AI 23.1 - Reentry Predictions Preliminary Survey

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Statement of the AI 23.1

The WG2 should review the current status of models and capability to predict the reentry time and location of uncontrolled space objects.

Statement of the AI 23.1

The objectives of the action item are to:

- assess the sources and levels of uncertainty inherent in existing approaches
- identify those aspects which have the greatest influence on the accuracy of short and long term predictions of reentry time and location, e.g. trajectory modeling, orbit determination accuracy, atmospheric modeling (structure + response to solar/geomagnetic activity), prediction of solar/geomagnetic activity, ballistic parameter modeling, effects of prediction process.
- propose measures to improve the accuracy/reliability of reentry predictions and define a common terminal altitude for comparisons.

Tools description

The following items have been described:

- orbit propagation;
- atmospheric models;
- input data;
- ballistic coefficient determination;
- nominal reentry altitude;
- reentry window and uncertainties.

Orbit propagation

ASI	**Numerical** - Cowell's method to solve for the equation of motion + a single step 8^{th} order Runge-Kutta method for their numerical integration;
CNES	**Numerical** method;
ESA	**Numerical** *Long term*: Adam-Bashforth/Adams-Multon predictor-corrector multi-step. *Short term*: self-starting Runge-Kutta/Shanks single-step method of order 8, with self-adjusted step size
NASA	**Numerical** - propagation by special perturbations theory.

Orbit propagation - Perturbations

ASI	luni-solar effects, solar radiation pressure (SRP), geopotential up to 40 $\times$ 40, air drag;
CNES	luni-solar effects, SRP, geopotential (20 models, up to 36 $\times$ 36), air drag
ESA	luni-solar effects, SRP, geopotential (up to degree 7), air drag
NASA	air drag,.....

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Orbit propagation - ESA Details

Geopotential: applying the Lagrange perturbation equations, analytically averaged with respect to mean anomaly by means of recursive expansions in eccentricity and inclination functions according to Kaula, Giacaglia, and Cook;
Long term: Only zonal harmonics up to J_7;
Short Term: different models (GEM-T1, EGM-96), up to deg. 7.

Solar radiation pressure: Gauss perturbation equations, analytically averaged w.r.t. mean anomaly according to Aksnes;
Long term: cylindrical, oblate Earth shadow, without penumbra; constant A/m and c_R.
Short Term: conical, oblate Earth shadow, with penumbra.

Orbit propagation - ESA Details (Cont.)

Lunisolar: Sun and Moon are assumed stationary point masses, during the averaging time interval.
The individual time rates of change are superimposed for the numerical prediction of the analytically averaged perturbation equations, without considering cross-coupling between perturbation effects.

Atmospheric models

ASI	Jacchia-Roberts 1971, Thermosphere Density model 1988, MSIS-86, MSISE-90, US-76
CNES	CIRA88 (Below 110 km) + MSIS-86 (Above 130 km), DTM, US-76, ...
ESA	MSISE-90, with a fairing to CIRA72 (Jacchia 71) below 200 km
NASA	Jacchia 70 is the standard + a variety of other models.

Orbital data

ASI	Two Line Elements (but can accept different data formats) (American and Russian)
CNES	Osculating state vectors
ESA	Many state formats, including TLE
NASA	Ephemerides are generated via a differential correction process of observational (normally radar) data. No TLEs are used.

Orbital data - Details

ASI — TLE converted to Cartesian coordinates by NORAD models

CNES — integrates osculating Cartesian state vectors in the Earth Fixed frame

ESA — *Long Term:* the input state is converted to singly averaged mean elements (wrt. M) prior to the start of predictions.
Short Term: the input state is converted into osculating Cartesian state vectors in a mean-of-date coordinate system prior to the start of predictions

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Ballistic coefficient determination

ASI The backward semi-major axis (historical TLE) decay is least-square fitted

CNES vehicle shape modeling (plat, sphere, cylinder, parallelepiped+solar arrays); c_D constant or depending on altitude or on Mach number and angle of attach

ESA The backward semi-major axis (historical TLE) decay is least-square fitted

NASA A term related to ballistic coefficient is derived from real-time observed orbital decay behavior. No fixed ballistic coefficient is employed, nor engineering estimates of cross-sectional area and mass.

Environment data

ASI	$F_{10.7}$ and A_P from NOAA (past, current and forecast values)
CNES	$F_{10.7}$ and A_P from *real values*
ESA	$F_{10.7}$ and A_P from NOAA; predicted by an ARIMA time-series model up to one solar rotation and by a McNish-Lincoln method up to one solar cycle
NASA	$F_{10.7}$ and A_P data taken into account

Nominal reentry altitude

ASI	**80 km** above the reference ellipsoid. The day preceding the estimated reentry switch to **10 km**
CNES	configurable according to type of integrator
ESA	*Long Term:* **90 km** *Short Term:* **3 km**
NASA	**10 km** above the surface of the Earth

Reentry window and uncertainties

ASI	Percentage variation of the C_D: $C_D \pm 30\%$ up to ≈ 20 d before estimated re-entry; $C_D \pm 20\%$ elsewhere
CNES	No, but possibility to estimate uncertainty by propagating several trajectories
ESA	$\pm 20\%$ of the remaining orbital lifetime, centered on the epoch of the terminal altitude
NASA	

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Comments by Delegations - ASI

- Identify the atmospheric models that better describe the atmospheric density as a function of a given level of solar activity.
- Identify semi-empirical rules to better estimate the ballistic coefficient, e.g., interpolation interval length or number of past orbital elements to be used in the fit.

Comments by Delegations - ESA

Major Items

- Timely availability of orbit determinations;
- Near real-time calibration of atmosphere model, from Catalog orbit information (as suggested by A.Nazarenko, B.Bowman, and others).

Comments by Delegations - NASA

Major Items

The variability and the uncertainty of atmospheric density along the satellite's path is normally the source of greatest error in reentry predictions. Atmospheric density, in turn, is largely dependent upon solar activity. However, our experience is that attitude changes in the satellite can, on occasion, result in comparable or even larger reentry prediction errors. On rare occasions in naturally decaying orbits, a lifting force at the point of atmospheric interface can dramatically alter the surface impact point (or debris footprint). The effects of atmospheric density and attitude can never be perfectly modeled. Therefore, the objective of the reentry process is to reduce these errors to the greatest extent feasible.

Comments by Delegations - NASA

Major Items

One assumption in the calculation for reentry location is that the equivalent area-to-mass ratio of the reentering object has not changed during reentry (ballistic coefficient does change with altitude).
Surviving debris will have a range of area-to-mass ratios, some greater than and some less than that of the intact object.
Assuming no change in area-to-mass ratio usually results in identifying a reentry location somewhere near the center of the actual debris footprint.

Comments by Delegations - NASA

Major Items

- NASA recommends using 10 km as the IADC standard (other IADC members use values of 10 or 3 km altitude for their reentry predictions);
- A goal of IADC could be to compare reentry prediction results and to identify if any biases appear to be present in specific reentry prediction models.