The Space-based Telescopes for Actionable Refinement of Ephemeris (STARE) mission

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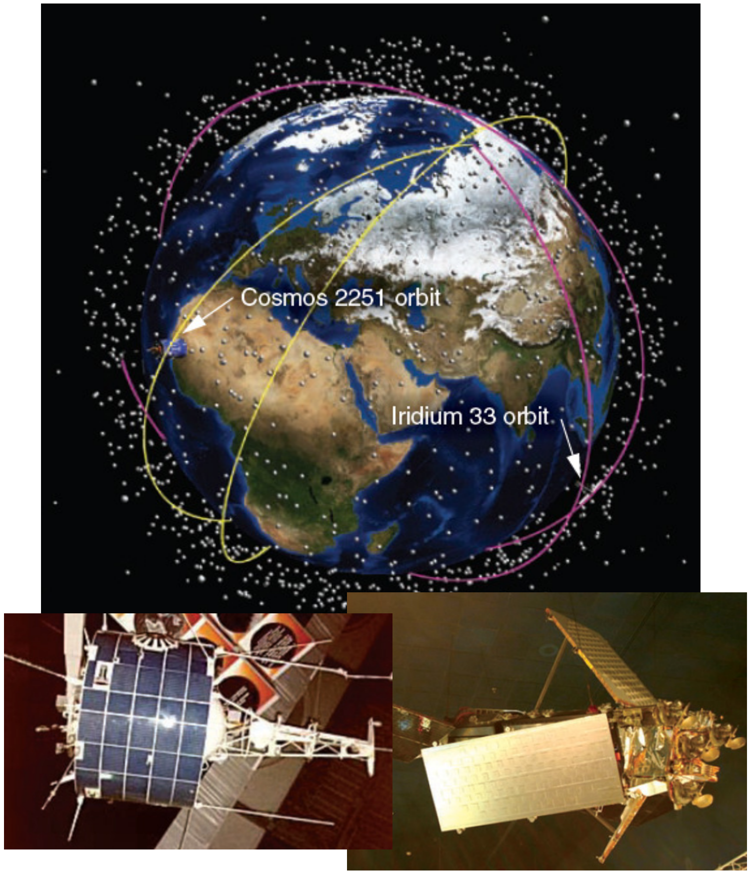
Motivation - Space Debris Problem and Mitigations



On February 10, 2009, the defunct Russian Cosmos 2251 satellite and the privately owned American Iridium 33 satellite collided in Low Earth orbit

- **Space communities as well as governing bodies recognize space debris as being a threat.**
- **Collision avoidance is one of the major mitigations to this problem**
- **Orbit refinement enables confidence in probability assessment of accidental Collision**

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Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space

Guideline 3: Limit the probability of accidental collision in orbit

In developing the design and mission profile of spacecraft and launch vehicle stages, the probability of accidental collision with known objects during the system's launch phase and orbital lifetime should be estimated and limited. If available orbital data indicate a potential collision, ad
manoeuvre should be considere

Some accidental collisions have
that, as the number and mass
space debris is likely to be fr

esa

Position Paper
Space Debris Mitigatic

Implementing Zero Debris Creatic

U.S. Government
Orbital Debris Mitigation Standard Practices

OBJECTIVE

3. SELECTION OF SAFE FLIGHT PROFILE AND OPERATIONAL CONFIGURATION

Programs and projects will assess and limit the probability of operating space systems becoming a source of debris by collisions with man-made objects or meteoroids.

MITIGATION STANDARD PRACTICES

3-1. *Collision with large objects during orbital lifetime:* In developing the design and mission profile for a spacecraft or upper stage, a program will estimate and limit the probability of collision with known objects during orbital lifetime.

3-2. *Collision with small debris during mission operations:* Spacecraft design will consider and, consistent with cost effectiveness, limit the probability that collisions with debris smaller than 1 cm diameter will cause loss of control to prevent post-mission disposal.

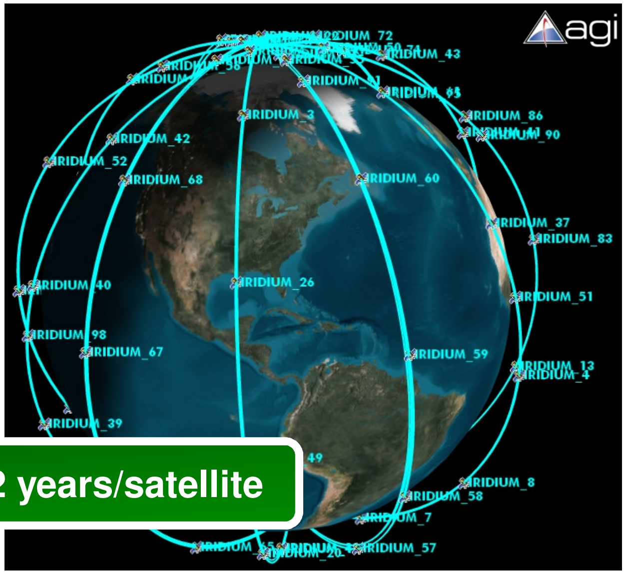
3-3. *Tether systems* will be uniquely analyzed for both intact and severed conditions.

STARE Mission Requirements for an operational orbit refinement system

Requirement	Value	Flow down
Conjunction alarm rate per object	< 1 during a satellite lifetime (~ 10year)	Satellite have limited moving capabilities (~1 time move)
Alarm advance notice	> 24 hours	24 hours needed operationally to orchestrate a move
Completeness	> 99%, objects > 10cm	Defined by stakeholders. To be adjusted

Iridium constellation (89 satellites) conjunction rate (Apr-May 2010)

Separation Threshold	Per Month On constellation	Per Day On constellation	Relative Rate Reduction
10000m	36574	1219	
1000m	354	11.8	99.03%
100m	3	0.1	99.99%

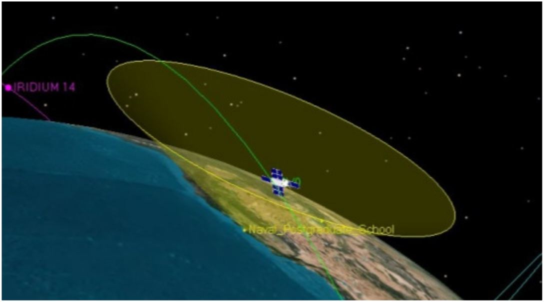


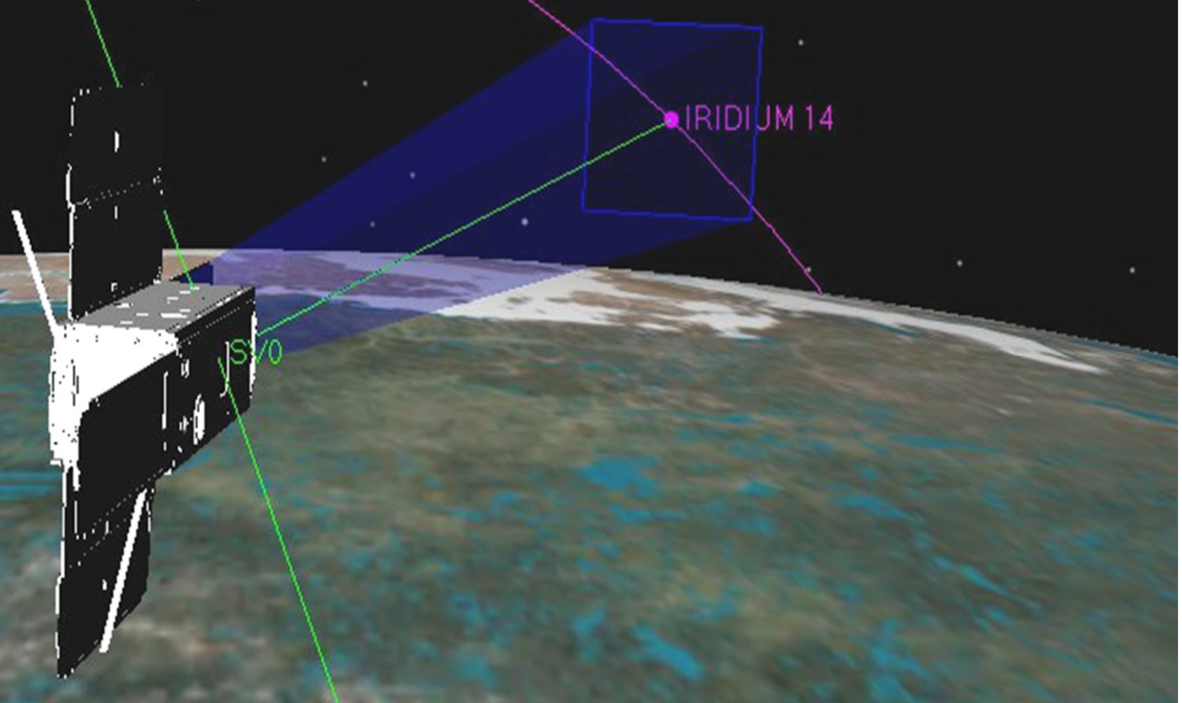
By the time σ < 100m, the number of alert is one every 2 years/satellite

Concept of Operations for LLNL Space-based Telescopes for Actionable Refinement of Ephemeris (STARE) Program

① Observe space object that is predicted to pass close to an operational satellite, based on conjunction analysis using AFSPC catalog

② Transmit images and position of observation to ground





③ Refine orbital parameters of space object to reduce uncertainty in position estimate and improve accuracy of conjunction analysis

④ Notify operators of high-probability collision

⑤ Move satellite to safe orbit

SV0 ICR Axes
14 Feb 2012 21:10:45.126 Time Step: 5.00 sec

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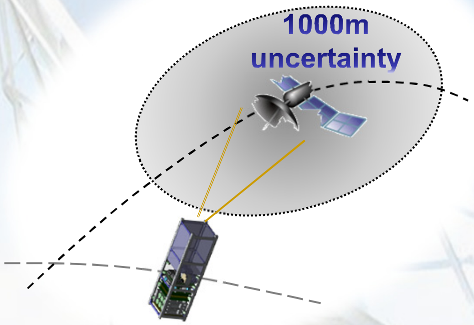
STARE processing and data flow both on the ground and in Space

Debris orbital parameters
Force model state vector from SP catalog

CubeSat Observation Parameters
3-axis imager pointing angles
Observation Start time in UTC

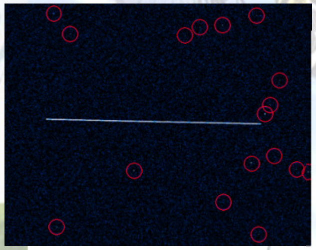


Observation Raw Data of debris

Ten observations:
- 1-sec exposure image
- 1-ms resolution UTC timestamp
- GPS WGS84 coordinates fix

Observation Pre-processed Data

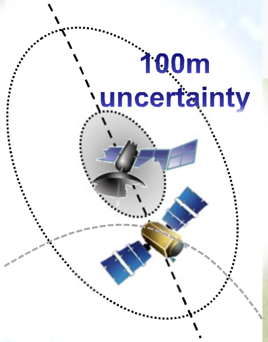
Ten observation data sets:
- Up to 100 star positions in pixel
- Pair of track end-points in pixel (if present)
- 1-sec exposure implied
- 1-ms resolution UTC timestamp
- GPS WGS84 coordinates fix



Observation celestial coordinate mapping

End-Points observation measurements
- Right ascension (RA)
- Declination (Dec)
- Epoch time

Sequential differential least squares for orbit refinement of debris
- refined orbital parameters for measurement epoch (6 parameters)
- updated covariance matrix applicable to refined estimated position for measurement epoch (6x6 matrix)

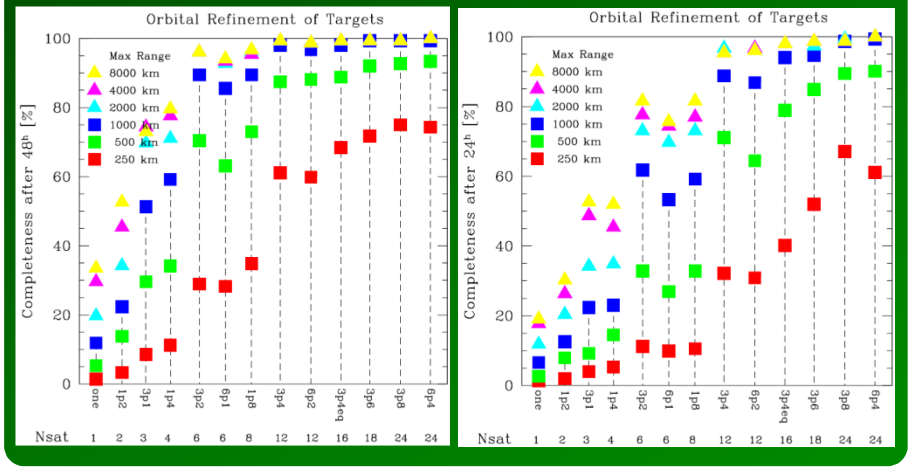


Propagation to time of conjunction
Force model propagation of state vector and covariance matrix

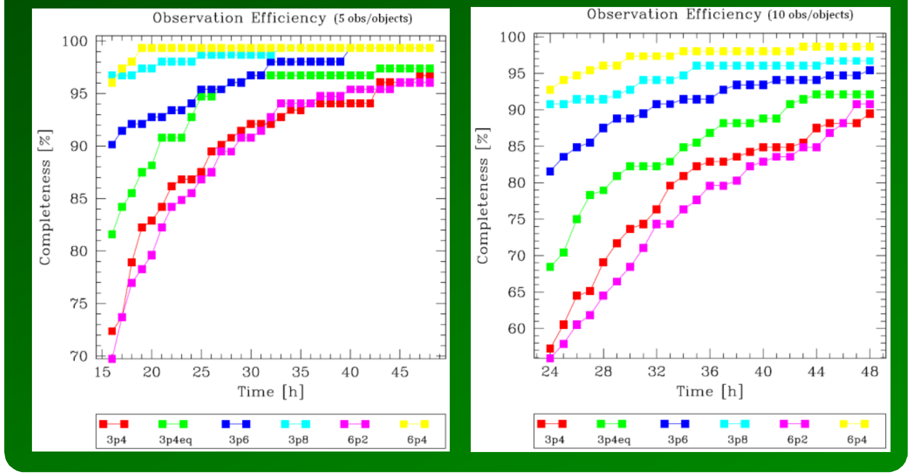
STARE Mission Key parameters are inform from an extensive Constellation design trade-study

Requirement	Value
Uncertainty refinement	< 100m from < 10,000m < 10” fitting accuracy > 3 observations/object
Constellation size	> 12, <18
Range	> 200km, < 1000km > 10cm
Relative velocity	< 10km/s
Observation time	48hrs (72hours before conjunction to 24hrs before conjunction)
Orbital configuration	3 planes, 700km

Observation Time

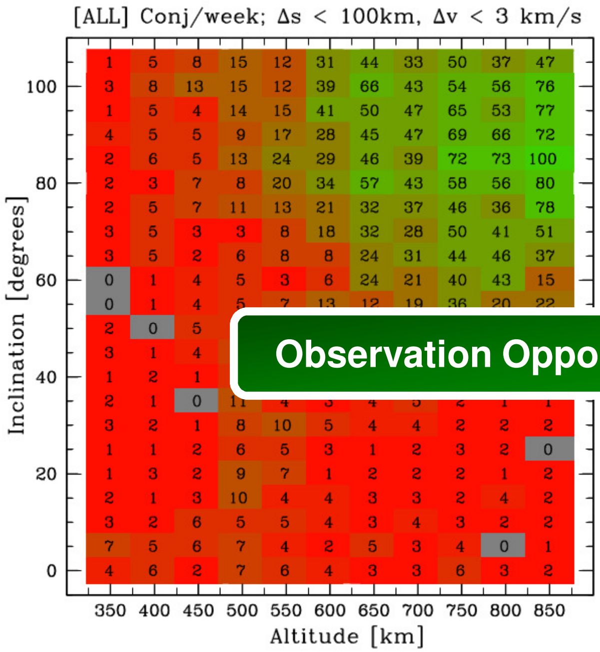


Constellation size



Concept of Operation was supported by capability trade studies for opportunities, GNSS coverage and Power budget at the spacecraft level

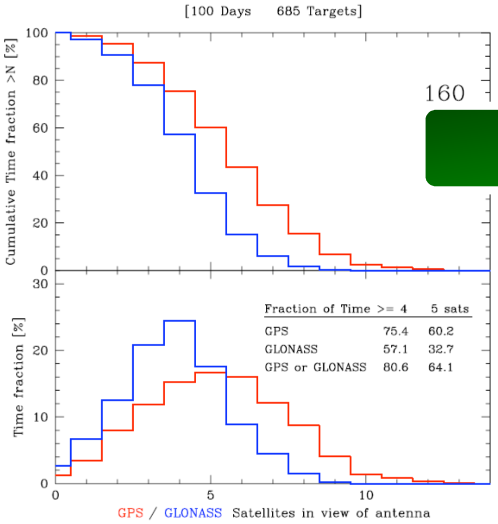
Observation Opportunities



Inclination [degrees]	350	400	450	500	550	600	650	700	750	800	850
	1	5	8	15	12	31	44	33	50	37	47
100	3	8	13	15	12	39	66	43	54	56	76
	1	5	4	14	15	41	50	47	65	53	77
	4	5	5	9	17	28	45	47	69	66	72
	2	6	5	13	24	29	46	39	72	73	100
80	2	3	7	8	20	34	57	43	58	56	80
	2	5	7	11	13	21	32	37	46	36	78
	3	5	3	3	8	18	32	28	50	41	51
	3	5	2	6	8	8	24	31	44	46	37
60	0	1	4	5	3	6	24	21	40	43	15
	0	1	4	5	7	13	12	19	36	20	22
	2	0	5								
	3	1	4								
40	1	2	1								
	2	1	0	11	4	3	4	5	2	1	1
	3	2	1	8	10	5	4	4	2	2	2
	1	1	2	6	5	3	1	2	3	2	0
20	1	3	2	9	7	1	2	2	2	1	2
	2	1	3	10	4	4	3	3	2	4	2
	3	2	6	5	5	4	3	4	3	2	2
	7	5	6	7	4	2	5	3	4	0	1
0	4	6	2	7	6	4	3	3	6	3	2

Weekly observation opportunities from various orbits to all objects in the NORAD catalog in April 2010. Observation range and transverse velocity limited for 100 km and 3 km/s respectively.

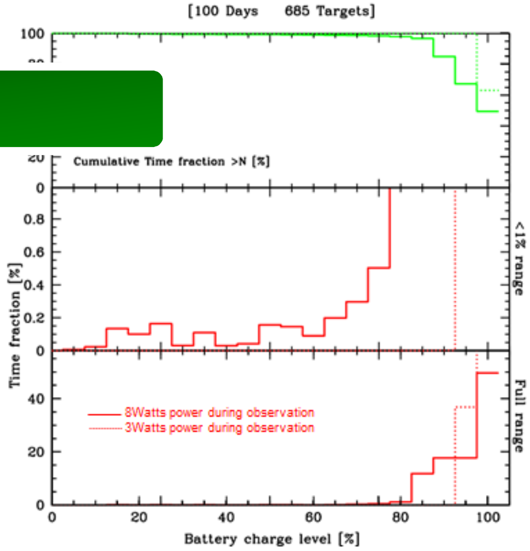
GNSS Coverage



Fraction of Time >= 4		5 sats
GPS	75.4	60.2
GLONASS	57.1	32.7
GPS or GLONASS	80.6	64.1

GNSS coverage analysis for a 700 km polar orbit conducted for a representative 100 day observation schedule with 685 targets. Antenna was assumed to have an effective angle of 172°.

Power Budget



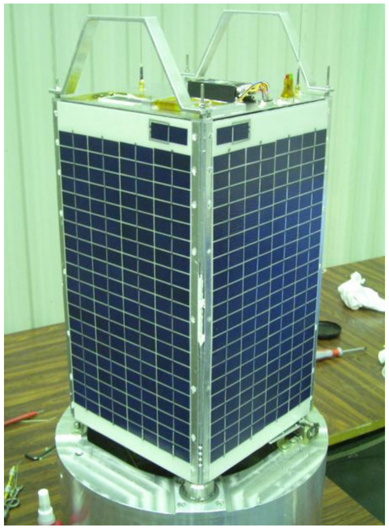
Power budget for a representative 100 day observation schedule for two power consumption rates during observation. Estimated collecting area of 0.15m2 with 15% efficiency. Estimated storage capacity of 32W hour and with charge efficiency of 90%. Top – Cumulative time fraction the battery is charged to a level greater than specified, middle/bottom - cumulative time fraction the battery is charged to a level less than specified (two scales presented)

STARE Spacecraft Key parameters

- The satellite key parameters are:
  - Fitting accuracy < 10 arcsecond (flowed from refining to less < 100 meters)
  - Field of view > 3 degreesx3degree (flowed from initial uncertainty knowledge < 10,000m, differential velocities < 10km/s, minimum range of 200km, flowed from constellation size of > 12 with > 99% completeness 24 hours in advance of conjunction, integration time set at 1sec)
  - 10cm objects < 1000km, 10km/s relative velocity sensitivity (flowed from constellation size of > 12 with > 99% completeness 24 hours in advance of conjunction)

Fitting Accuracy [arcsecond RMS]	Transverse Error at 200 km [km]	Initial $\sigma_{combined}$ [km]	1st Obs $\sigma_{combined}$ [km]	2nd Obs $\sigma_{combined}$ [km]	3rd Obs $\sigma_{combined}$ [km]	4th Obs $\sigma_{combined}$ [km]
1.8	0.002	1.101	0.339	0.099	0.040	0.019
3.6	0.004	1.101	0.347	0.111	0.069	0.036
7.2	0.007	1.101	0.361	0.124	0.096	0.063
14.4	0.014	1.101	0.378	0.154	0.111	0.093
28.8	0.028	1.101	0.388	0.214	0.116	0.110
115.2	0.112	1.101	0.401	0.309	0.125	0.123

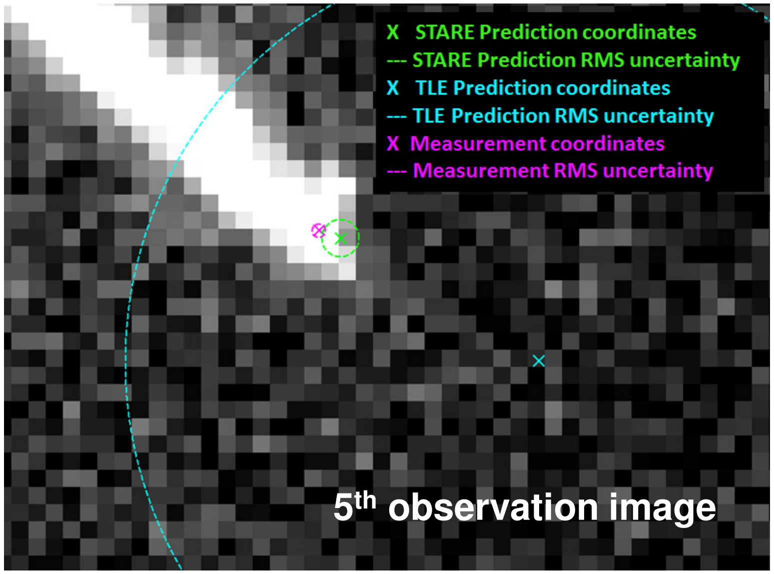
Set of 4 observations for SaudiSat2 with various fitting accuracy



Performance validation was conducted with flight hardware on the ground

Obs. number	Delay [hours]	Obs. range [km]	End point	Error in STARE Prediction vs. Measured [m]	Error in TLE Prediction vs. Measured [m]
5th	12.75	1526.737-1529.293	START	24.9	520.75
			END	54.6	614.64
6th	35.5	1277.265-1279.703	START	30.0	575.74
			END	29.3	526.34

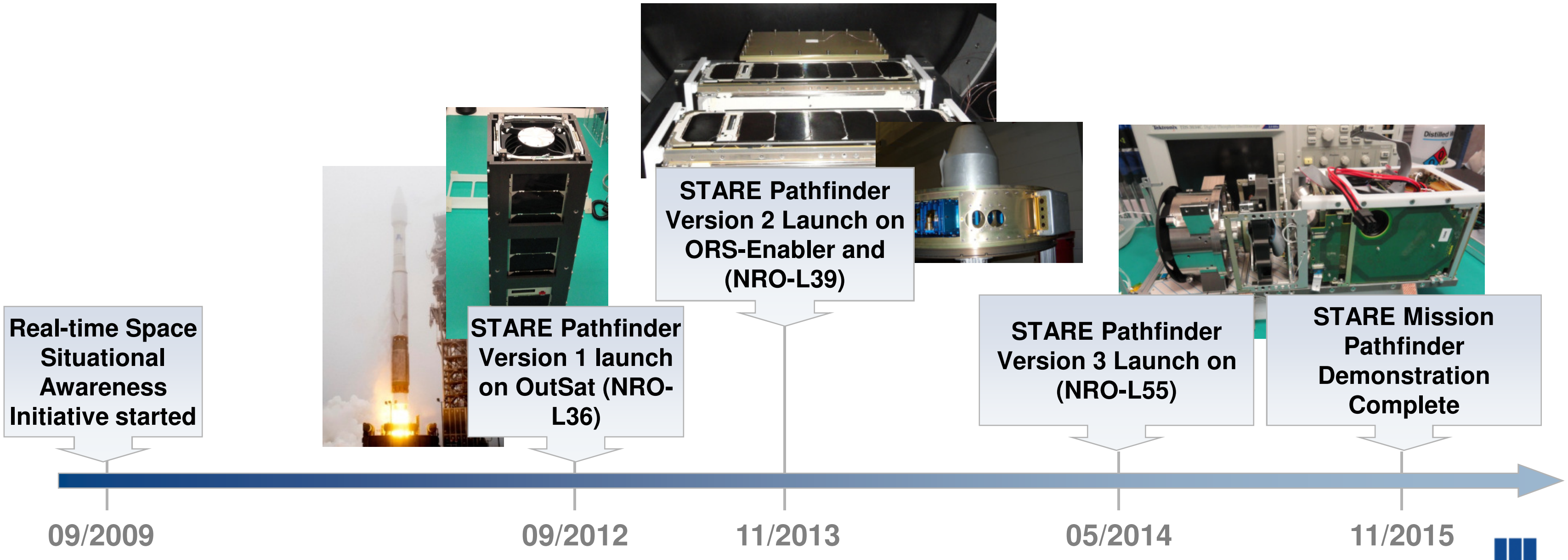
NORAD 27006 orbit refinement performances using the STARE pathfinder flight hardware. Refinement was conducted using the first 4 observations and compared against the last two observation used as true reference



5th observation image

STARE Development Summary at LLNL

- **Pathfinder Phase 1 (2009 to 2012):**
  - Internally funded at LLNL in collaboration with NRO (Colony II bus) and NPS/TAMU
  - Develop nano-satellite optical imaging capability (version 1 STARE payload)
  - Demonstrate space qualification of miniature optical design and advanced bus technology
- **Pathfinder Phase 2 (2012 to 2014):**
  - Internally funded at LLNL in collaboration with NRO (Next Generation Colony II bus) and NPS/TAMU
  - Performance driven design updates (V2 STARE payload)
- **Pathfinder Phase 3 (2012 to 2015):**
  - Internally funded at LLNL in collaboration with NRO (Next Generation Colony II bus) and NPS/TAMU
  - Performance driven design updates (V3 STARE payload, upgraded Colony II)



Real-time Space Situational Awareness Initiative started

STARE Pathfinder Version 1 launch on OutSat (NRO-L36)

STARE Pathfinder Version 2 Launch on ORS-Enabler and (NRO-L39)

STARE Pathfinder Version 3 Launch on (NRO-L55)

STARE Mission Pathfinder Demonstration Complete