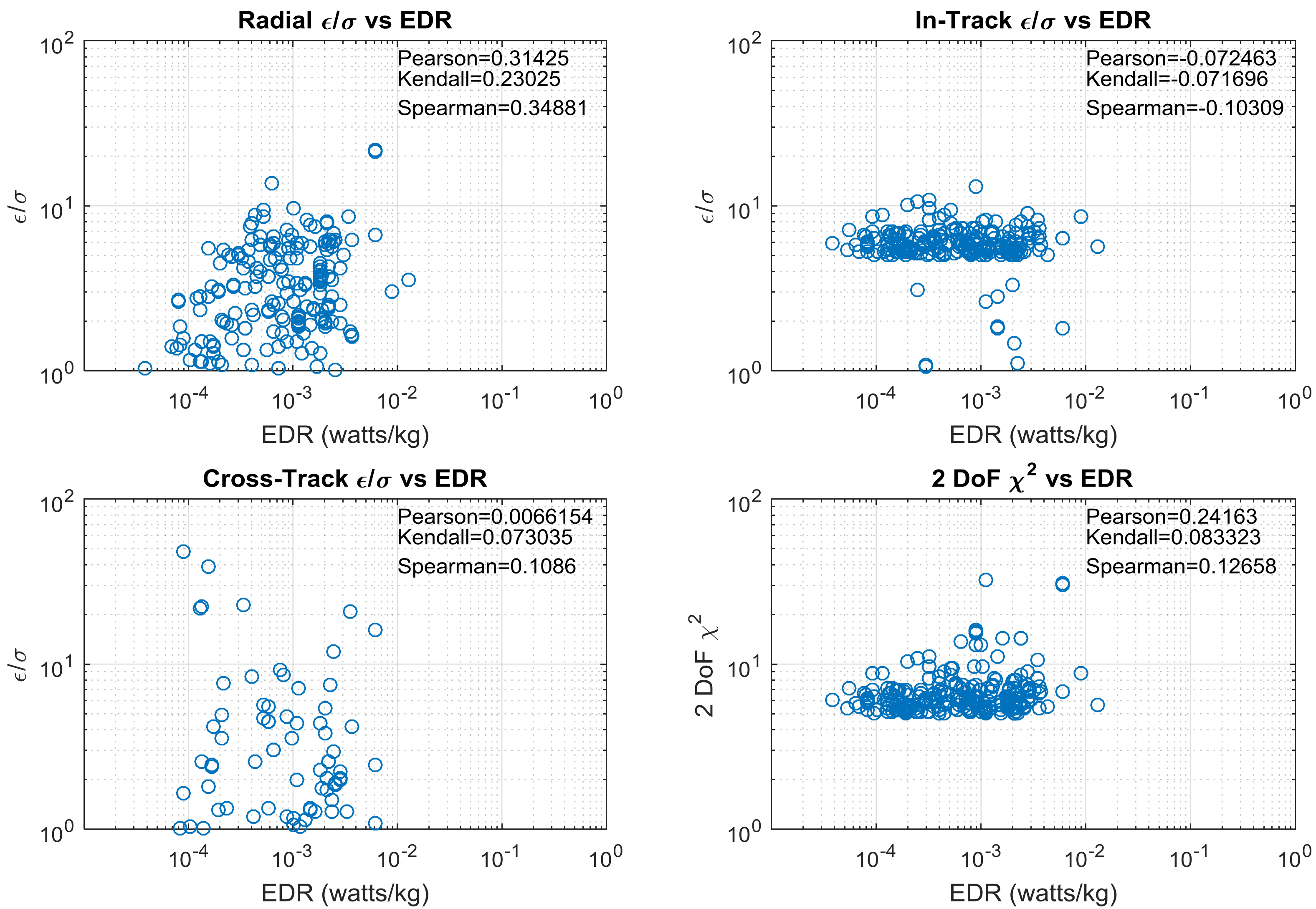








ε/σ vs EDR of Secondary: Radial or In-Track abs(ε/σ) > 5



ε/σ vs EDR of Secondary: Interpretation

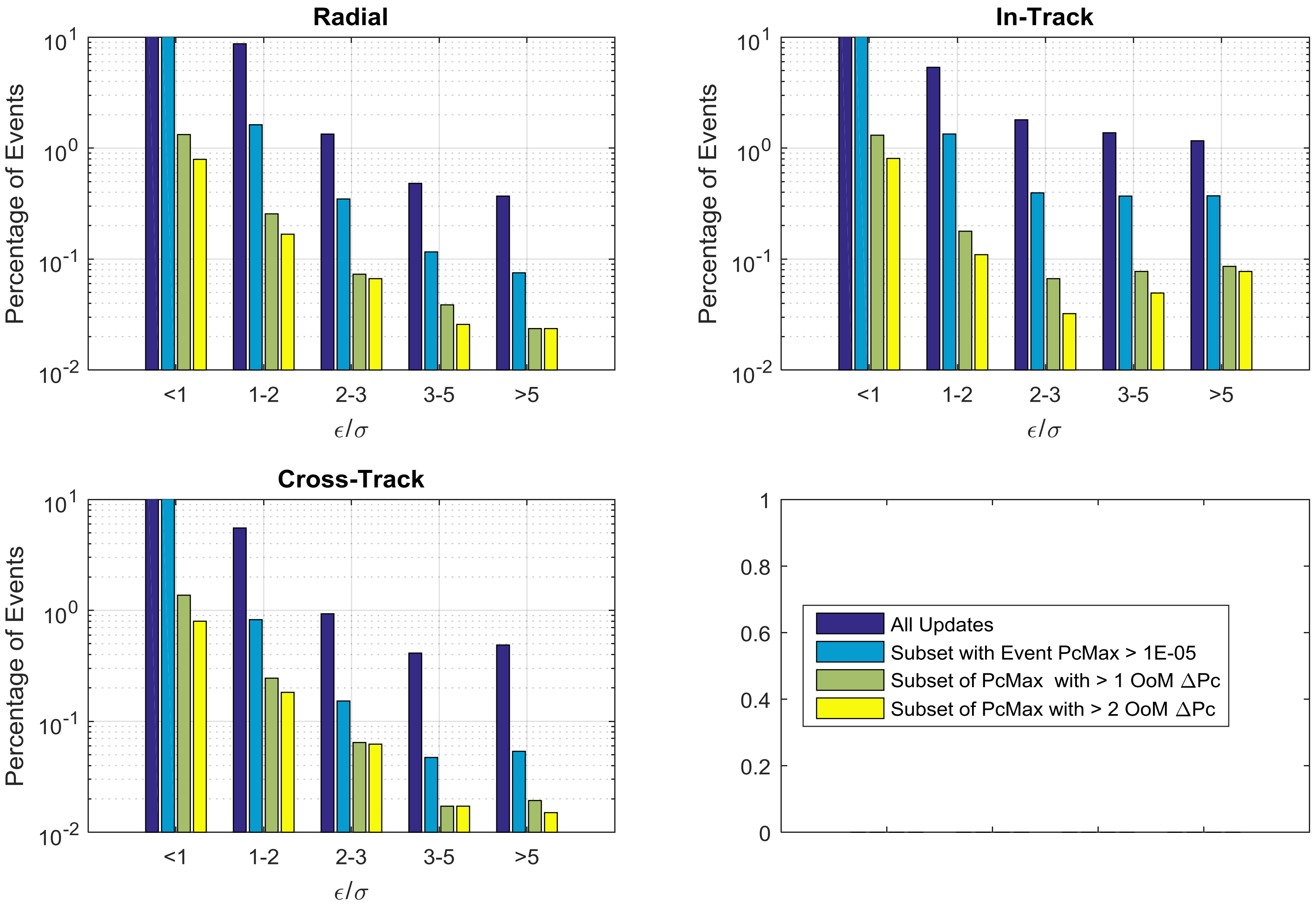
- **Correlation rather weak**
- **Somewhat stronger correlation when dataset limited to the higher ε/σ values, but even then not significant**

Higher EDR values for secondary do not correlate with larger state errors

Combined Situation

STATE-CHANGE FREQUENCY AND COMPARISON TO THEORY

Frequency of Large State Changes: Miss vs Combined Sigma

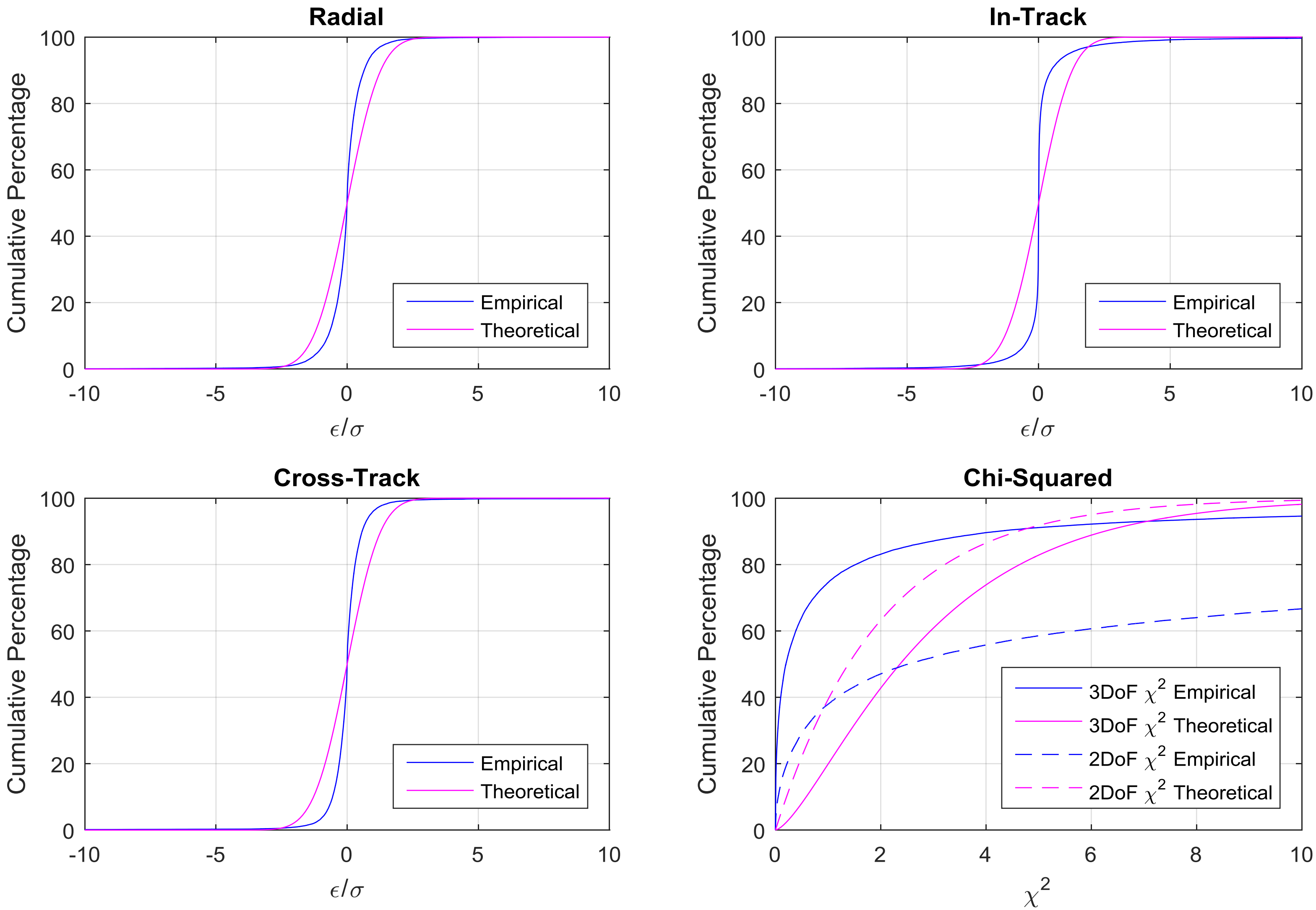


Frequency of Large State Changes: Tabular Summary

	Percent of Events in which abs(ε/σ) exceeds 3											
	Overall			Event Pc > 1E-05			> 1E-05 & ΔPc > 1 OoM			> 1E-05 & ΔPc > 2 OoM		
	Primary	Secondary	Combined	Primary	Secondary	Combined	Primary	Secondary	Combined	Primary	Secondary	Combined
Radial	1.57	1.33	0.85	0.37	0.30	0.19	0.09	0.08	0.06	0.08	0.06	0.05
In-Track	5.88	3.31	2.54	1.00	0.41	0.74	0.26	0.16	0.16	0.23	0.15	0.13
Cross-Track	13.53	7.10	0.90	2.64	0.88	0.10	0.34	0.13	0.04	0.22	0.09	0.03

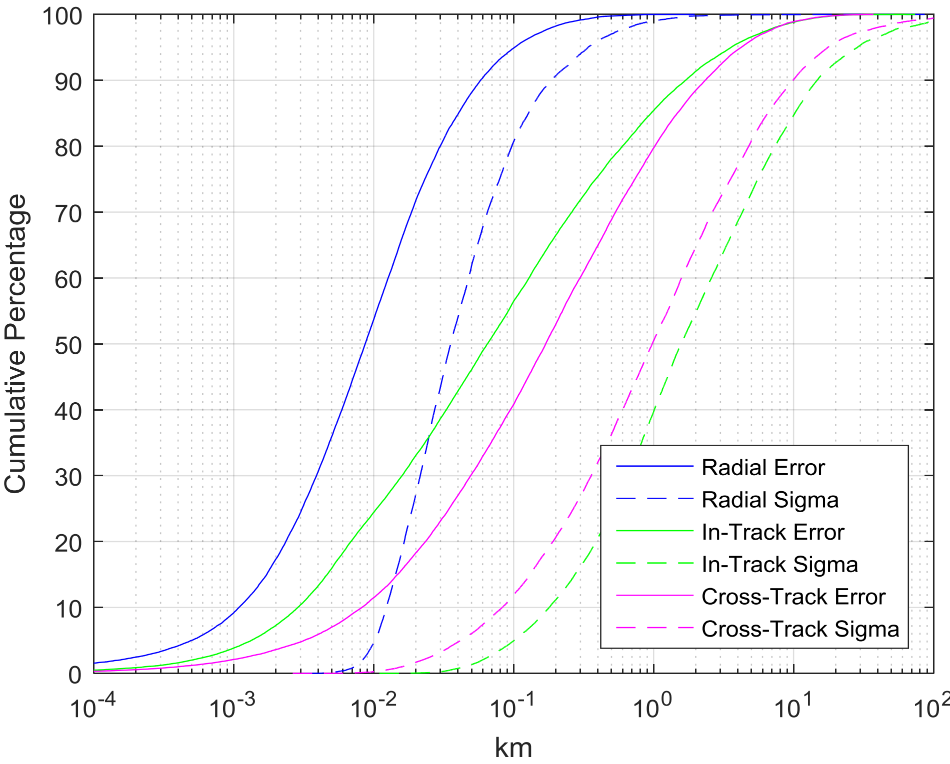
- **Values much closer to theoretical expectation, especially for radial and cross-track**
  - In-track is expected to be the most vulnerable to modeling errors, so not surprising that non-compliance largest in this component

Comparison of ε/σ to Theory: Miss Component vs Combined Sigma



Error and Sigma CDFs by Component: Combined Case

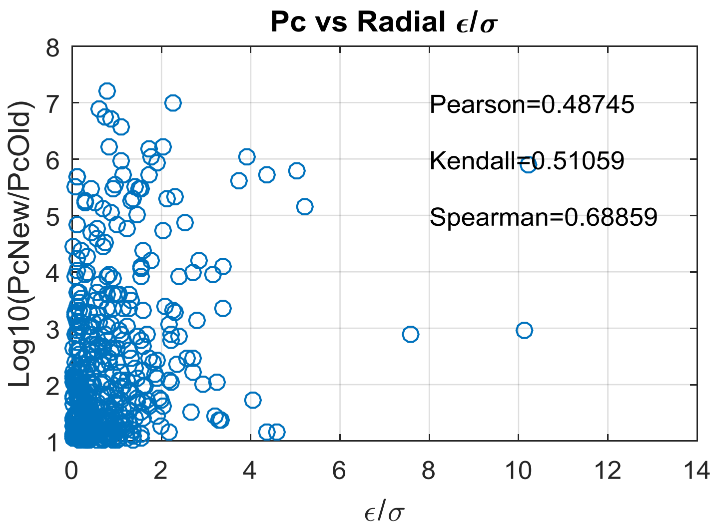
- **Better behaved than individual satellite results, especially for cross-track component**

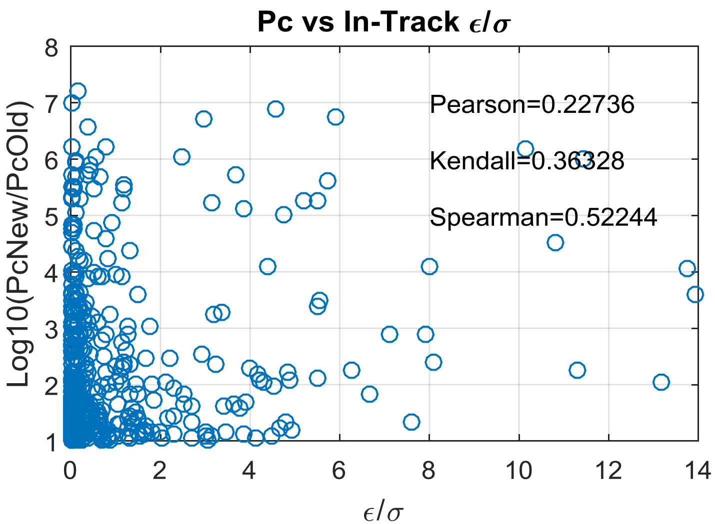


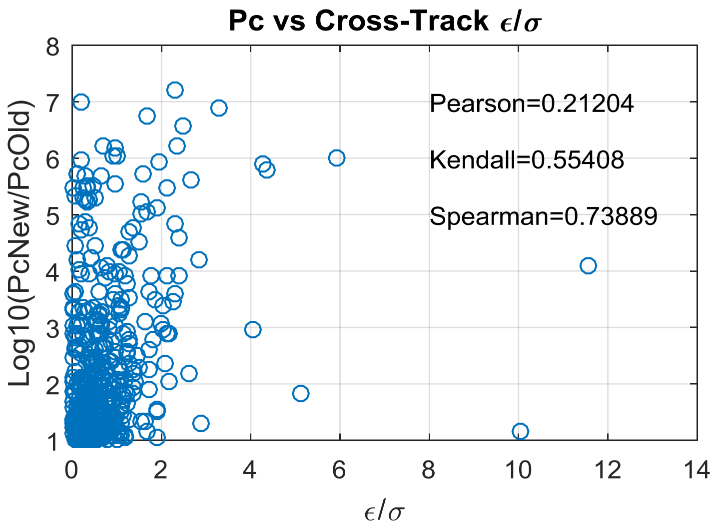
Combined Situation

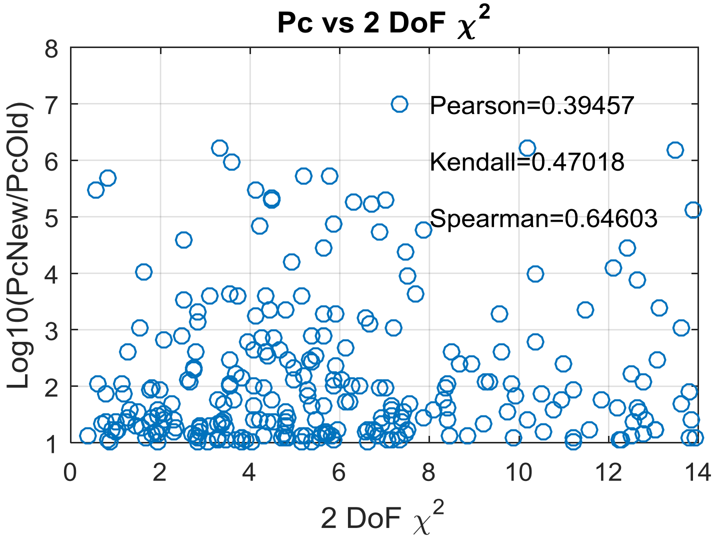
CORRELATION INVESTIGATIONS

Positive Change in Pc vs ε/σ









Positive Change in Pc vs ε/σ: Tabular Summary

	Radial	In-Track	Cx-Track	Chi-Sq
Primary	0.15	0.34	0.14	0.34
Secondary	0.50	0.54	0.37	0.60
Combined	0.51	0.36	0.55	0.47

- **Notable levels of correlation endure here, although less impressive than for secondaries alone**
- **Large state changes are with some frequency associated with positive change in Pc**
  - The larger the state change, the larger the Pc change

Large unexpected changes in miss distance are somewhat often associated with larger changes in resultant Pc value

Correlations with OD Tracking and EDR: Tabular Summary

- **Correlations are in most cases not significant and in an inverse relationship to what is expected**
  - Expect inverse correlation with tracking level and get regular correlation
  - Expect regular correlation with EDR and get inverse correlation
- **Difficult to see meaningful correlations with these indices**

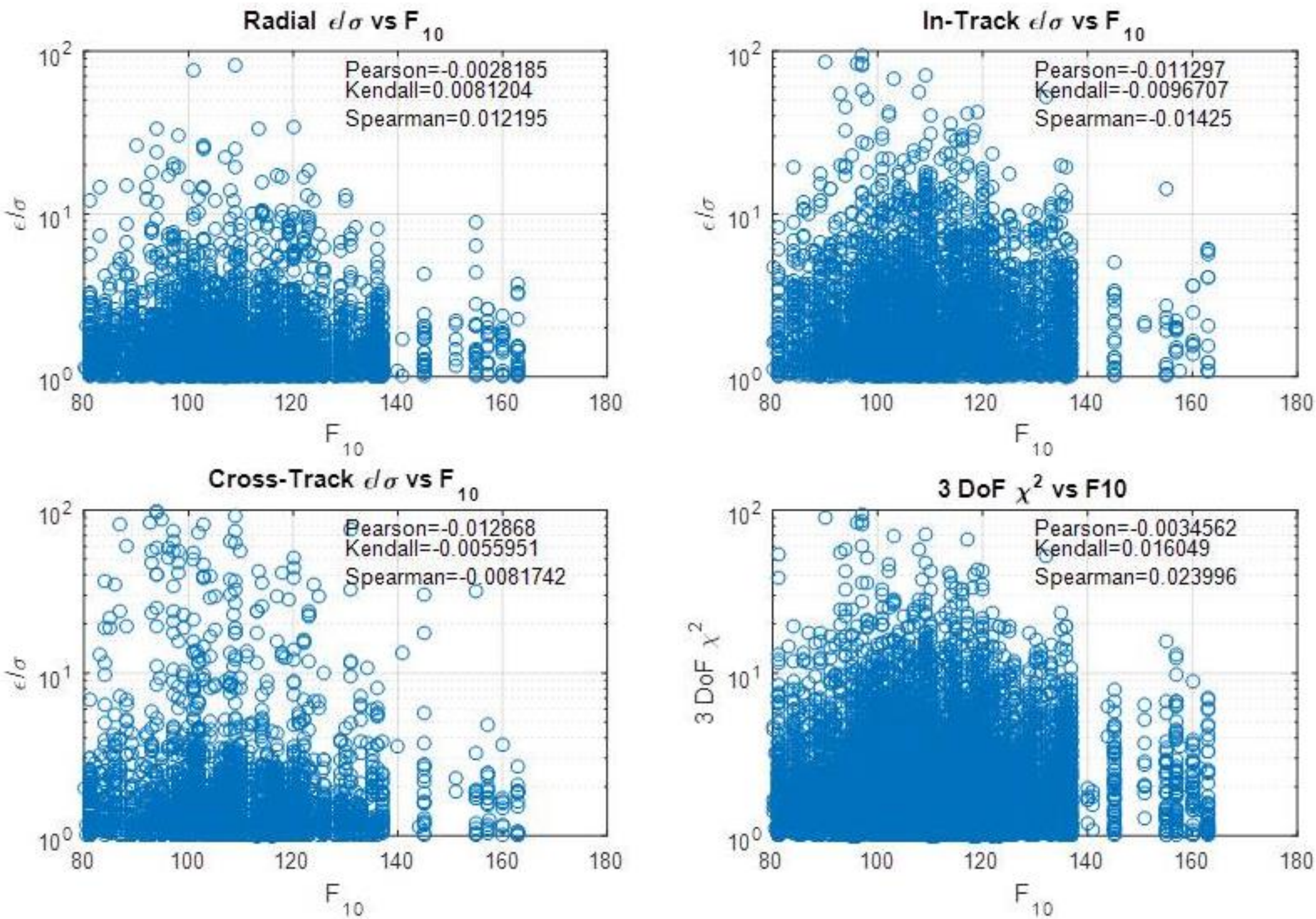
	Radial	In-Track	Cx-Track	Chi-Sq
Tracks in OD: Kendall				
All Data	0.17	0.11	0.15	0.10
$\varepsilon/\sigma > 3$	0.10	0.01	0.29	0.00
$\varepsilon/\sigma > 5$	0.18	0.02	0.37	0.07
Tracks in OD: Pearson				
All Data	0.07	0.02	0.05	0.01
$\varepsilon/\sigma > 3$	0.20	0.21	0.29	0.21
$\varepsilon/\sigma > 5$	0.30	0.32	0.43	0.33
EDR of Secondary				
All Data	-0.05	-0.10	-0.06	0.02
$\varepsilon/\sigma > 3$	-0.07	0.01	-0.27	0.04
$\varepsilon/\sigma > 5$	-0.19	-0.02	-0.39	-0.06

No meaningful correlation between secondary EDR value and large unexpected changes in relative miss

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, Ap)
  - 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 Ap over prediction interval
  - Peak Ap over prediction interval
- **Will investigate the latter with case studies**

Combined ε/σ vs Median F_{10}: All Data



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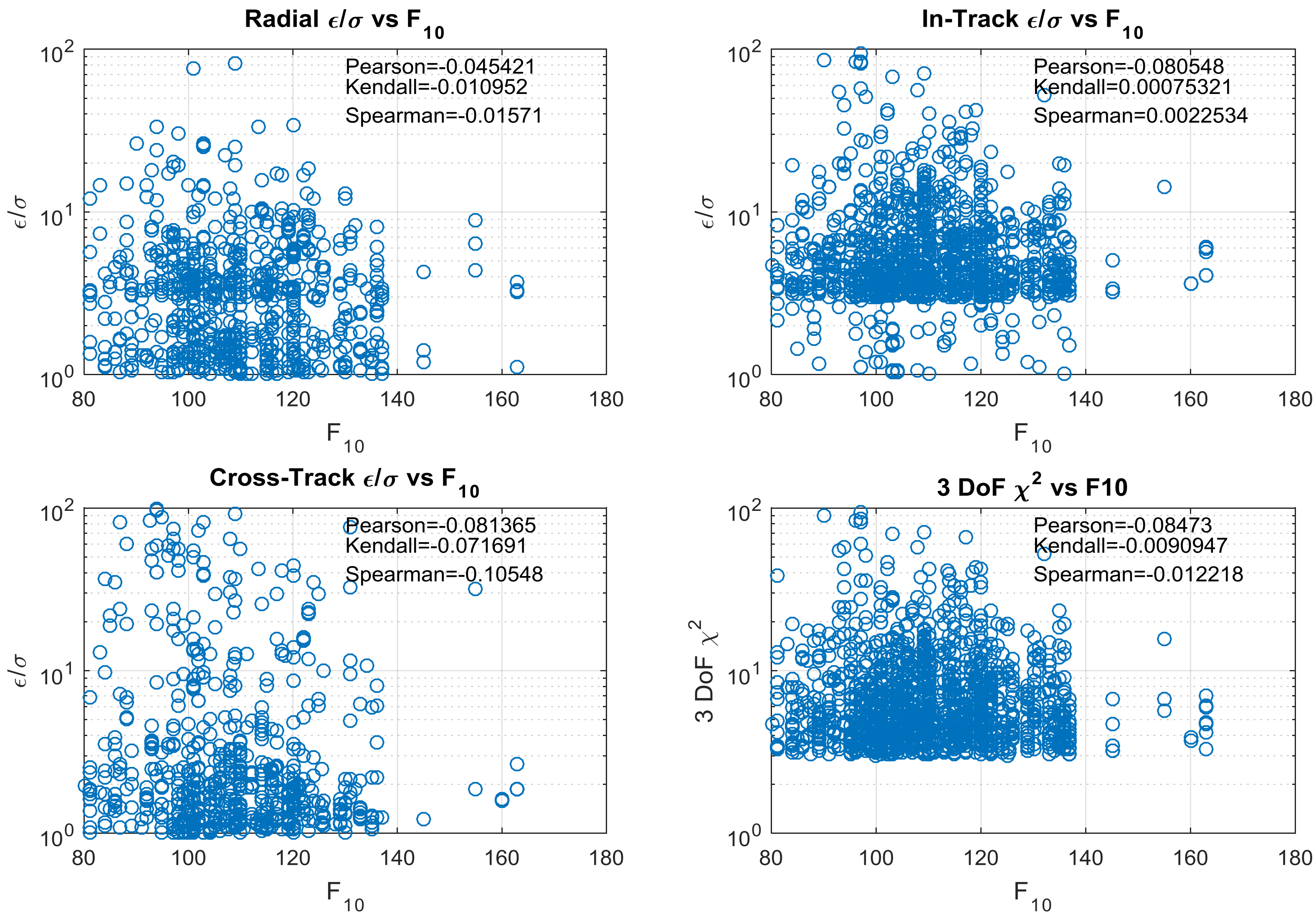
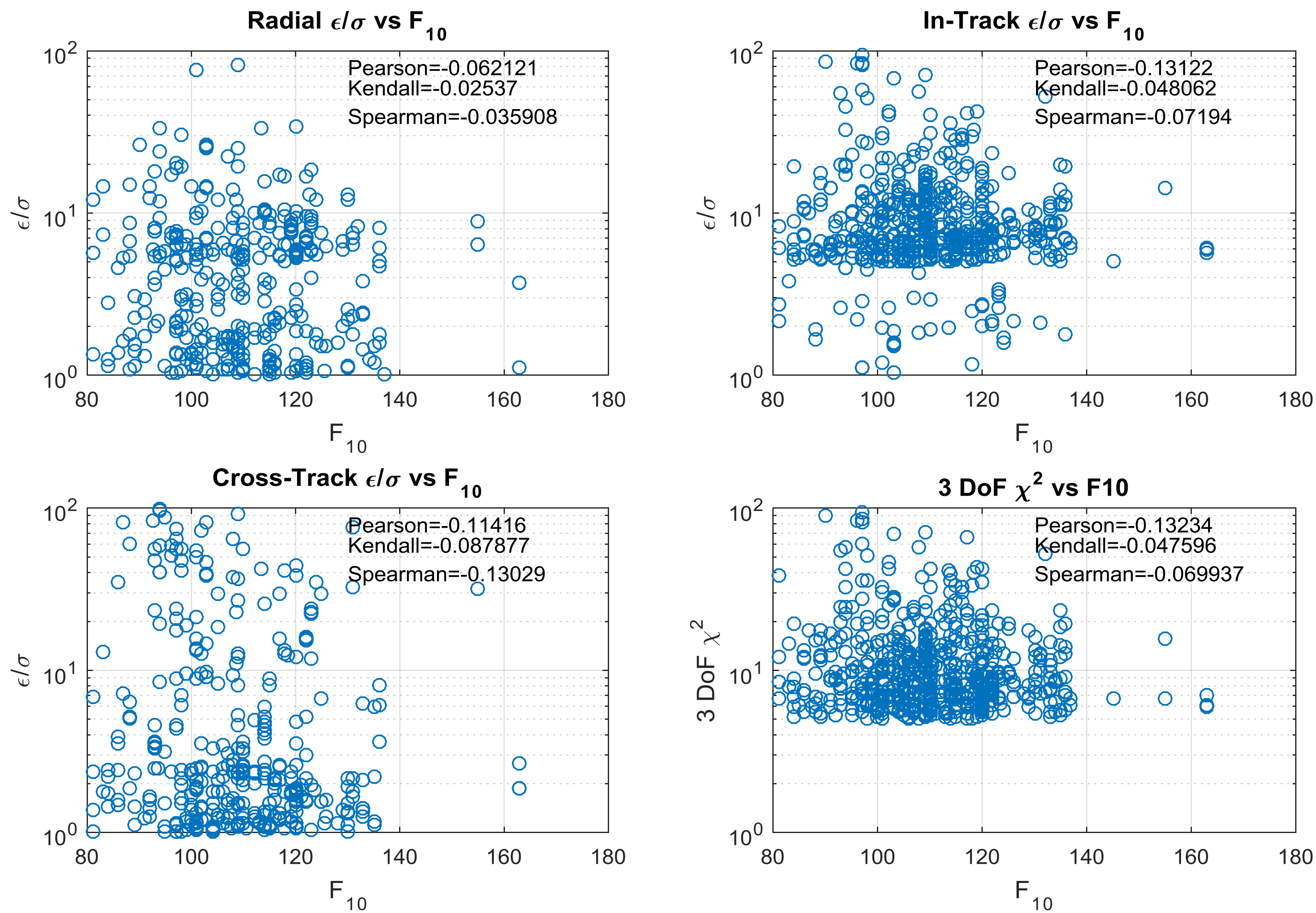
Combined ε/σ vs Median F_{10} : Any Component abs(ε/σ) > 3



Combined ε/σ vs Median F_{10} : Any Component abs(ε/σ) > 5



Combined ε/σ vs Solar Indices: Tabular Summary

	Radial	In-Track	Cx-Track	Chi-Sq
Median F10: Kendall				
All Data	0.008	0.01	0.006	0.02
ε/σ > 3	0.01	0.001	0.07	0.01
ε/σ > 5	-0.03	-0.05	-0.09	-0.05
Median Ap: Kendall				
All Data	0.02	-0.0001	0.02	0.02
ε/σ > 3	-0.05	-0.01	0.06	-0.04
ε/σ > 5	-0.003	-0.003	0.03	0.01
Peak Ap: Kendall				
All Data	0.03	0.009	0.03	0.04
ε/σ > 3	-0.04	-0.01	0.03	-0.04
ε/σ > 5	-0.04	-0.01	-0.02	-0.04

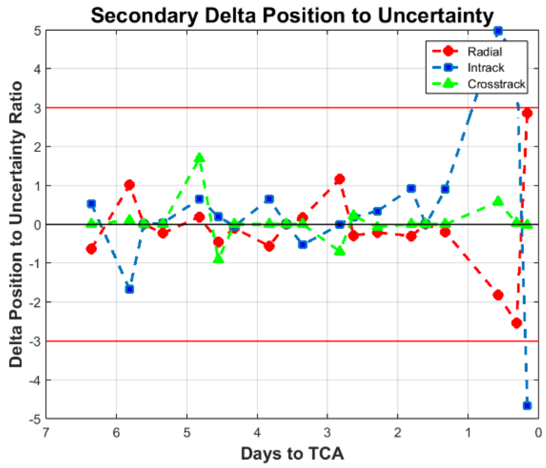
- **Correlations are essentially nonexistent in all areas**

Simple elevated levels of solar activity do not correlate with large changes in relative miss

CASE STUDIES

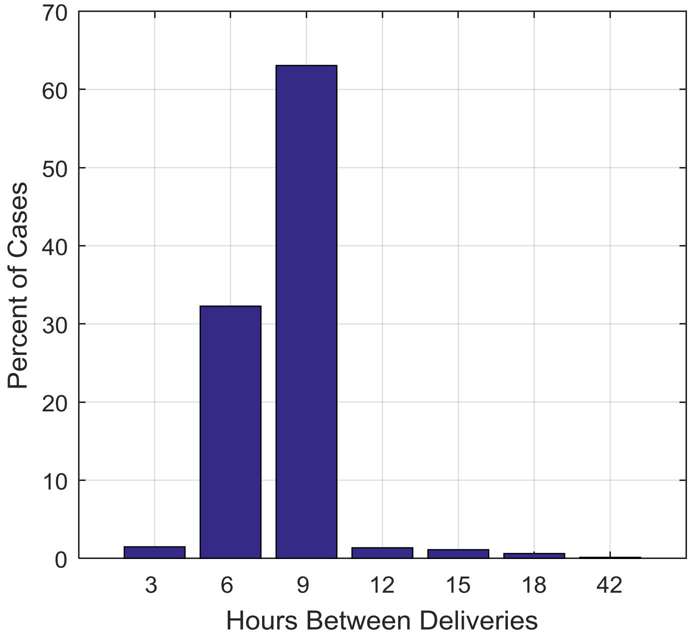
Late-Notice HIE Case Studies

- **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 201
  – Aura vs 89477; TCA 29 AUG 2015
  – Terra vs 37131; TCA 19 DEC 2015
  – GPM vs 28685; TCA 5 SEP 2015
- **Will look at**
  – ε/σ vs time (same as Δ position to uncertainty plots from daily/HIE report, like at right)
  – Pc vs time (same as from daily/HIE report)
  – Dst and Ap; prediction vs actual
    - Segmented by what is available in support of each update



JSpOC Space Weather Information Files: Delivery Information

- **Calculated externally at two different sites, through an arrangement with SET**
- **Forwarded three times a day to JSpOC**
- **Nominally at 0600, 1500, and 2100 Zulu**
- **Delivery goals met most of the time, but not always**
  - Occasionally files late or missing, as shown in graph at right
  - 4.7% of file spacings deviate from nominal cadence of 9 hrs, 9 hrs, and 6 hrs



JSpOC Space Weather Information Files: File Contents

YYYY	DDD	HH	MM	S10	S54	M10	M54	Y10	Y54	F10	F54	a_p	Dst	dTC	SRC
2001	87	00	00	212.7	169.1	202.2	152.8	201.8	154.2	273.4	155.9	15	-51	94	I
2001	87	06	00	214.1	169.3	204.4	153.0	202.1	154.5	274.4	156.4	56	-41	148	I
2001	87	12	00	215.5	169.5	206.6	153.1	202.3	154.7	275.0	157.0	94	-39	69	I
2001	87	18	00	216.6	169.7	208.7	153.3	202.6	154.9	274.5	157.5	15	-64	182	I
2001	88	00	00	217.4	169.9	210.8	153.5	202.9	155.1	272.5	158.0	22	-53	148	N
2001	88	06	00	217.8	170.1	212.6	153.7	203.2	155.4	269.2	158.5	39	-31	105	N
2001	88	12	00	218.0	170.3	214.2	153.9	203.5	155.6	265.4	159.0	18	-27	115	N
2001	88	18	00	218.0	170.4	215.3	154.2	203.7	155.8	262.2	159.5	7	-23	105	N
2001	89	00	00	218.2	170.6	216.1	154.4	203.8	156.1	261.1	160.1	16	-31	115	P
2001	89	06	00	218.4	170.8	216.3	154.6	203.9	156.3	261.2	160.7	16	-6	74	P
2001	89	12	00	218.3	171.0	216.1	154.8	203.8	156.5	261.6	161.3	16	4	88	P
2001	89	18	00	217.9	171.2	215.3	155.0	203.7	156.7	261.6	161.9	16	19	88	P
2001	90	00	00	217.0	171.3	214.1	155.2	203.3	156.9	260.4	162.4	16	35	88	P
2001	90	06	00	215.8	171.5	212.5	155.4	202.8	157.1	258.8	162.8	16	-131	218	P
2001	90	09	00	215.1	171.6	211.7	155.5	202.5	157.2	257.9	163.0	16	-298	410	P
2001	90	12	00	214.5	171.7	210.9	155.6	202.3	157.3	257.0	163.3	16	-321	461	P
2001	90	15	00	213.9	171.7	210.1	155.7	202.1	157.4	256.1	163.5	16	-352	459	P
2001	90	18	00	213.4	171.8	209.6	155.8	201.9	157.5	255.3	163.7	16	-283	341	P
2001	90	21	00	212.9	171.9	209.1	155.9	201.8	157.7	254.5	163.9	16	-259	237	P
2001	91	00	00	212.4	172.0	208.7	156.0	201.7	157.8	253.6	164.1	16	-238	142	P
2001	91	03	00	211.9	172.0	208.2	156.1	201.6	157.9	252.7	164.3	16	-222	54	P
2001	91	06	00	211.4	172.1	207.8	156.2	201.6	158.0	251.8	164.5	16	-199	88	P
2001	91	09	00	210.8	172.2	207.3	156.3	201.5	158.1	250.9	164.7	16	-176	88	P
2001	91	12	00	210.3	172.3	206.7	156.4	201.5	158.3	249.9	164.9	16	-148	88	P
2001	91	15	00	209.7	172.3	206.1	156.4	201.5	158.4	248.9	165.1	16	-133	88	P
2001	91	18	00	209.1	172.4	205.4	156.5	201.5	158.5	247.8	165.3	16	-115	88	P

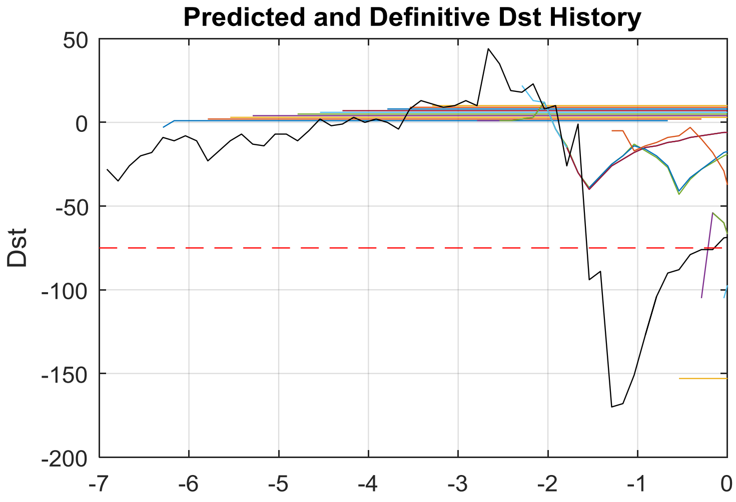
JSpOC Space Weather Information Files: Data Currency

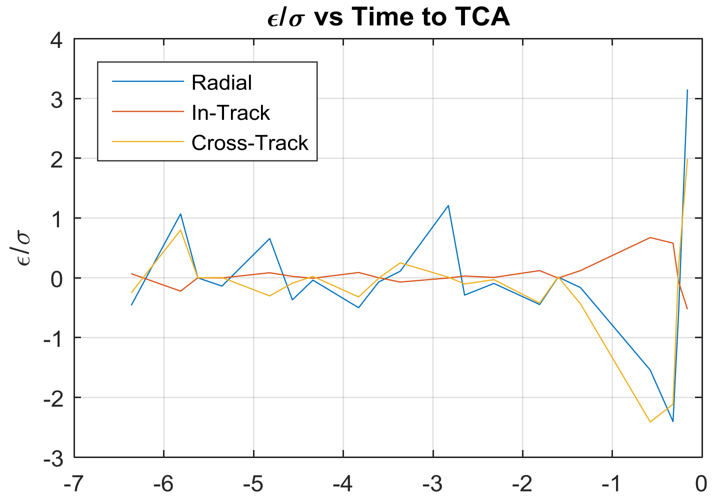
- **Three types of data in file**
  - "Issued" – definitive values for the solar/geomagnetic index, subjected to full availability of feeder data and consistency tests
  - "Nowcast" – initial observations of values, hand-scaled and not subject to consistency tests
    - Measurements stay in "nowcast" 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

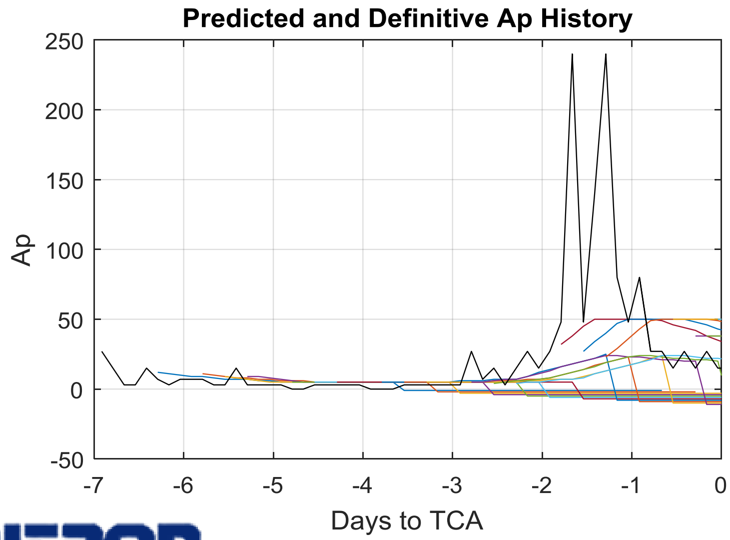
Space Weather Evolution Charts

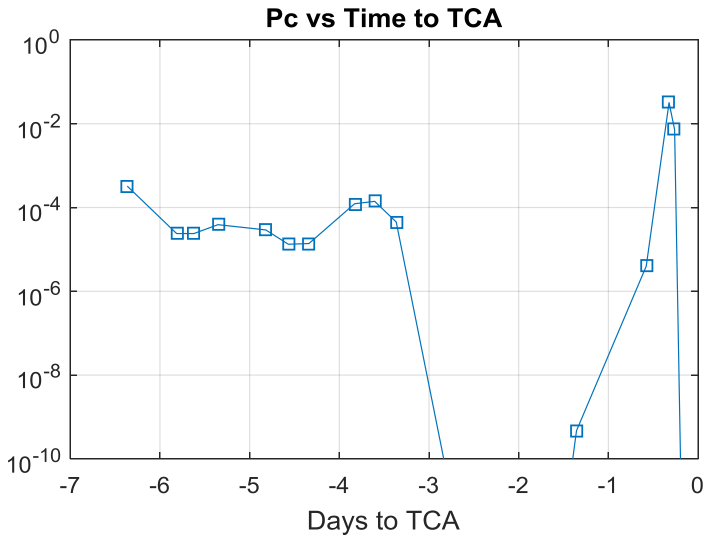
- **Upper left shows Dst; lower left shows Ap**
- **Black line is "issued" (definitive) data**
- **Colored lines are predicted data**
  - Each line begins when a given OD update executed
  - Each line shows predicted values of the geomagnetic index of choice
    - When Dst lines move to small positive value, prediction stops (zeroes in file)
    - When Ap lines move to small negative value, prediction stops (ones in file)
- **Dst threshold for solar storm compensation engagement also shown**
- **Upper right shows ε/σ for each component**
  - Miss distance vs combined covariance
- **Lower right shows Pc vs time**

Case Study #1: Terra vs 38192, TCA 24 JUN 2015



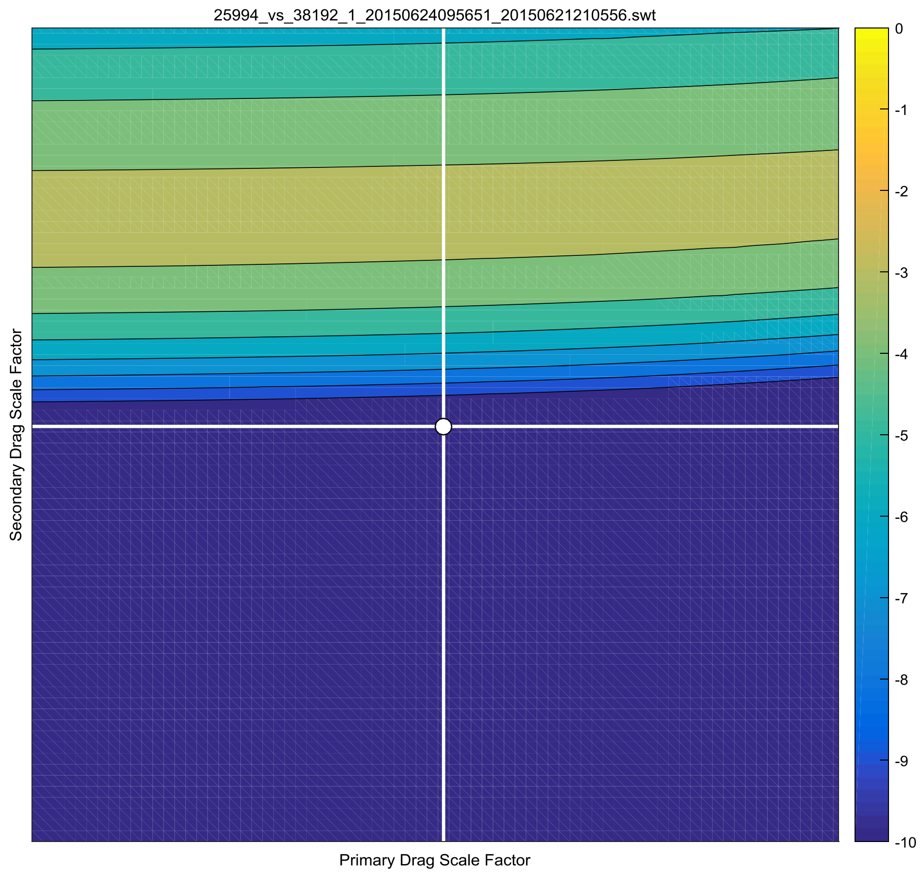






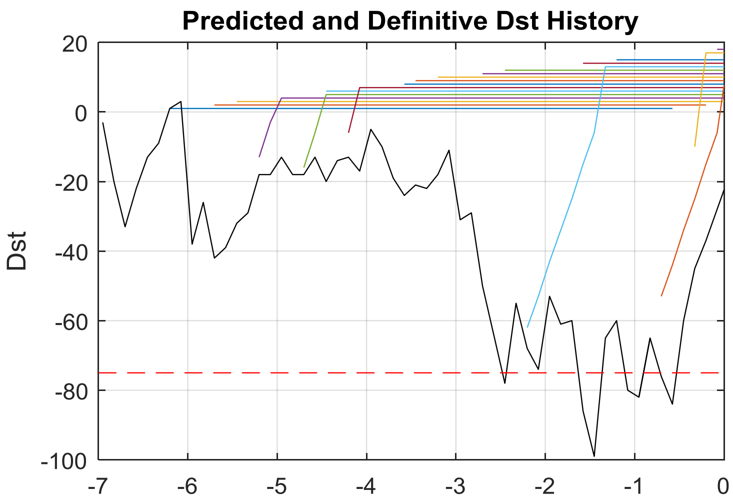
Space Weather Trade-Space Result: 61 Hours to TCA

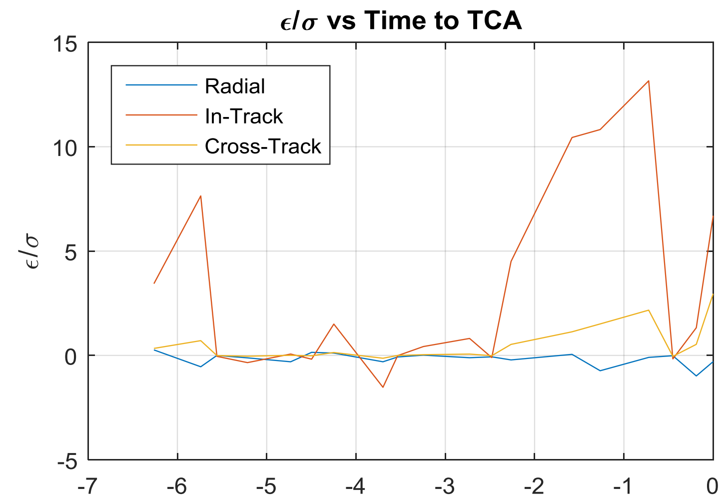
- **About half a day before spike in Ap/Dst begins**
  - Some predicted increased Dst activity, but not of severity actually realized
  - Predictions at very end of storm over-predict Dst
  - Final prediction and shrinking covariance produces Pc dropoff
- **SWTS indicates conjunction vulnerable to large Pc changes due to density mismodeling**

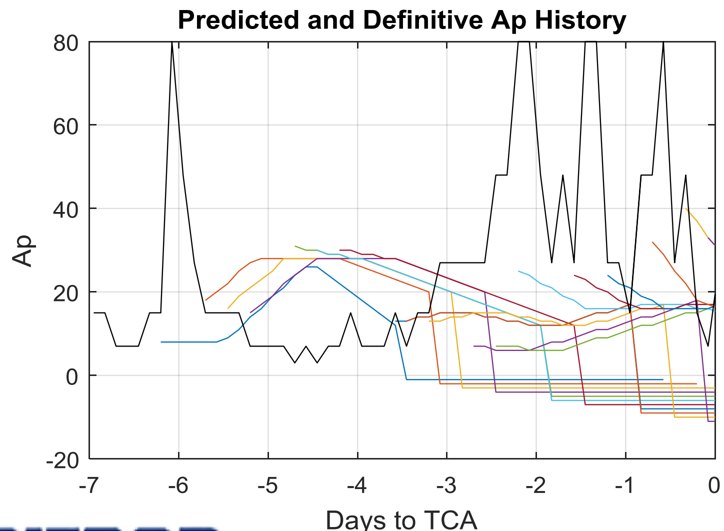


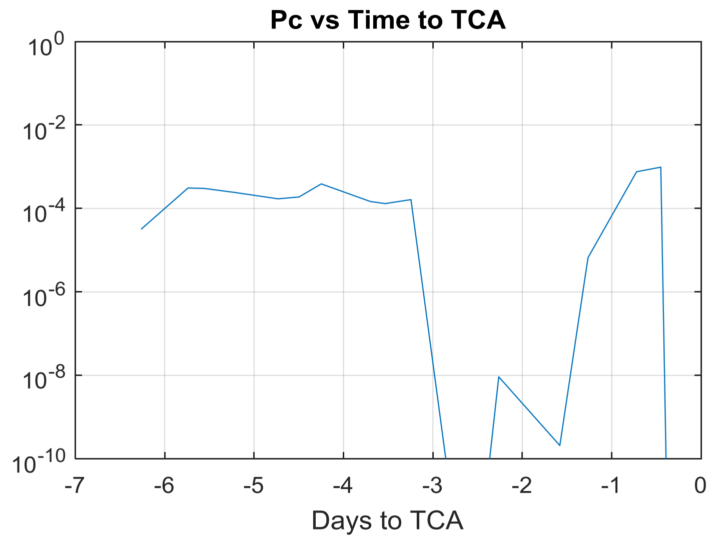
- **Bottom line: missed solar storm and subsequent prediction failures produced late changes**

Case Study #2: Aura vs 89477; TCA 29 AUG 2015



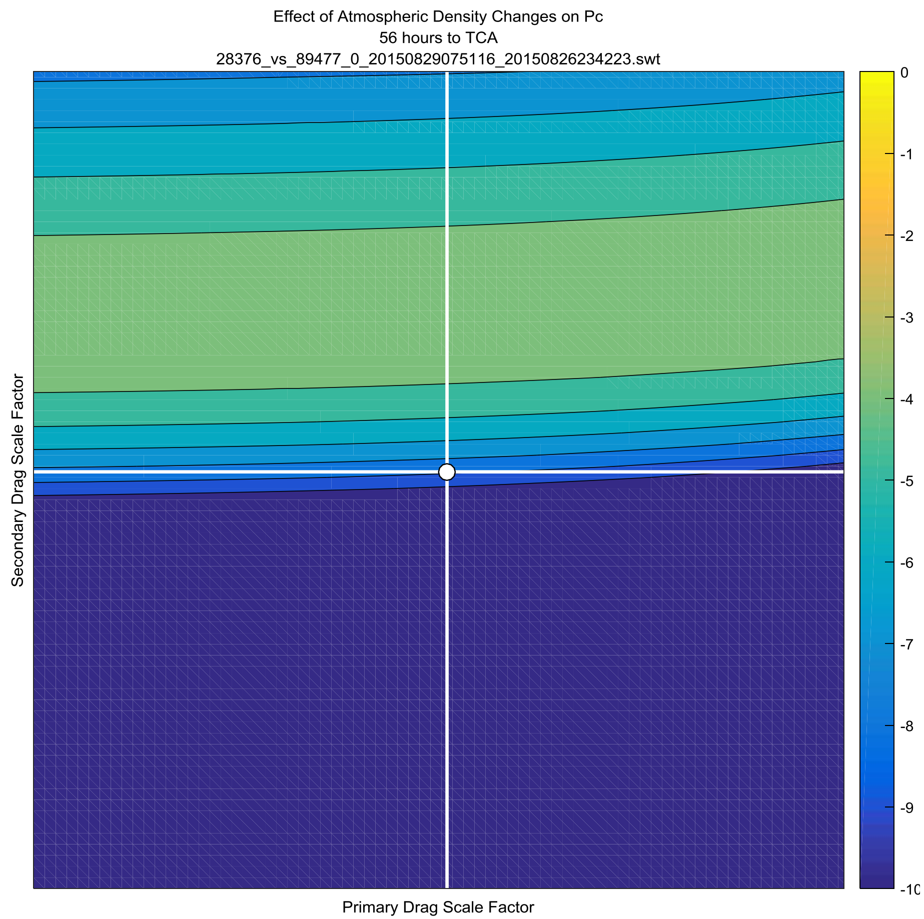






Space Weather Trade-Space Result: Aura vs 89477; 56 Hours to TCA

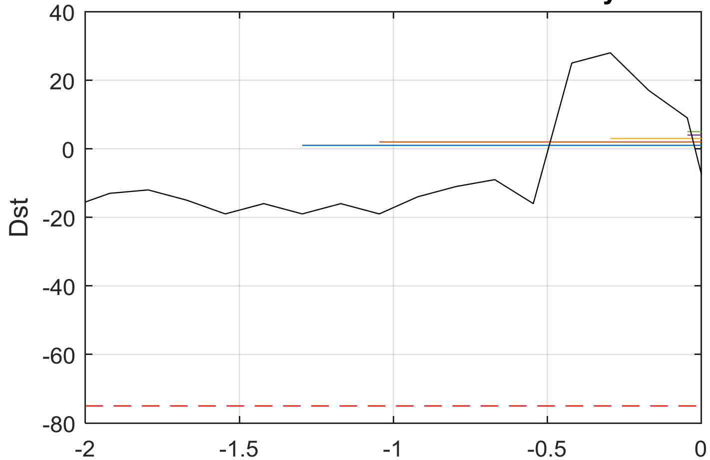
- **Run from update right as spike in Ap/Dst is beginning**
  - No predicted spike in relevant ASW space weather file
- **Indicates that conjunction vulnerable to large Pc changes due to atmospheric mismodeling**



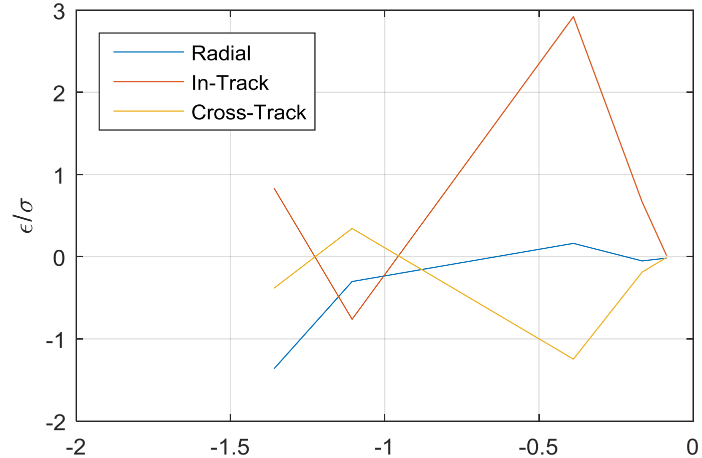
- **Bottom line: space weather predictions missed significant solar storm**
  - Most likely cause of late-breaking change in Pc

Case Study #3: Terra vs 37131; TCA 19 DEC 2015

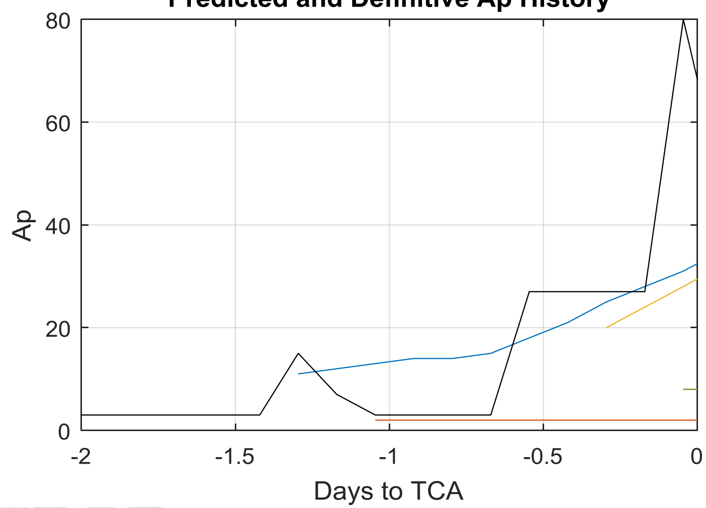
Predicted and Definitive Dst History



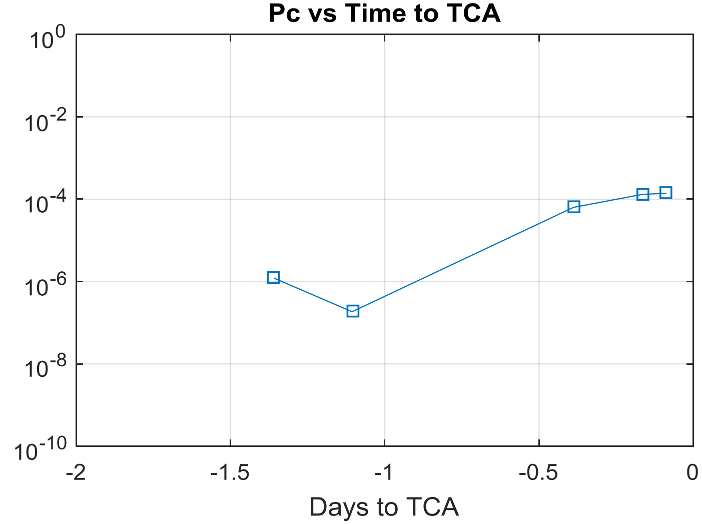
ϵ/σ vs Time to TCA



Predicted and Definitive Ap History

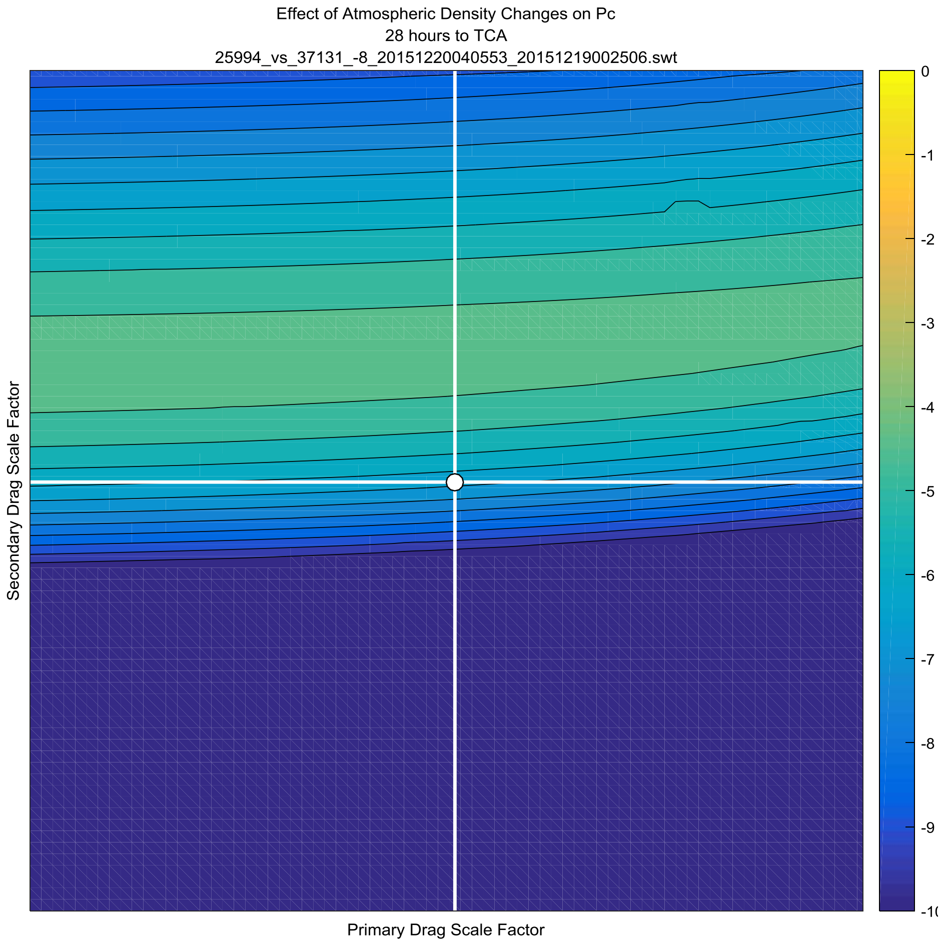


Pc vs Time to TCA



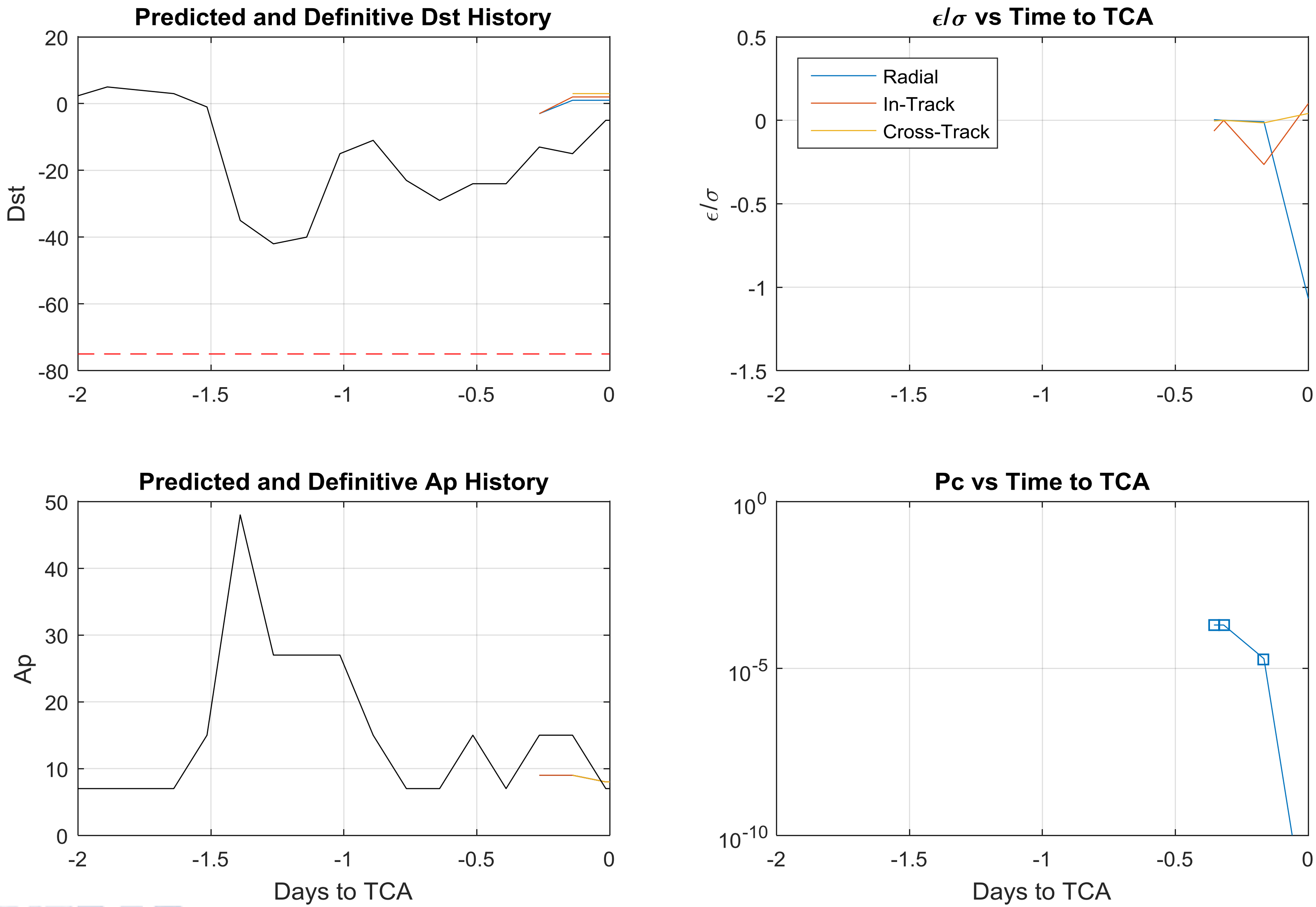
Space Weather Trade-Space Result: Terra vs 37131; 28 Hours to TCA

- **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 mismodeling**



- **Bottom line: odd space weather behavior, and deviation from predication, probably responsible for modest increase in Pc**

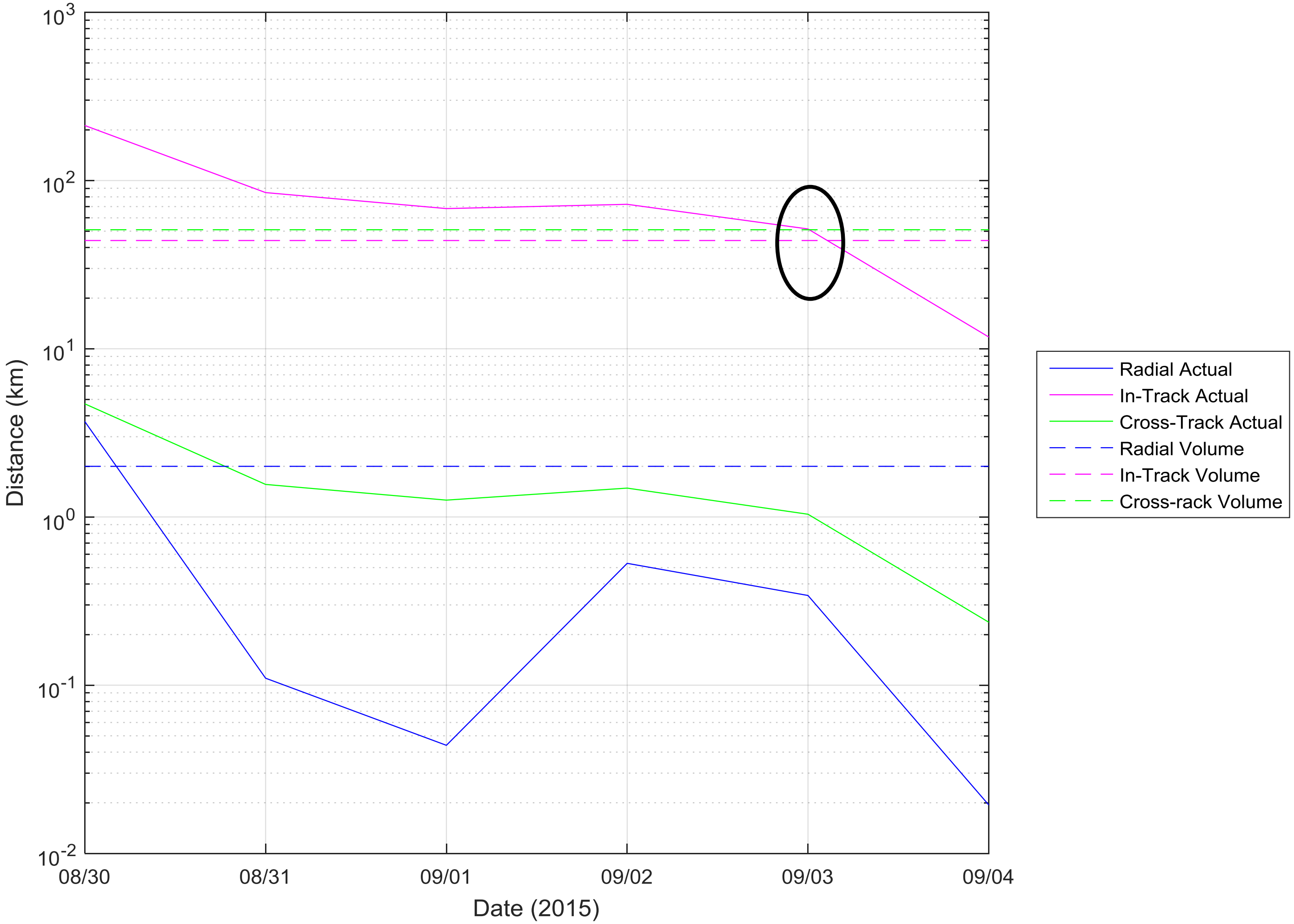
Case Study #4: GPM vs 28685; TCA 5 SEP 2015



Case Study #4: Situation

- **No particular space weather anomalies here**
- **Rather, simply a late-notice event**
- **When did this event first appear in the screenings?**
  - Because of ongoing screening-volume study, results from “large screening” experiment available during this period
    - 50 x 250 x 250
  - Can see how object fared against operational screening volume

Case Study #4: Screening Results (TCA on 09/05)



Case Study #4: Screening Results Discussion

- **Late-notice situation here mostly bad luck**
  - R and C components within screening volume ~6 days before TCA
  - In-track component above threshold for several days, barely above threshold two days before TCA, and violates it about 17 hours before TCA
  - CDM appears to have been generated as part of run subsequent to screening
- **Increased speed of current processes will improve this situation somewhat in future**
  - 3 screenings/day will find such edge cases faster
  - Faster processing will get CDM out faster after conjunction discovery

SUMMARY AND WAY FORWARD

Late-Breaking HIEs: Overall Summary

- **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 Predictions: What are we Doing? (1 of 2)

- **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

Solar Storm Predictions: What are we Doing? (2 of 2)

- **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**

Screening Volume Sizing: What are we Doing?

- **First, must recognize that edge cases will exist with any volume size**
- **Study of proper screening volume sizing presently in work**
  - Preliminary results set briefed to JSpOC in March
  - Set of refinements presently being performed; expect to issue a definitive update in next couple of months
- **Certain philosophical issues need to be adjudicated**
  - *e.g.,* increasing screening volume size to produce a large number of additional events, all with a Pc of 0, does nothing to provide better situational awareness
- **In the end, two changes will probably take place**
  - Screening volume sizes will increase
  - Some sort of additional winnowing test on captured candidates will be performed in order to identify events worthy of increased attention/tasking
- **Stay tuned!**

BACKUP SLIDES

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**

$$Z_q^2 + Z_r^2 = \chi^2_{2\,dof}$$

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**

$$Z_u^2 + Z_v^2 + Z_w^2 = \chi^2_{3dof}$$

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 ε is position difference between state estimate and precision ephemeris, and covariance consists only of variances along the diagonal**
  - Inverse of covariance matrix is straightforward

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

- **Resultant simple formula for chi-squared variables**

$$\varepsilon C^{-1} \varepsilon^T = \frac{\varepsilon_u^2}{\sigma_u^2} + \frac{\varepsilon_v^2}{\sigma_v^2} + \frac{\varepsilon_u^2}{\sigma_w^2} = \chi^2_{3\,dof}$$

- **Extension to case with off-diagonal terms straightforward**