(U)Dynamic Density Modeling and Related Space Weather Impacts on Prediction Errors for the De-Orbiting Timeline of Resident Space Objects

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Dedicated To Dr. James N Bass
1941-Feb 16, 2012

(U) Goal – Investigate Means to Improve Predictions of RSO De-Orbiting Lifetimes

(U) Strategy:

- (U) Use orbit integrator with current dynamic density models
- (U) Add fluctuations to density models
- (U) Test variable ballistic coefficient models

(U) Milestones:

- (U) Upgrade orbital integrator
- (U) Perform case studies for selected decayed RSOs:
  - (U) Repeat old case to validate modifications to code
  - (U) Two recent cases with fully archived geophysical inputs
  - (U) One recent case with forecast geophysical inputs
- (U) Improve drag force term modeling: variable drag scaling factors
- (U) Add thermosphere winds: do they help?

(U) Orbit Propagators - Types:

- (U) Special Perturbation – ***Integrates*** equations of motion
  - (U) Cowell's Method:

$$\ddot{\vec{r}} = \left(\sum_i GM_i \frac{(\vec{r} - \vec{r})}{|\vec{r} - \vec{r}_i|^3} \right) + \sum_m \ddot{\vec{r}}_m + \sum_k \ddot{\vec{r}}_k$$

Central Force Gravitational | Gravitational Accelerations | Non-Gravitational Accelerations

- (U) General Perturbation – ***Integrated*** equations of motion
  - (U) Analytic integrated expressions based on truncated expansion
  - (U) Keplerian elements are usually the basis variables
- (U) Semi-analytic Formulation
  - (U) Secular and long-term perturbations: integration
  - (U) Short-term perturbations: modeled at end of integration steps

(U) Why we use Artificial Satellite Analysis Program (ASAP) for orbit propagation:

- (U) Cowell's Method: Vector Sum of Accelerations
- (U) Integration in Cartesian coordinates
  - (U) Numerically and physically straightforward
  - (U) Environment models accept Cartesian coordinates
  - (U) Easy to transform, display and compare to other data sets
- (U) No need to reformulate orbital models to add perturbations
- (U) Simplified code design:
  - (U) Can easily add modules for
    - (U) Model improvements
    - (U) Environment models
    - (U) Additional forcing terms
  - (U) Can easily modify the input parameters
  - (U) Validated (in original version) for specific cases

(U) Artificial Satellite Analysis Program (Original Version):

- (U) F77 codes by J. H. Kwok of JPL
  - (U) Version 2.03 – 18 Apr 1988 (latest)
  - (U) JPL Reference: JPL EM 312/87-153 (20 Apr 1987)
- (U) Runge-Kutta 8th order integration with step size control
- (U) Solar, planetary, and Earth models:
  - (U) Based on IAU 1982 and JPL DE118
  - (U) ECI, B1950 Cartesian coordinate system, no polar perturbation
- (U) Cowell's method of special perturbation with forcing due to:
  - (U) GEM (Goddard Earth Model) version 10 order 36 X 36 (default)
  - (U) Luni-solar gravity fields
  - (U) Atmospheric drag
  - (U) Solar radiation pressure
- (U) Drag calculations use static density model:
  - (U) Exponential model, or
  - (U) Static 1977 Earth model (US76)

(U) ASAP Code Key Upgrades, circa 1995:

- (U) Added dynamic thermosphere density models:
  - (U) Jacchia 1970-Extended (Jacchia-Bass model)
    - (U) Standard model used by NORAD for OD processing
    - (U) Extended densities from 90 km to sea level
  - (U) MSISE-90 Mode A (Single Ap) and Mode B (Ap history)
- (U) Added Ap F10.7 database interface to drive thermosphere
- (U) Implemented WGS-84 & gravity model EGM96

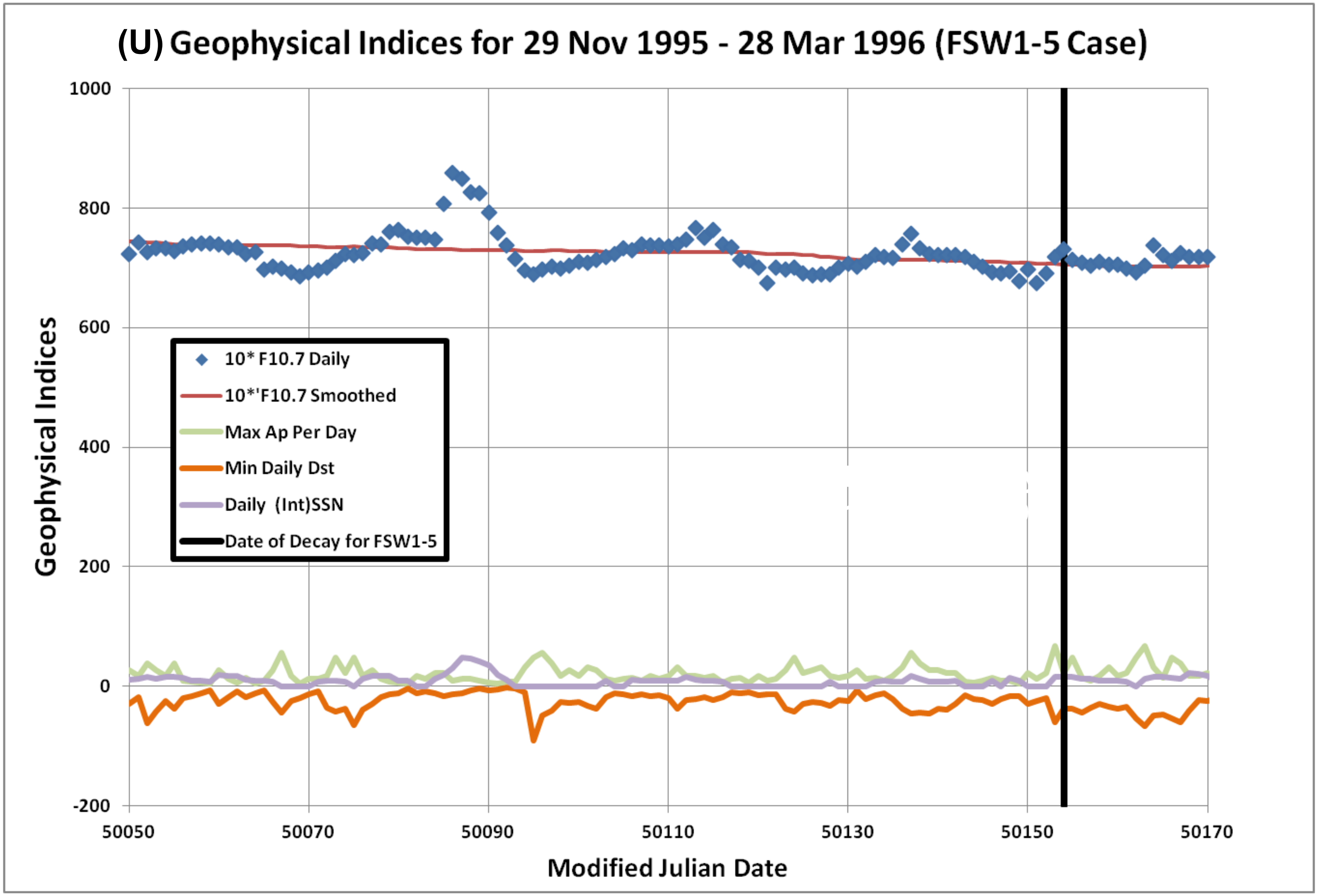
  (U) (Ref: NASA/TP-1998-206861)
- (U) Added SGP4-SDP4 interface
  - (U) Simplified General Perturbations (SGP) model series used by USAF
  - (U) Used to translate the NORAD TLE sets to initial state vectors (SV)
    - (U) Sequential SVs fitted by adjusting ballistic coefficient
  - (U) SVs in True Equator Mean Equinox (TEME) of epoch ECI frame
- (U) Updated ECI reference frame to J2000

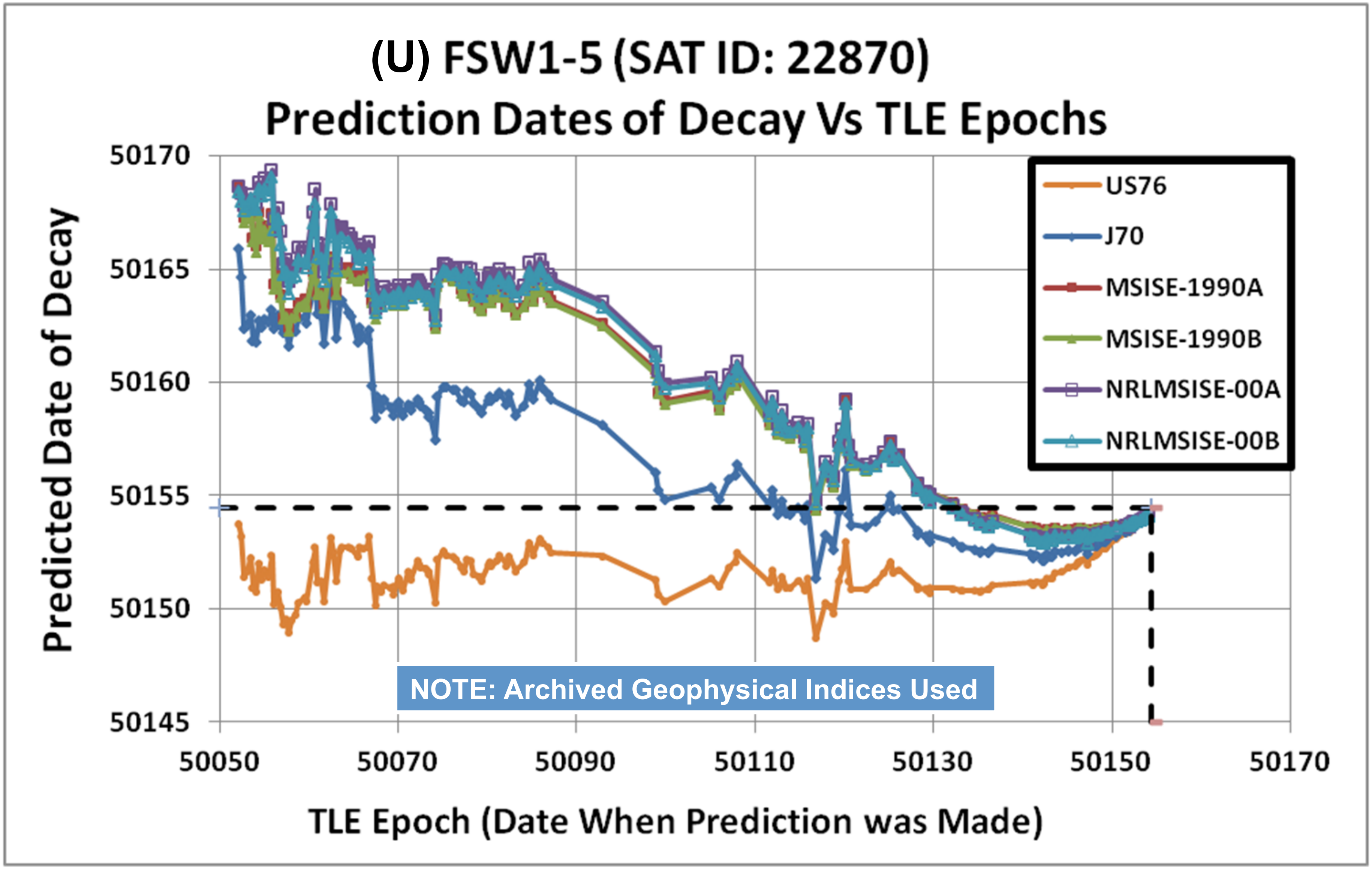
(U) ASAP Code Key Upgrades, 2011:

- (U) Upgraded to FORTRAN 95
- (U) Updated to Earth Model to WGS-1984 Extended (GPS variant)
- (U) Updated dynamic density models:
  - (U) Added NRLMSISE-00
  - (U) Added Jacchia-Bowman 2008 (JB2008)
    - (U) Source: http://sol.spacenvironment.net/~JB2008/index.html
    - (U) Based on Jacchia 1971 (CIRA 1972) model
    - (U) Geophysical indices used:
      - (U) Uses Dst for geomagnetic storm expansion
      - (U) Solar indices (from http://spacewx.com):
        - (U) F10 Radio 10.7 cm
        - (U) S10 EUV 26-34 nm
        - (U) M10 FUV 160 nm
        - (U) Y10 X-Ray, L-α 0.1-0.8, 121 nm
    - (U) Altitude range is 90 - 800 km: NRLMSISE-00 used for exceptions

(U) Historical De-orbit Case Study: FSW1-5 (SAT ID 22870)

- (U) PRC FSW1 class reconnaissance satellite
- (U) Launch: 8 October 1993
- (U) Decay: 12 March 1996 at 11:05 ET (South Atlantic)
- (U) Mass: 2.1 metric tons
- (U) Blunt conical shape:
  (U) length 3.14 m, max diameter 2.2 m
- (U) Initial Operational Orbit:
  - (U) 209 km by 300 km
  - (U) 57 deg inclination
- (U) Planned 7-10 day mission
  - (U) Flight control command anomaly
  - (U) Satellite boosted to higher elliptical orbit:
    - (U) 179 km by 3031 km
- (U) Designed to survive re-entry, triggering concerns
- (U) Satellite tumbled during re-entry and disintegrated

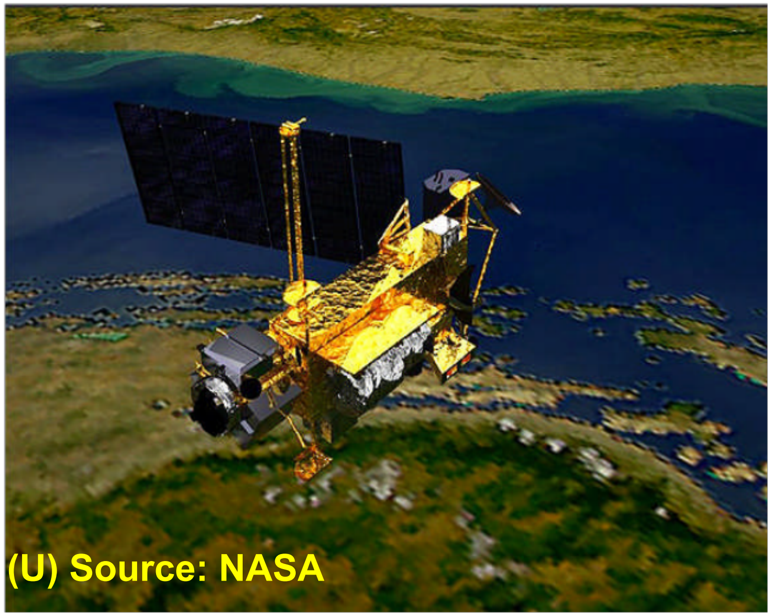

(U) Geophysical Indices for 29 Nov 1995 - 28 Mar 1996 (FSW1-5 Case)
Geophysical Indices
1000
800
600
400
200
0
-200
50050
50070
50090
50110
50130
50150
50170
Modified Julian Date
10* F10.7 Daily
10*'F10.7 Smoothed
Max Ap Per Day
Min Daily Dst
Daily (Int)SSN
Date of Decay for FSW1-5


(U) FSW1-5 (SAT ID: 22870)
Prediction Dates of Decay Vs TLE Epochs
Predicted Date of Decay
50170
50165
50160
50155
50150
50145
50050
50070
50090
50110
50130
50150
50170
TLE Epoch (Date When Prediction was Made)
US76
J70
MSISE-1990A
MSISE-1990B
NRLMSISE-00A
NRLMSISE-00B
NOTE: Archived Geophysical Indices Used

(U) Recent De-orbit Case Study: UARS (SAT ID 21701)

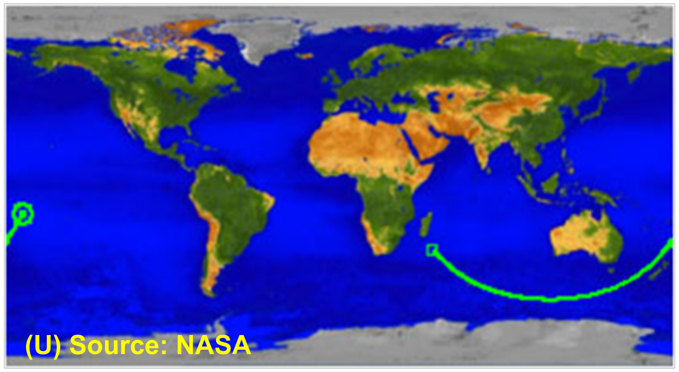
- (U) Upper Atmosphere Research Satellite (UARS)
- (U) Launch: 15 Sep 1991
- (U) Decay: 24 Sep 2011 04:00:00 GMT
- (U) Dry mass: 5668 kg
- (U) Size: length 35 ft, diameter 15 ft
- (U) Initial operational orbit:
    - (U) 575 km by 580 km
    - (U) 57 deg inclination
- (U) Decommissioned on 14 Dec 2005
    - (U) Orbit lowered

((U) source: NASA Orbital Debris Program Office)


(U) Source: NASA

(U) From TIP (Tracking & Impact Prediction) report (space-track.org):

(U) Report Date/Time	2011-09-27 14:53 GMT
(U) Predicted Decay Time	2011-09-24 04:00 GMT +/- 1 min
(U) Predicted Decay Location	14.1° S, 189.8° E
(U) Direction	ascending
(U) Inclination	56.9°
(U) Revolution Number	10921


(U) Source: NASA

(U) Recent De-orbit Case Study: ROSAT (SAT ID 20638)

- (U) ROentgen SATellite (ROSAT)
- (U) Launch: 1 Jun 1990
- (U) Decay: 23 Oct 2011 01:50:00 GMT (Bay of Bengal)
- (U) Launch mass: 2,426 kilograms
- (U) Size: 2.20 m x 4.70 m x 8.90 m
- (U) Initial operational orbit:
  - (U) 580 km mean altitude
  - (U) 53 deg inclination
- (U) Decommissioned on 12 Feb 1999

(source: German DLR Aerospace Center, NASA)

(U) Source: NASA

(U) From TIP (Tracking & Impact Prediction) report (space-track.org):

(U) Report Date/Time	2011-10-23 03:41:00 GMT
(U) Predicted Decay Time	2011-10-23 01:50:00 GMT +/- 7 min
(U) Predicted Decay Location	7° N, 90° E
(U) Direction	ascending
(U) Inclination	53°
(U) Revolution Number	19462
(U) High Interest Object	N

(U) Recent De-orbit Case Study: PHOBOS-GRUNT (SAT ID 37872)

- (U) Russian Phobos-Grunt Mars sample return mission
- (U) Launch: 8 Nov 2011 – failed to leave orbit for Mars
- (U) Decay: 15 Jan 2012 17:45 UTC (Pacific Ocean)
- (U) Mass: 13,500 kg (11,150 kg of fuel)
- (U) Initial Orbit:
  - (U) 349 km by 207 km,
  - (U) inclination 51.423 deg
- (U) Size: Not explicitly stated
- (U) Chinese Yinghuo 1 spacecraft onboard

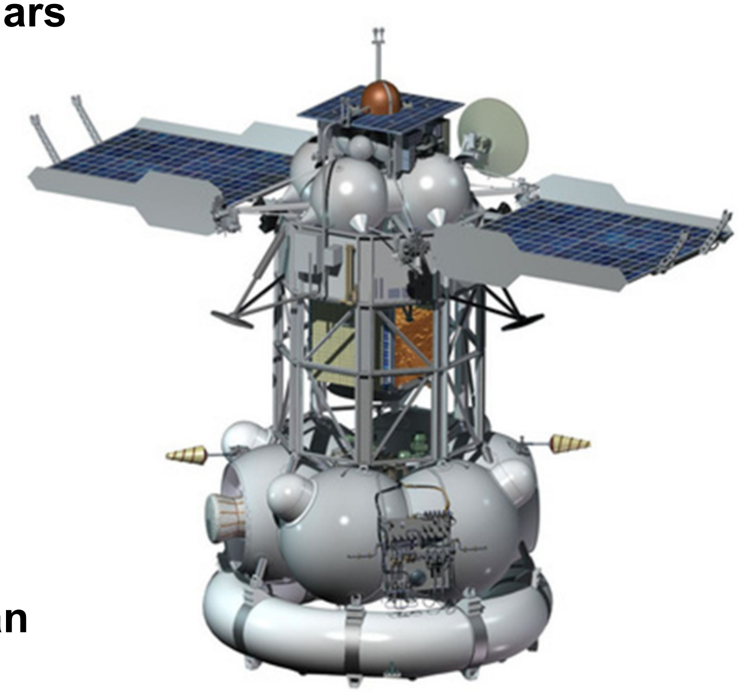
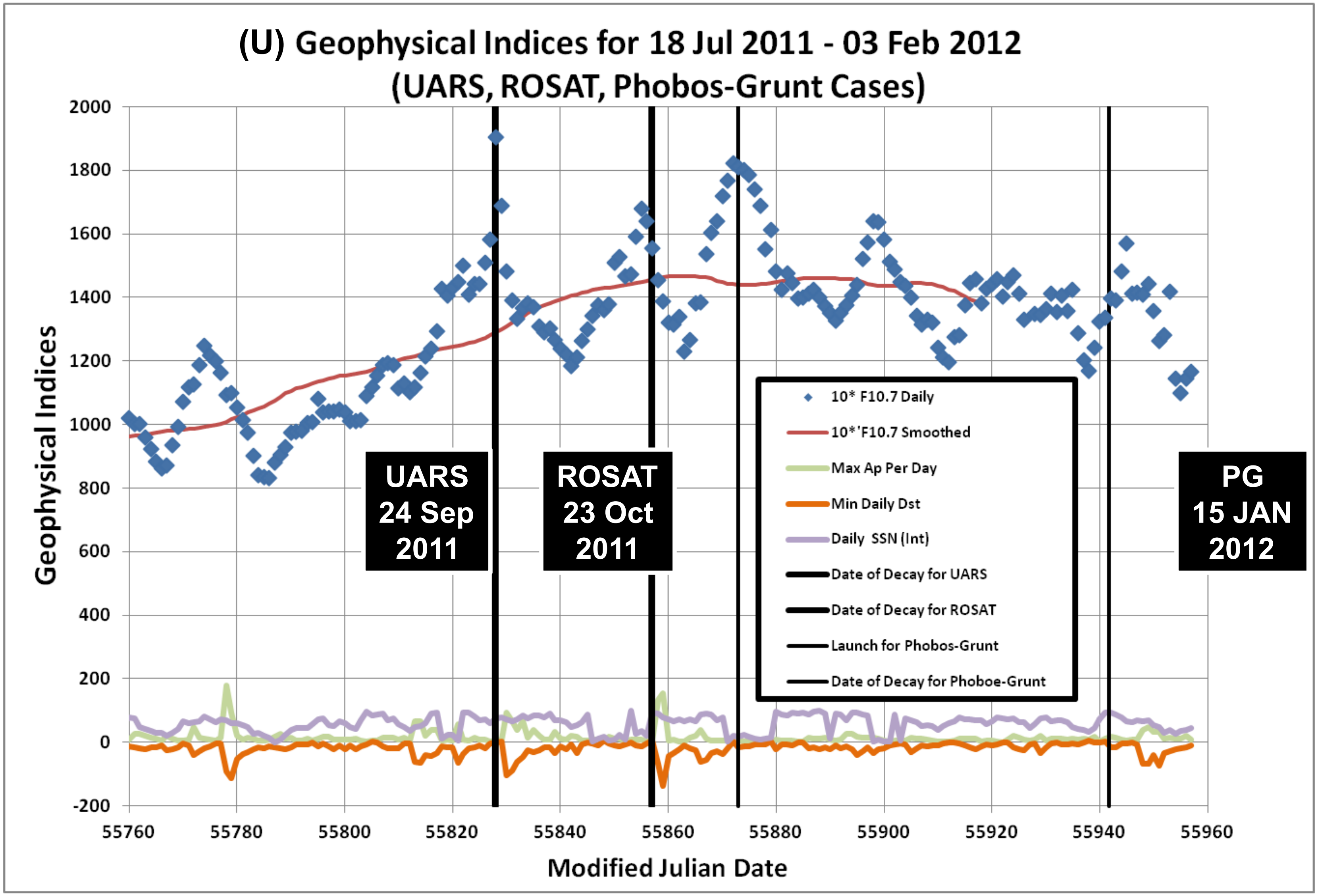
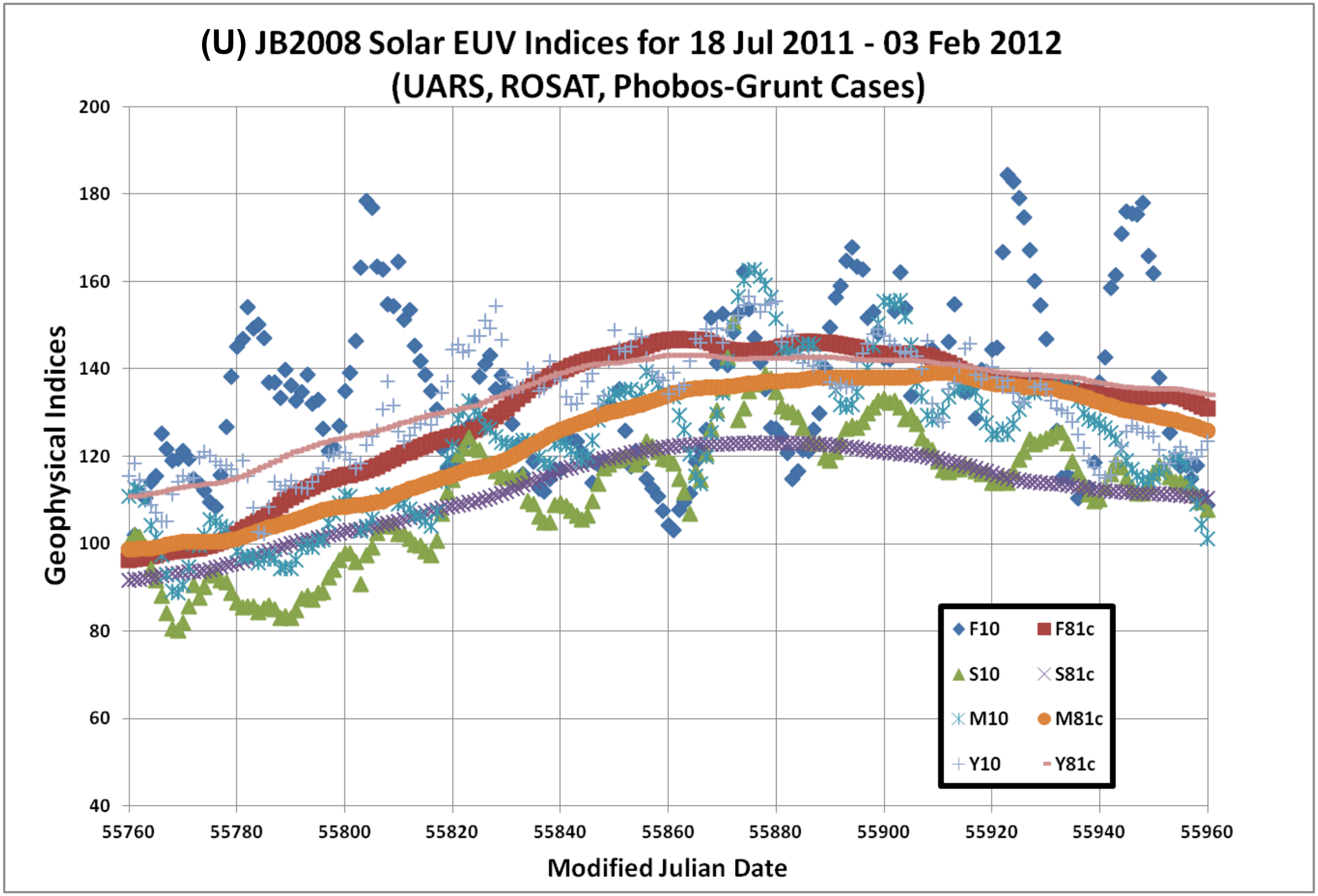


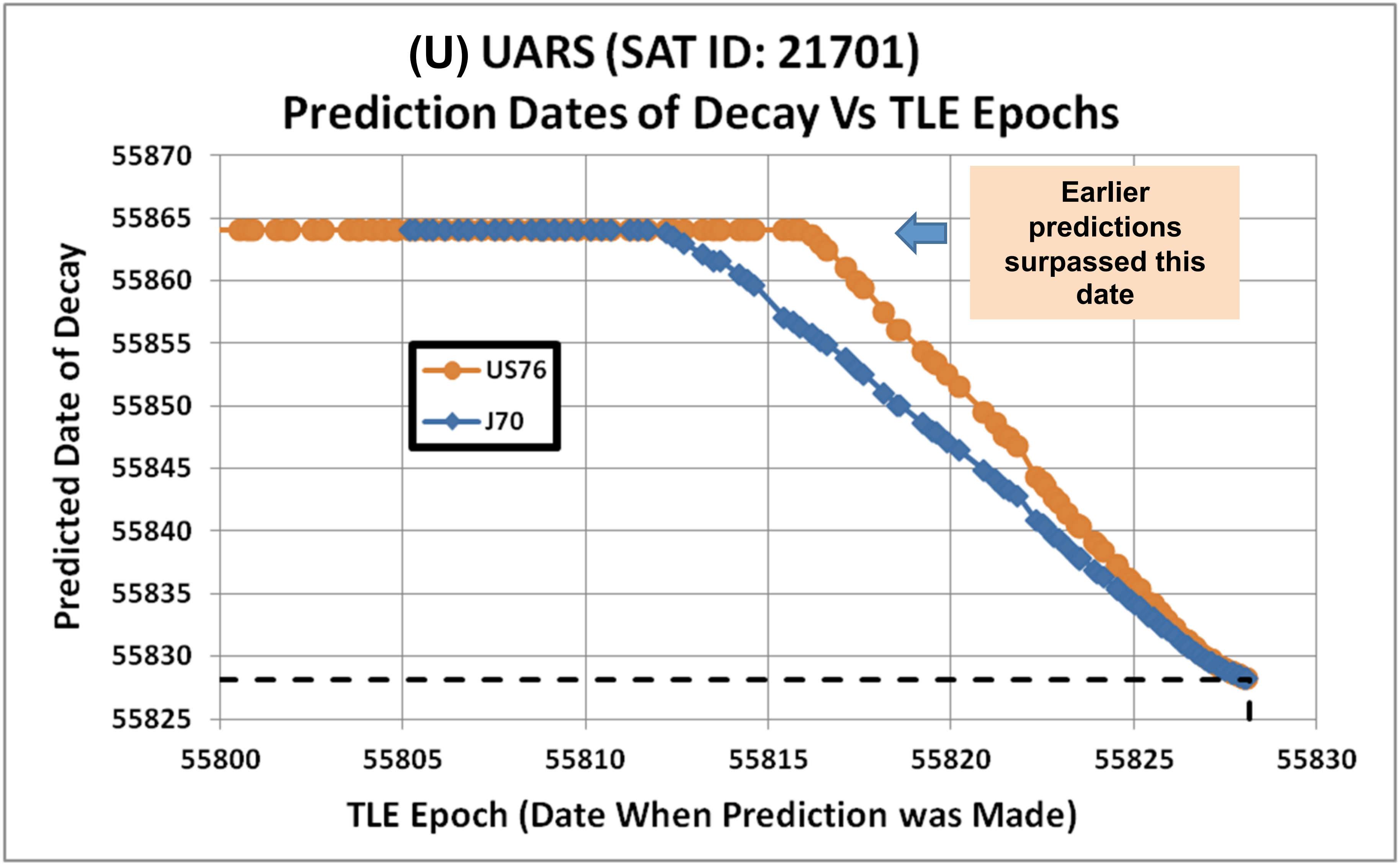
Image: Lavochkin Association

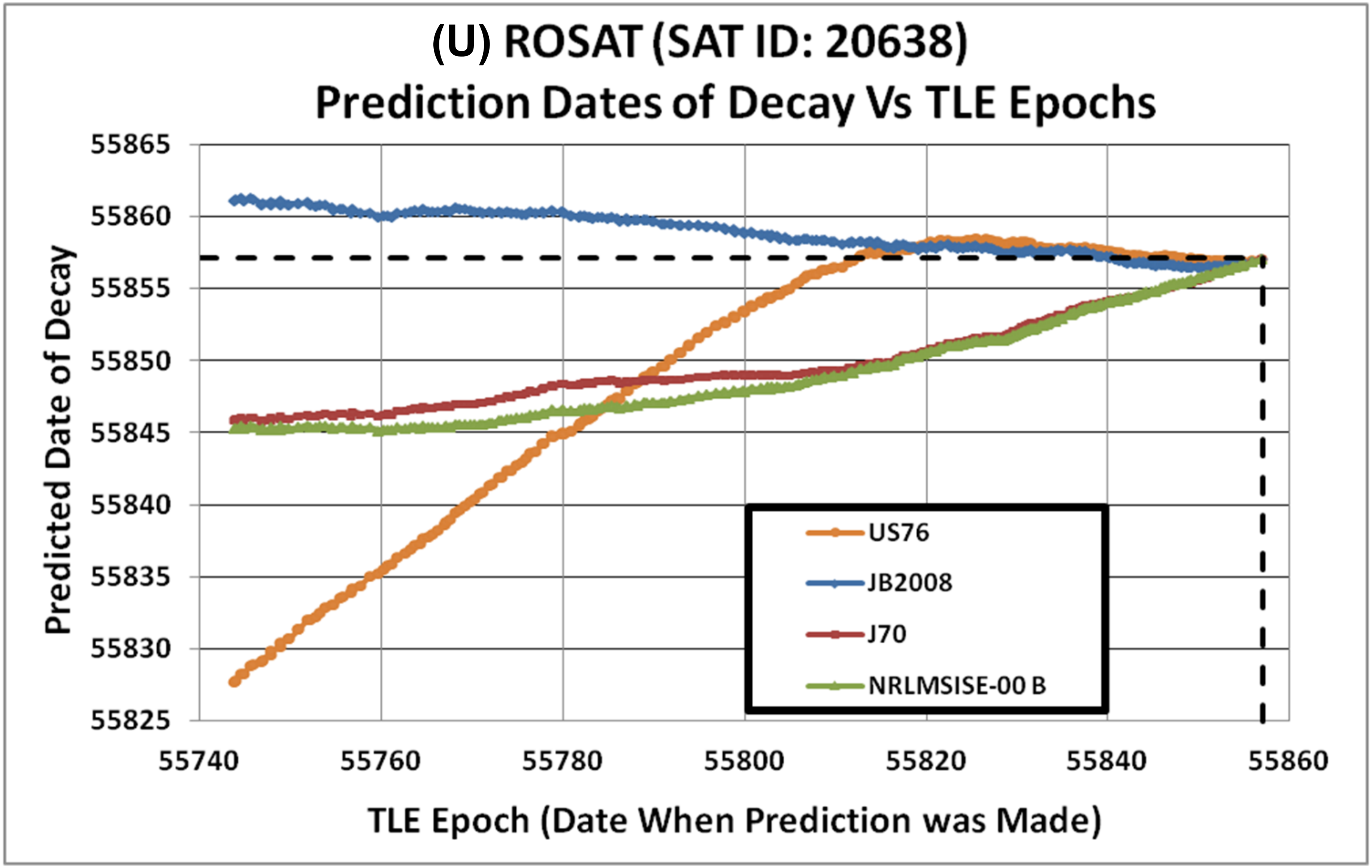
- (U) Perigee decreased until Nov 14 – 21, then began increasing (but with apogee dropping)
- (U) Nov 27: object 'G' separated; decayed on Nov 29
- (U) Nov 30: object 'H' separated; decayed on Dec 2

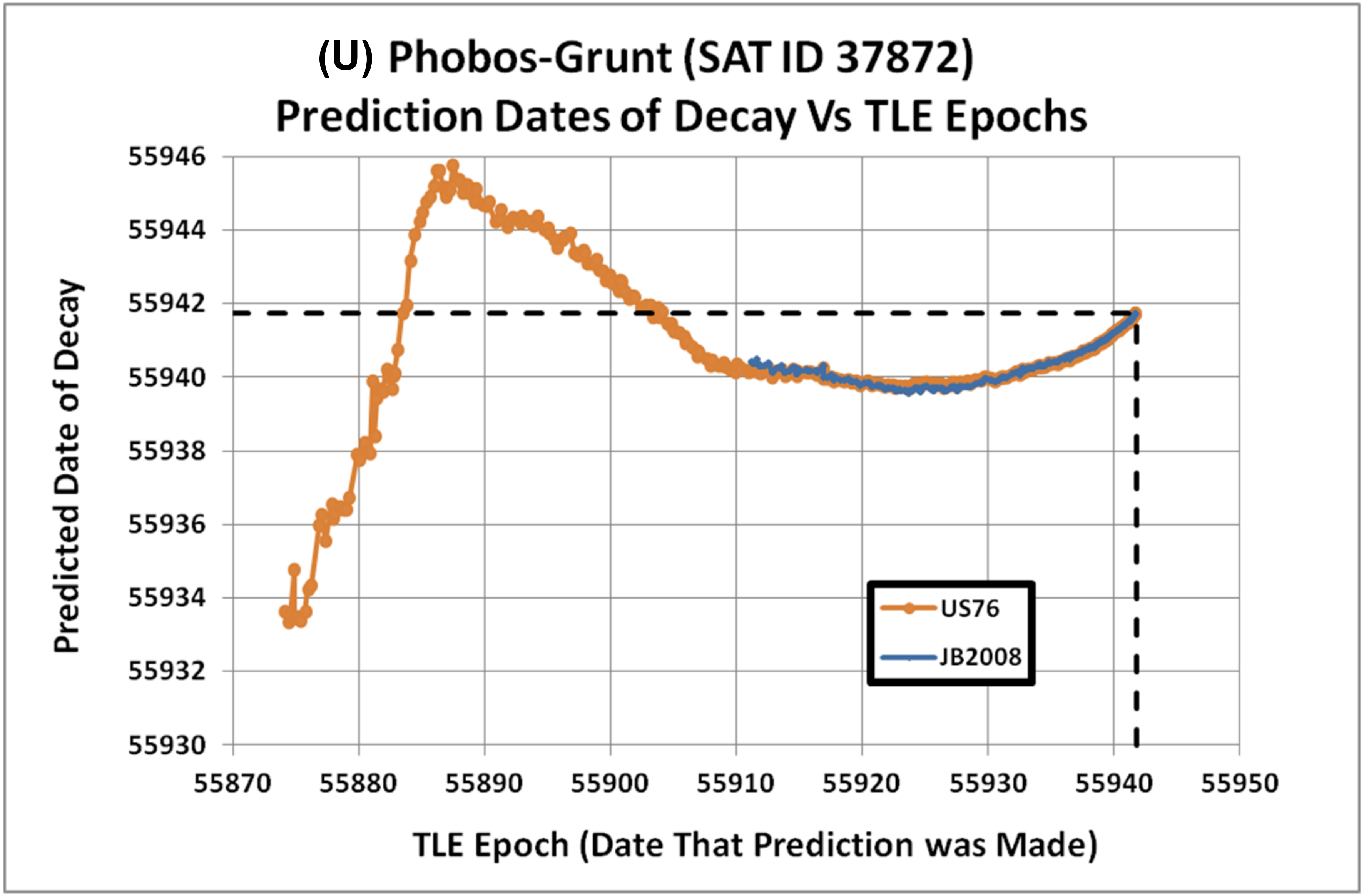
Source: spaceflight101.com


(U) Geophysical Indices for 18 Jul 2011 - 03 Feb 2012
(UARS, ROSAT, Phobos-Grunt Cases)
Geophysical Indices
Modified Julian Date
2000
1800
1600
1400
1200
1000
800
600
400
200
0
-200
55760
55780
55800
55820
55840
55860
55880
55900
55920
55940
55960
UARS 24 Sep 2011
ROSAT 23 Oct 2011
PG 15 JAN 2012
10* F10.7 Daily
10*'F10.7 Smoothed
Max Ap Per Day
Min Daily Dst
Daily SSN (Int)
Date of Decay for UARS
Date of Decay for ROSAT
Launch for Phobos-Grunt
Date of Decay for Phoboe-Grunt


(U) JB2008 Solar EUV Indices for 18 Jul 2011 - 03 Feb 2012
(UARS, ROSAT, Phobos-Grunt Cases)
Geophysical Indices
200
180
160
140
120
100
80
60
40
55760
55780
55800
55820
55840
55860
55880
55900
55920
55940
55960
Modified Julian Date
F10
F81c
S10
S81c
M10
M81c
Y10
Y81c


(U) UARS (SAT ID: 21701)
Prediction Dates of Decay Vs TLE Epochs
Predicted Date of Decay
55870
55865
55860
55855
55850
55845
55840
55835
55830
55825
55800
55805
55810
55815
55820
55825
55830
TLE Epoch (Date When Prediction was Made)
US76
J70
Earlier predictions surpassed this date


(U) ROSAT (SAT ID: 20638)
Prediction Dates of Decay Vs TLE Epochs
Predicted Date of Decay
55865
55860
55855
55850
55845
55840
55835
55830
55825
55740
55760
55780
55800
55820
55840
55860
TLE Epoch (Date When Prediction was Made)
US76
JB2008
J70
NRLMSISE-00 B


(U) Phobos-Grunt (SAT ID 37872)
Prediction Dates of Decay Vs TLE Epochs
Predicted Date of Decay
55946
55944
55942
55940
55938
55936
55934
55932
55930
55870
55880
55890
55900
55910
55920
55930
55940
55950
TLE Epoch (Date That Prediction was Made)
US76
JB2008

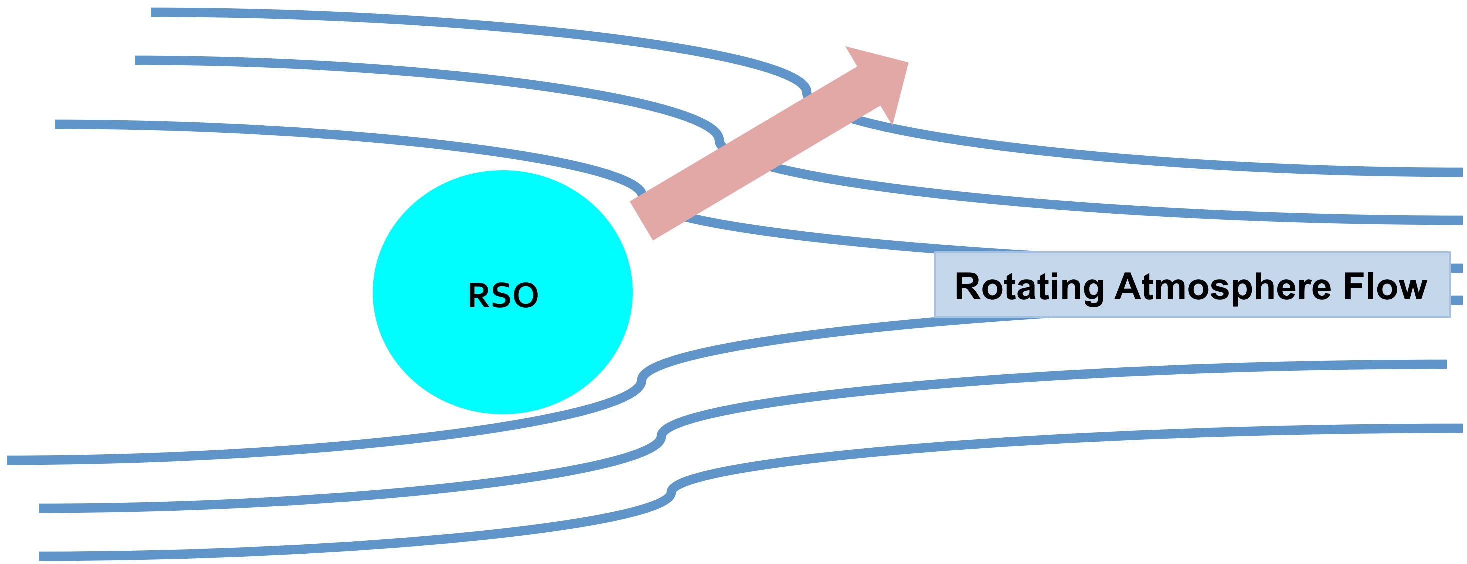
(U) Current Work and Path Forward

- (U) Test orbit predictions well before expected de-orbit
- (U) Use high-precision ephemeris in place of TLE's
- (U) Test approach using calibration sphere data
- (U) Test thermosphere neutral wind drag models
    - (U) Examine ionospheric coupling in wind modeling efforts
- (U) Model effect of thermospheric density fluctuations
- (U) Optimize method to estimate shape and mass of RSO
    - (U) Adjust trial area and mass to minimize in-track and cross-track error differences between propagated and HP ephemeris
    - (U) Account for in-track and cross-track RSO drag surfaces
- (U) Examine gravity wave effects

(U) Drag Calculation – Original Model:

(U) DRAG TERM – Original Expression:

$$\vec{a}_D = -\frac{1}{2}\frac{C_d A}{m}\rho(\vec{r})\left|\vec{V}_D\right|^2 \hat{V}_D \quad ; \vec{V}_D = \vec{V} - \omega_e \hat{z} \times \vec{r}$$

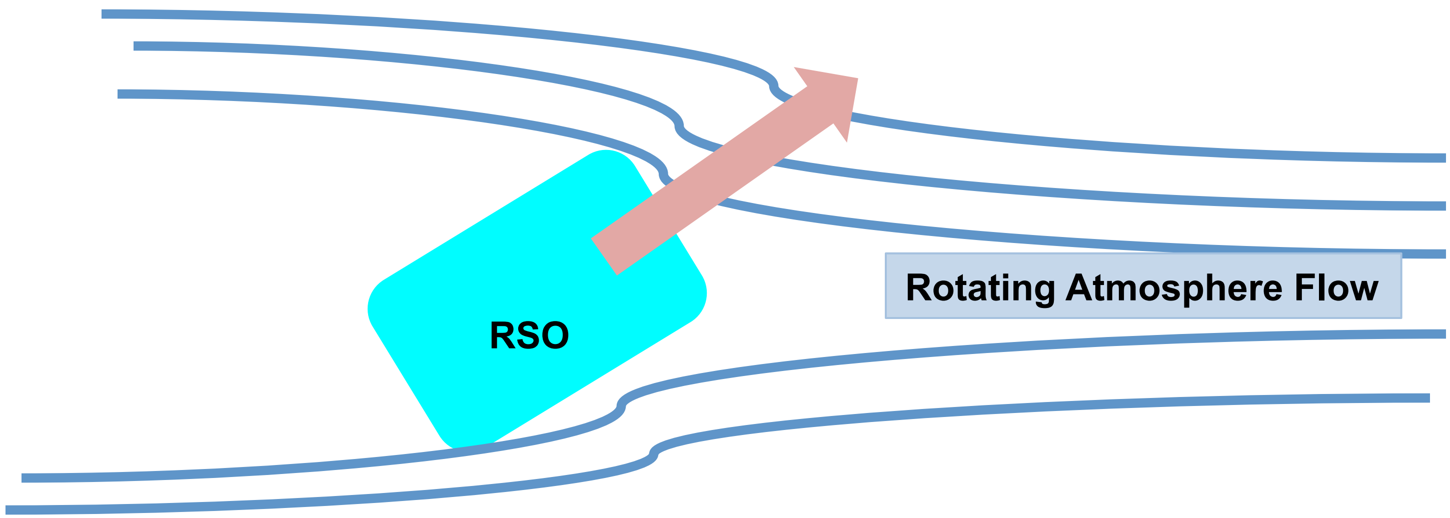


(U) This is a simplified scenario that does not account for true shape of RSO

(U) Drag Calculation – Updated Model

(U) Corrections for time-varying mass, attitude changes, and error in drag force:

$$\vec{a}_D = -\varsigma_D(t)\frac{1}{2}\frac{C_d A(t)}{m(t)}\rho(\vec{r})\left|\vec{V}_D\right|^2 \widehat{V}_D$$



(U) Adjusting also for rotating atmosphere impacting different areas of RSO:

$$\vec{V}_D = \vec{V} - \chi_{ITE}(t)\hat{e}_{ITE}(\hat{e}_{ITE}\cdot(\omega_e\widehat{z}\times\vec{r})) - \chi_{XTE}(t)\hat{e}_{XTE}(\hat{e}_{XTE}\cdot(\omega_e\widehat{z}\times\vec{r}))$$

(U) Determine the ζ and χ terms from reducing in-track and cross-track errors

(U) Summary

- (U) Modern density models have been integrated with ASAP
- (U) ASAP was used to predict de-orbit times for recent RSO decays
- (U) Results are inconclusive; further testing is needed
- (U) Next efforts will focus on:
  - (U) Use of model stack for non-decaying orbit predictions
  - (U) Statistical comparisons of predicted orbits with high-precision ephemeris data
  - (U) Modeling variable thermospheric density structures
  - (U) Prediction accuracy during geomagnetic storms with JB2008

(U) Questions?

(U) For additional details, contact :

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