National Aeronautics and Space Administration

Predicting Space Weather Effects on Close Approach Events

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Agenda

- Pc and Pc error modeling
- Atmospheric drag basics
- The JBH09 atmospheric model and the *Anemomilos* solar storm compensation model
- Determining conjunction event sensitivity to atmospheric density mismodeling
- The Space Weather Trade Space (SWTS)
  - Three canonical response types
- SWTS response statistics
- Conclusions

Computing Pc

- The Probability of Collision (Pc) represents the probability that two satellites will come within a specified miss distance of each other
- In most cases, it can be calculated by the area integral below:

$$P_c = \frac{1}{2\pi\sqrt{\|C\|}} \iint_A e^{-\frac{1}{2} r^T \mathbf{C}^{-1} r} \, dxdz$$

  - r is the nominal miss distance between the satellites
  - C is the combination of the two objects' covariance matrices
  - A is the area representing the combined size of the two objects
- Calculation thus considers the uncertainty in the state estimates (as represented by the covariance) in forming the probability

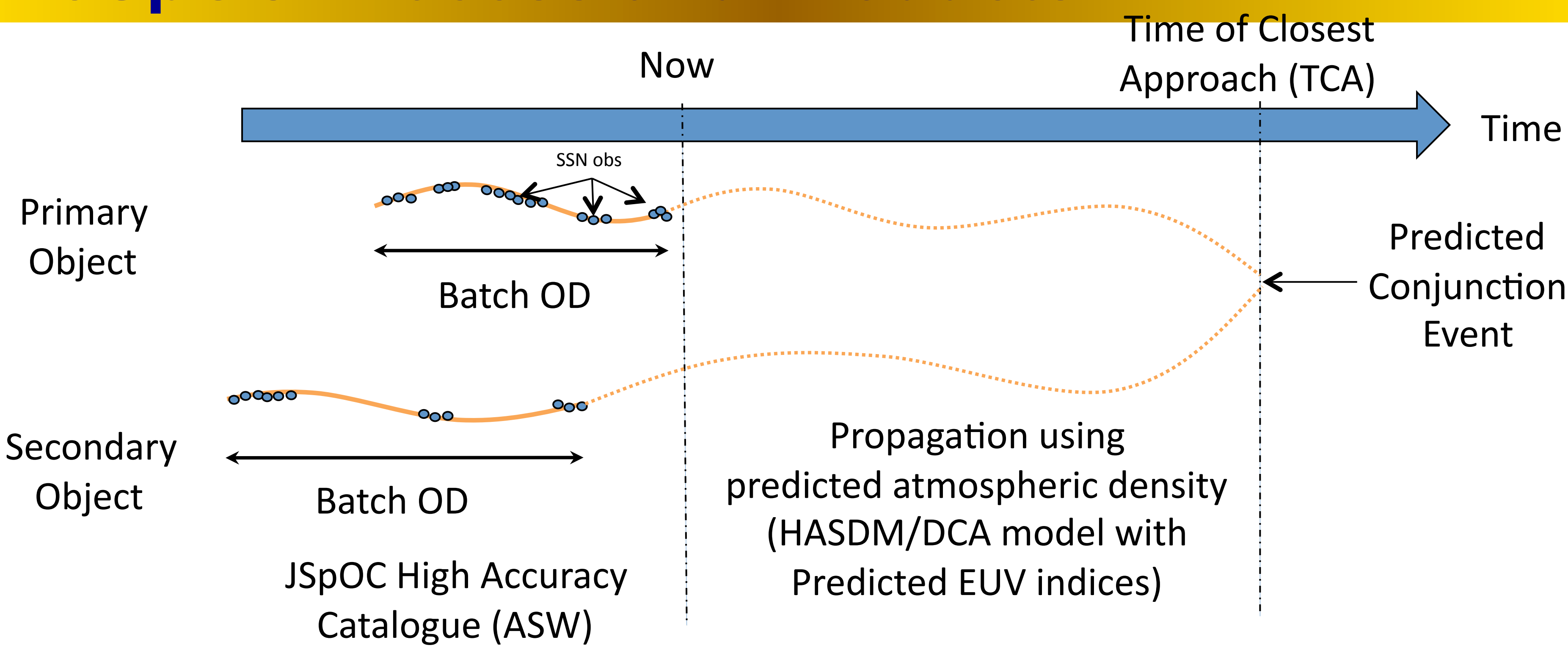
Evaluating Pc

- Is it *realistic*?
  - Reflects errors properly and accurately (is the covariance appropriately sized?)
  - **JSpOC recently added improved consider parameters and other enhancements; covariance realism notably improved**
- Is it *complete*?
  - Attempts to take cognizance of all of the known error sources
  - **Many sources with varying levels of availability**
    - Position estimate uncertainties (reasonably known)
    - Satellite sizes (sometimes known)
    - Atmospheric drag (generally not as well known/predicted)

Atmospheric Drag

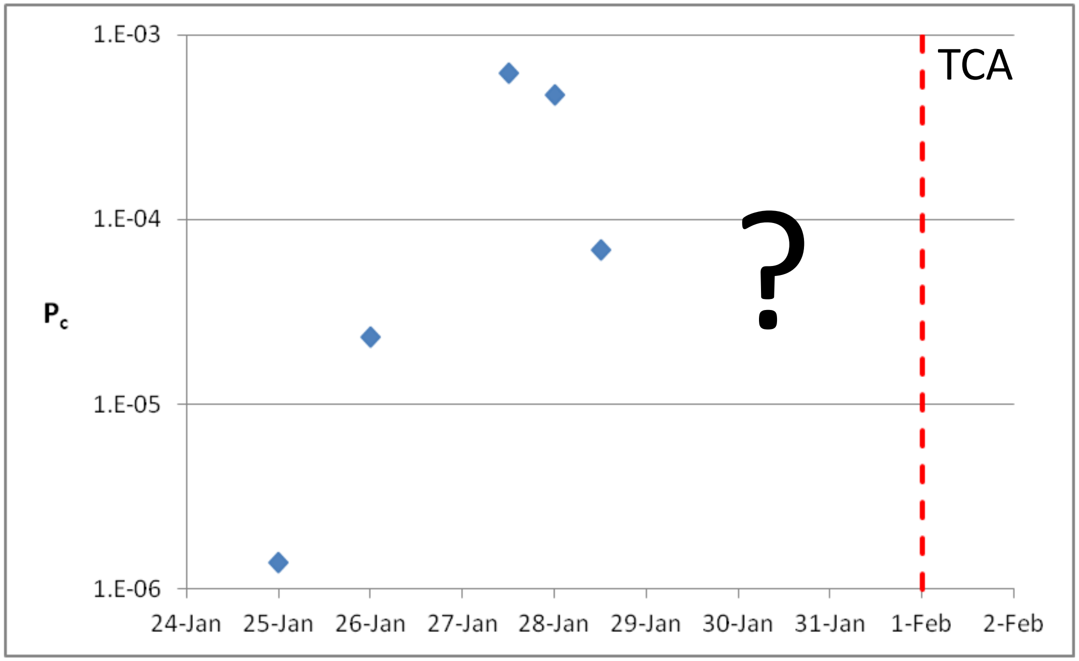
- Atmospheric drag magnitude: $a_{drag} = \frac{1}{2}\beta\rho v^2$
  - $\beta = \frac{c_D A}{m}$ is ballistic coefficient
    ρ is atmospheric density
    $v \cong v_{\text{sat}}$
    - Atmospheric rotation changes satellite-atmosphere relative velocity slightly
  - Solar cycle and space weather have strong impact on neutral atmospheric density
    - Solar storms represent particularly difficult density estimation situation
  - Uncertainties in β and ρ not separable
    - Effect of changes in drag can be emulated by varying β

Conjunction Assessment: JSpOC Process and Products



- Conjunction Data Message (CDM) provided for each screening:
  - Includes both objects' state vector and position covariance at TCA
    - Allows computation of probability of collision (P_c)

Space Weather and Conjunction Assessment: A Notional Event



25 Jan: first identification of possible conjunction on 1 Feb
27-28 Jan: P_c first increases to level of concern before starting to fall (looking safer)
29 Jan: Alert of a Coronal Mass Ejection (CME) heading for Earth on 31 Jan

Spacecraft O/O wants to know if (and how) CME will impact conjunction event

- Does the new space weather prediction make this event safer or riskier?
- Might performing a maneuver make the conjunction event worse?

Jacchia-Bowman-HASDM-2009 Atmospheric Model

- Product of AFSPC/A9 and Solar Environment Technologies
- Updates/enhancements to many of the internal empirical models
- Employs DCA for optimized performance during fit-span
- Solar storm modeling included (more on this later)
- Accepts frequent updates of expanded set of solar indices (11 EUV indices)
- Accepts 6-day predictions of solar indices and employs them for propagations up to 6 days
- Improves accuracy of predictions up to 72 hours by 20-45%

JBH09 Solar Storm Predictions

- Solar storms detected ~10 min after event, but can take 50 hours to reach Earth
  - Want to predict effects after detection, without waiting for traditional geomagnetic indices to reflect storm presence (“chasing the action”)
- JBH09 includes *Anemomilos* solar storm prediction model
  - X-ray magnitude of the flare used to determine mass of ejecta; this gives size and severity of storm
  - Flare intensity used as proxy for acceleration; integral gives storm velocity and therefore estimate of time of arrival
  - Heliolocation gives storm direction and therefore likelihood of hitting the Earth
  - These data can be used to predict atmosphere temperatures as function of time and therefore neutral density estimate
    - However, no error analysis with model

Event Sensitivity to Solar Storms

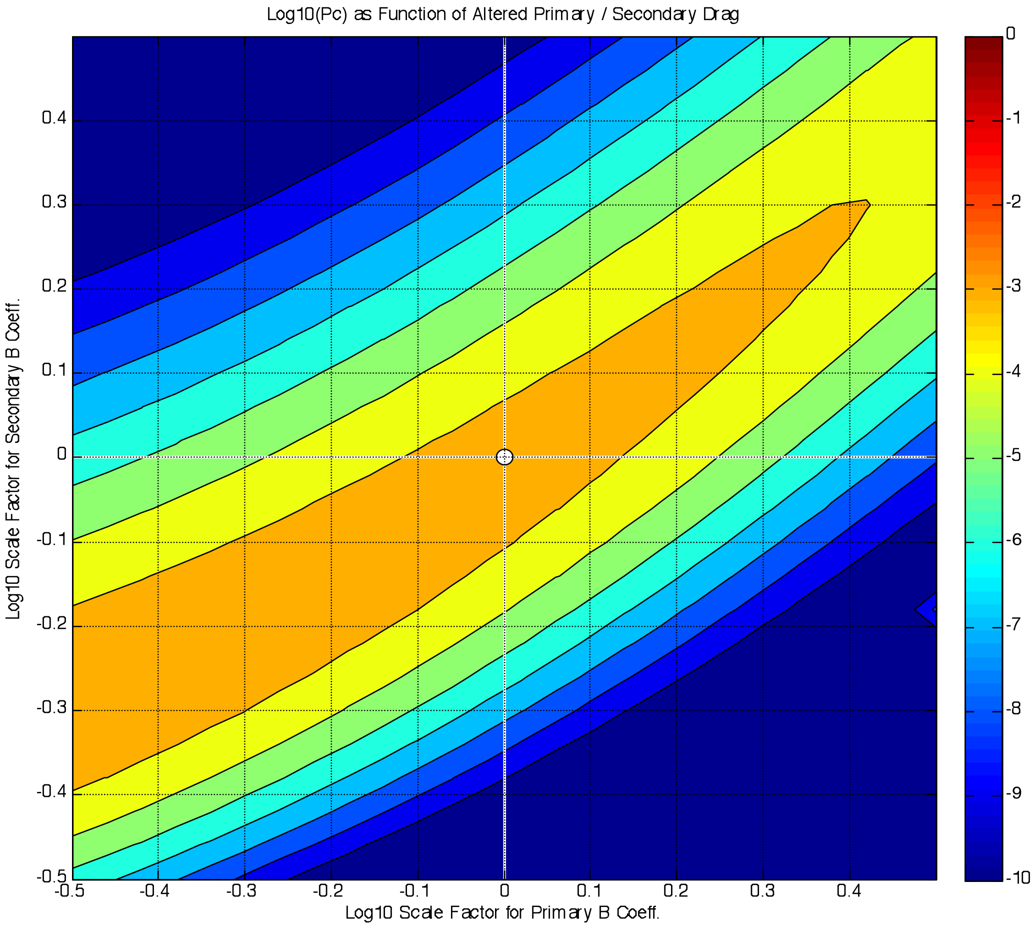
- Previously, in presence of solar storm, drag model error magnitude not known but "direction" known
  - Models did not attempt to predict solar storm effects in advance of arrival, but solar storm bound to increase drag over quiescent case
- With solar storm compensation, model error undoubtedly smaller, but direction indeterminate—could over- or under-compensate
- Thus, need to determine solution's sensitivity to density mismodeling
- Can do this by systematically varying the ballistic coefficient
  - Recall that density and ballistic coefficient coupled—varying one has similar effect to varying the other: $a_{drag} = \frac{1}{2}\beta\rho v^2$
  - If done systematically, can generate an entire trade-space of effects of potential density forecasting errors

The Space Weather Trade Space

- Space Weather Trade Space (SWTS) tool developed by CARA to evaluate conjunction event's sensitivity to solar storm drag mismodeling
- Ballistic coefficient for primary and secondary satellites each varied ± half an order of magnitude about the event nominal values
- Pc calculated for each pair of ballistic coefficient alterations
- Trade-space plots constructed
  - X-axis gives variation of primary satellite's ballistic coefficient
  - Y-axis gives variation of secondary satellite's ballistic coefficient
  - Contour color gives resultant Pc value
- Pc absolute values not important but contour pattern in relation to nominal value
  - Is the response contoured or flat?
  - Is the nominal value at a ridge or off the peak?

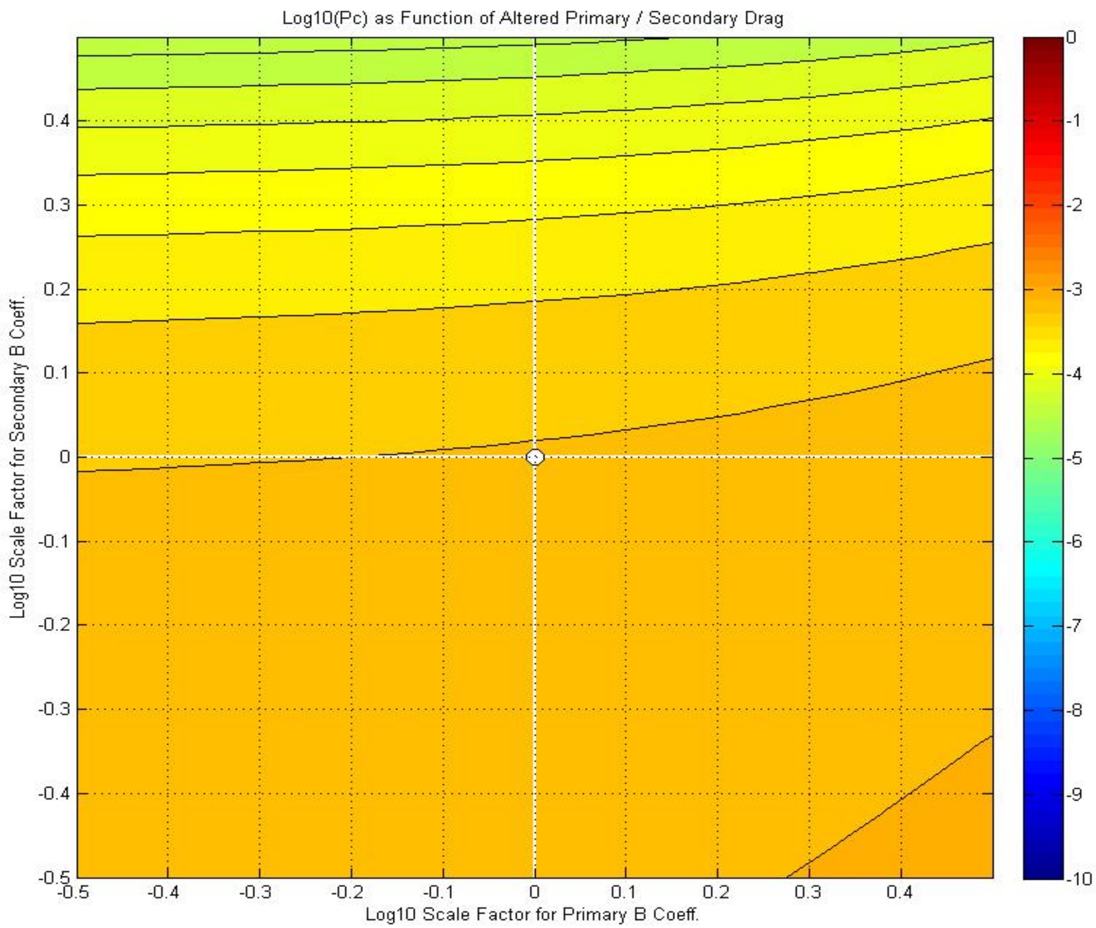
SWTS "On-ridge" Situation

- Pc on or within half an order of magnitude of highest contour
- Mis-modelling in drag will only cause Pc to decrease
- Operator can confidently make mitigation decision using this data because worst case already exists



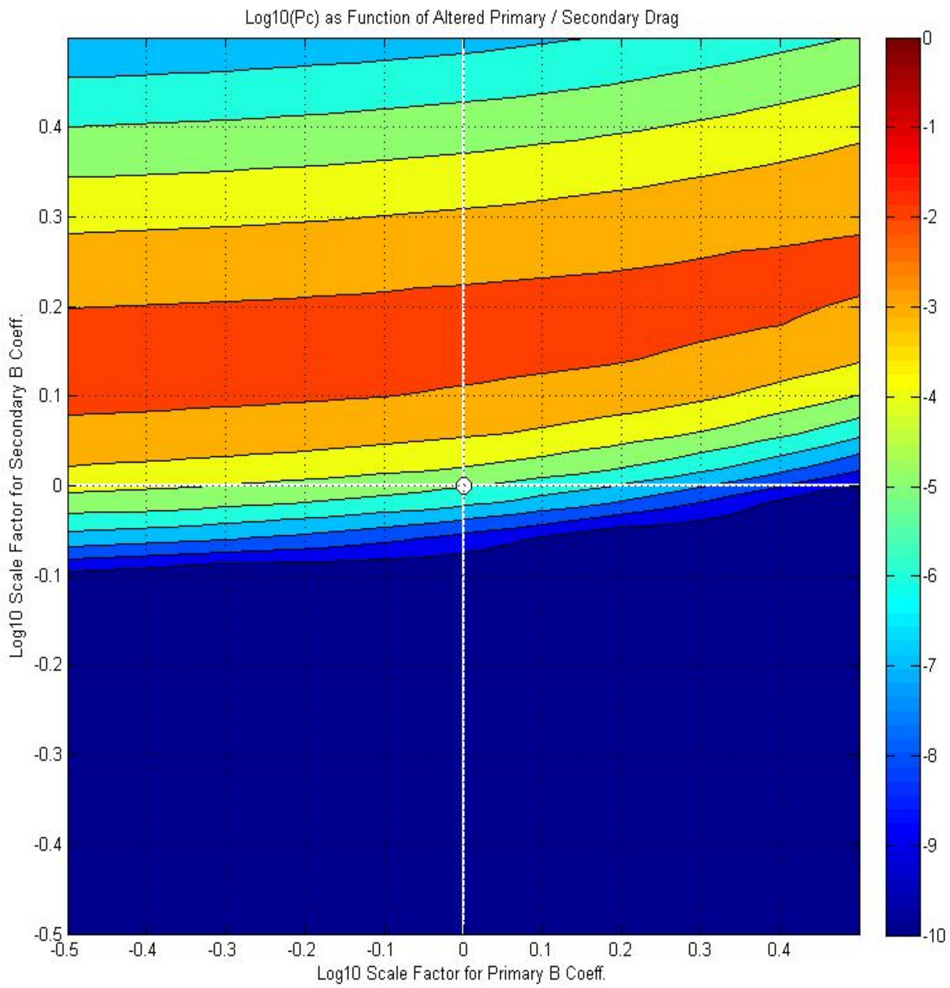
SWTS "Flat" Situation

- Pc varies less than an order of magnitude across the full trade space
- Drag mismodelling will thus have no effect on Pc
- Operator can confidently make mitigation decision using this data because Pc is unaffected by mismodelling



SWTS "Off-peak" Situation

- Pc varies by more than an order of magnitude across the trade space
- Nominal Pc is more than half an order of magnitude from the maximum
- Density mismodelling could either increase or decrease the risk of the event
- The tool does not provide any helpful information to the Owner/Operator in this case



SWTS Type Frequencies

- SWTS useful only in “on peak” or “flat” situations
  - How prevalent are these situations?
- Developed software to analyze 16,000 SWTS plots generated since function implemented operationally 18 months ago
- Categorized results by orbit regime of primary object, as defined in table below

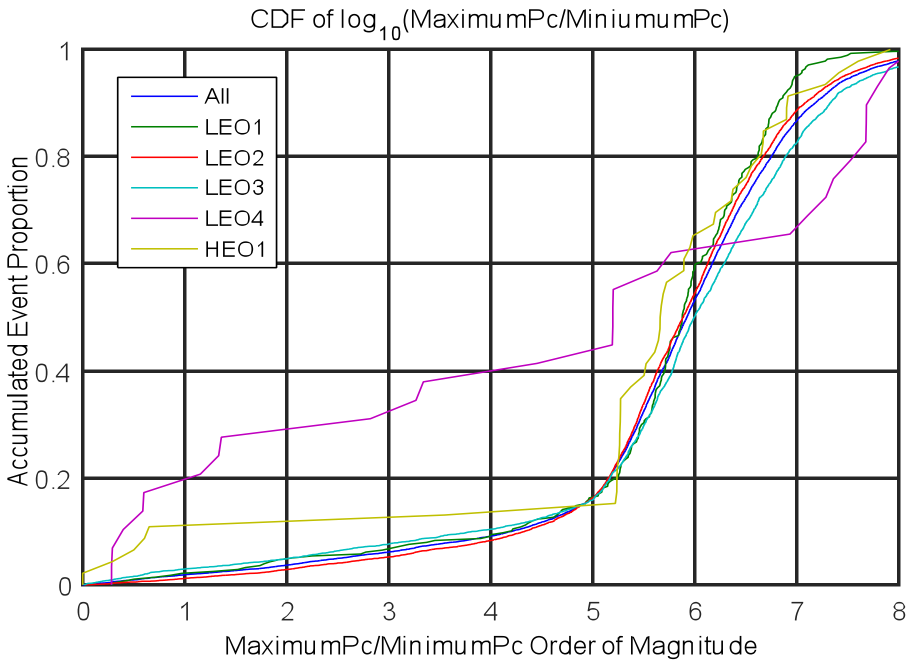
Orbital Regime	Definition
LEO #1	Perigee ≤ 500 km & Eccentricity < 0.25
LEO #2	500 km < Perigee ≤ 750 km & Eccentricity < 0.25
LEO #3	750 km < Perigee ≤ 1200 km & Eccentricity < 0.25
LEO #4	1200 km < Perigee ≤ 2000 km & Eccentricity < 0.25
HEO #1	Perigee ≤ 2000 km & Eccentricity > 0.25

"Max Pc 0"

- Special case of "Flat" category
- If Pc exceeds 1E-05, plots are generated from that time through the time of closest event.
- If Pc "rolls off" (goes to zero) during that time, the plot reflects a Pc of 0 – a flat case
- Tabulated separately because these cases are discarded

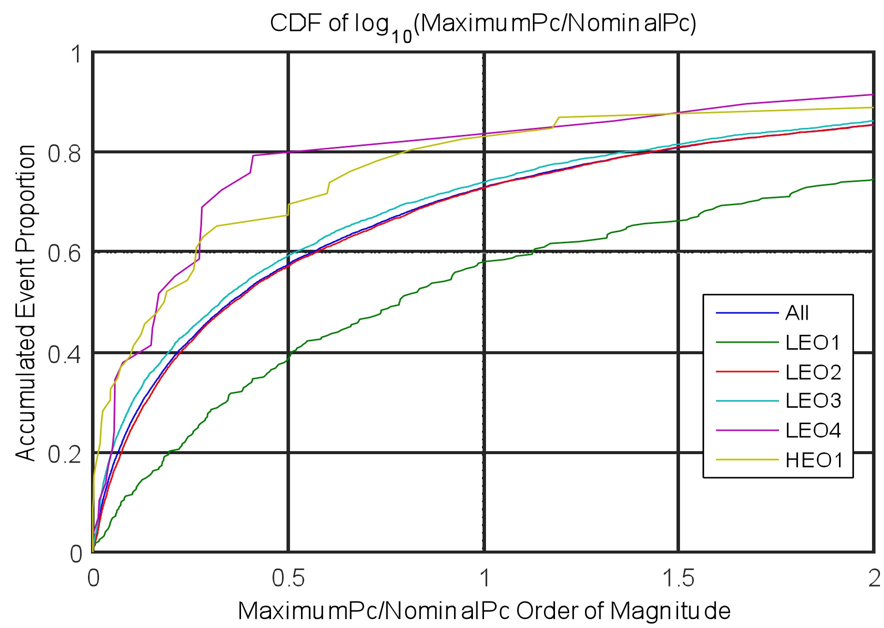
Max Pc / Min Pc

- Plot shows ratio of maximum to minimum Pc
- 80% have dynamic range between 4 and 7 OoM
  - Thus, most cases ridged
- Only a few percent have ratio smaller than one order of magnitude
  - Thus, very few “flat” response situations



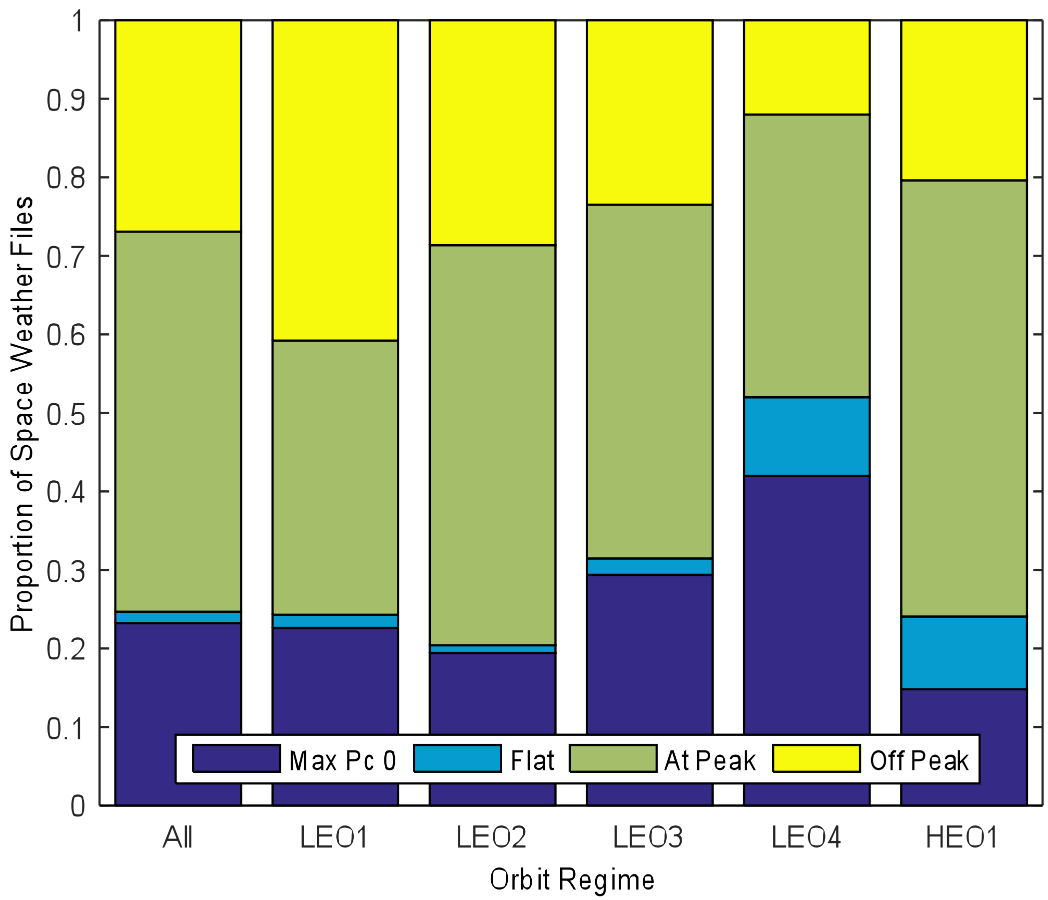
Max Pc / Nominal Pc

- Plot shows ratio of maximum Pc to the event nominal Pc
- 60% of LEO 2 and 3 (most of CARA primaries) show less than half an OoM difference between max and nominal
  - Either “on ridge” or “flat”
- Thus, majority of time tool results are informative
- Results somewhat worse for high-drag satellites (LEO1)



Combined Results

- Max Pc = 0 included here for completeness
- "At peak" a majority result for most orbit regimes
  - If Max Pc = 0 removed, then a supermajority
- Thus, most useful "at peak" category represents a considerable majority of cases (75% in LEO 2)



Conclusions

- While actual atmospheric density estimation errors not available, possible to identify situations in which remediation decisions can be insulated from these errors
- SWTS identifies such situations by contour pattern and placement of nominal solution value within the pattern
- Majority of cases allow the conclusion that the nominal Pc can be used as a conservative evaluation of the situation, despite unmodeled solar storm atmospheric density errors
- Improvements to situation will probably come from physics-based atmospheric models
  - A problem for space physicists