Improving Safety of Space Operations

Dr. T.S. Kelso

Overview

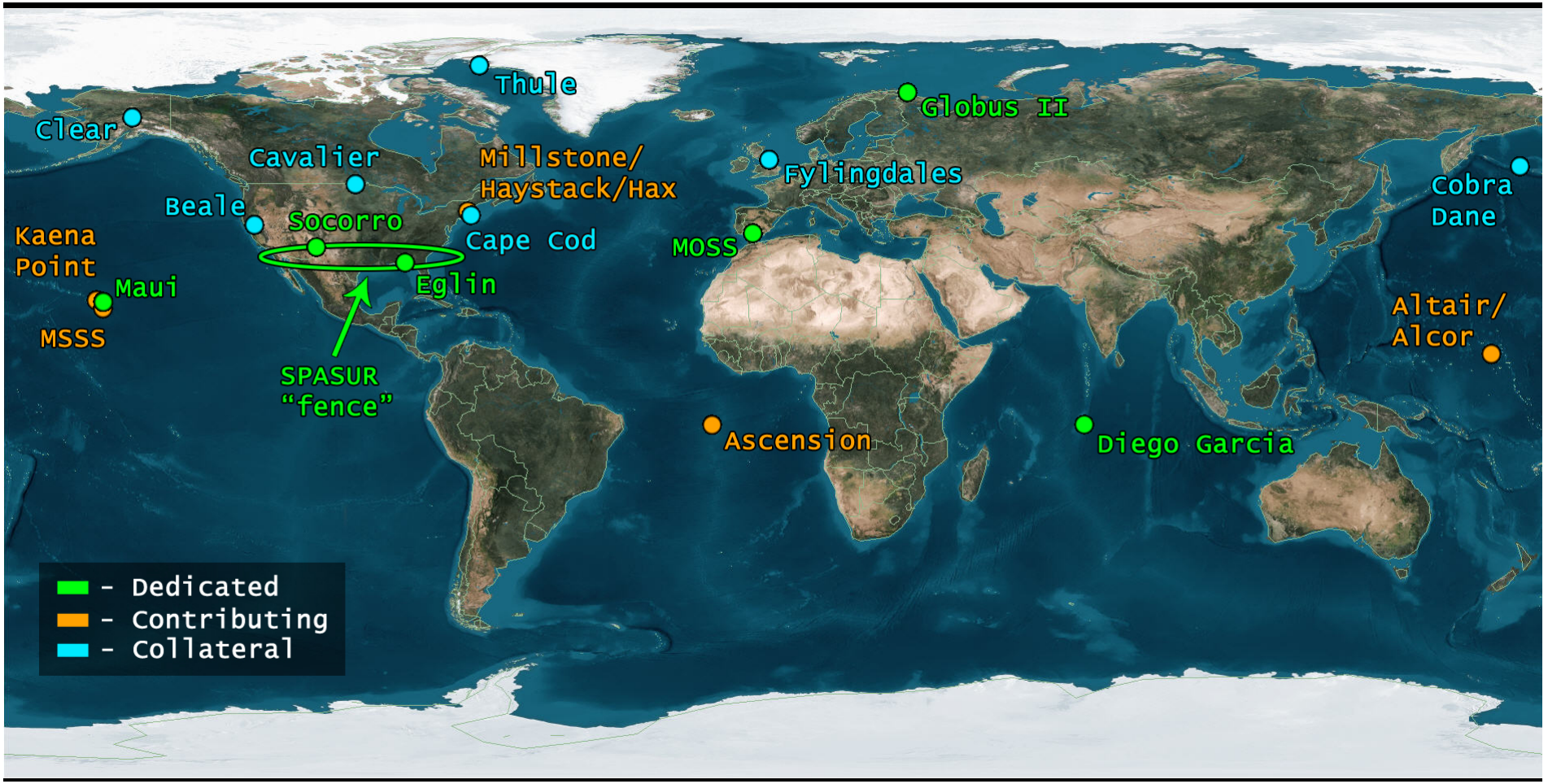
- Satellite Tracking: Who? How?
- Motivation: Why Do We Care?
  - Background
  - Proposed Solution
  - Validation
- Case Studies
- Space Data Center
  - Demo
- Summary & Conclusions

Satellite Tracking: Who? How?

Satellite Tracking: Who?

- North American Aerospace Defense Command (NORAD)
- US Strategic Command (USSTRATCOM)
  - Joint Forces Component Command-Space (JFCC-Space)
    - Joint Space Operations Center (JSpOC)
- Air Force Space Command (AFSPC)
  - 14th Air Force
    - 614 Air and Space Operations Center (614 AOC)

US Space Surveillance Network



SSA Products

- Orbital Data
  - Two-Line Element Sets (TLEs)
    - General Perturbations Theory (Mean Elements)
      - Requires SGP4/SDP4 propagator
    - Available to the public for most satellites
      - Analyst catalog (~6,000 objects) not available
  - Vector Covariance Messages (VCMs)
    - Special Perturbations Theory (Osculating Elements)
    - Very limited availability due to US policy

TLE Format: Line 1

```
1 25544U 98067A   11262.42784589  .00012060  00000-0  14491-3 0   935
2 25544  51.6424  46.3642 0010617 212.0972 261.3054 15.61271842735628
```

- Line number
- NORAD Catalog Number
- Classification (U = Unclassified)
- International Designator (YYNNNAAA)
- Epoch (YYDDD.DDDDDDDD)
- First time derivative of mean motion ($n_0/2$)
- Second time derivative of mean motion ($n_0/6$; NNNNN-E = 0.NNNNN×10^E)
- BSTAR (ER^{-1}; NNNNN-E = 0.NNNNN × 10^E)
- Ephemeris type (1=SGP, 2=SGP4, 3=SDP4, 4=SGP8, 5=SDP8; always 0)
- Element set number
- Modulo-10 checksum

Reference:
T.S. Kelso, "Frequently Asked Questions: Two-Line Element Sets," *Satellite Times*, January 1998.

TLE Format: Line 2


```
1 25544U 98067A   11262.42784589  .00012060  00000-0  14491-3 0   935
2 25544  51.6424  46.3642 0010617 212.0972 261.3054 15.61271842735628
```

- Line number
- NORAD Catalog Number
- Inclination (i, degrees)
- Right Ascension of the Ascending Node (Ω, degrees)
- Eccentricity (e, implied leading decimal)
- Argument of Perigee (ω, degrees)
- Mean Anomaly (M, degrees)
- Mean Motion (n, revs per day)
- Revolution number at epoch (revs)
- Modulo-10 checksum

Reference:

T.S. Kelso, "Frequently Asked Questions: Two-Line Element Sets," *Satellite Times*, January 1998.

Orbital Propagators

- Simplified General Perturbations (SGP)
  - Based on Kozai Theory (1959)
  - Drag handled via mean motion derivatives
  - Developed 1960, operational 1964
- SGP4/SDP4
  - Based on Brouwer Theory (1959)
  - Drag handled via BSTAR (modified ballistic coefficient)
  - Operational 1970
- Both designed to minimize computational load, storage, and bandwidth

Orbital Propagators

- Others
  - SGP8/SDP8
  - HANDE
- Must use correct propagator with TLE (SGP4)
  - TLEs contain mean elements
- Must use proper mathematical technique
  - Motivated release of Spacetrack Report Number 3

Reference:
D.A. Vallado, P. Crawford, R. Hujsak, and T.S. Kelso, "Revisiting Spacetrack Report #3," presented at the AIAA/AAS Astrodynamics Specialist Conference, Keystone, CO, 2006 August 21–24.

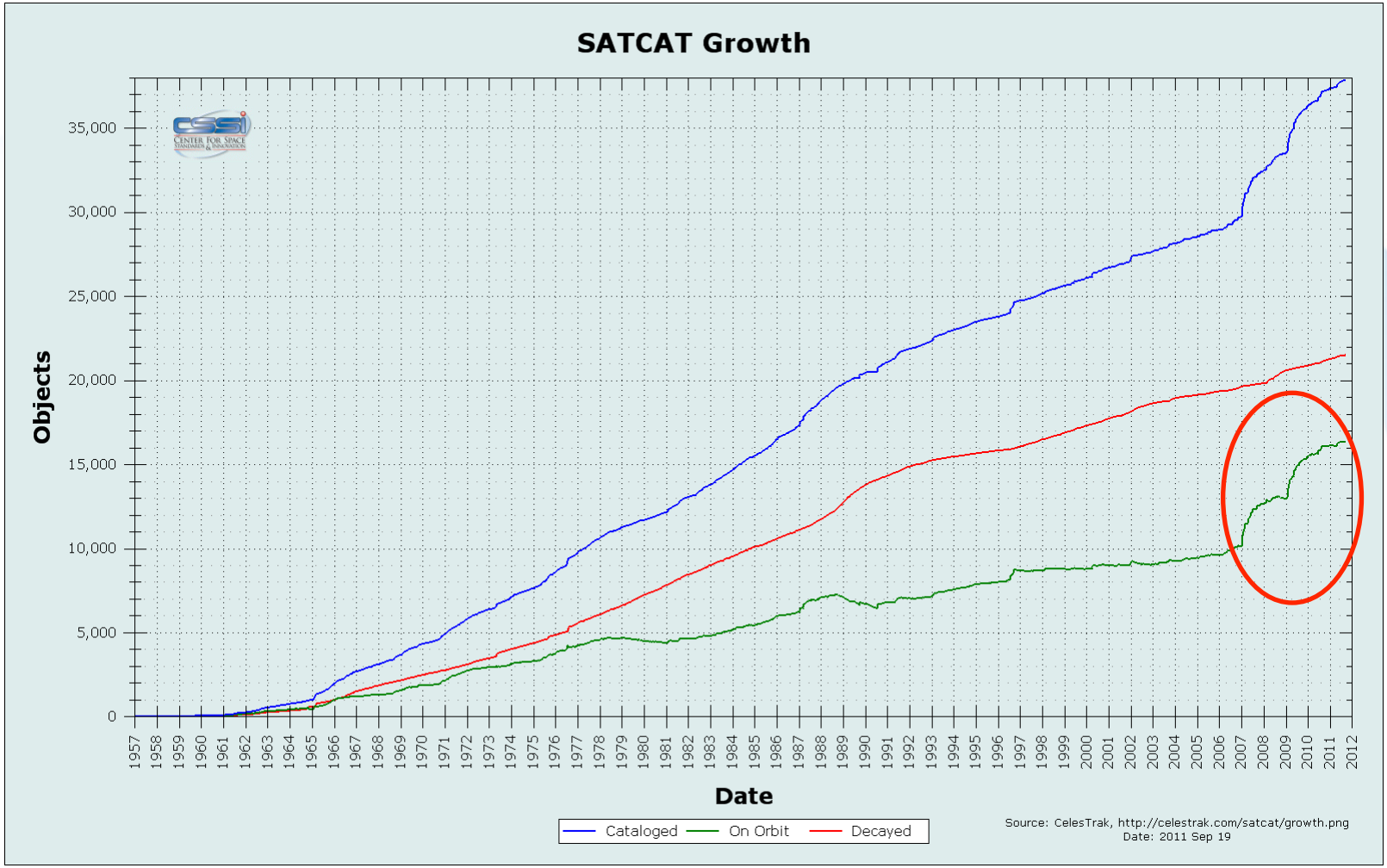
Reference: F.R. Hoots, P.W. Schumacher, and R. A. Glover. 1995. “History of Analytical Orbit Modeling in the U.S. Space Surveillance System.” *Journal of Guidance, Control, and Dynamics*, Vol. 27, No. 2, March–April 2004.

Motivation: Why Do We Care?

Motivation

- 61 percent increase in size of known on-orbit population since 2007 Jan 1
  - 2007 Jan 1: 10,136
  - 2011 Sep 20: 16,319
- 83 percent of growth due to two events
  - Chinese ASAT test (2007 Jan 11)
    - 3,180 pieces cataloged to date (only 152 decayed)
  - Iridium 33/Cosmos 2251 collision (2009 Feb 10)
    - 2,035 pieces cataloged to date (only 175 decayed)
- Does not include another 6,000+ 'analyst' objects

SATCAT Growth: 1957 to Present



Catalog

Decayed

On-Orbit

Motivation

- ~1,068 operational satellites in Earth orbit
  - Adding roughly 100 satellites each year
    - 87 in 2008; 101 in 2009; 94 in 2010; 62 so far in 2011
- More satellites = more conjunctions
- Implications of a collision are significant
  - Potential loss of satellites & associated revenues
  - Further increase in debris, putting all satellites at risk

Background

- Conjunction analysis needs full-catalog orbital data
- Current SSA limited to non-cooperative tracking
  - US SSN uses combination of radar & optical resources
- Maneuvering satellites most difficult to track
  - Maneuvers typically not known to SSN ahead of time
  - Delays in detection can result in poor accuracy or even 'lost' satellites
  - Requires more SSA resources to maintain orbits

Background

- SOCRATES started as proof-of-concept in 2004
  - Show it isn't hard to screen all payloads, using:
    - COTS software & hardware
    - Standard orbital data products
  - Produce timely reports
    - Screens 3,114 payloads vs. 14,722 objects over 7-day window in 79 minutes on a 3 GHz Core 2 Duo with 4 GB RAM
  - Raise awareness of the magnitude of the problem
    - As of 2011 Sep 23, 17,706 occasions where something comes within 5 km of one of 3,114 payloads over a 7-day period
  - Point out limitations of existing orbital data sources

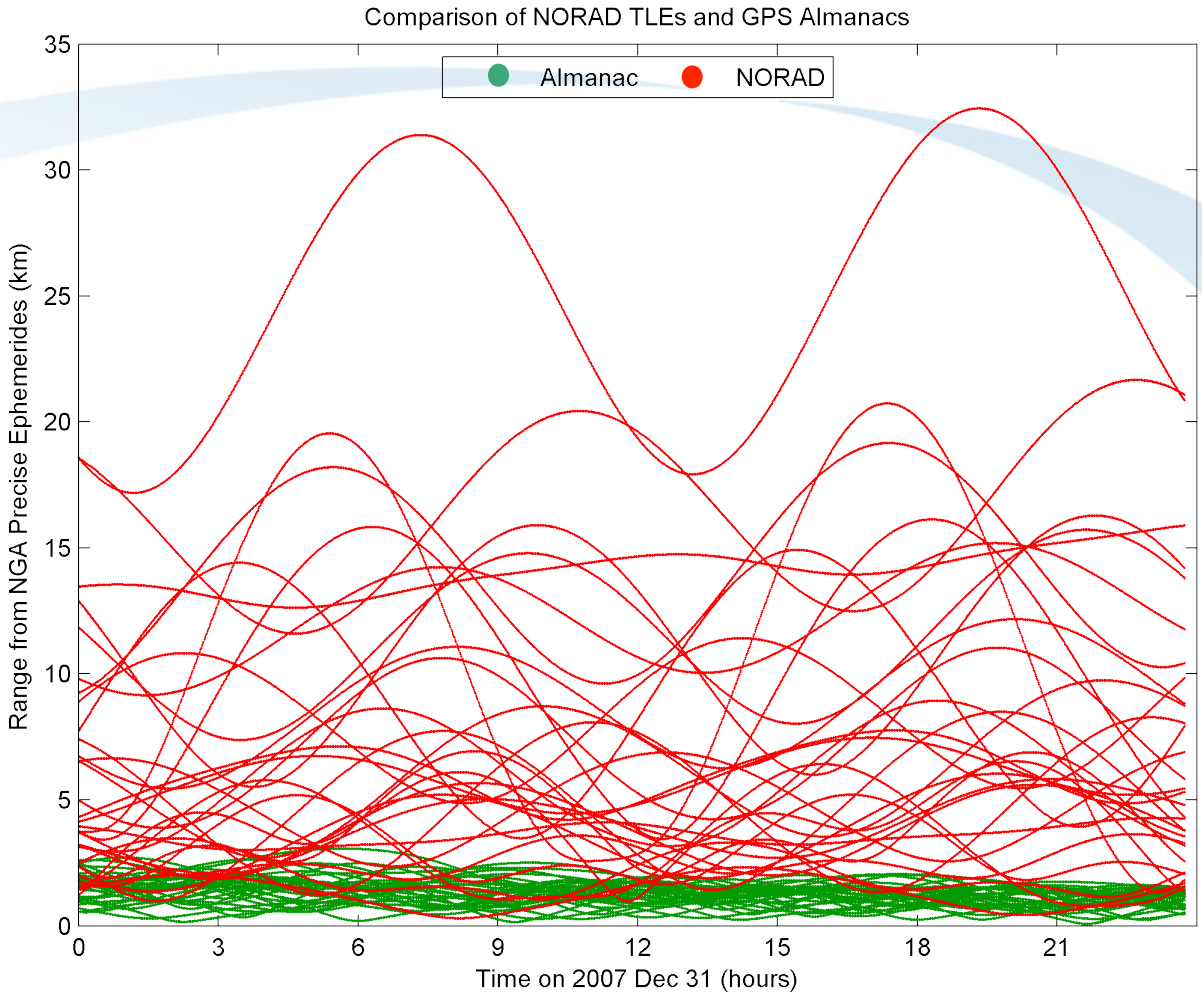
Proposed Solution

- Satellite operators already maintain orbits
  - Active ranging, GPS can be very accurate
- Develop Data Center to collect operator data
  - Use operator data to improve conjunction analysis
  - Provide analysis/data to all contributors
- Requires validation of accuracy assumption

GPS Almanacs vs. TLEs

Mean: 7.544 km

Max: 32.449 km



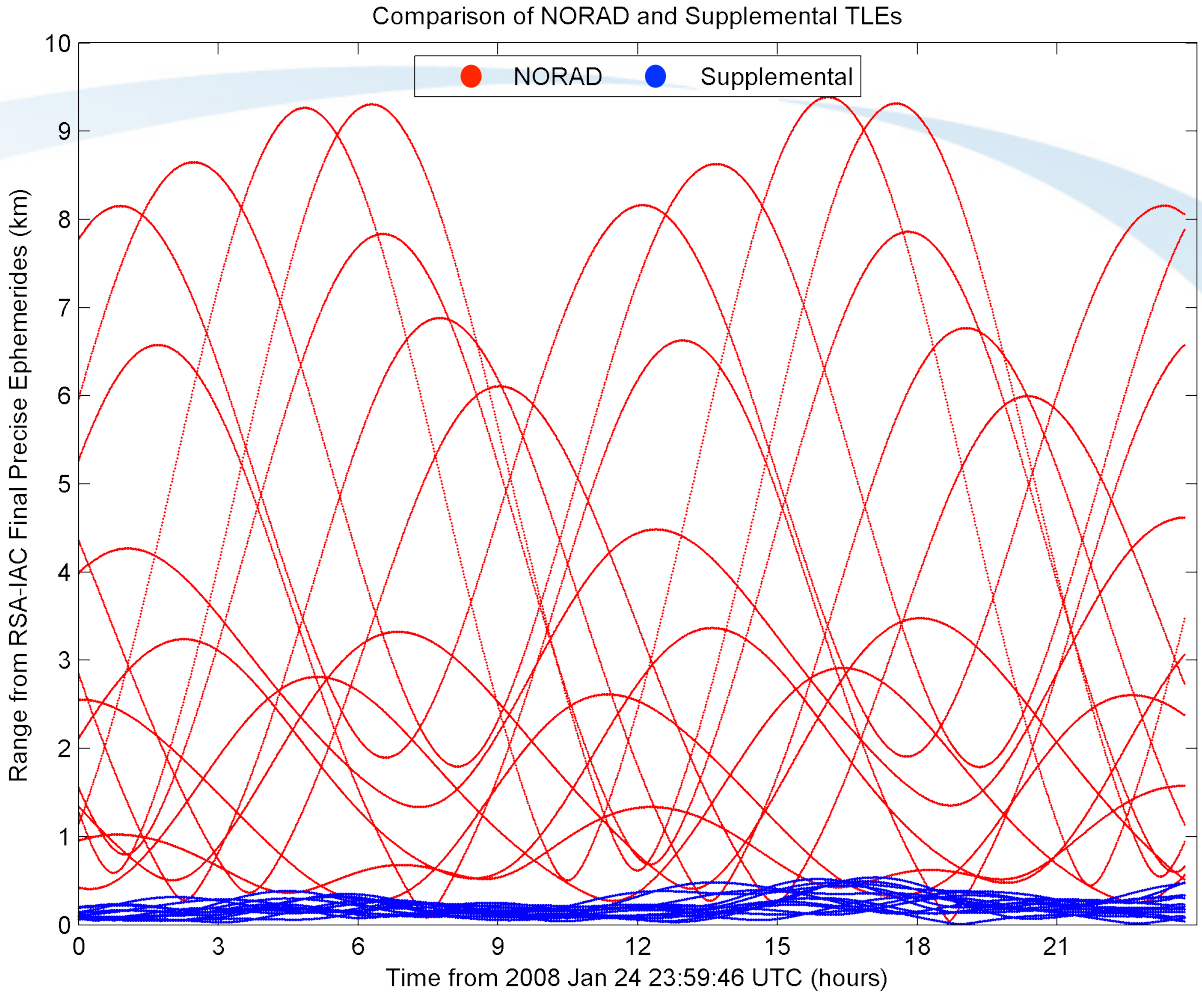
Mean: 1.292 km

Max: 3.073 km

GLONASS Supplemental TLEs

Mean: 3.301 km

Max: 9.388 km



Mean: 0.201 km

Max: 0.539 km

Sources of Orbital Data

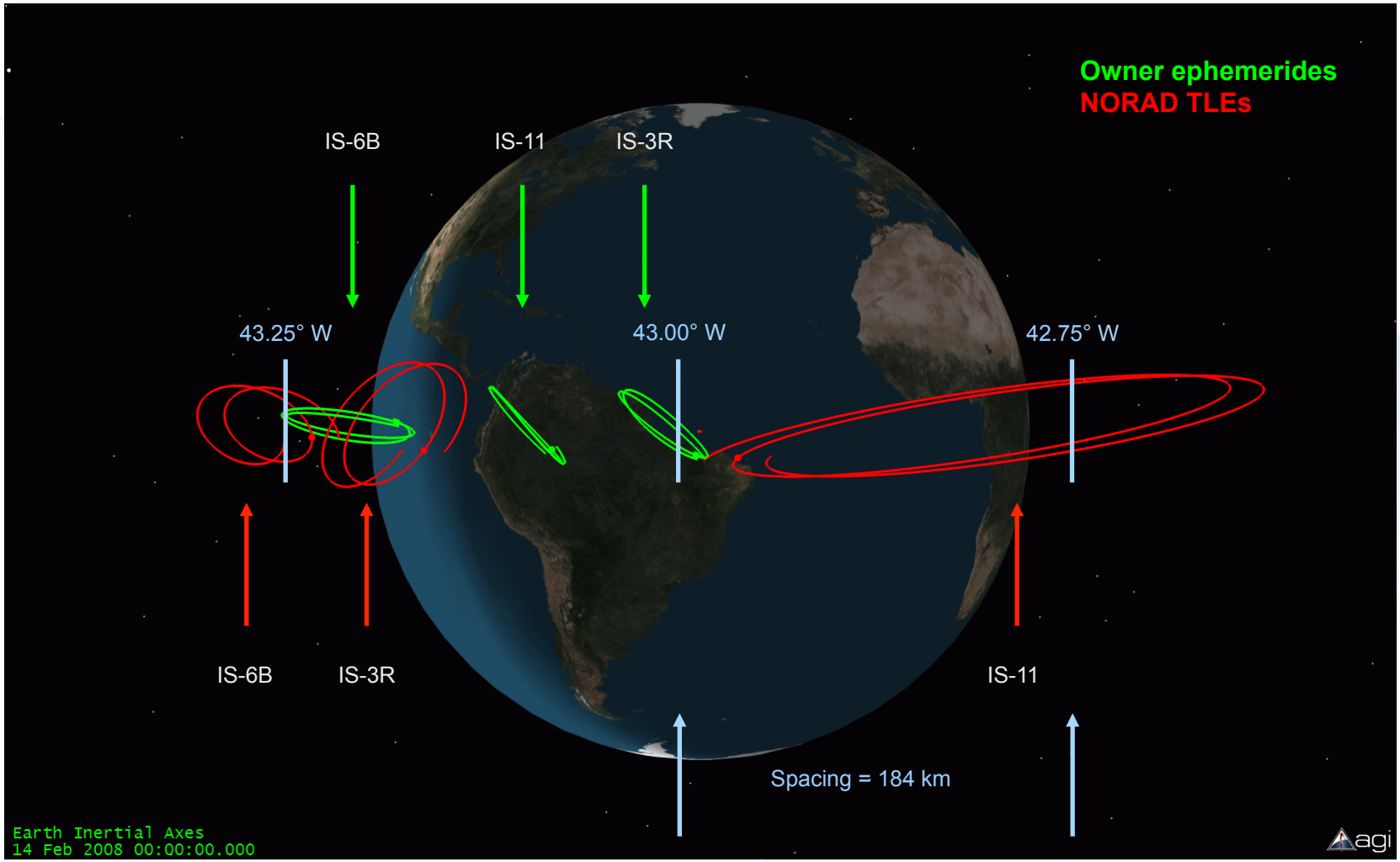
- Many sources of operator orbital data
  - Public sources
    - GPS (almanacs, rapid/final precise ephemerides)
    - GLONASS (rapid/final precise ephemerides)
    - Intelsat (11-parameter data, ephemerides)
    - NOAA, EUMETSAT (state vectors)
  - Direct from satellite operator (Space Data Center)
- Challenges
  - User-defined data formats
  - Variety of coordinate frames & time systems used

Case Studies

Case Studies

- Intelsat: Missed maneuver & cross-tagging
- Astra 1 Cluster
- Astra 1M & 3B: Early orbit
- DIRECTV 10 & 12: Maneuver modeling
- GPS 2F-1 and 2F-2: Missed maneuvers

Intelsat Data Comparisons

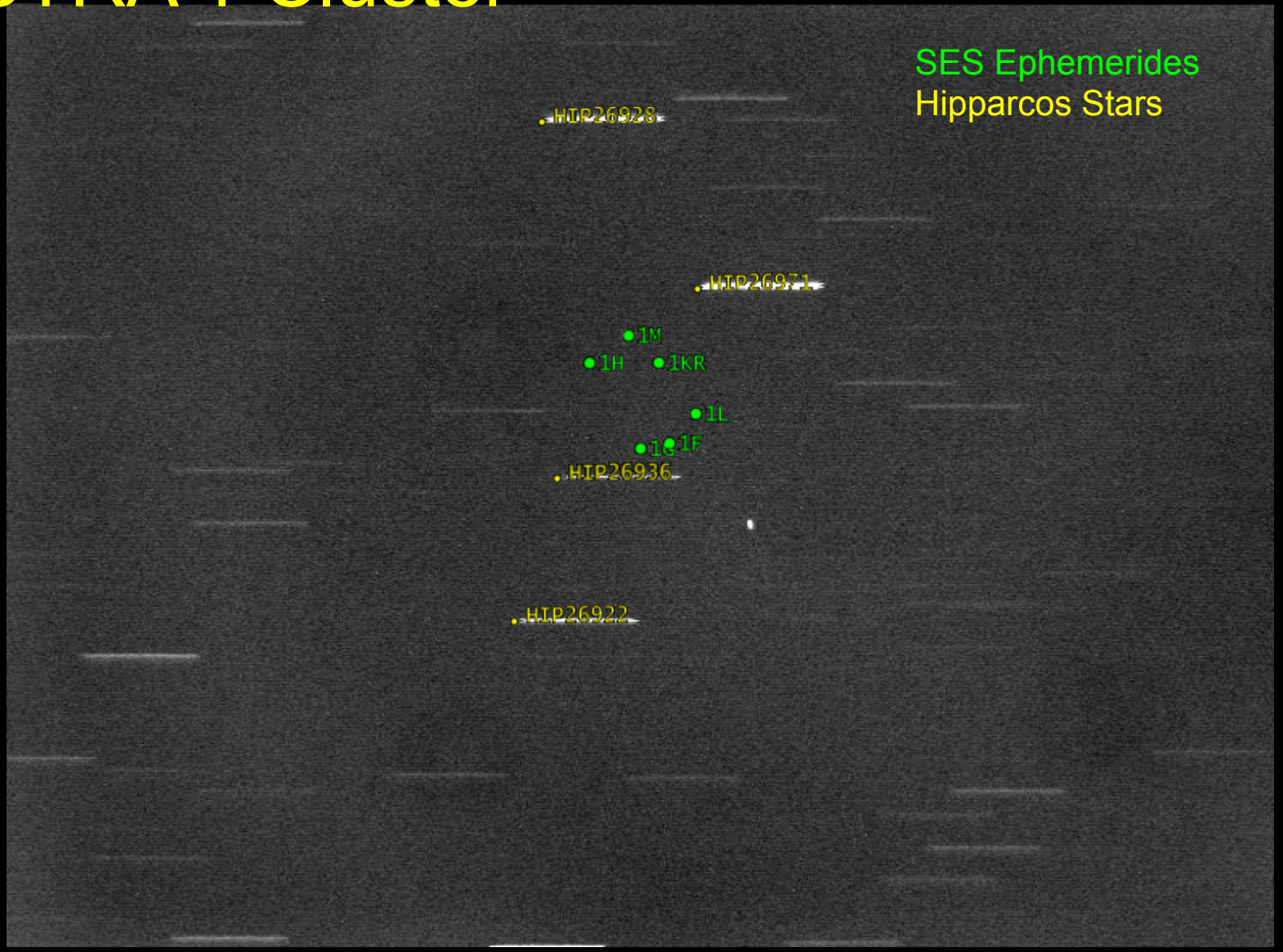


ASTRA 1 Cluster

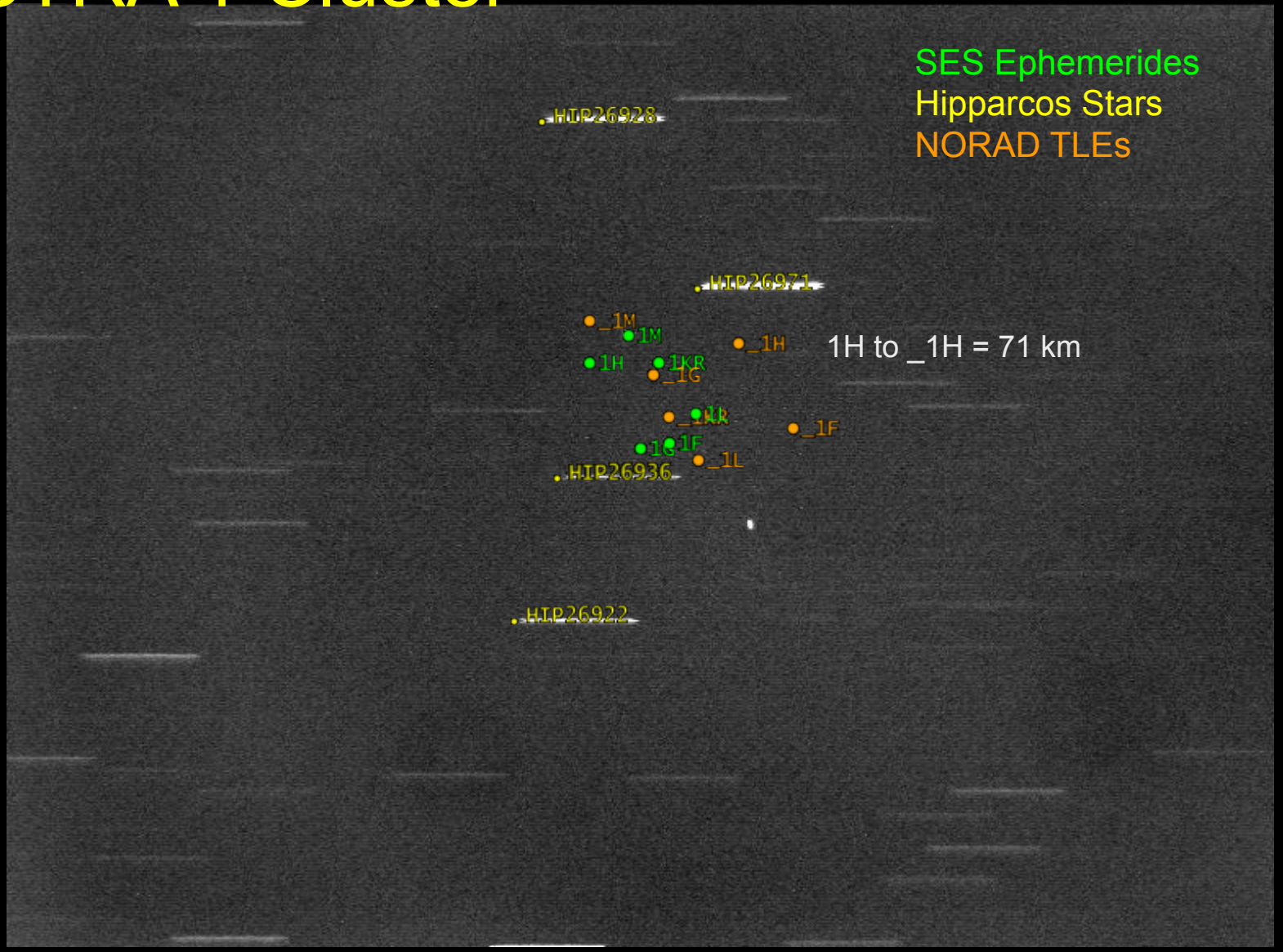
- Open source image of cluster
  - http://www.foton.co.za/assa_imaging.htm
- Taken 2009 Jan 21 at 20:21:11 UTC
- Site location: 33.94058 S, 18.51294 E, 10 m
  - Pinelands, a suburb of Cape Town, South Africa
- Telescope: 6-inch, f/2.7 reflector
- FOV: 54.7 x 40.2 arcminutes; 20-sec exposure
- Compared SES ephemerides and latest TLEs

ASTRA 1 Cluster

ASTRA 1 Cluster



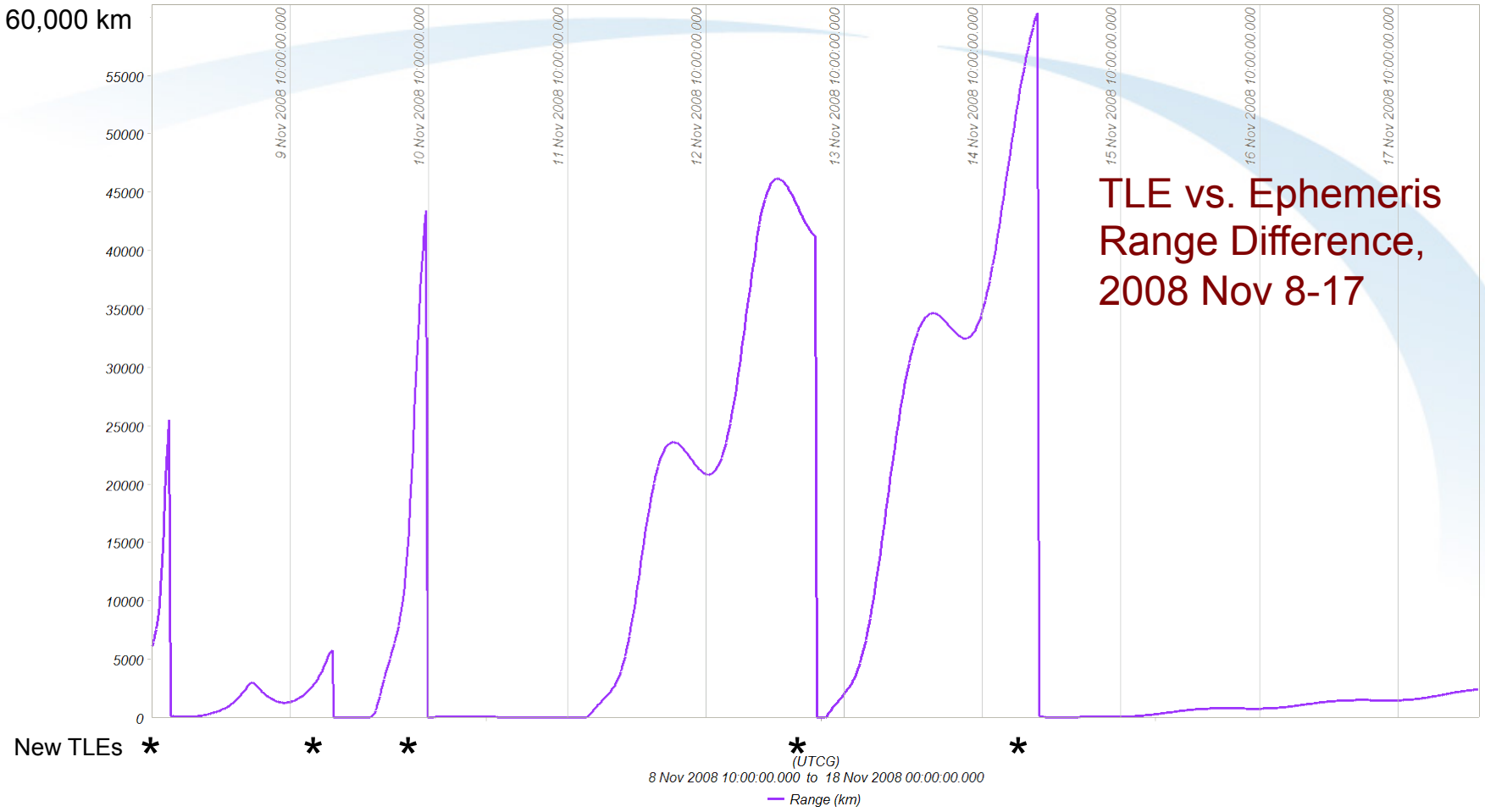
ASTRA 1 Cluster



Astra 1M Early Orbit

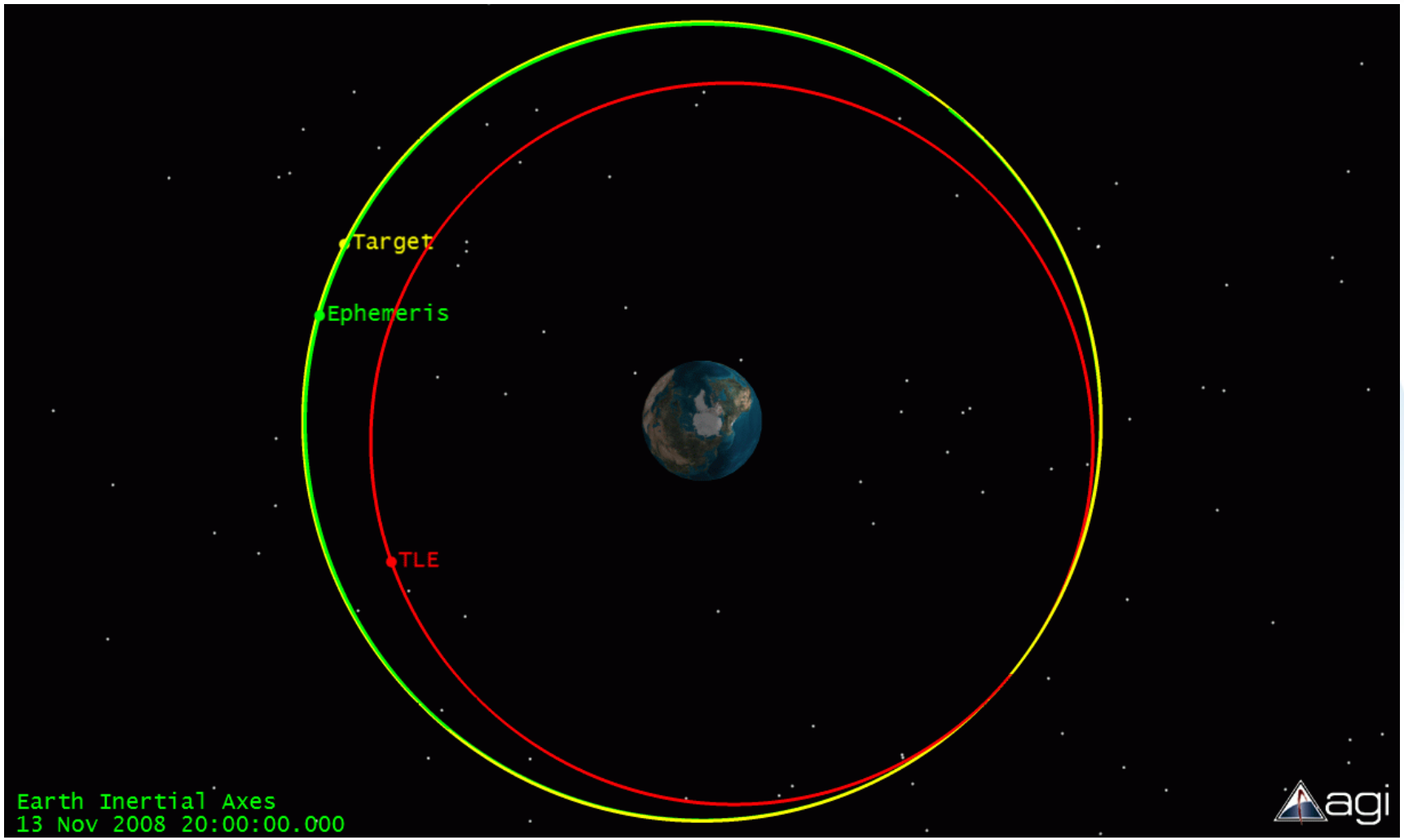
- Launched from Baikonur
  - 2008 Nov 5 @ 2044 UTC
- Data Center received first data
  - 2008 Nov 8 @ 1000 UTC
  - Updated every two hours

Astra 1M Early Orbit



TLE vs. Ephemeris Range Difference, 2008 Nov 8-17

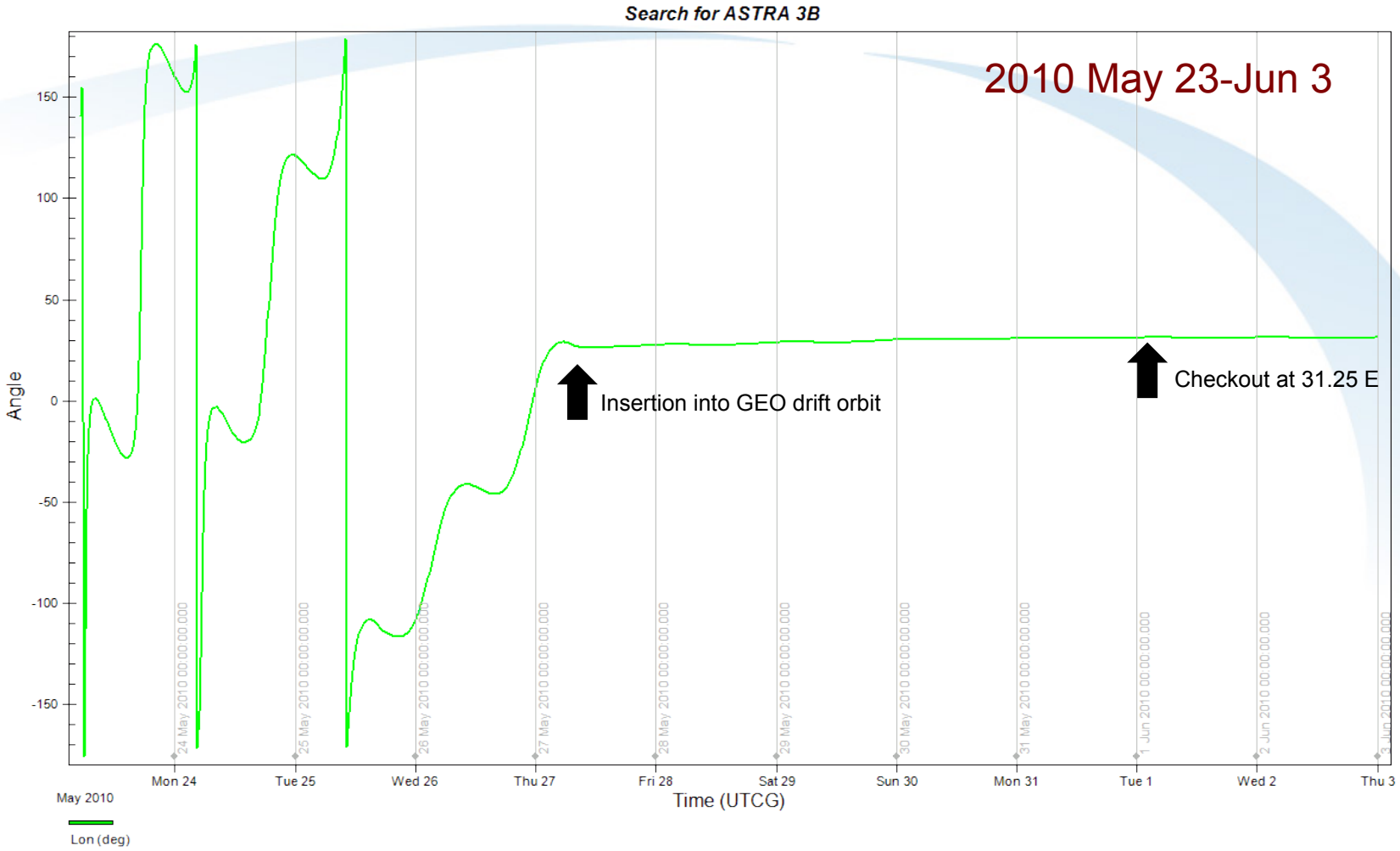
Astra 1M Early Orbit



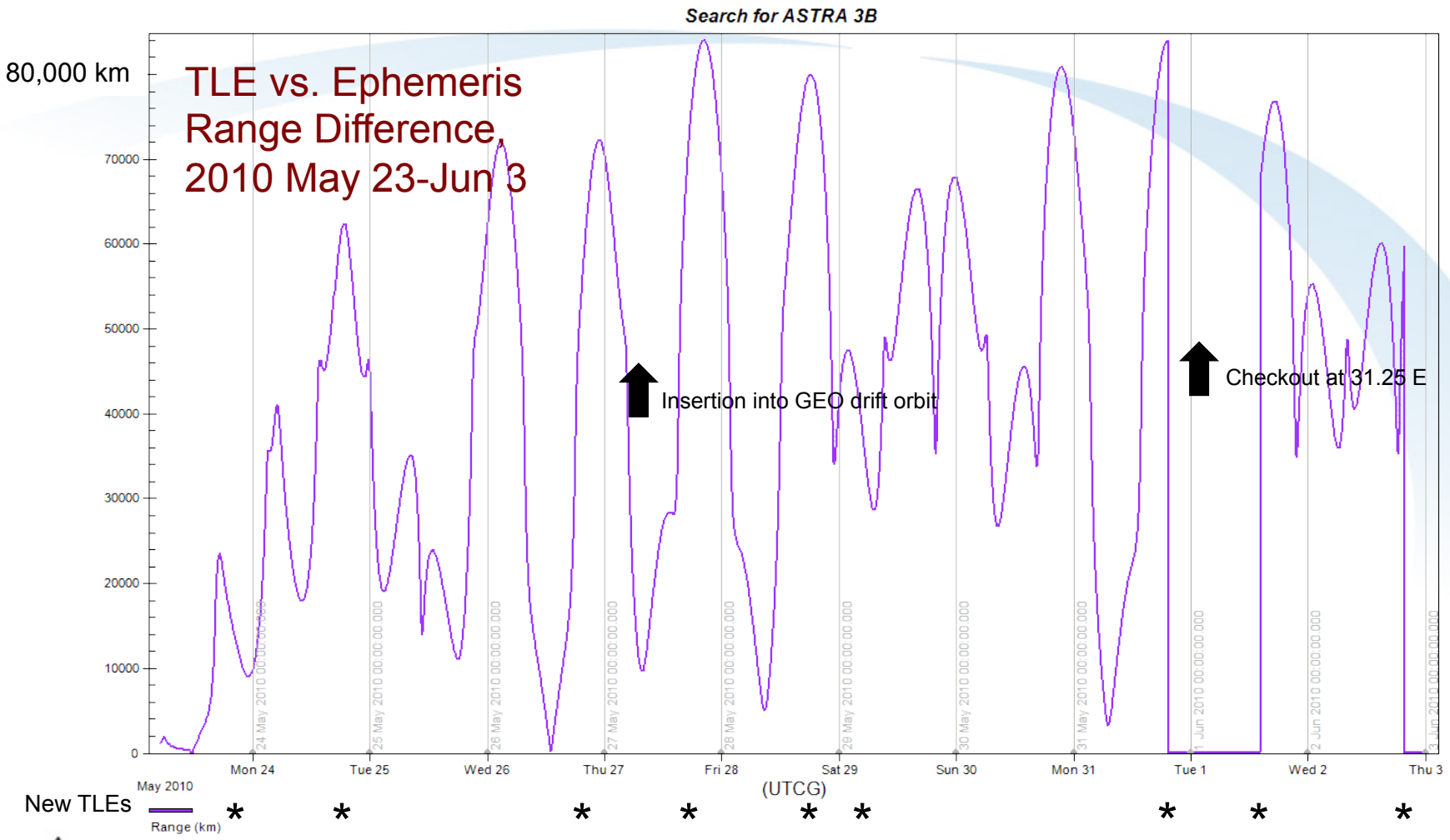
Astra 3B Early Orbit

- Launched from Europe's Spaceport
  - 2010 May 21 @ 2201 UTC
- Data Center received first data
  - 2010 May 23 @ 0830 UTC
  - Updated every 2-3 hours
- Three phases examined
  - Search: 2010 May 23-June 3
  - Refine: 2010 June 3-16
  - Current: 2010 June 16-28

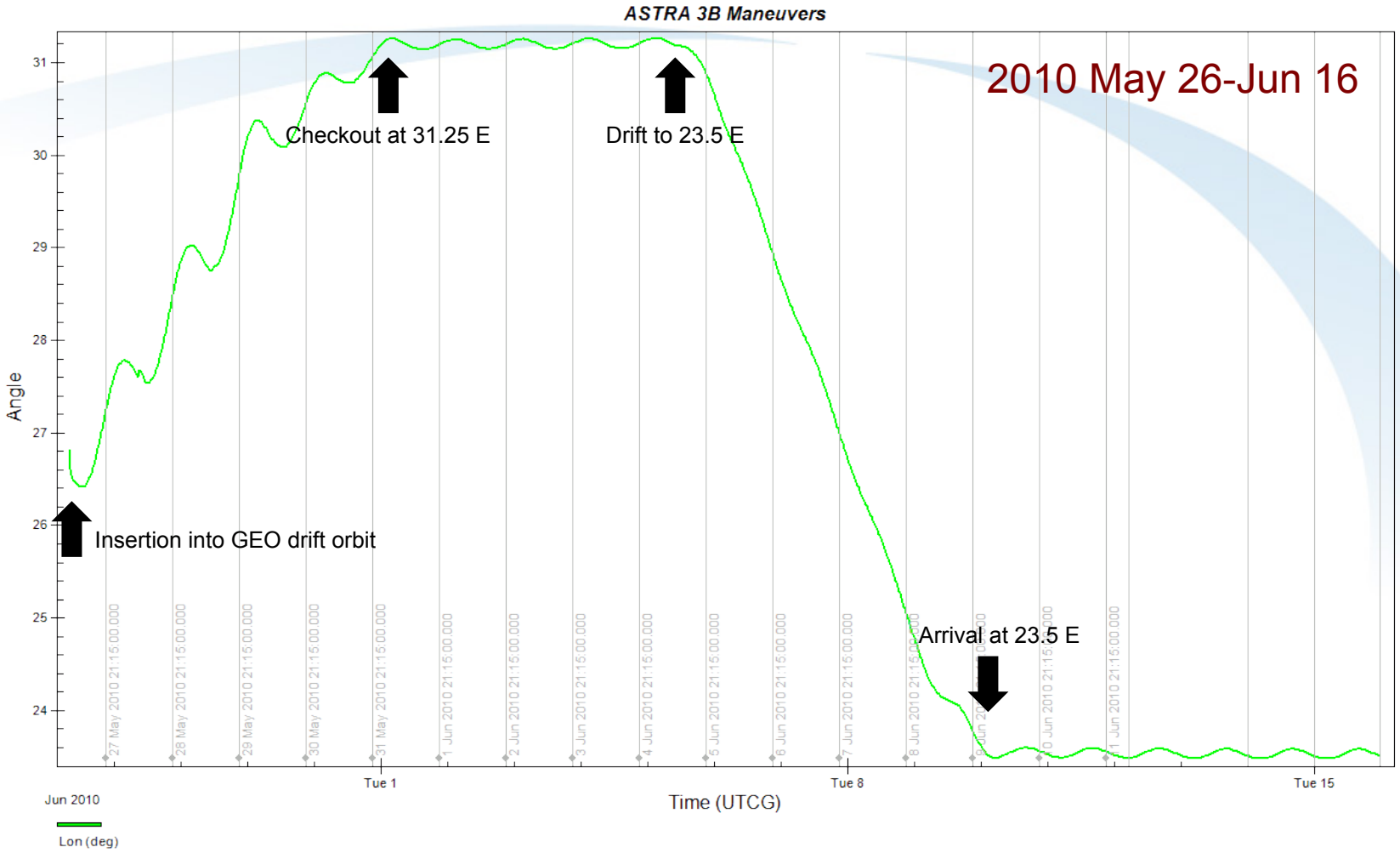
Astra 3B: Longitude (Search)



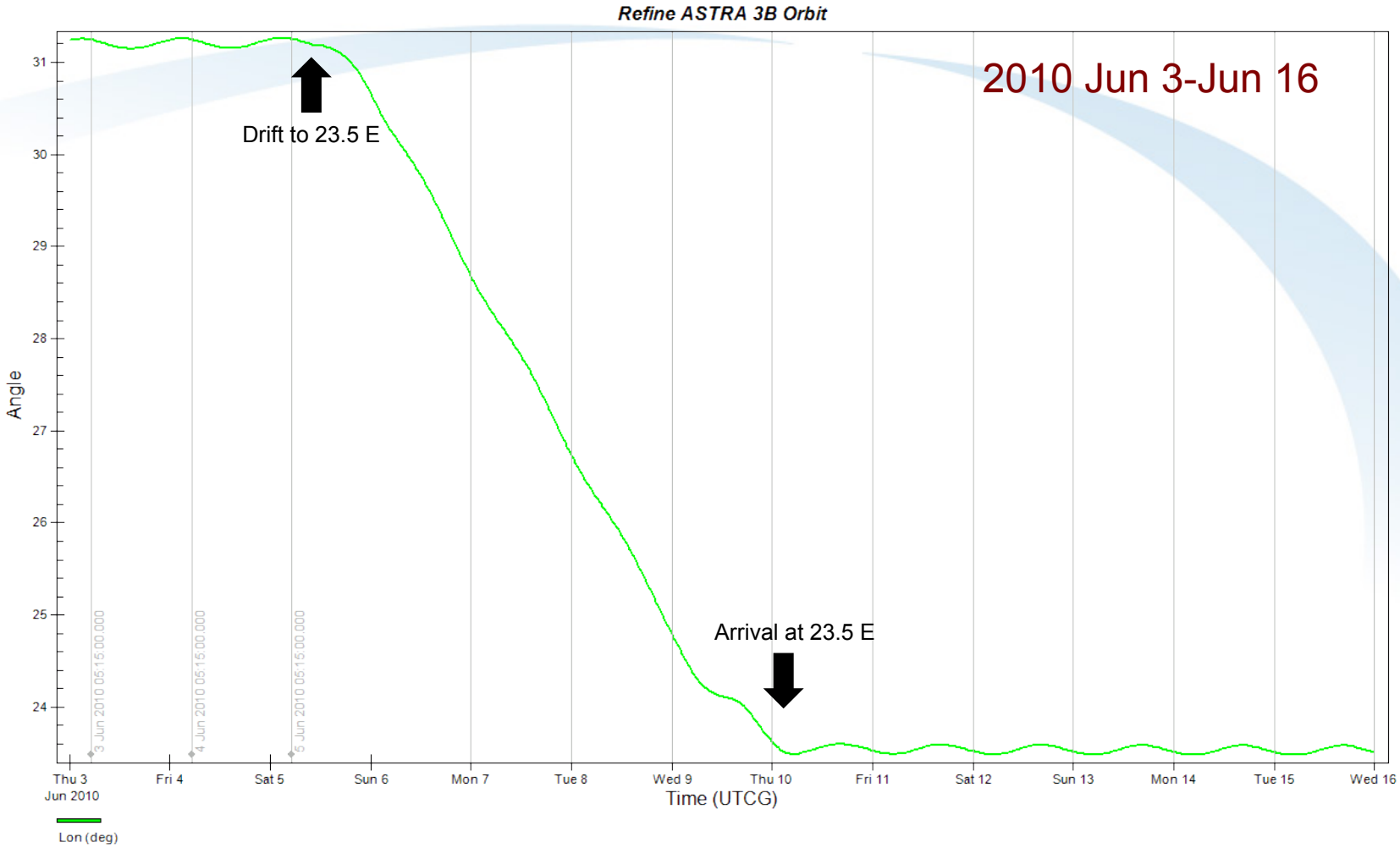
Astra 3B: Range (Search)



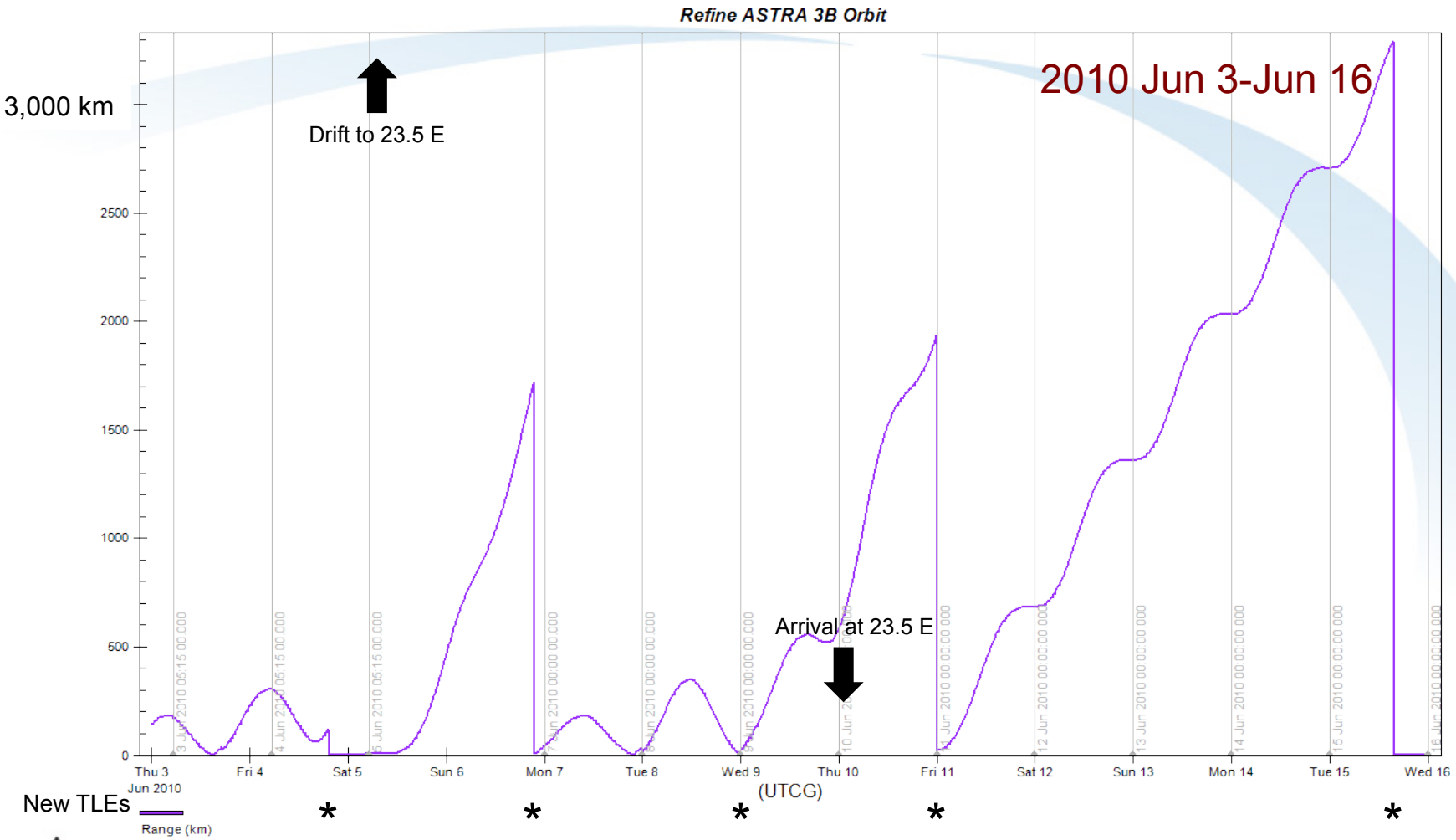
Astra 3B: Longitude with Maneuvers



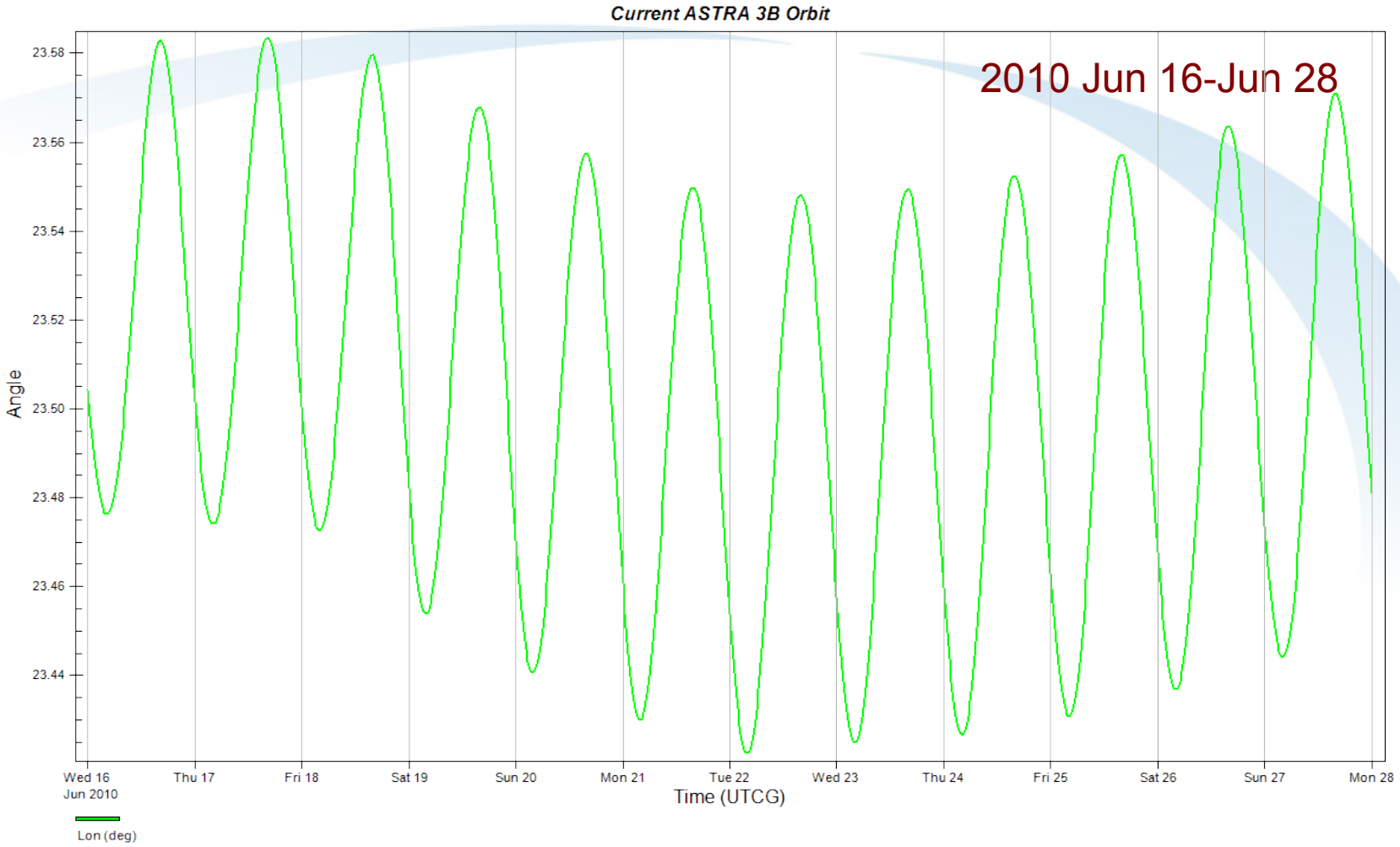
Astra 3B: Longitude (Refine)



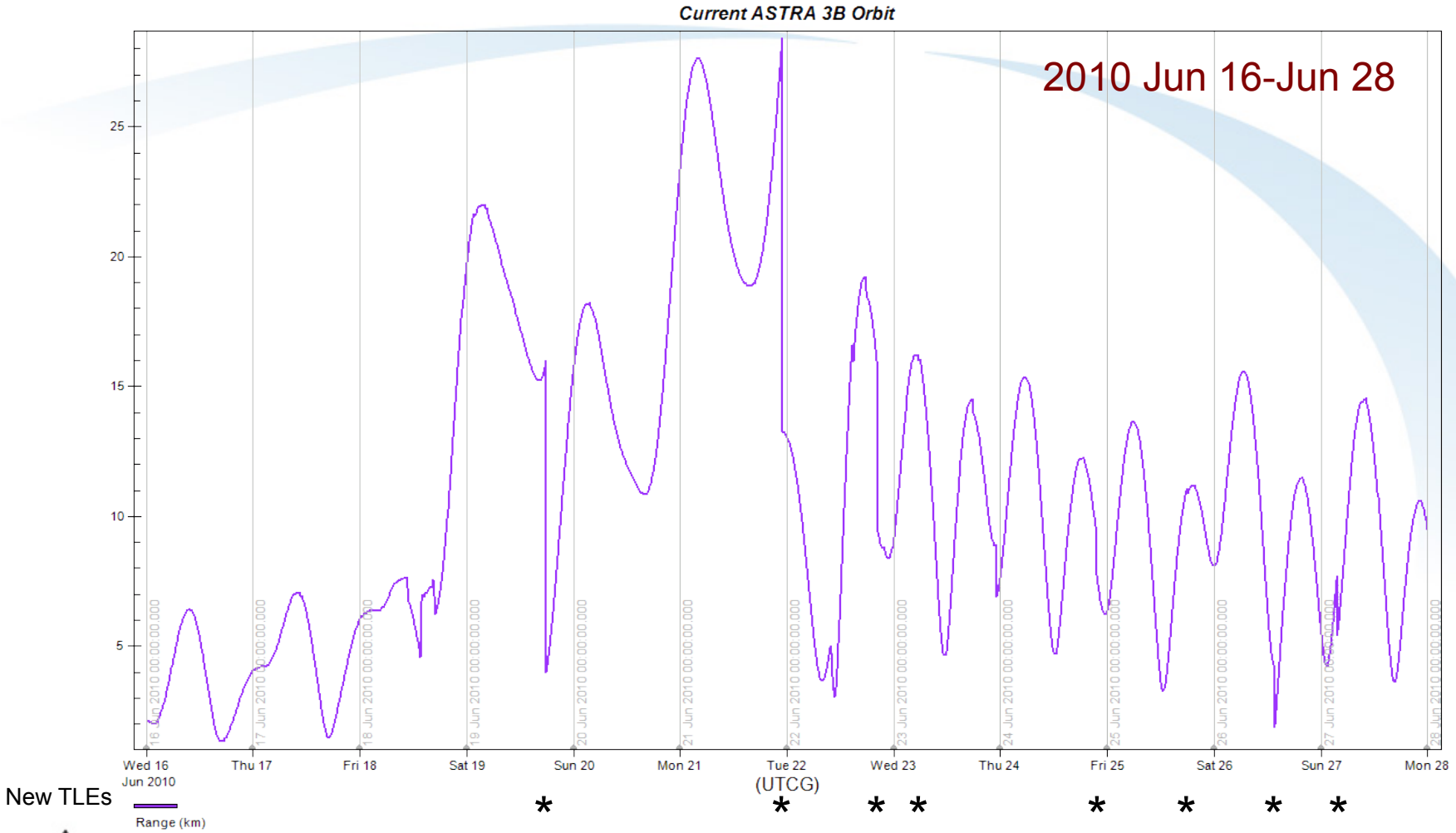
Astra 3B: Range (Refine)



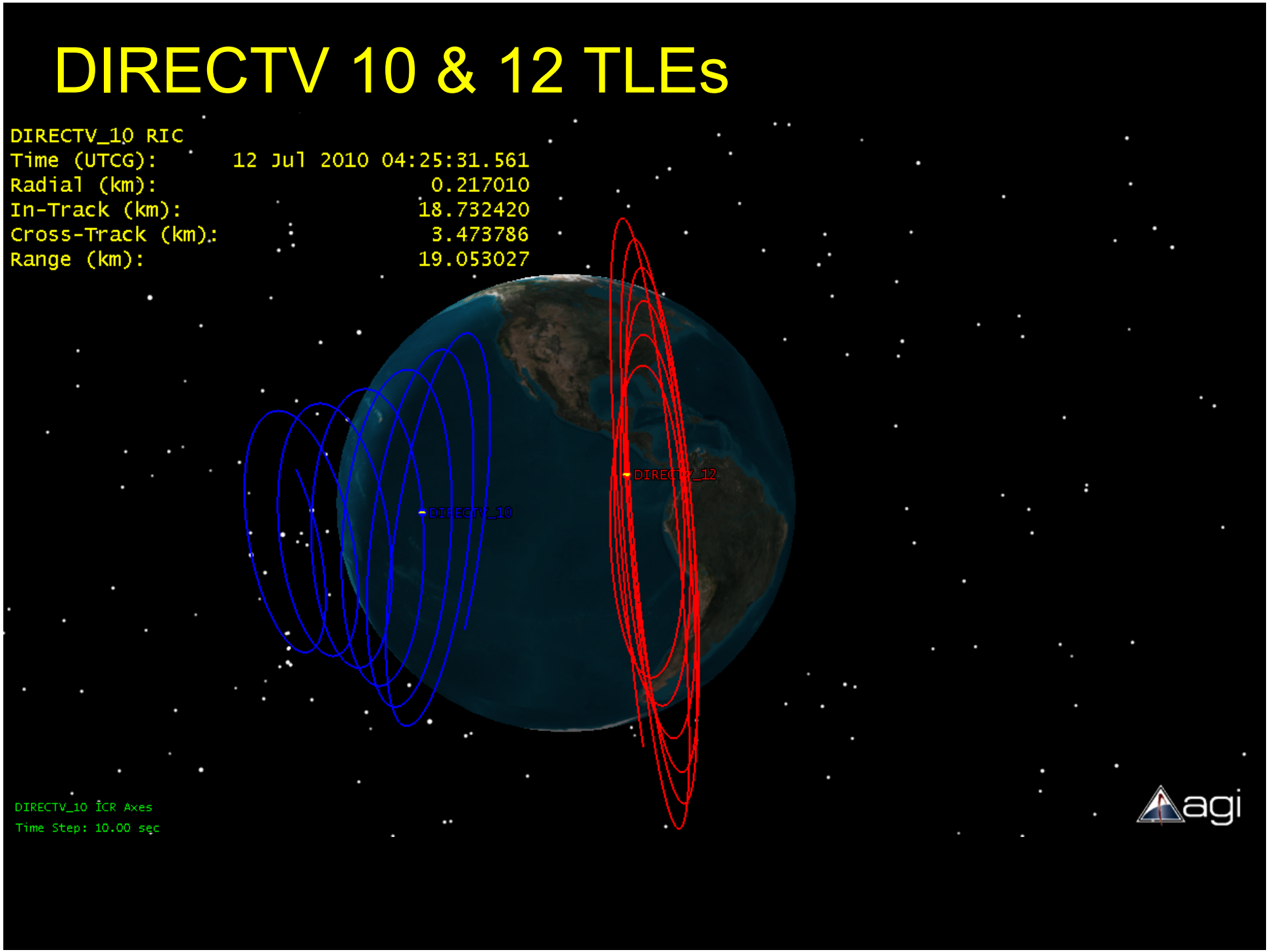
Astra 3B: Longitude (Current)



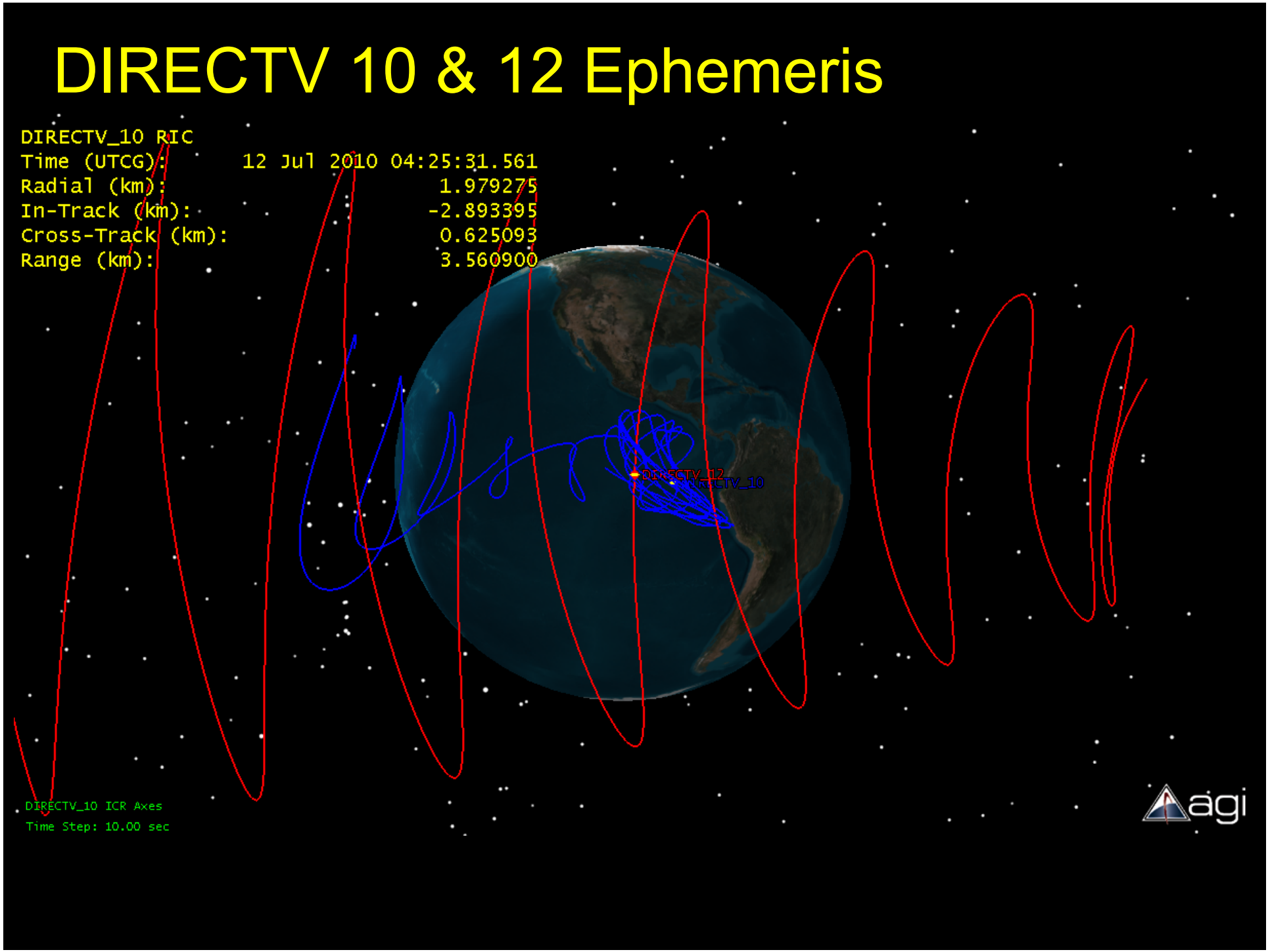
Astra 3B: Range (Current)



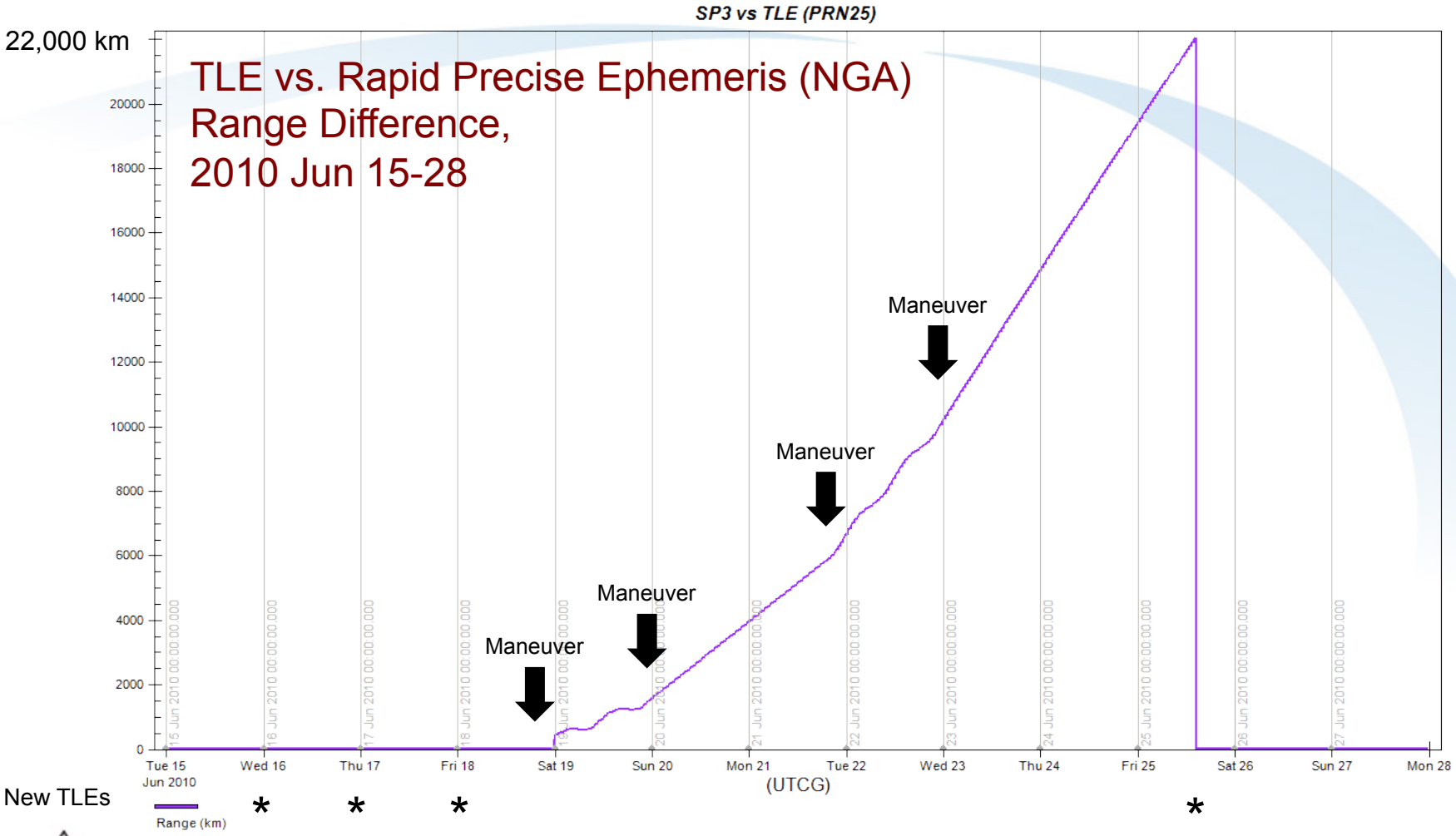
DIRECTV 10 & 12 TLEs



DIRECTV 10 & 12 Ephemeris



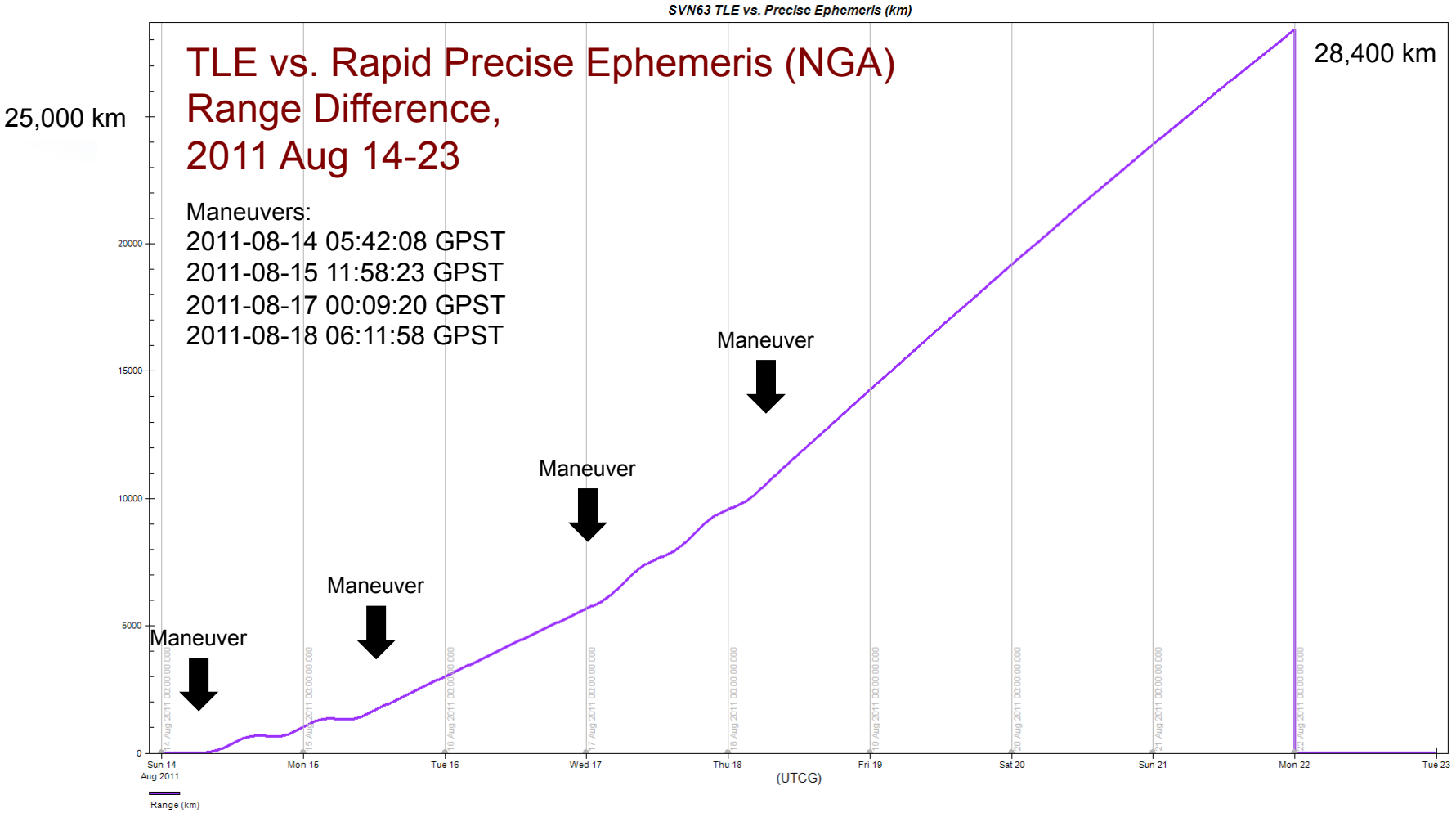
GPS 2F-1 Missed Maneuvers



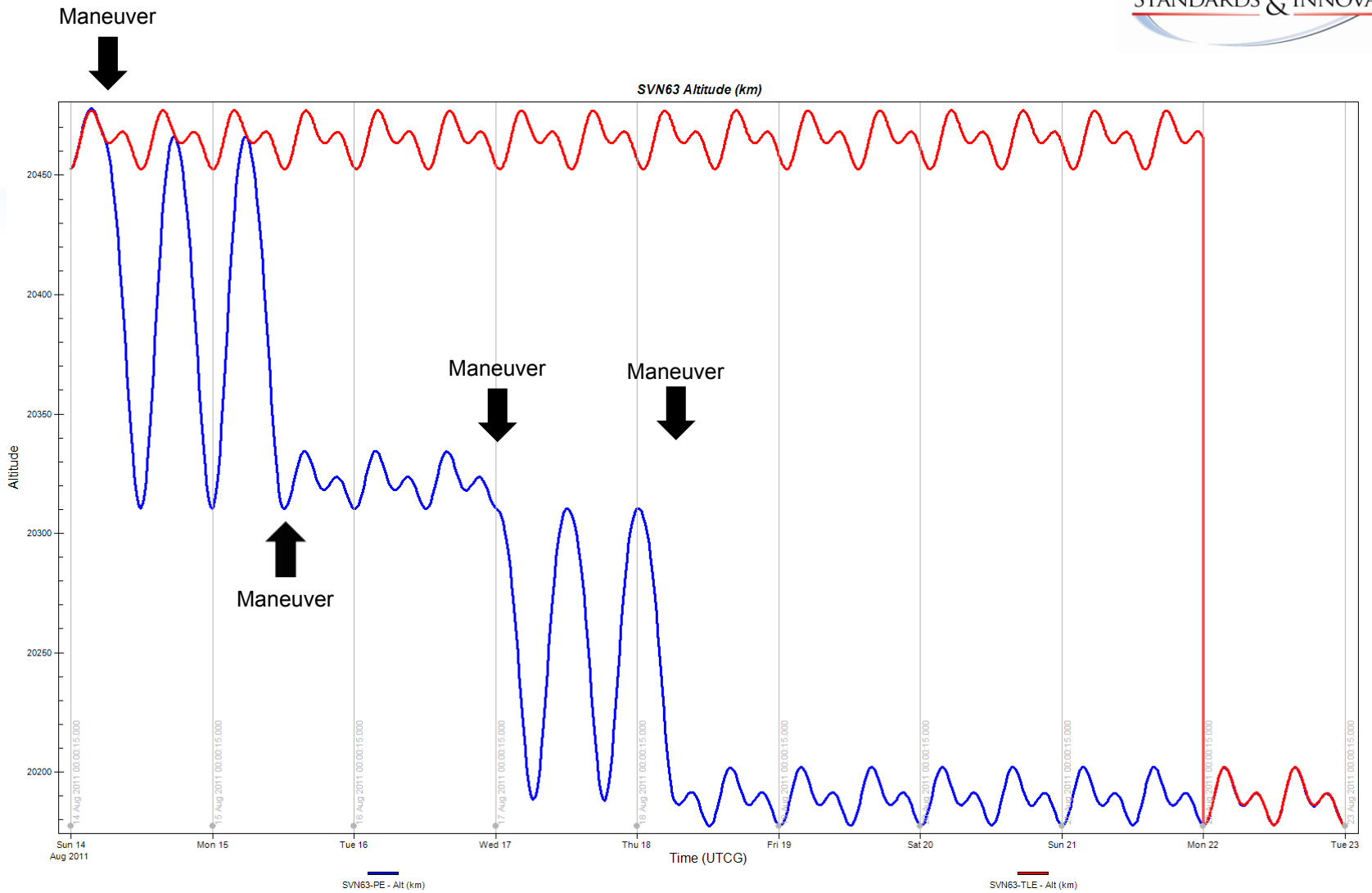
GPS 2F-2 Missed Maneuvers

- GPS 2F-2, SVN63, SSC 37753
  - Launched 2011-07-16
  - Conducted 4 orbit-lowering maneuvers
    - 2011-08-14 05:42:08 GPST
    - 2011-08-15 11:58:23 GPST
    - 2011-08-17 00:09:20 GPST
    - 2011-08-18 06:11:58 GPST
  - TLE updates:
    - 2011-08-13 @ 05:49:44 UTC (Day 225.2429)
    - 2011-08-21 @ 23:59:45 UTC (Day 233.9998)
    - TLE over 28,400 km from GPS precise ephemerides at update

TLE Range to GPS 2F-2 PE



GPS 2F-2 Altitude



Space Data Center

Current Operator Participation

Operator	HQ	Satellites	Operator	HQ	Satellites
Intelsat	Luxembourg	75 GEO	Optus	Australia	5 GEO
Inmarsat	UK	12 GEO	Indovision	Indonesia	2 GEO
EchoStar	US	8 GEO	Sky Perfect JSAT	Japan	10 GEO
SES	Luxembourg	47 GEO	Arabsat	Egypt	5* GEO
NOAA	US	5 GEO	Iridium	US	73 LEO
Star One	Brazil	5 GEO	Orbcomm	US	28 LEO
Telesat	Canada	22 GEO, 1 LEO	GeoEye	US	2 LEO
EUMETSAT	Germany	3 GEO	DigitalGlobe	US	3 LEO
IAI	Israel	2 GEO	Canadian Space Agency	Canada	2 LEO
Paradigm	UK	7 GEO	GISTDA	Thailand	1 LEO
Eutelsat	France	23 GEO			
Total: 231 GEO, 110 LEO					

SOCRATES-GEO & LEO Today

- GEO (2011 Sep 21)
  - Includes all objects which pass ±250 km of GEO
  - Screens 225 payloads vs. 1,333 total objects
  - 585 conjunctions within 50 km over 7 days
  - Run time ~9 minutes
- LEO (2011 Sep 21)
  - Includes all objects that pass below 2,500 km altitude
  - Screens 111 payloads vs. 13,057 total objects
  - 2,433 conjunctions within 5 km over 7 days
  - Run time ~11 minutes
- Uses best data sources available

SOCRATES-GEO & LEO Today

- Runs generate standard reports
  - Provides links to standard orbital data
    - CCSDS Orbital Ephemeris Message
    - JSpOC format
- Allows user-defined notification criteria
  - Metrics: Min range, max probability
  - Individual thresholds
- Automatically sends notification via e-mail
- Web access to latest data via secure system

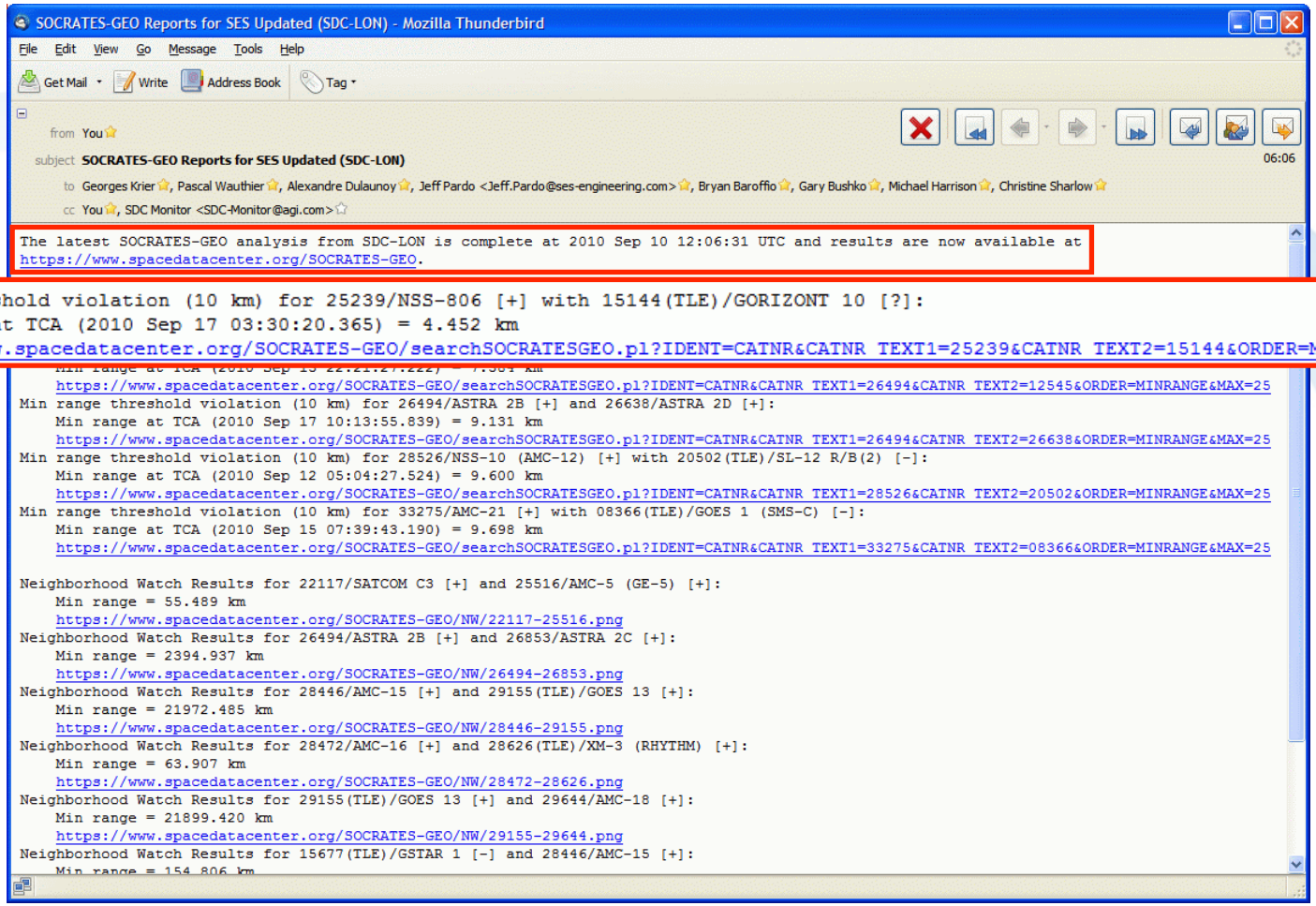
Space Data Association

- Space Data Association established in 2009
  - Dedicated to safe and responsible satellite operations
    - Prevention of collisions in space
    - Improving satellite communications
  - Establishing Space Data Center
    - Automated space situational awareness system
      - Reduce risk of on-orbit collisions
      - Mitigate radio frequency interference
    - Selected AGI to develop and operate: 2010 Apr 12
      - Initial Operational Capability: 2010 Jul 27
      - Fully Operational Capability: 2011 Sep 15

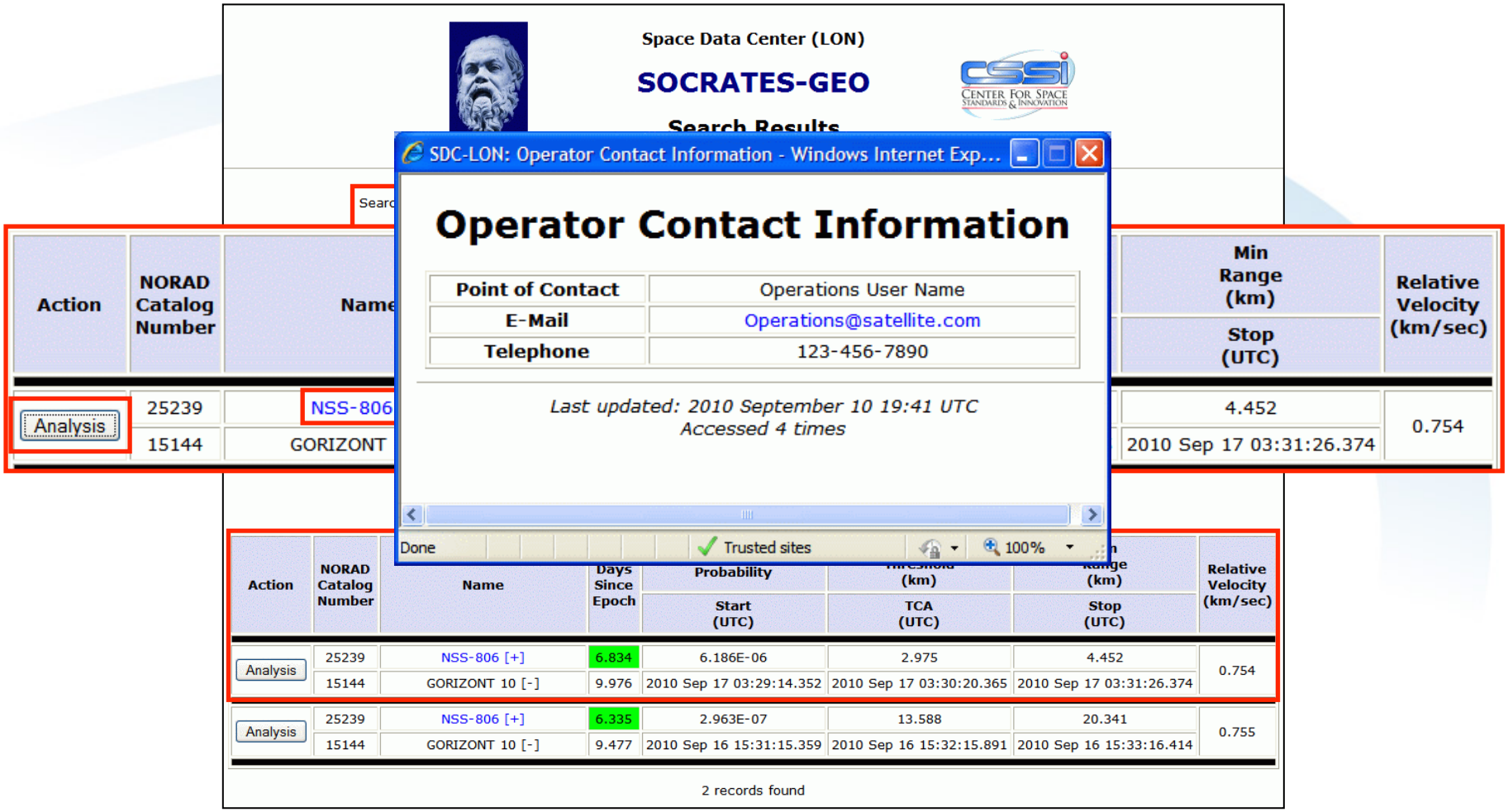
Space Data Center Demo

Online Tutorial @
https://www.spacedatacenter.org/help/

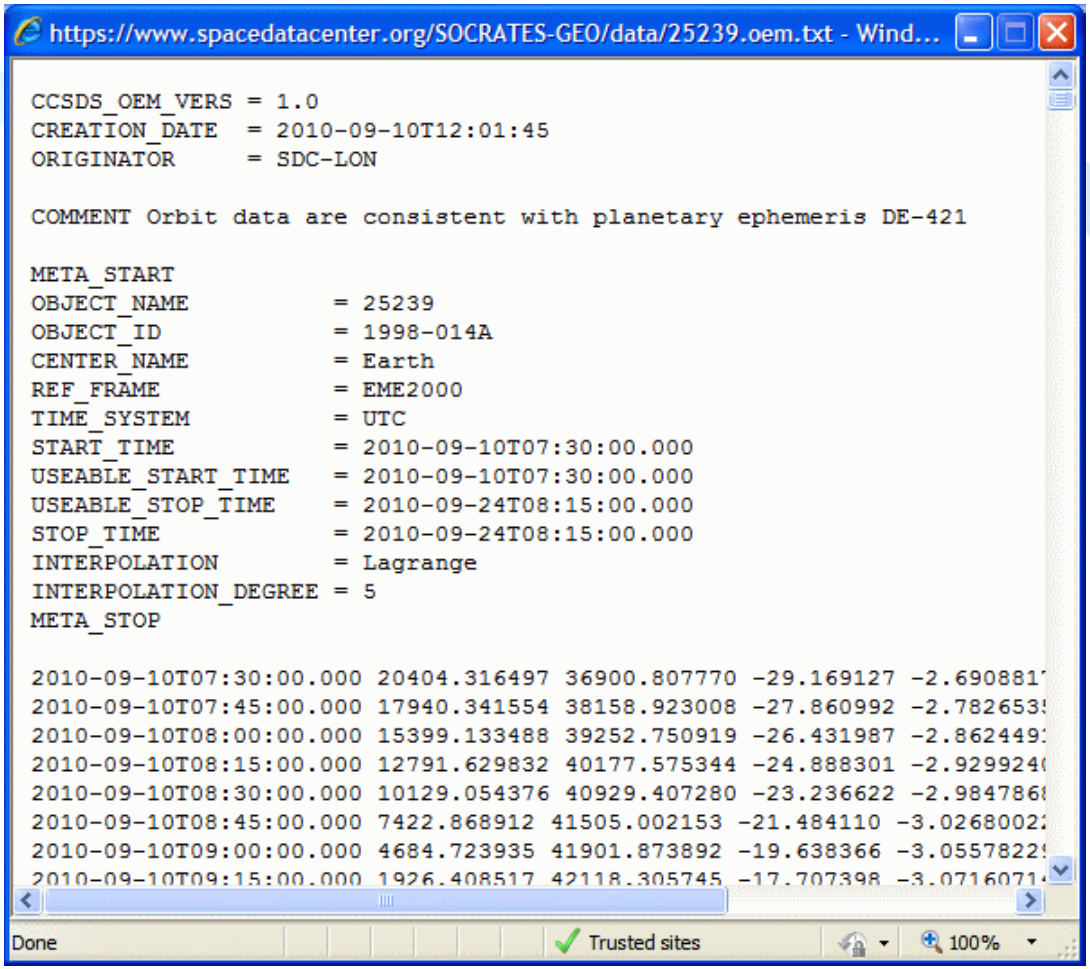
Automatic Notification Message

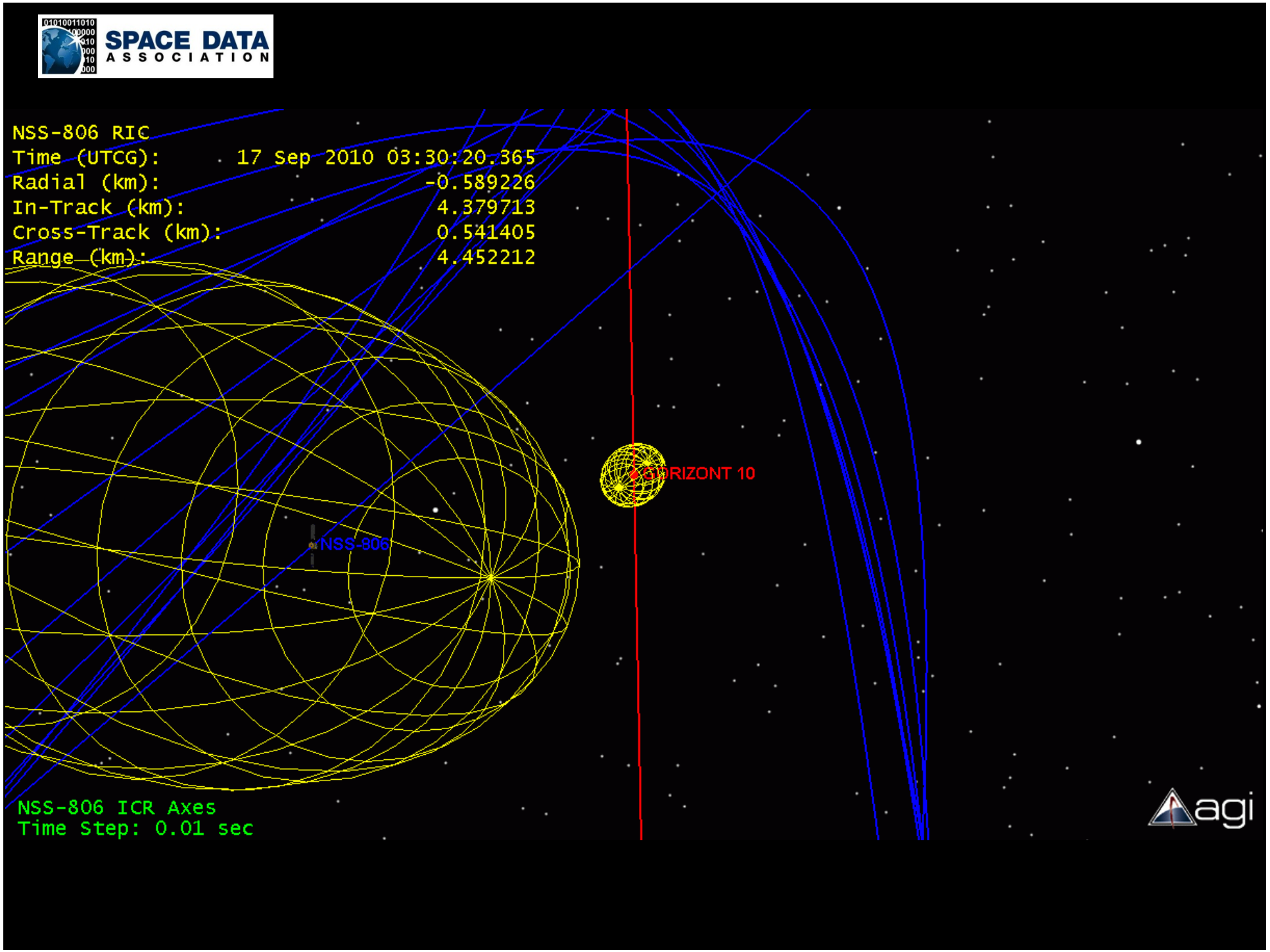


Web Access

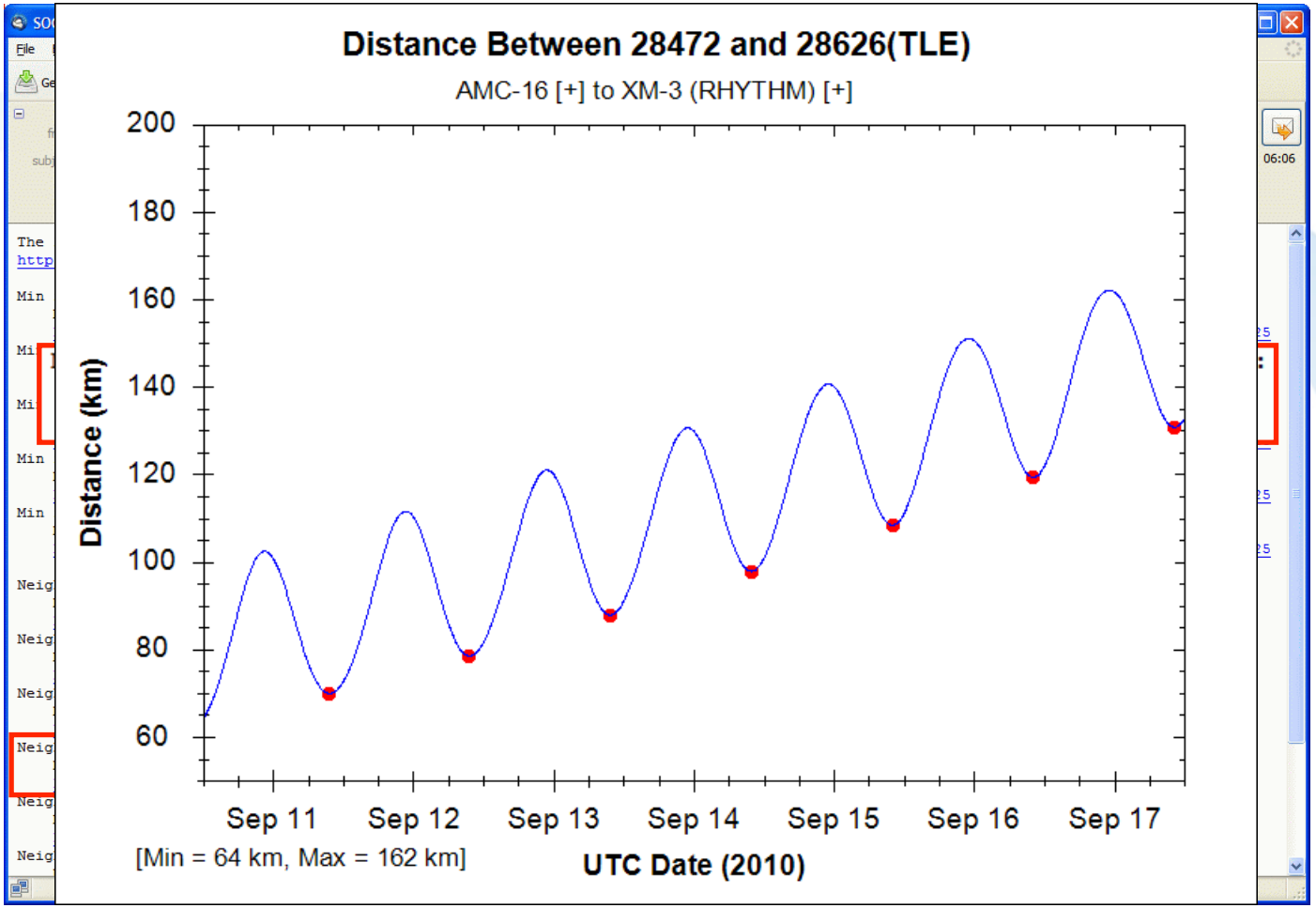

Space Data Center (LON)
SOCRATES-GEO
Search Results
SDC-LON: Operator Contact Information - Windows Internet Exp...
Operator Contact Information
Point of Contact
Operations User Name
E-Mail
Operations@satellite.com
Telephone
123-456-7890
Last updated: 2010 September 10 19:41 UTC
Accessed 4 times
Done
Trusted sites
100%
Action
NORAD Catalog Number
Name
Days Since Epoch
Probability
Start (UTC)
TCA (UTC)
Stop (UTC)
Min Range (km)
Relative Velocity (km/sec)
Analysis
25239
NSS-806 [+]
6.834
6.186E-06
2.975
4.452
0.754
15144
GORIZONT 10 [-]
9.976
2010 Sep 17 03:29:14.352
2010 Sep 17 03:30:20.365
2010 Sep 17 03:31:26.374
Analysis
25239
NSS-806 [+]
6.335
2.963E-07
13.588
20.341
0.755
15144
GORIZONT 10 [-]
9.477
2010 Sep 16 15:31:15.359
2010 Sep 16 15:32:15.891
2010 Sep 16 15:33:16.414
2 records found

Analysis Window



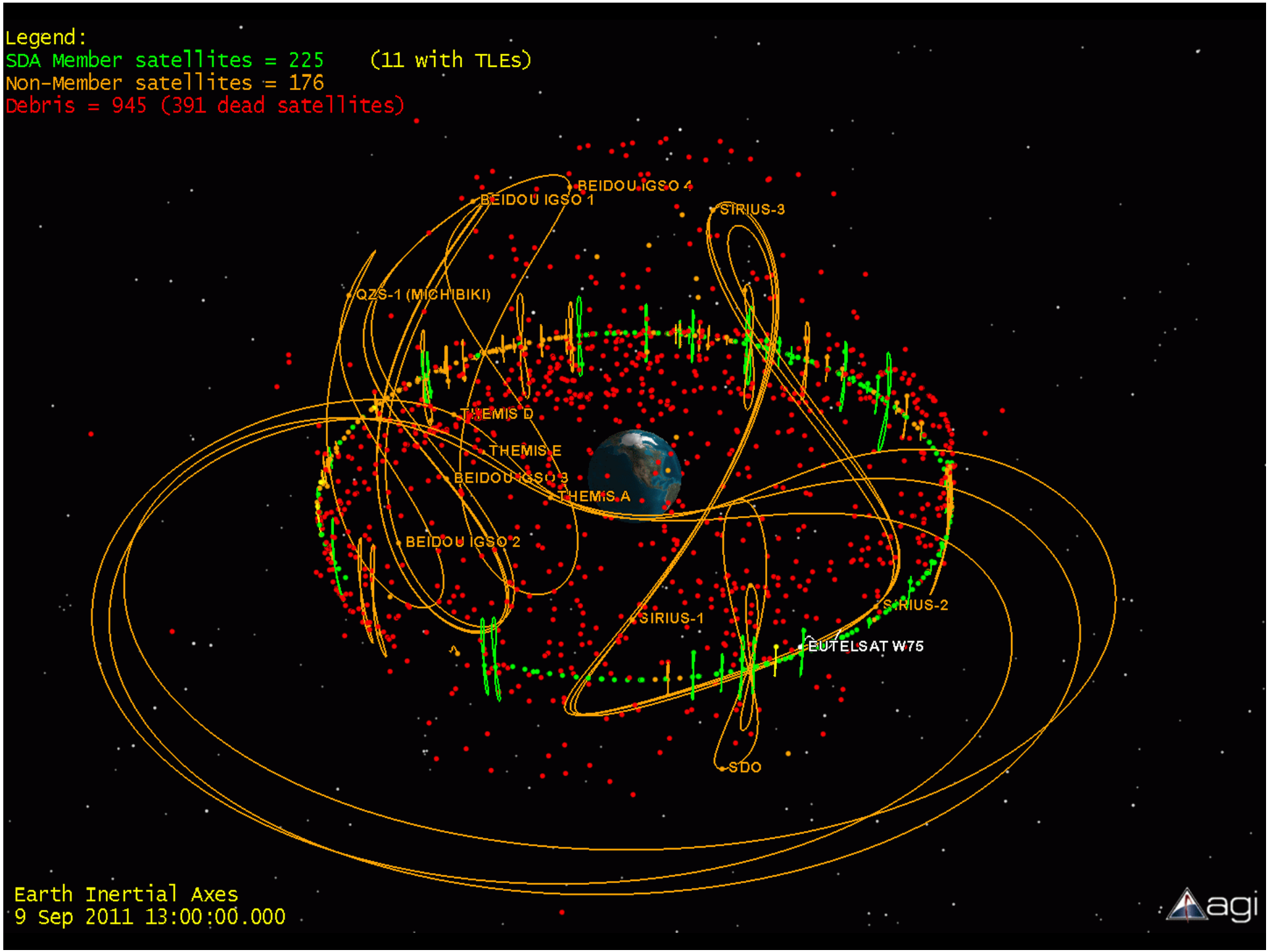

SPACE DATA ASSOCIATION
NSS-806 RIC
Time (UTCG): 17 Sep 2010 03:30:20.365
Radial (km): -0.589226
In-Track (km): 4.379713
Cross-Track (km): 0.541405
Range (km): 4.452212
GORIZONT 10
NSS-806
NSS-806 ICR Axes
Time Step: 0.01 sec
agi

Neighborhood Watch



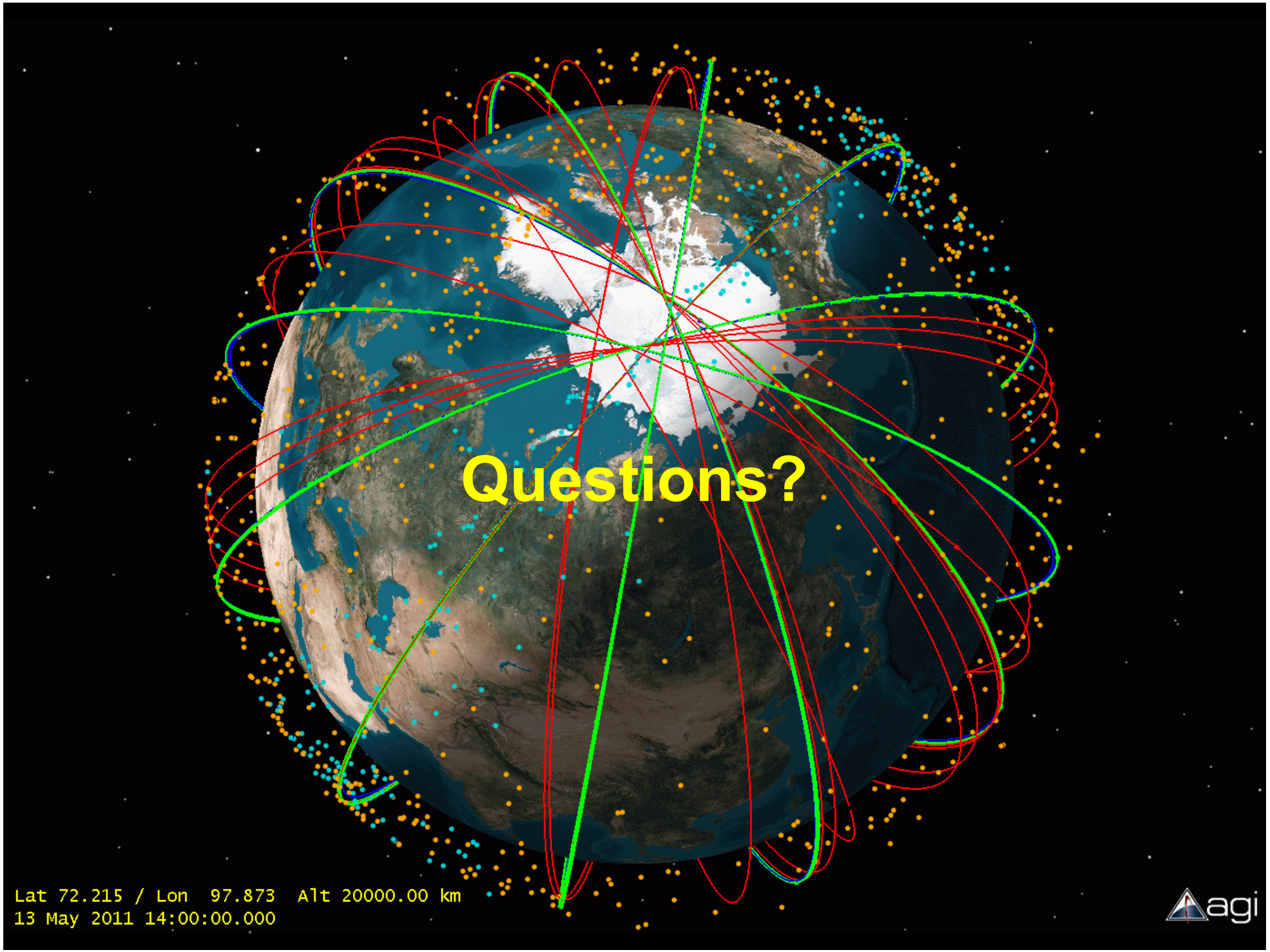
Future Enhancements (FOC)

- Process new data as received
  - Parallel analysis tool for maneuver planning
- Collection of RFI data for mitigation


Legend:
SDA Member satellites = 225 (11 with TLEs)
Non-Member satellites = 176
Debris = 945 (391 dead satellites)
BEIDOU IGSO 4
BEIDOU IGSO 1
SIRIUS-3
QZS-1 (MICHIBIKI)
THEMIS D
THEMIS E
BEIDOU IGSO 3
THEMIS A
BEIDOU IGSO 2
SIRIUS-1
SIRIUS-2
BUTELSAT W75
SDO
Earth Inertial Axes
9 Sep 2011 13:00:00.000
agi

Summary & Conclusions

- Bottom line:
  - Technical solution is easy
- Biggest obstacle:
  - Data sharing policies
- Other issues:
  - Organization
  - Resources & Funding
- Together we can work today to mitigate risk


Questions?
Lat 72.215 / Lon 97.873 Alt 20000.00 km
13 May 2011 14:00:00.000
agi