



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

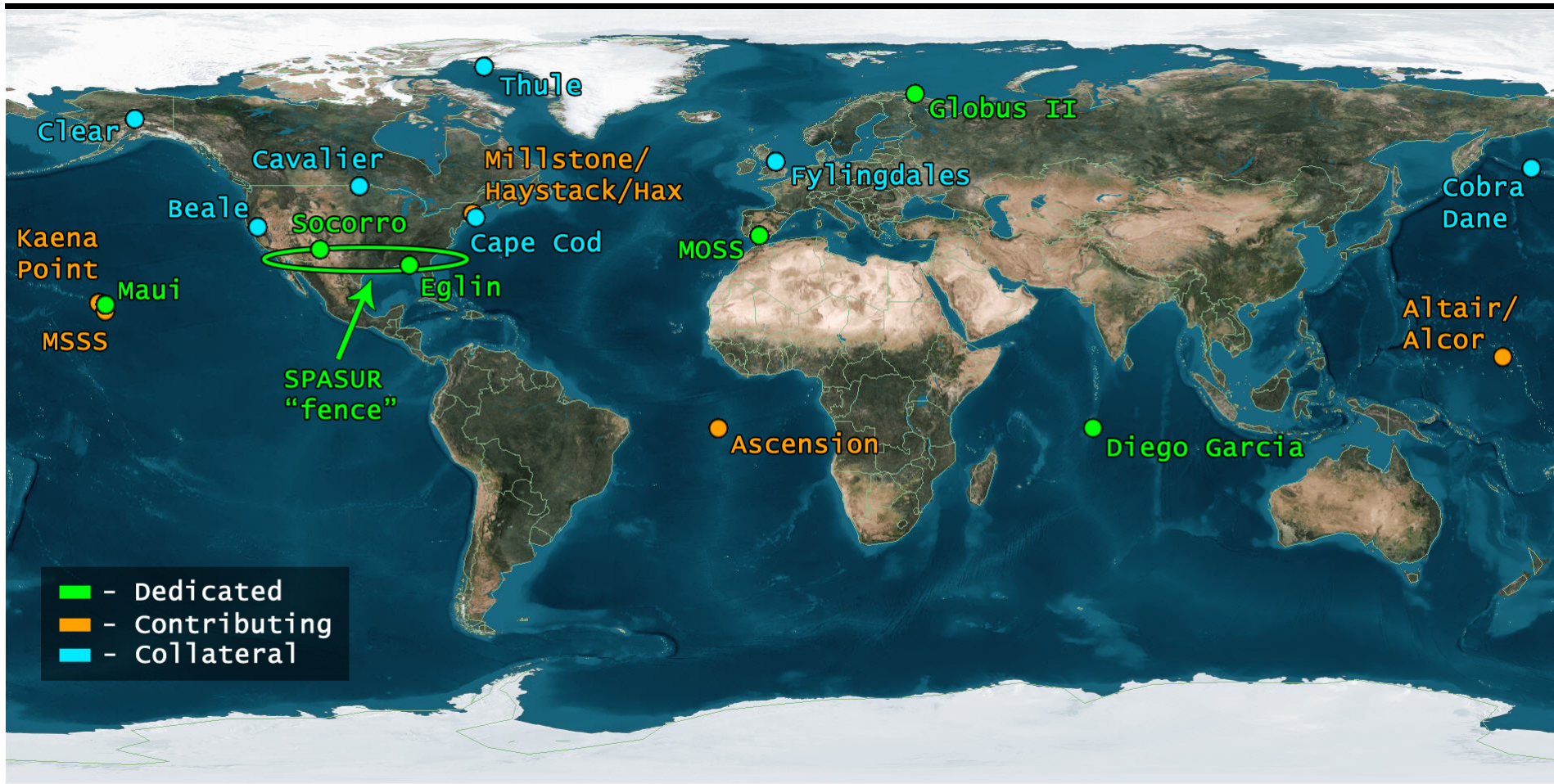


Satellite Tracking: Who? How?

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 = $0.NNNNN \times 10^E$)
- BSTAR (ER^{-1} ; NNNNN-E = $0.NNNNN \times 10^E$)
- 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

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–

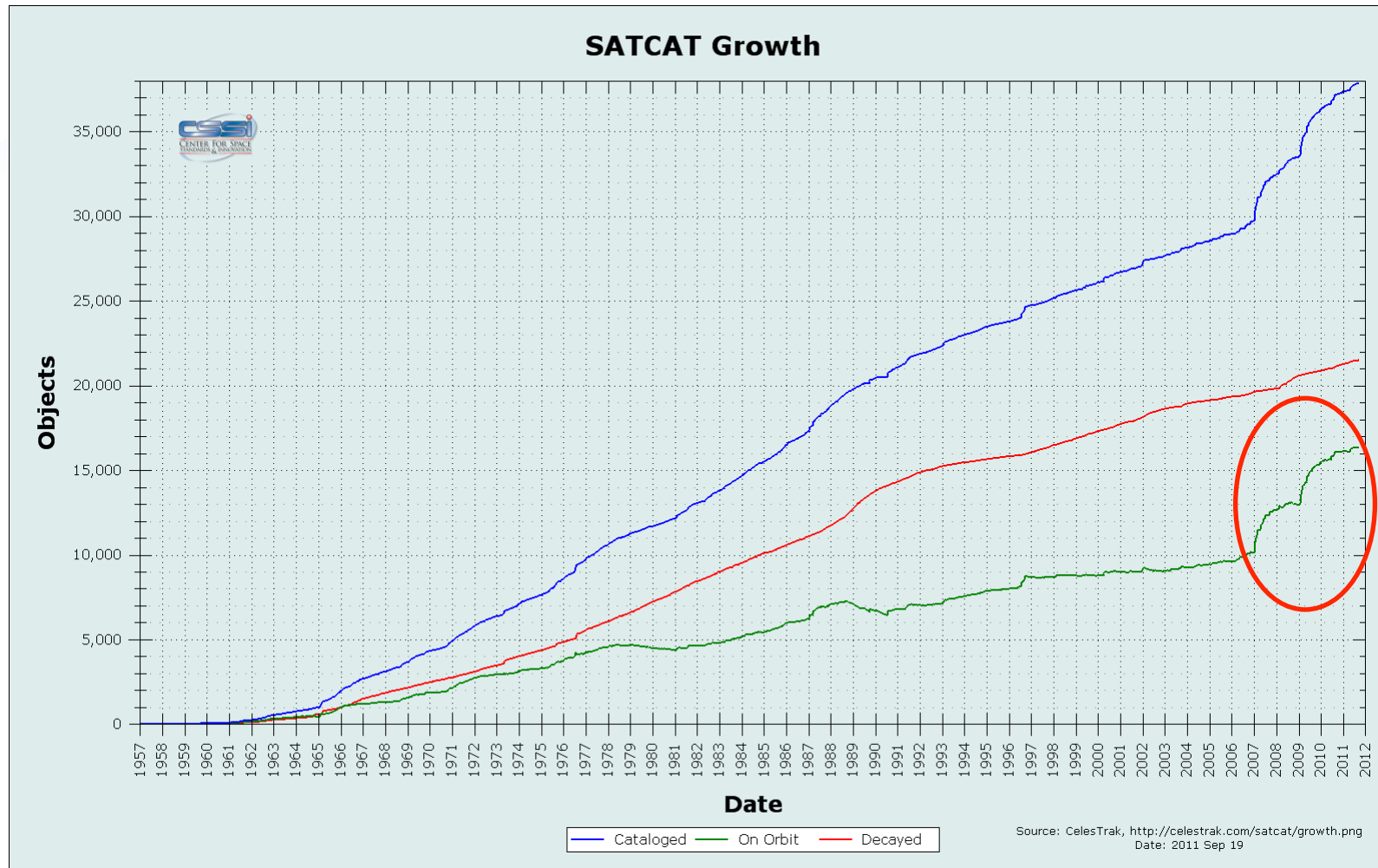


Motivation: Why Do We Care?

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

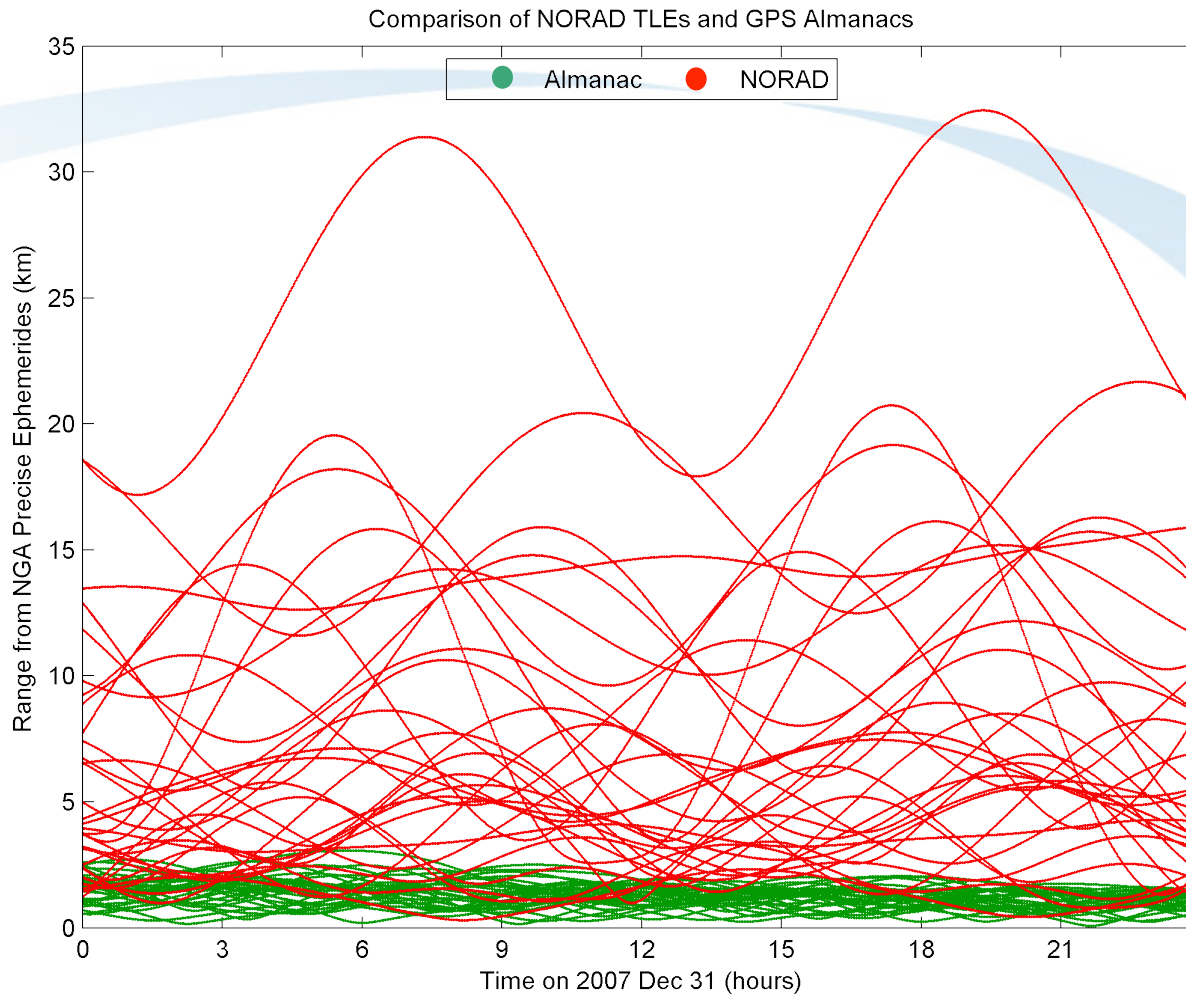
- Satellite operators already maintain orbits
 - Active ranging, GPS can be very accurate
- Develop Data Center to collect operator data
 - Use operator data to improve conjunction analysis
 - Provide analysis/data to all contributors
- Requires validation of accuracy assumption

GPS Almanacs vs. TLEs



Mean: 7.544 km

Max: 32.449 km



Mean: 1.292 km

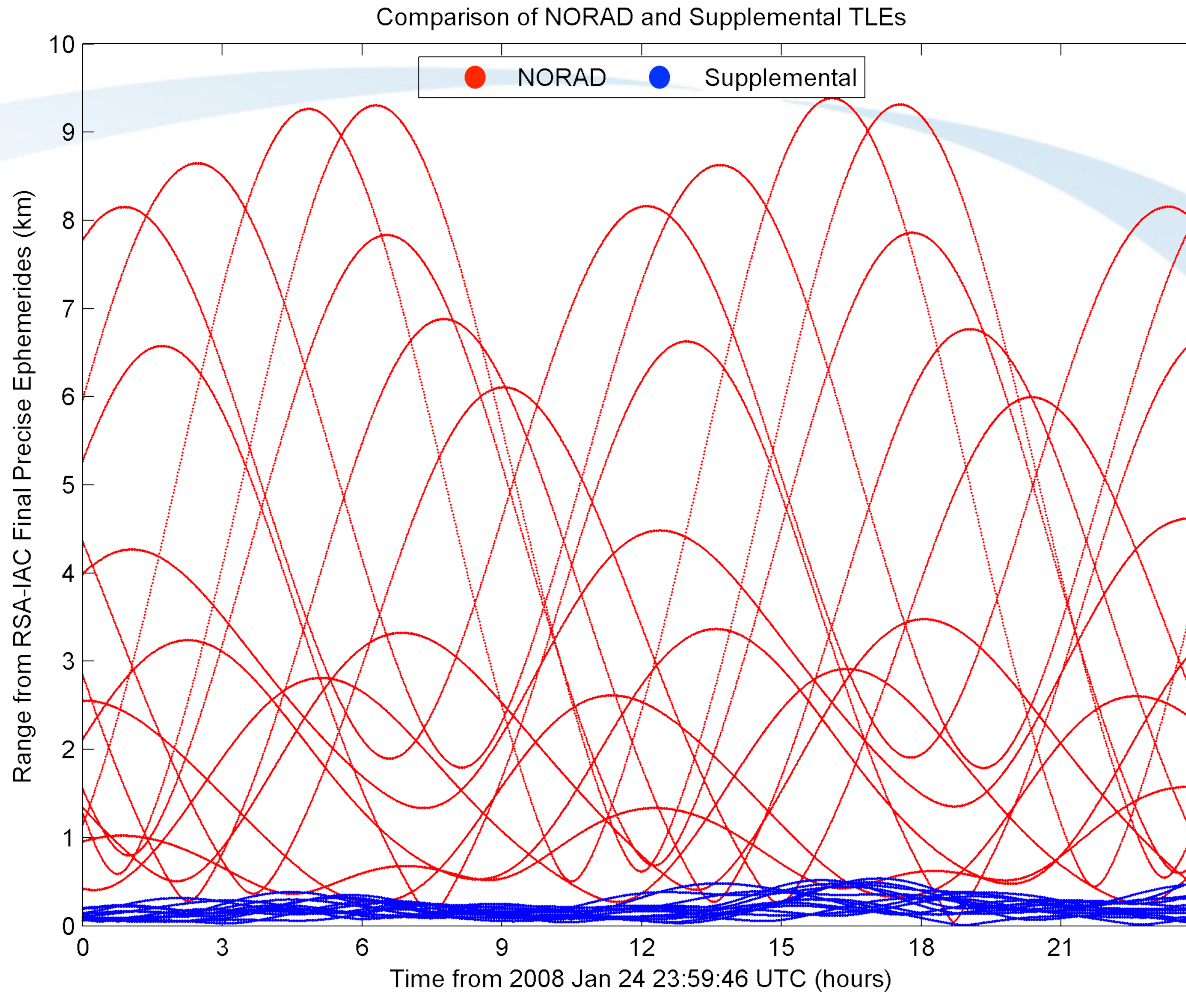
Max: 3.073 km



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

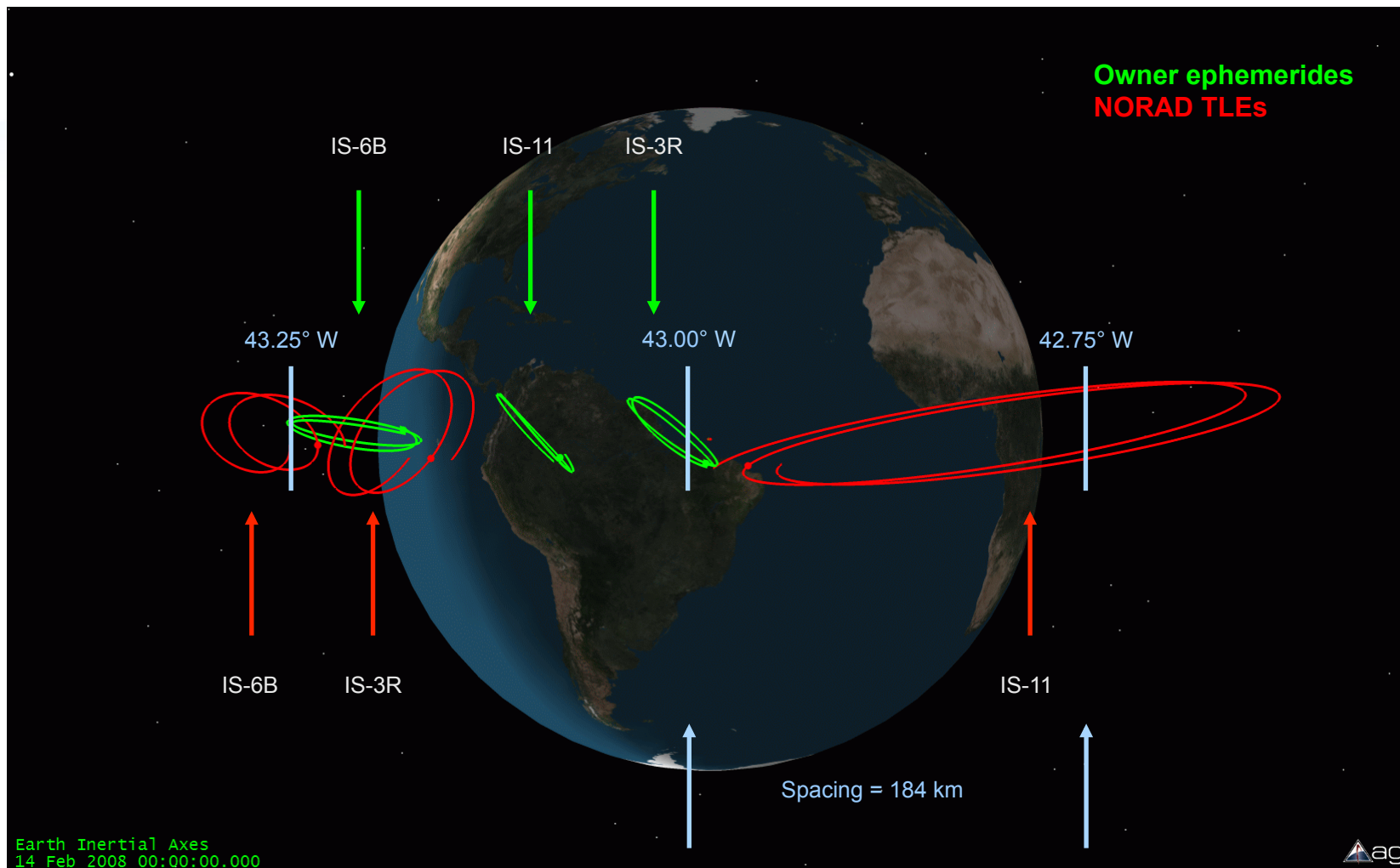


Case Studies

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



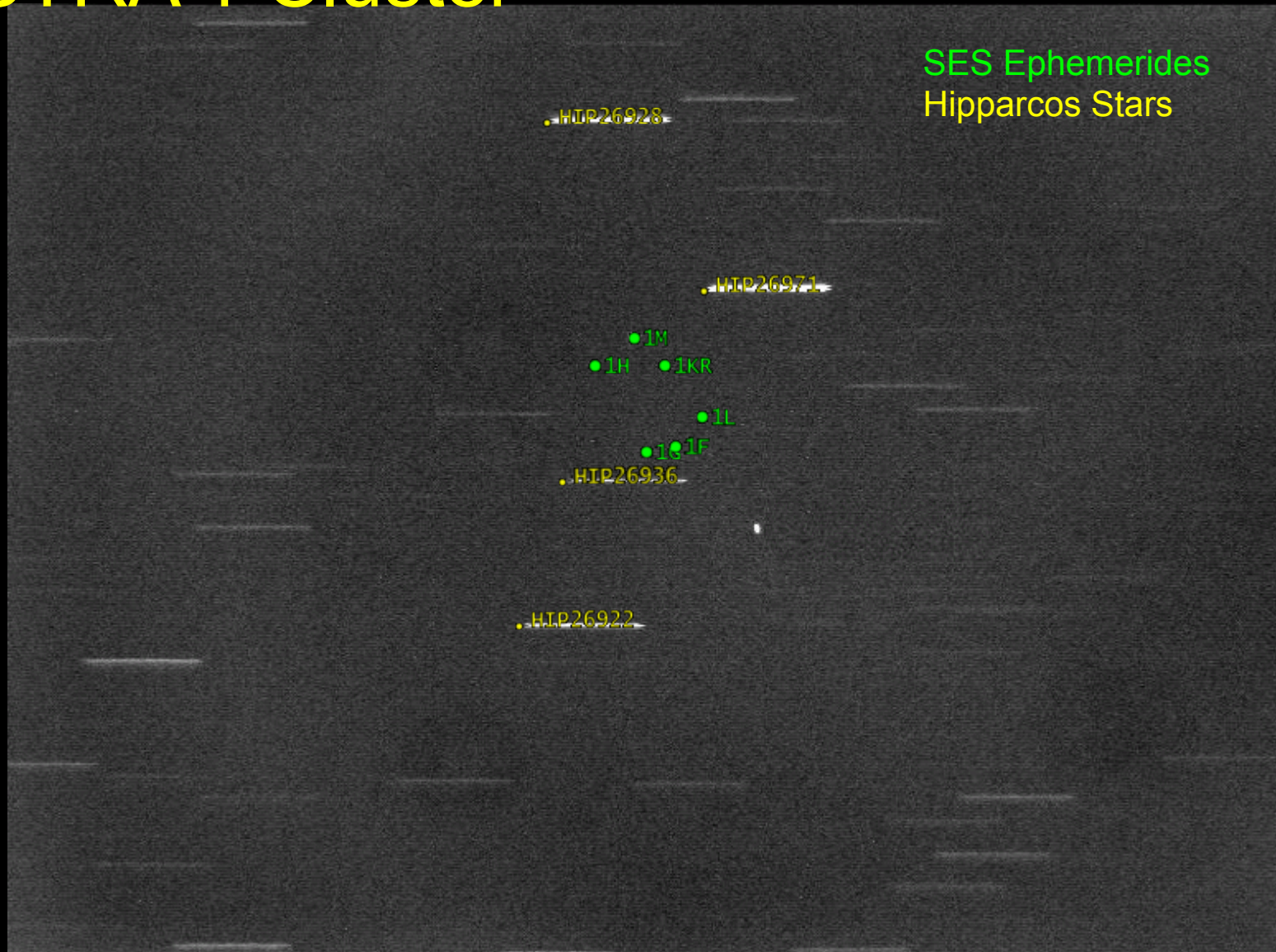
ASTRA 1 Cluster

- 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

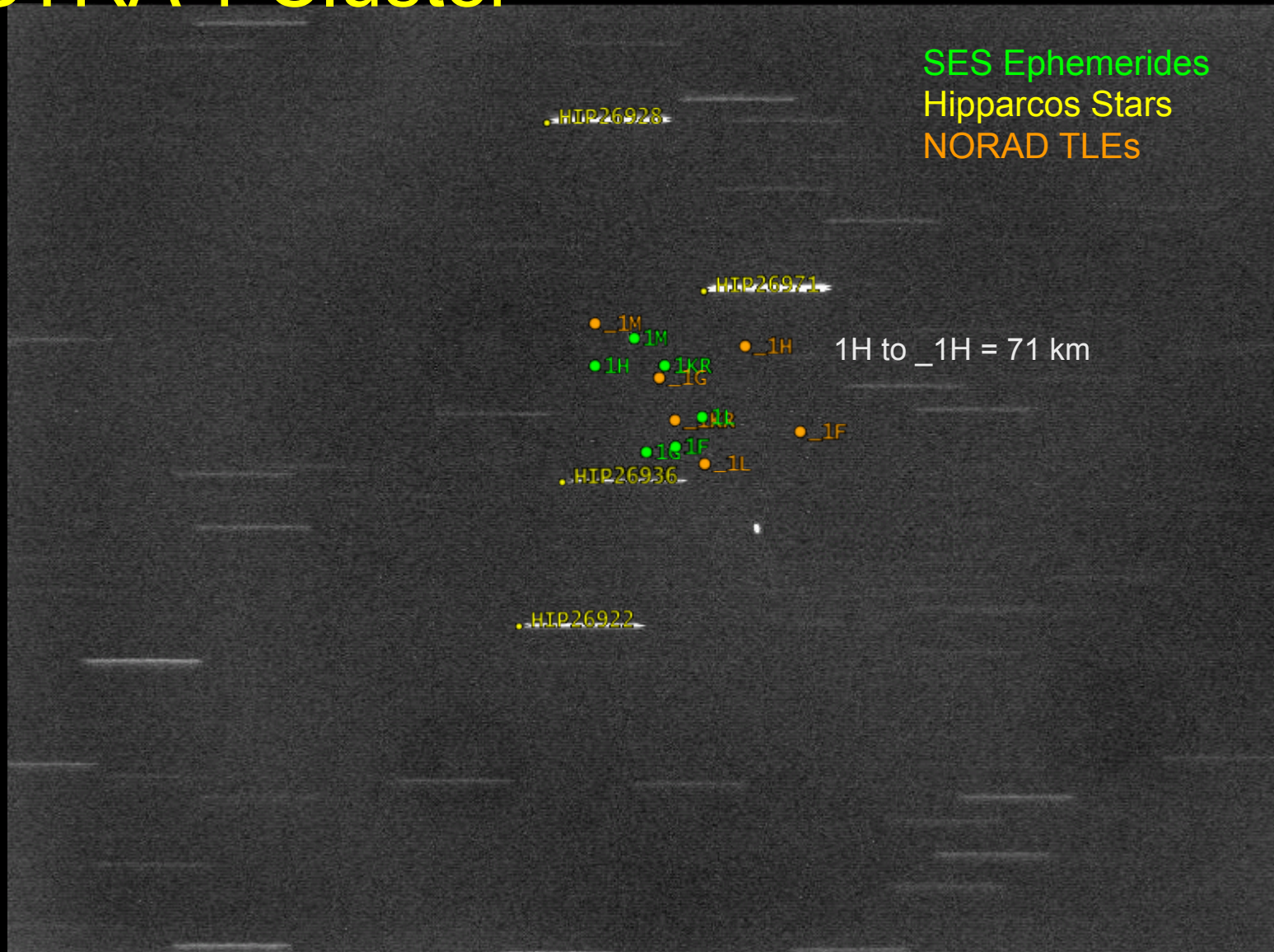
ASTRA 1 Cluster



ASTRA 1 Cluster



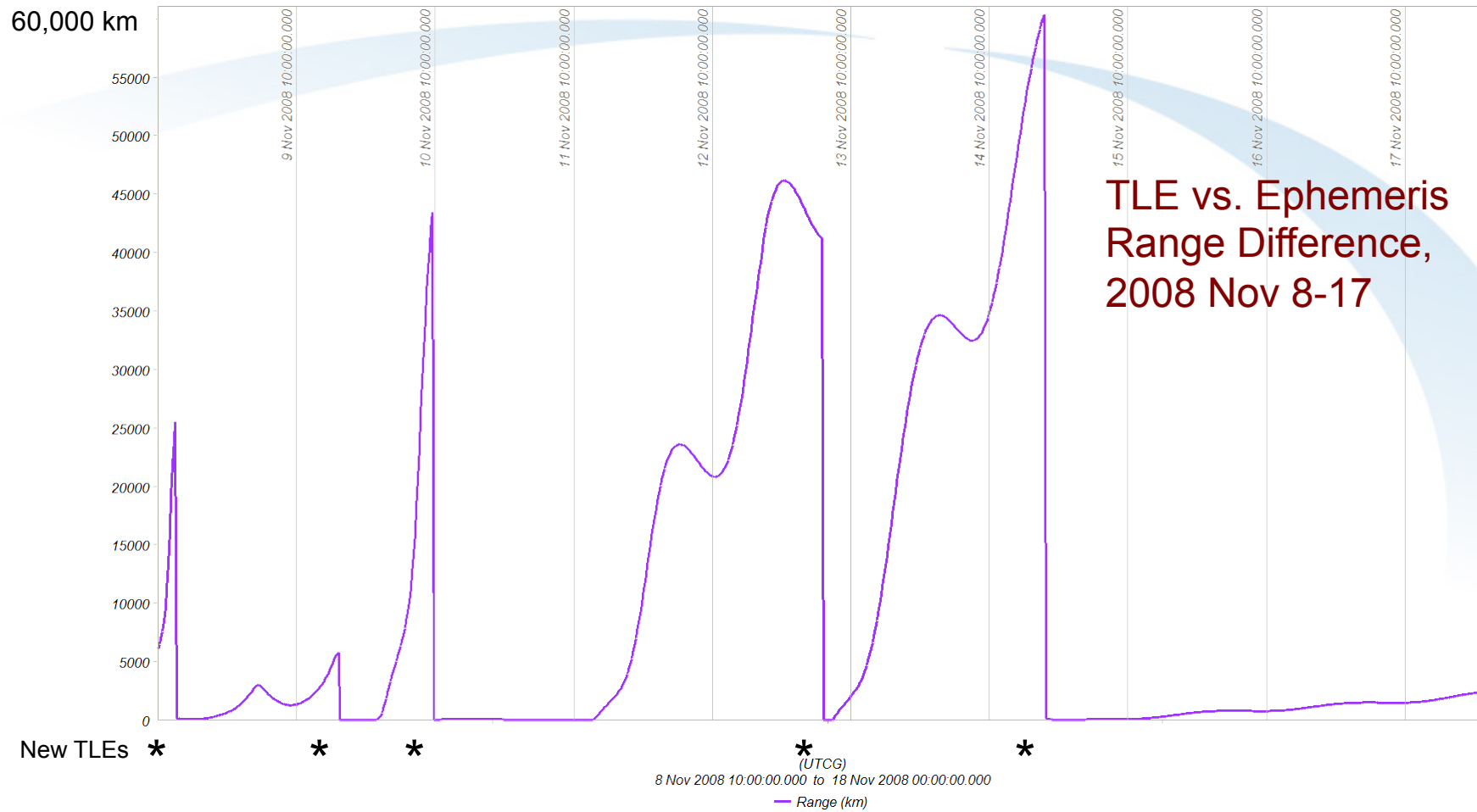
ASTRA 1 Cluster



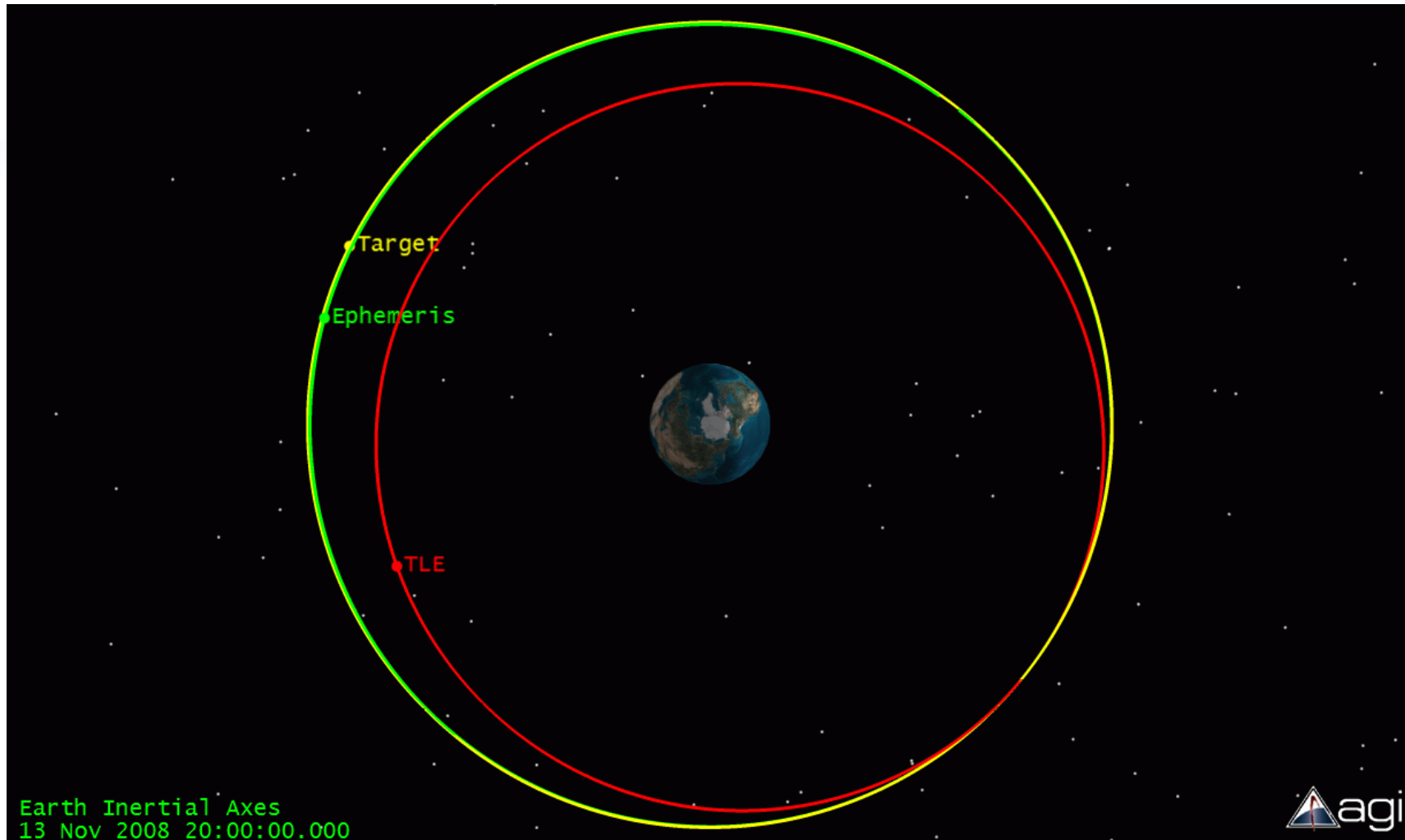
Astra 1M Early Orbit

- 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



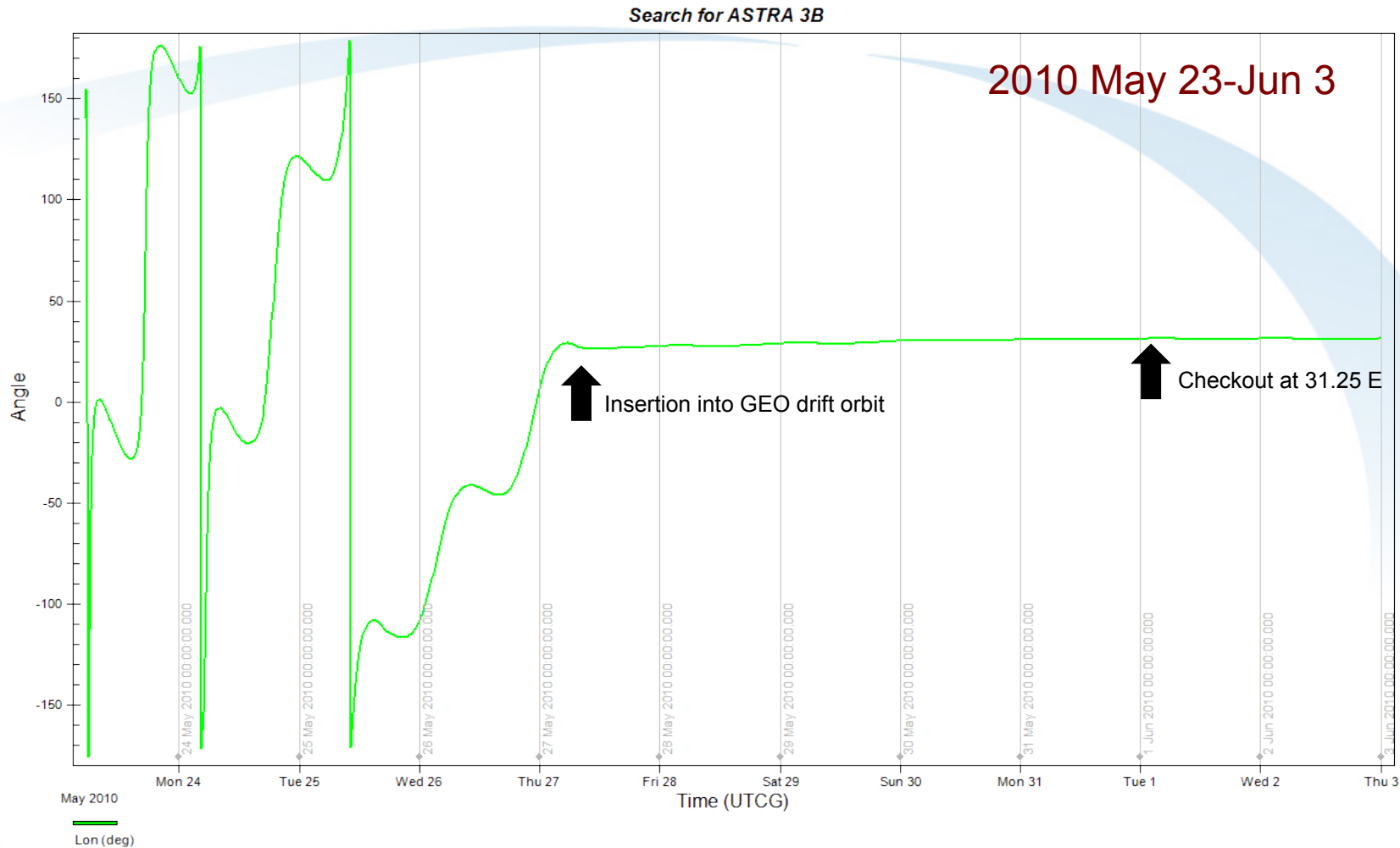
Astra 1M Early Orbit



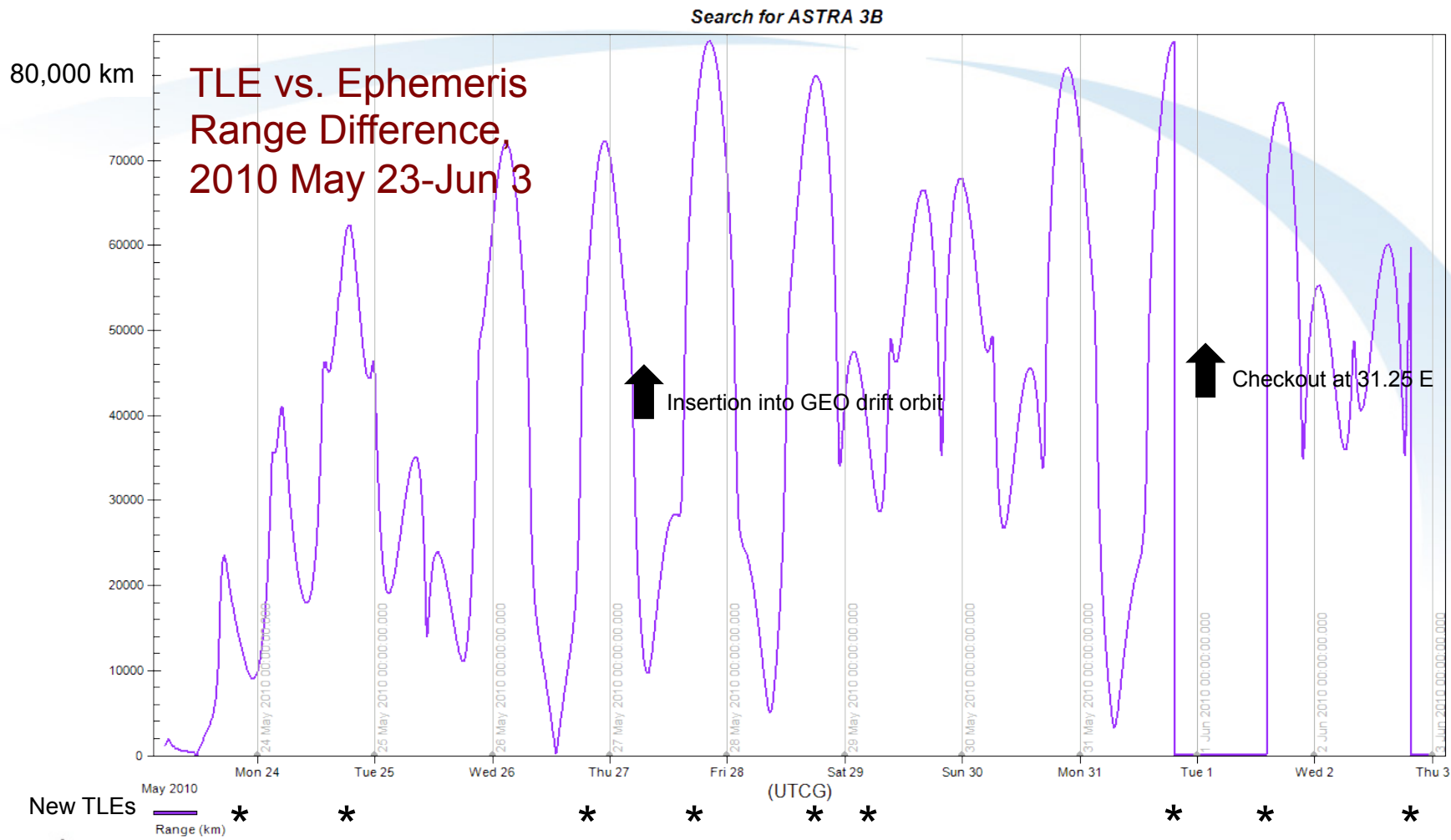
Astra 3B Early Orbit

- 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

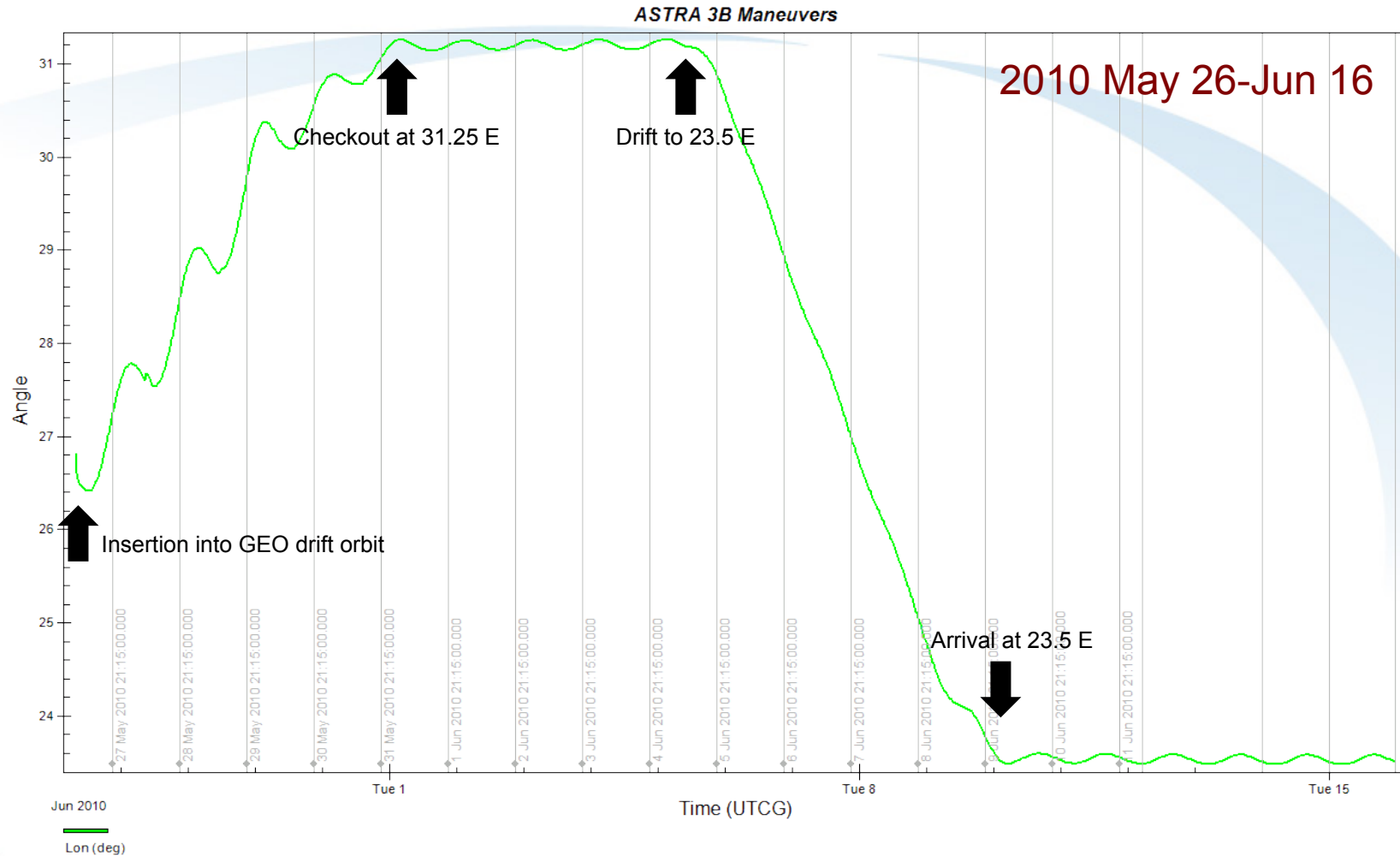
Astra 3B: Longitude (Search)



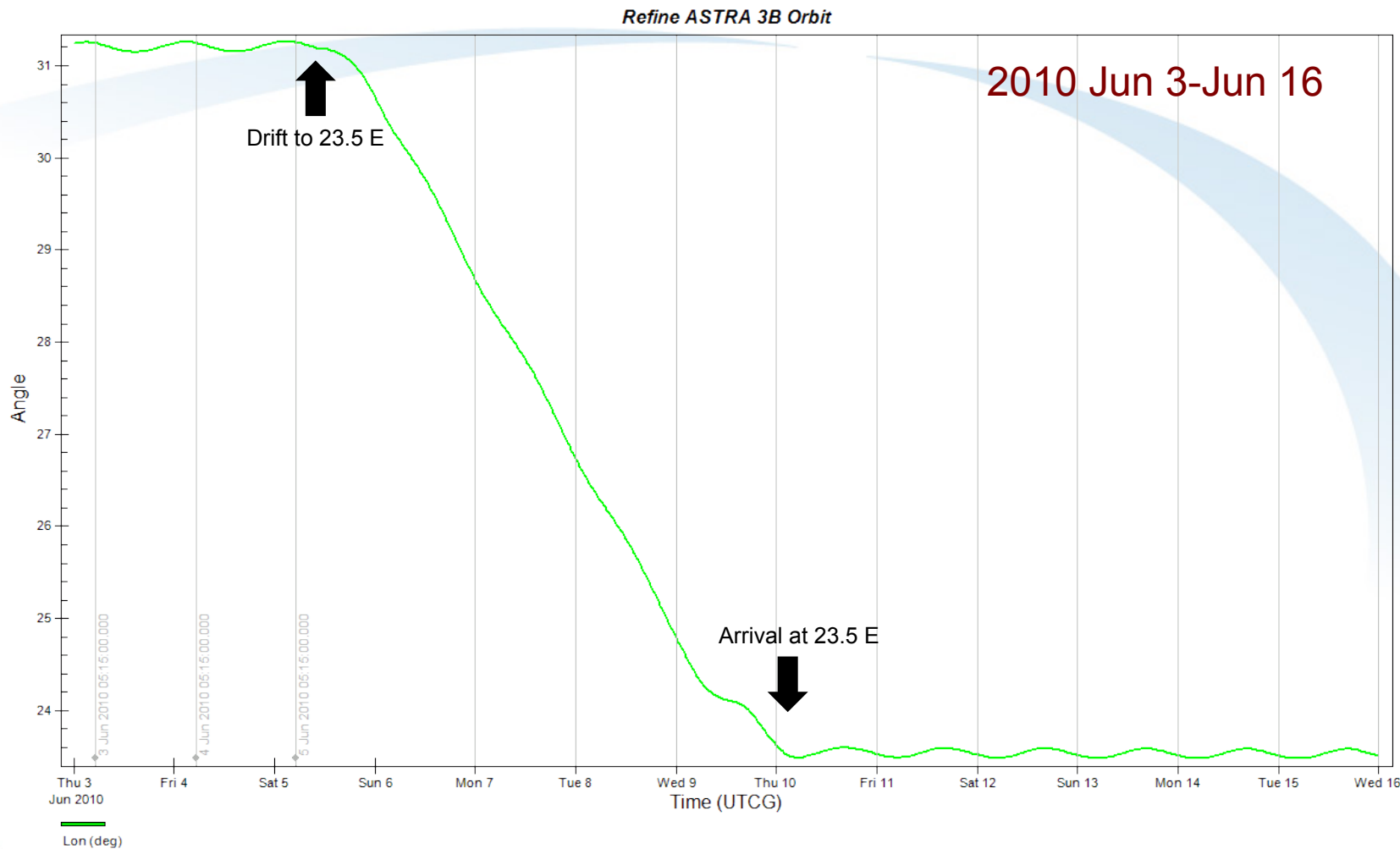
Astra 3B: Range (Search)



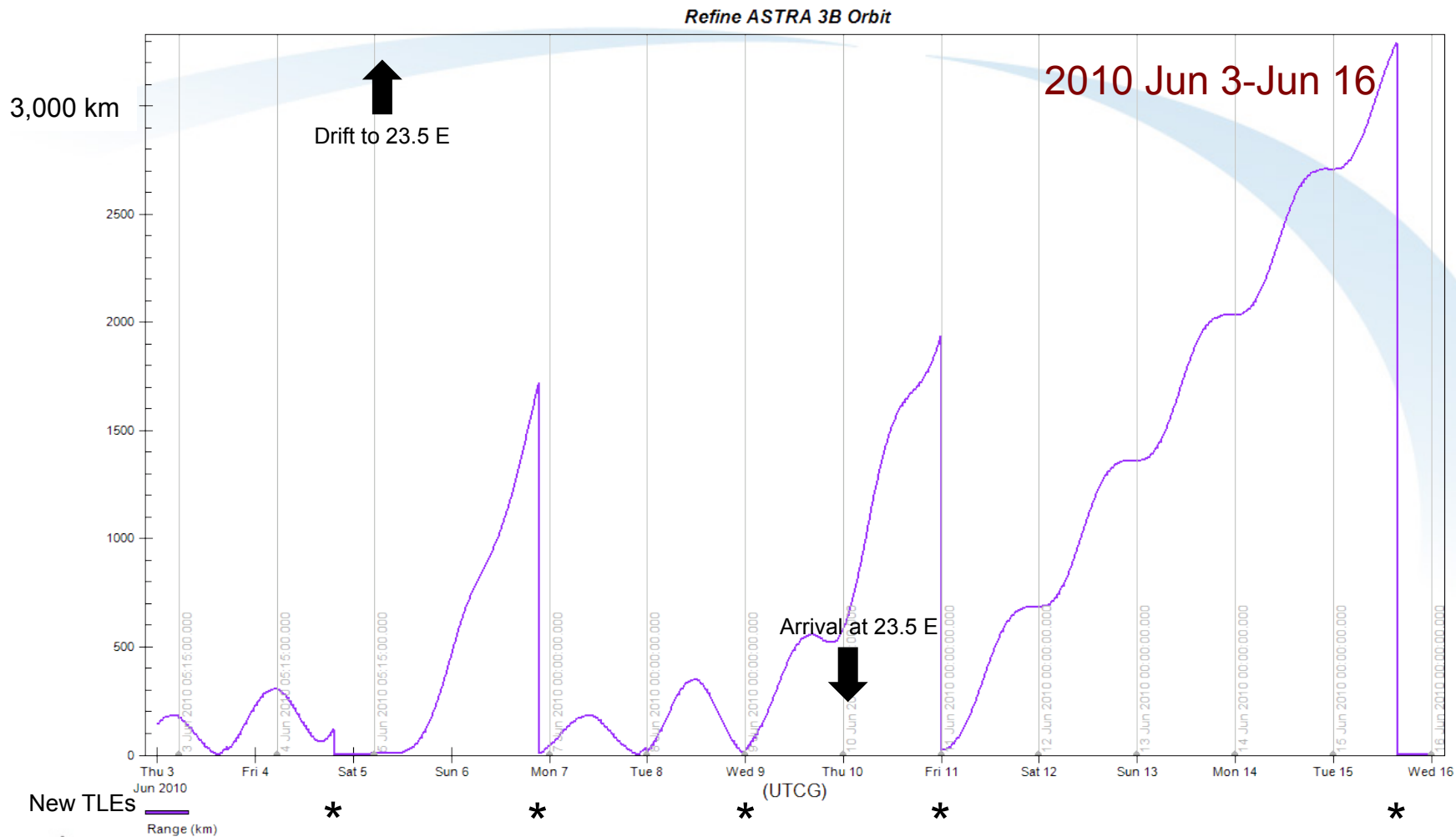
Astra 3B: Longitude with Maneuvers



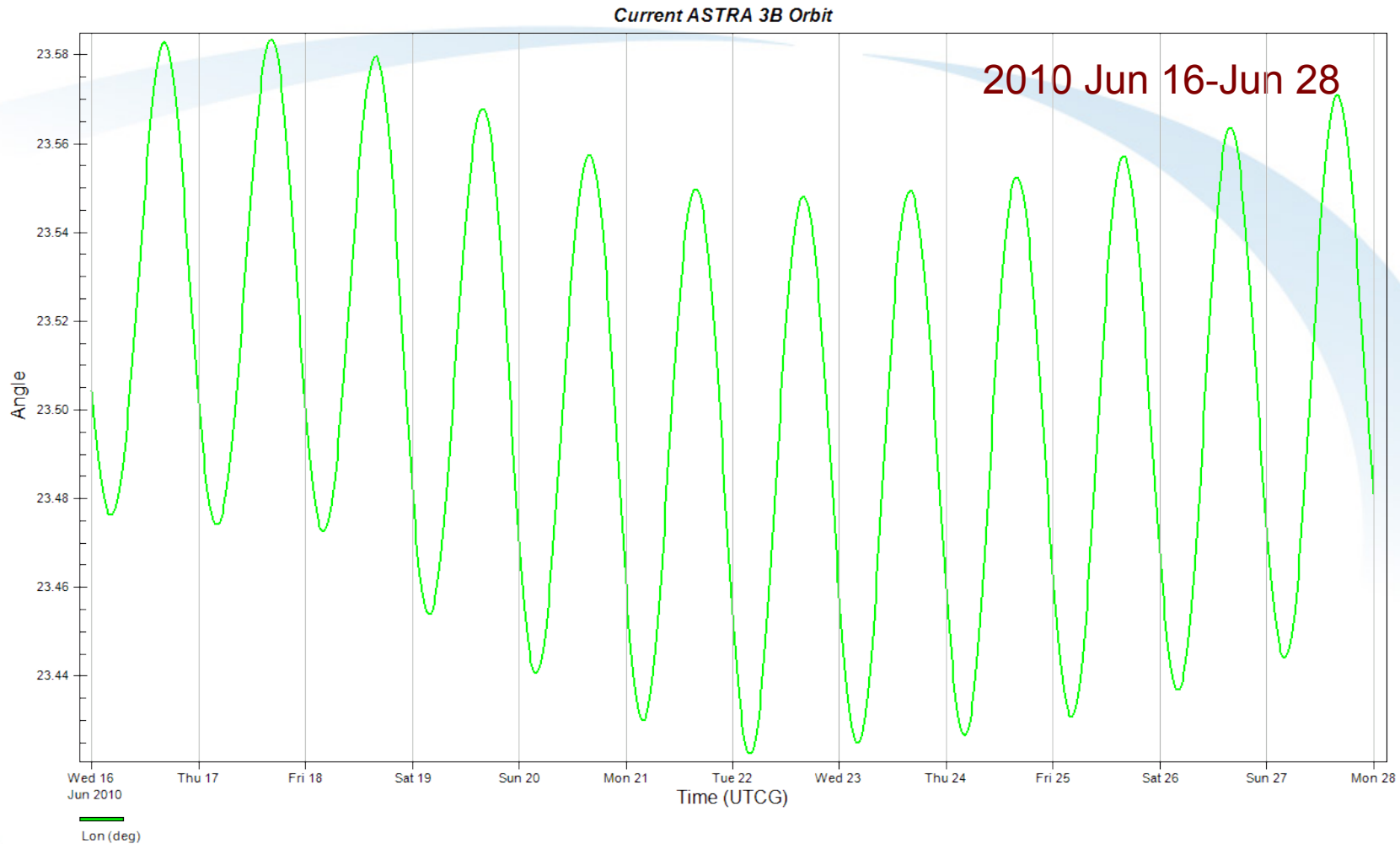
Astra 3B: Longitude (Refine)



Astra 3B: Range (Refine)



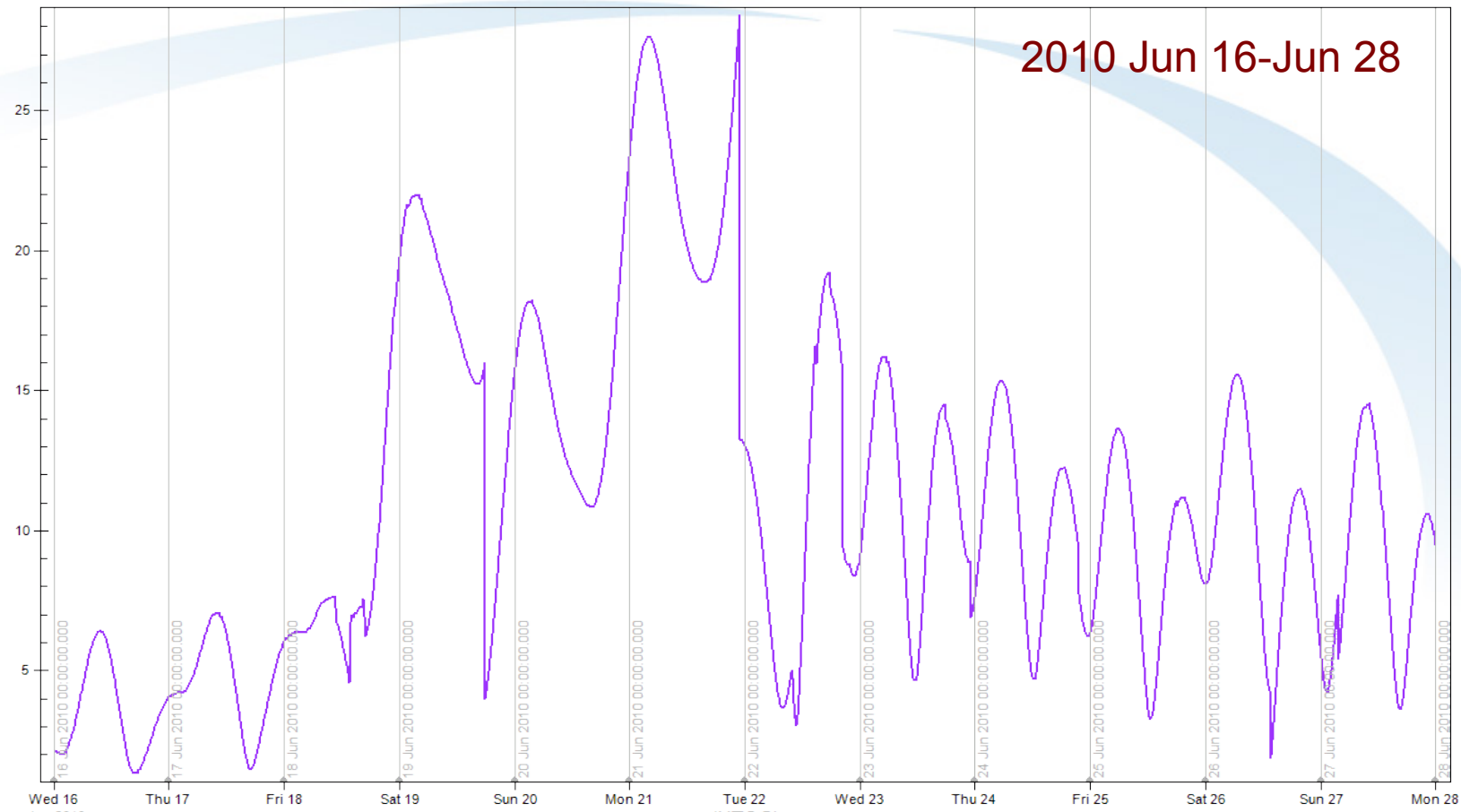
Astra 3B: Longitude (Current)



Astra 3B: Range (Current)



Current ASTRA 3B Orbit



New TLEs

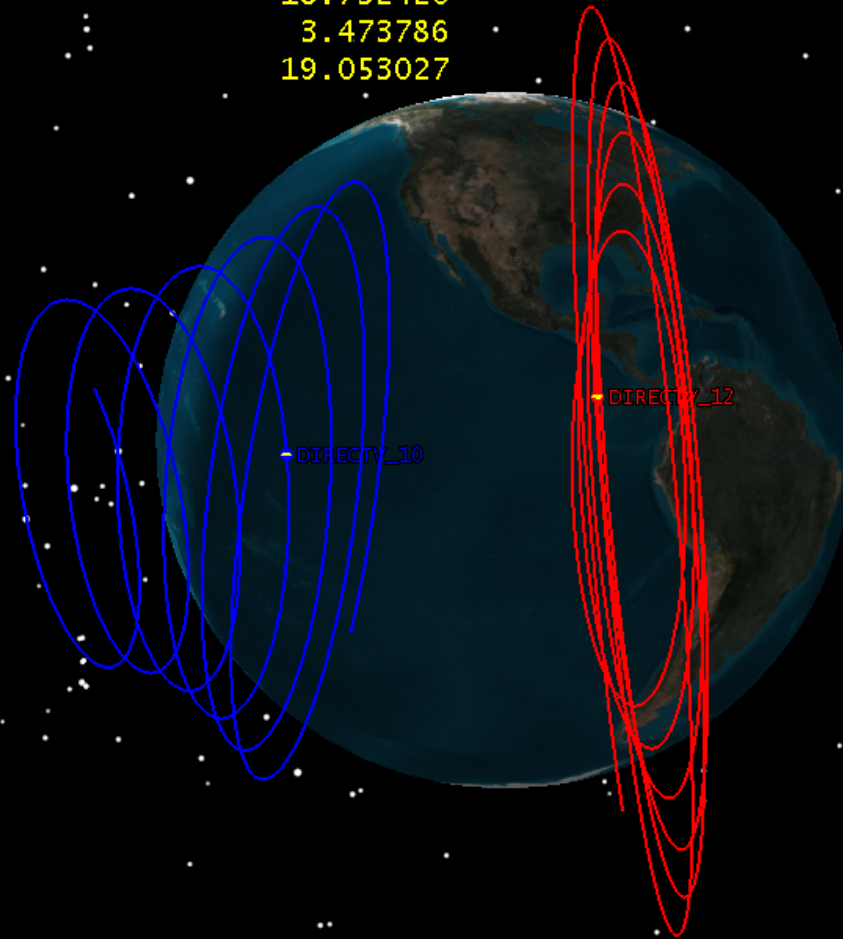
Range (km)

* * * * *



DIRECTV 10 & 12 TLEs

DIRECTV_10 RIC
Time (UTCG): 12 Jul 2010 04:25:31.561
Radial (km): 0.217010
In-Track (km): 18.732420
Cross-Track (km): 3.473786
Range (km): 19.053027



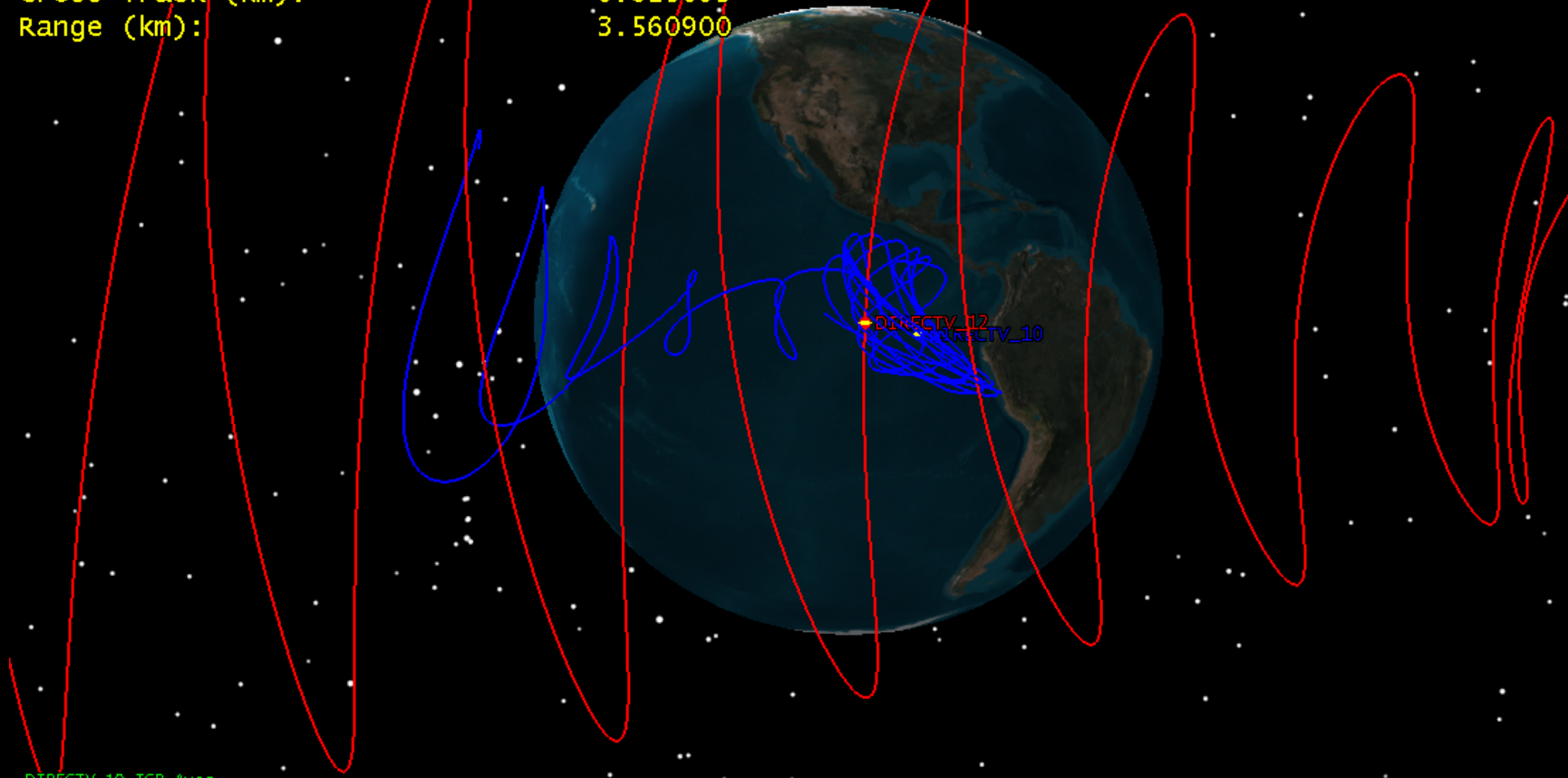
DIRECTV_10 ICR Axes
Time Step: 10.00 sec



DIRECTV 10 & 12 Ephemeris

DIRECTV_10 RIC

Time (UTCG): 12 Jul 2010 04:25:31.561
Radial (km): 1.979275
In-Track (km): -2.893395
Cross-Track (km): 0.625093
Range (km): 3.560900



DIRECTV_10 ICR Axes
Time Step: 10.00 sec



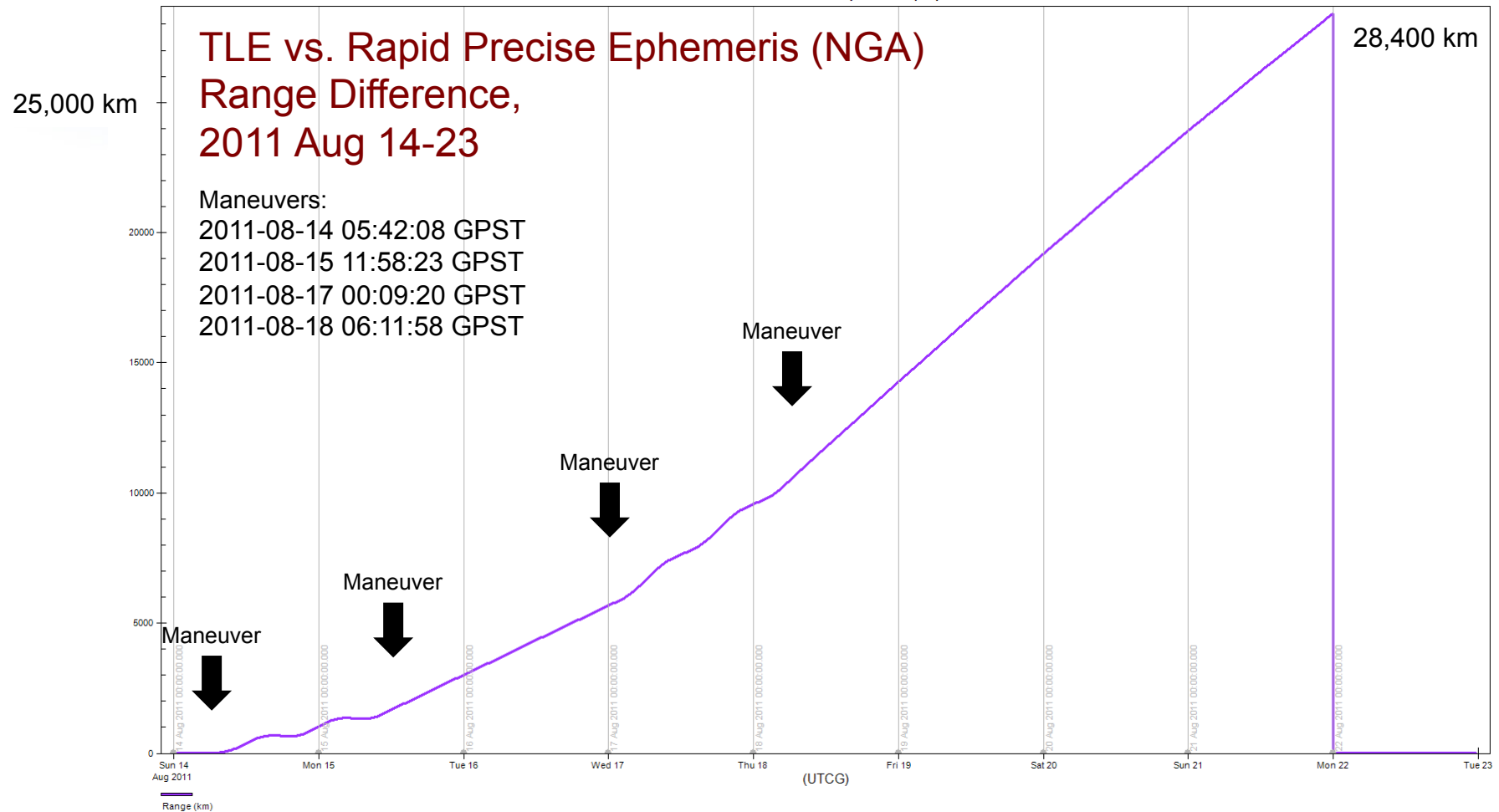
GPS 2F-2 Missed Maneuvers

- 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

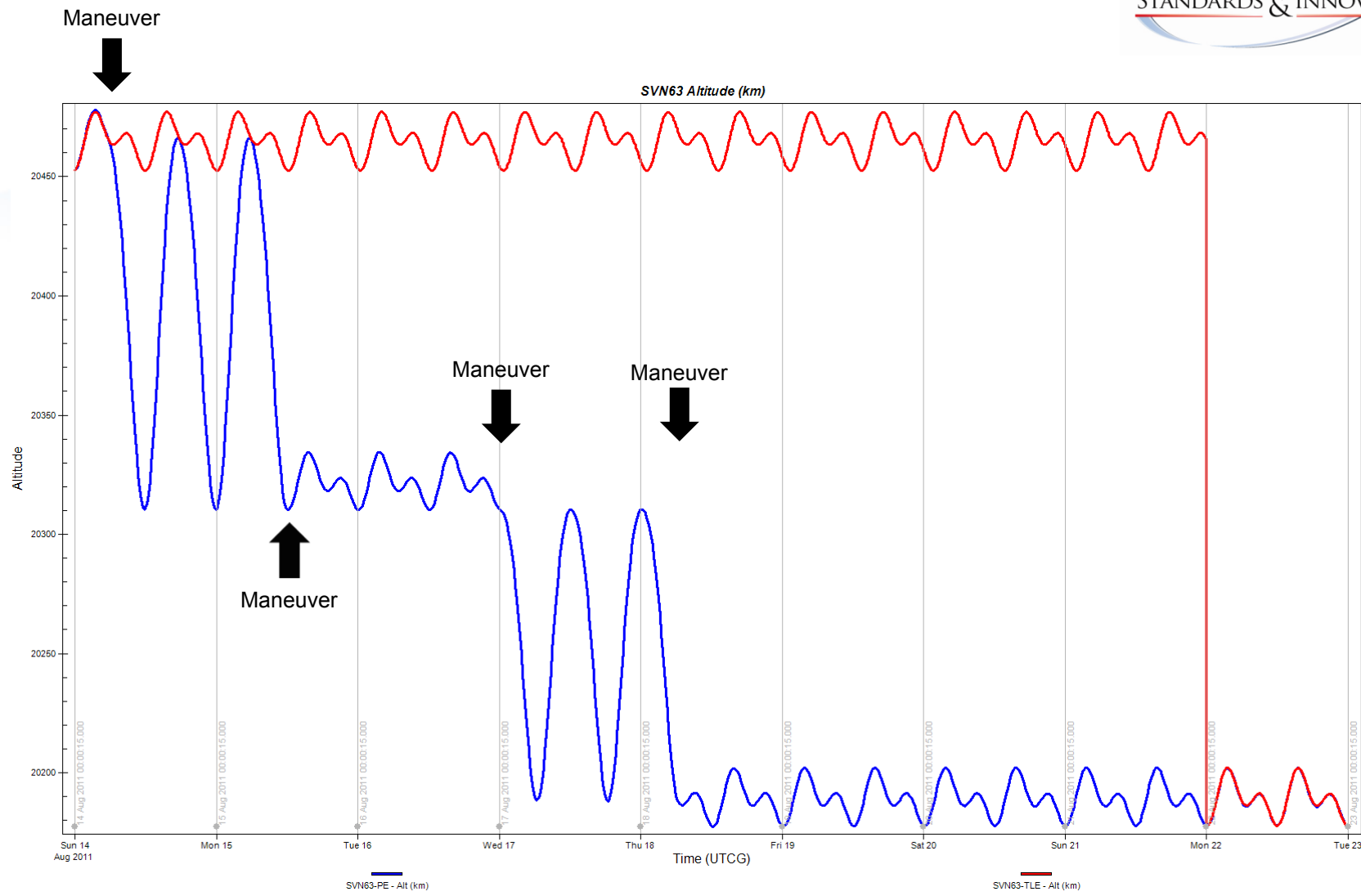
TLE Range to GPS 2F-2 PE



SVN63 TLE vs. Precise Ephemeris (km)



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

SOCRATES-GEO Reports for SES Updated (SDC-LON) - Mozilla Thunderbird

from You

subject **SOCRATES-GEO Reports for SES Updated (SDC-LON)**

to Georges Krier, Pascal Wauthier, Alexandre Dulaunoy, Jeff Pardo <Jeff.Pardo@ses-engineering.com>, Bryan Baroffio, Gary Bushko, Michael Harrison, Christine Sharlow

cc You, SDC Monitor <SDC-Monitor@agi.com>

The latest SOCRATES-GEO analysis from SDC-LON is complete at 2010 Sep 10 12:06:31 UTC and results are now available at <https://www.spacedatacenter.org/SOCRATES-GEO>.

Min range threshold violation (10 km) for 25239/NSS-806 [+] with 15144 (TLE)/GORIZONT 10 [?]:
 Min range at TCA (2010 Sep 17 03:30:20.365) = 4.452 km
<https://www.spacedatacenter.org/SOCRATES-GEO/searchSOCRATESGEO.pl?IDENT=CATNR&CATNR TEXT1=25239&CATNR TEXT2=15144&ORDER=MINRANGE&MAX=25>

Min range at TCA (2010 Sep 17 10:13:55.839) = 9.131 km
<https://www.spacedatacenter.org/SOCRATES-GEO/searchSOCRATESGEO.pl?IDENT=CATNR&CATNR TEXT1=26494&CATNR TEXT2=12545&ORDER=MINRANGE&MAX=25>

Min range threshold violation (10 km) for 26494/ASTRA 2B [+] and 26638/ASTRA 2D [+:
 Min range at TCA (2010 Sep 12 05:04:27.524) = 9.600 km
<https://www.spacedatacenter.org/SOCRATES-GEO/searchSOCRATESGEO.pl?IDENT=CATNR&CATNR TEXT1=26494&CATNR TEXT2=26638&ORDER=MINRANGE&MAX=25>

Min range threshold violation (10 km) for 28526/NSS-10 (AMC-12) [+] with 20502 (TLE)/SL-12 R/B(2) [-]:
 Min range at TCA (2010 Sep 15 07:39:43.190) = 9.698 km
<https://www.spacedatacenter.org/SOCRATES-GEO/searchSOCRATESGEO.pl?IDENT=CATNR&CATNR TEXT1=28526&CATNR TEXT2=20502&ORDER=MINRANGE&MAX=25>

Min range threshold violation (10 km) for 33275/AMC-21 [+] with 08366 (TLE)/GOES 1 (SMS-C) [-]:
 Min range at TCA (2010 Sep 15 07:39:43.190) = 9.698 km
<https://www.spacedatacenter.org/SOCRATES-GEO/searchSOCRATESGEO.pl?IDENT=CATNR&CATNR TEXT1=33275&CATNR TEXT2=08366&ORDER=MINRANGE&MAX=25>

Neighborhood Watch Results for 22117/SATCOM C3 [+] and 25516/AMC-5 (GE-5) [+:
 Min range = 55.489 km
<https://www.spacedatacenter.org/SOCRATES-GEO/NW/22117-25516.png>

Neighborhood Watch Results for 26494/ASTRA 2B [+] and 26853/ASTRA 2C [+:
 Min range = 2394.937 km
<https://www.spacedatacenter.org/SOCRATES-GEO/NW/26494-26853.png>

Neighborhood Watch Results for 28446/AMC-15 [+] and 29155 (TLE)/GOES 13 [+:
 Min range = 21972.485 km
<https://www.spacedatacenter.org/SOCRATES-GEO/NW/28446-29155.png>



Neighborhood Watch Results for 28472/AMC-16 [+] and 28626 (TLE)/XM-3 (RHYTHM) [+:
 Min range = 63.907 km
<https://www.spacedatacenter.org/SOCRATES-GEO/NW/28472-28626.png>

Neighborhood Watch Results for 29155 (TLE)/GOES 13 [+] and 29644/AMC-18 [+:
 Min range = 21899.420 km
<https://www.spacedatacenter.org/SOCRATES-GEO/NW/29155-29644.png>

Neighborhood Watch Results for 15677 (TLE)/GSTAR 1 [-] and 28446/AMC-15 [+:
 Min range = 154.806 km

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*

Action	NORAD Catalog Number	Name	Min Range (km)	Relative Velocity (km/sec)
Analysis	25239	NSS-806	4.452	0.754
	15144	GORIZONT	2010 Sep 17 03:31:26.374	

Action	NORAD Catalog Number	Name	Days Since Epoch	Probability		Min Range (km)		Relative Velocity (km/sec)
				Start (UTC)	TCA (UTC)	Stop (UTC)	Stop (UTC)	
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

```
https://www.spacedatacenter.org/SOCRATES-GEO/data/25239.oem.txt - Wind...

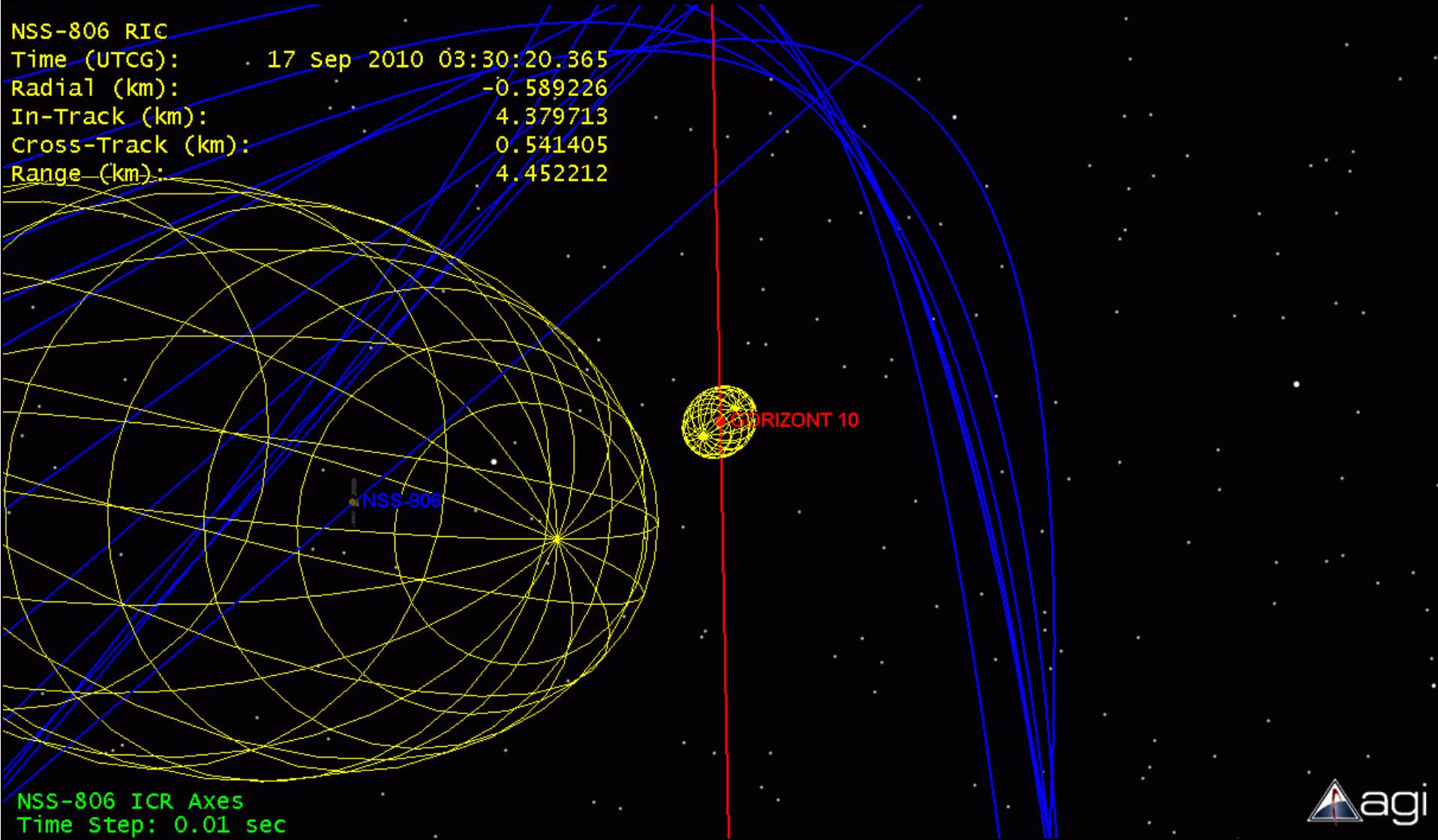
CCSDS_OEM_VERS = 1.0
CREATION_DATE  = 2010-09-10T12:01:45
ORIGINATOR     = SDC-LON

COMMENT Orbit data are consistent with planetary ephemeris DE-421

META_START
OBJECT_NAME    = 25239
OBJECT_ID      = 1998-014A
CENTER_NAME    = Earth
REF_FRAME      = EME2000
TIME_SYSTEM    = UTC
START_TIME     = 2010-09-10T07:30:00.000
USEABLE_START_TIME = 2010-09-10T07:30:00.000
USEABLE_STOP_TIME  = 2010-09-24T08:15:00.000
STOP_TIME      = 2010-09-24T08:15:00.000
INTERPOLATION  = Lagrange
INTERPOLATION_DEGREE = 5
META_STOP

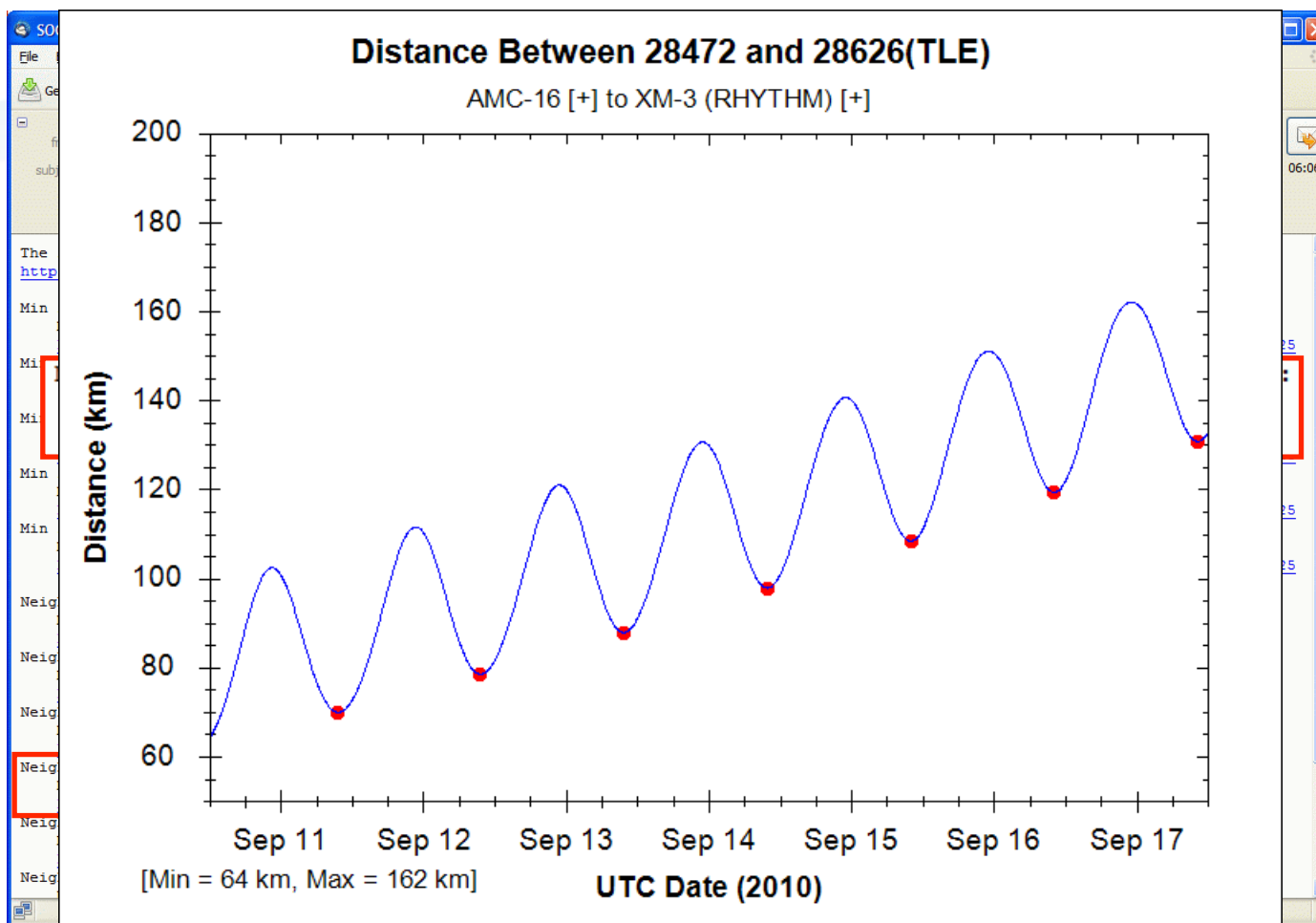
2010-09-10T07:30:00.000 20404.316497 36900.807770 -29.169127 -2.690881
2010-09-10T07:45:00.000 17940.341554 38158.923008 -27.860992 -2.782653
2010-09-10T08:00:00.000 15399.133488 39252.750919 -26.431987 -2.862449
2010-09-10T08:15:00.000 12791.629832 40177.575344 -24.888301 -2.929924
2010-09-10T08:30:00.000 10129.054376 40929.407280 -23.236622 -2.984786
2010-09-10T08:45:00.000 7422.868912 41505.002153 -21.484110 -3.026800
2010-09-10T09:00:00.000 4684.723935 41901.873892 -19.638366 -3.055782
2010-09-10T09:15:00.000 1926.408517 42118.305745 -17.707398 -3.071607
```

NSS-806 RIC
Time (UTC): 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



NSS-806 ICR Axes
Time Step: 0.01 sec

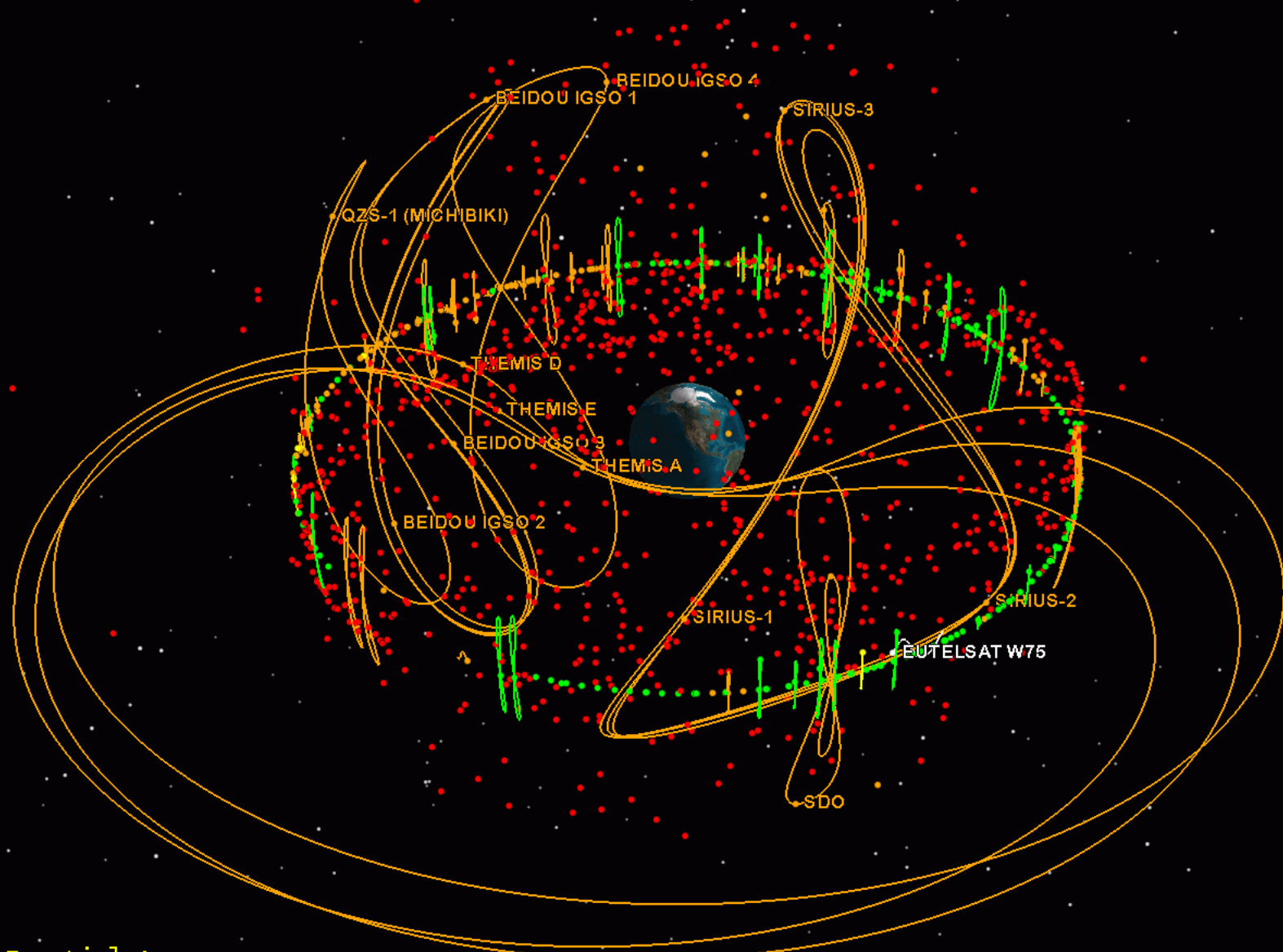
Neighborhood Watch



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)



Earth Inertial Axes
9 Sep 2011 13:00:00.000



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