CA Event Actionability

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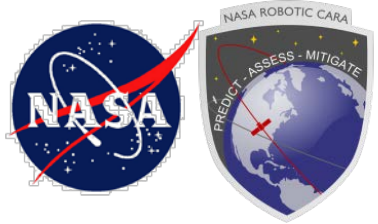
November 2018

“Actionable” Definition

- **“Whether the conjunction orbital data are of sufficient quality to serve as a basis for a CA risk remediation decision”**
- **Two areas of consideration related to orbital data:**
  - Whether the OD fit for the secondary (and also the primary) allows a reasonable statement of the epoch state and covariance
  - Whether the prediction interval and conditions for the secondary (and also the primary) allow a reasonable statement of the state and covariance at TCA (or a series of TCAs in a Monte Carlo setting)
- **One area of consideration related to the risk assessment paradigm itself:**
  - Whether the risk assessment method is in the present circumstances sufficiently robust to provide a durable (or sufficiently conservative) estimate of collision risk
  - Separate analysis task addressed in separate presentation



ORBIT FIT EVALUATION

OD Fit Evaluation

- **Evaluating an OD fit is ultimately a prudential decision**
  - Trained analyst examines a number factors
    - Amount, distribution, and quality of input observational data
    - Propriety of force model settings and DC controls
    - OD fit quality indices and degree of state change
    - OD graphical results, including residual plots
  - Ultimately, expert opinion from analyst who performs such updates daily
- **Purpose of OD fit quality rules not to evaluate absolute OD quality**
  - Rather, to identify situations in which a manual review should take place
  - OD fits embraced by an OSA's manual review are considered enabling for CA remediation decisions
- **Thus, areas and thresholds outlined subsequently define circumstances to seek manual review of OD fit**

OD Fit Evaluation: Particular Areas of Enquiry

- **Force model settings and reasonability of values**
- **Batch OD fit-span (LUPI) within minimum and maximum values**
- **Low residual acceptance percentage**
- **High weighted RMS**
- **Default covariance**

OD Fit Evaluation: Force Model Settings/Values

- **Geopotential**
  - Is the geopotential fidelity high enough for the particular orbit?
    - Zonal and tesseral harmonics always treated as the same value
- **Atmospheric drag**
  - Should it be solved for for this particular orbit?
  - Is the solved-for B-term reasonable for this particular orbit and object type?
- **Solar radiation pressure**
  - Should it be solved for for this particular orbit?
  - Is the solved-for SRP reasonable for this particular orbit and object type?
- **Lunar/solar perturbations**
  - Are they enabled?
- **Solid earth tides**
  - Are they enabled?

OD Fit Evaluation: Batch OD Fit-Span Lengths

- **Batch corrections need to determine an appropriate orbit determination update interval of observations**
  - Adequate number of observations needed for robust correction
  - Excessively long OD intervals increase prediction error
  - Excessively short OD intervals produce poor drag solutions
- **Dynamic LUPI (length of update interval) algorithm attempts to adjudicate competing goods listed above**
  - Begins with an upper bound and tries to shrink LUPI
  - Can grow LUPI beyond upper bound under certain conditions in order to force a correction and thus a SP catalogue update
    - Such ODs typically not of needed quality for CA
- **Manual update can shorten LUPI to less than minimum, especially after a maneuver**
- **ODs with LUPIs outside of minima and maxima usually not acceptable for CA; requires manual review**

OD Fit Evaluation: Percent Residual Acceptance

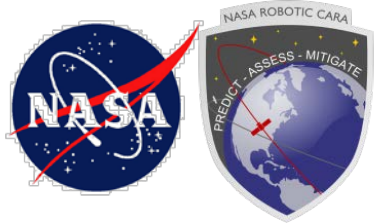
- **Percent residual acceptance is the percentage of the residuals in the fit interval that are retained in the final iteration of the correction**
- **A credible correction must include a reasonably high portion of the residuals**
  - Corrections can look better by throwing out data, especially older data
- **Circumstances do exist in which residual acceptance percentages should be low**
  - *e.g.,* post-maneuver situations; cross-tagging resolution
  - Relatively infrequent
- **ODs with residual acceptance below desired value require manual review**

OD Fit Evaluation: Weighted RMS

- **WRMS is the root-mean square of the OD residuals, weighted by the expected error in the measurements themselves**
  - Ideal value is unity—error in the fit on same order as expected error in measurements
  - Large WRMS can indicate poor fit of observational data
    - Also can indicate poor estimate of observation error
  - Small WRMS more unusual but not necessarily bad—usually possible only with small number of observations in fit
    - Typically indicates that sensor weights are unrealistic
- **Canonical WRMS limits established over time**
  - Different limits for each object type (payload / rocket body / debris)
  - ODs with WRMS values exceeding the appropriate limit require manual review

OD Fit Evaluation: Presence of Default Covariance

- **In some circumstances, SP correction will fail and a covariance will not be formed**
  - State represented by GP element set, and screening results generated from this
- **To identify such situations, covariance set to default value**
  - Position covariance diagonal matrix with values of ten earth radii
- **Such situations represent non-actionable ODs for CA**
  - Manual review may or may not be able to repair such a situation



ORBIT PREDICTION EVALUATION

OD Prediction Evaluation

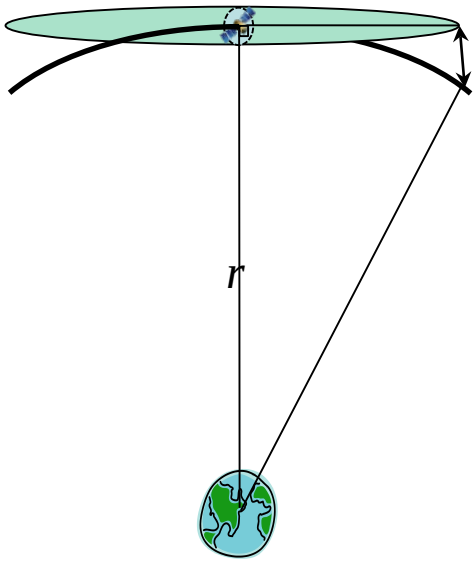
- **Presuming adequate OD fit, question is whether propagation of states and covariances to TCA will be trustworthy to allow a Pc calculation**
  - Same issue abides for Monte Carlo from epoch, as all of the trials will require this same propagation
- **Potential issues with propagation**
  - Covariance becomes non-positive-definite during propagation
  - Propagation interval exceeds viability of Cartesian covariance
  - Propagation interval exceeds viability of linearized dynamics
  - Propagation accumulates excessive atmospheric density error, resulting in incorrect in-track and radial positions and errors
  - Long propagation required due to lack of tracking data, which raises questions about quality of epoch state estimate
    - E.g., is the satellite “lost”?

OD Prediction Evaluation: Covariance Positive Definiteness

- **In order to represent real error hyperellipsoid, covariance matrix eigenvalues must all be positive (“positive definite” matrix)**
- **OD theory ensures that matrix be positive definite**
  - Actually, ensures that must be positive semi-definite, but presumption is linear independence of rows/columns
- **Numerical truncation, covariance interpolation, and certain observability conditions can force matrix outside of positive definiteness**
- **Test of 6 x 6 covariance in equinoctial elements best overall diagnostic**
- **While disquieting, NPD matrices can be handled straightforwardly**
  - For 2-D Pc, most NPD problems disappear before projection into conjunction plane
  - For Monte Carlo, repair of matrices simple, using any of a number of methods

OD Prediction Evaluation: Viability of Cartesian Covariance

- **Covariance for Pc calculation expressed in Cartesian coordinates, whereas orbits actually follow curvilinear coordinates**
- **When in-track covariance component becomes large, disjunction arises between in-track error volume and actual orbit trajectory**
  - Typically, durable Pc can be calculated with Monte Carlo using covariances converted to equinoctial elements
- **Straightforward test for situation**
  - Convert covariance to equinoctial elements
  - Perform random sampling in this reference frame
  - Convert all samples back to Cartesian frame
  - Test set of samples for conformity to Gaussian (individual components) or chi-square (ensemble) distribution



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OD Prediction Evaluation: Viability of Linearized Dynamics

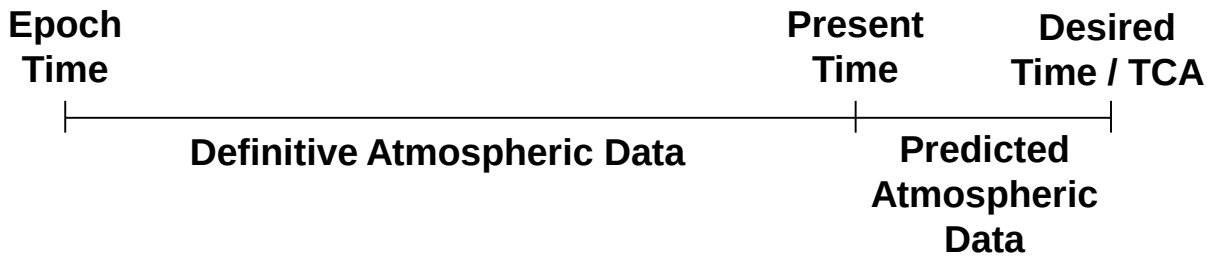
- **Propagation of covariance to future time takes place through a linearized process**
  - Covariance propagated in ASW through pre- and post-multiplication by state transition matrix ($\Phi * C * \Phi^T$)
  - State transition matrix is a linearization of the dynamics used to predict future positions
  - This linearization has a finite viability period
- **Past investigations indicate that covariances in equinoctial elements have long duration (Sabol 2011)**
  - Much longer propagation intervals required for linearizations failures in equinoctial frame
- **Test described previously for Gaussianity should test for a general linearized dynamics failure as well**
- **In short, unlikely to be an issue in nearly all CA situations**

OD Prediction Evaluation: Atmospheric Density Forecast Errors

- **Claim: propagations not reliable due to atmospheric uncertainty**
  - Space weather index forecasts good only for a few days at best, and even then not very reliable
  - Solar storms make prediction even more problematic
  - Therefore, periods of non-tracking (perhaps three days or longer) force too long of a prediction and render the data unsuitable for CA
- **Two aspects to a full response**
  - Difference in types (and significance) of propagation situations
  - Compensation in covariance for atmospheric density forecast error

OD Prediction Evaluation: Different Propagation Situations

- **Situation 1: propagation from epoch time to present time**
  - Uses definitive (issued) space weather indices and HASDM values
  - No atmospheric density forecast error; only (relatively small) atmospheric density model error
  - Drag error combination of model error (small) and satellite frontal area fluctuation (object-dependent)
- **Situation 2: propagation from present time to desired future time**
  - Atmospheric density model error and satellite fontal area fluctuation in play
  - However, also have atmospheric density forecast error
    - Typically much greater than other propagation error sources
- **For CA, long propagation times are typically mostly Situation 1**



OD Prediction Evaluation: Atmospheric Density Forecast Error

- **Dynamic Consider Parameter (DCP) formulated to compensate for atmospheric density forecast error**
  - JBH09 density prediction error characterized for different altitude bands at different levels of solar activity
  - Polynomial fits of density prediction error variance as a function of perigee height, for different solar activity bands
  - This variance added to ballistic coefficient variance in covariance; increases covariance size under propagation to account for density forecast error
- **Thus, this particular problem has presently integrated solution**
  - Error due to atmospheric density forecast uncertainty will exist in state estimate (position and velocity), but covariance will be properly sized to consider this error

OD Prediction Evaluation: Tracking Lacunae

- **When encountering stale ODs, one is tempted to speculate on the reason for the lack of tracking**
  - Is a vector age of this length typical for this satellite?
  - Was the last OD reasonably tracked and of a comparable quality to previous updates for this satellite?
  - Is there a known reason why tracking may have ceased?
  - Is it likely that the update was poor (even if update indices appeared favorable) and the satellite is now lost?
- **Access to object update history helpful**

Summary: OD Fit

- **No hard-and-fast rules for absolute evaluations of quality**
- **However, number of areas and thresholds for determining when a manual review of OD fit is prudent**
  - If all associated values stay within thresholds, OD fit can be presumed to be adequate as a basis for CA risk assessment
- **For NASA CARA, these evaluations part of OSA daily worklist**
  - Automated software to check for threshold failures
  - Sets priority for manual review of secondary object ODs

Summary: OD Prediction

- **Distended covariances can present problems**
  - But straightforward test described
- **For CA, most extended propagation is in the past**
  - Definitive atmospheric data available, so propagation error bounded
- **Atmospheric density forecast error modeled through DCP**
  - And with maneuver commit points at ~2 days to TCA, actual propagation through forecasted space weather relatively short
- **Tracking lacunae can be investigated by looking at update history for particular secondary**
  - May be specific explanations for particular tracking gaps

Overall Summary

- **If OD fit parameters meet thresholds or sustain manual review, presume OD fit an adequate basis for CA**
- **Unless an unusual, particular objection exists, presume that propagated solution and covariance constitute an adequate basis for CA**
  - So long as propagated covariance is realistic, it will reflect the expected error for that propagated state
  - If despite large covariance Pc is still large, then event is serious and should be remediated
  - If large covariance depresses Pc value, then situation not precisely enough understood to counsel remediation
- **Presume that an OD and propagated state are actionable unless explicitly shown to be otherwise**
- **No old wives' tales like "secondaries not tracked in five days are not actionable" are appropriate**