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
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:

\[ P_c = \frac{1}{2\pi \sqrt{||C||}} \int_A \int \frac{1}{2} r^T C^{-1} r \, dx \, dz \]

- \( r \) 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 \( \text{Pc} \)

- **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: \( a_{\text{drag}} = \frac{1}{2} \beta \rho v^2 \)
  - \( \beta = \frac{c_D A}{m} \) is ballistic coefficient
  - \( \rho \) is atmospheric density
  - \( v \approx v_{\text{sat}} \)

- 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 \( \beta \) and \( \rho \) not separable
  - Effect of changes in drag can be emulated by varying \( \beta \)
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 ($P_c$)
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%
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
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: \( a_{\text{drag}} = \frac{1}{2} \beta \rho v^2 \)
  – 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
- \( P_c \) 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 \( P_c \) value
- \( P_c \) 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
• 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
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

<table>
<thead>
<tr>
<th>Orbital Regime</th>
<th>Definition</th>
</tr>
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<tbody>
<tr>
<td>LEO #1</td>
<td>Perigee ≤ 500 km &amp; Eccentricity &lt; 0.25</td>
</tr>
<tr>
<td>LEO #2</td>
<td>500 km &lt; Perigee ≤ 750 km &amp; Eccentricity &lt; 0.25</td>
</tr>
<tr>
<td>LEO #3</td>
<td>750 km &lt; Perigee ≤ 1200 km &amp; Eccentricity &lt; 0.25</td>
</tr>
<tr>
<td>LEO #4</td>
<td>1200 km &lt; Perigee ≤ 2000 km &amp; Eccentricity &lt; 0.25</td>
</tr>
<tr>
<td>HEO #1</td>
<td>Perigee ≤ 2000 km &amp; Eccentricity &gt; 0.25</td>
</tr>
</tbody>
</table>
“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
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 $P_c$ 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