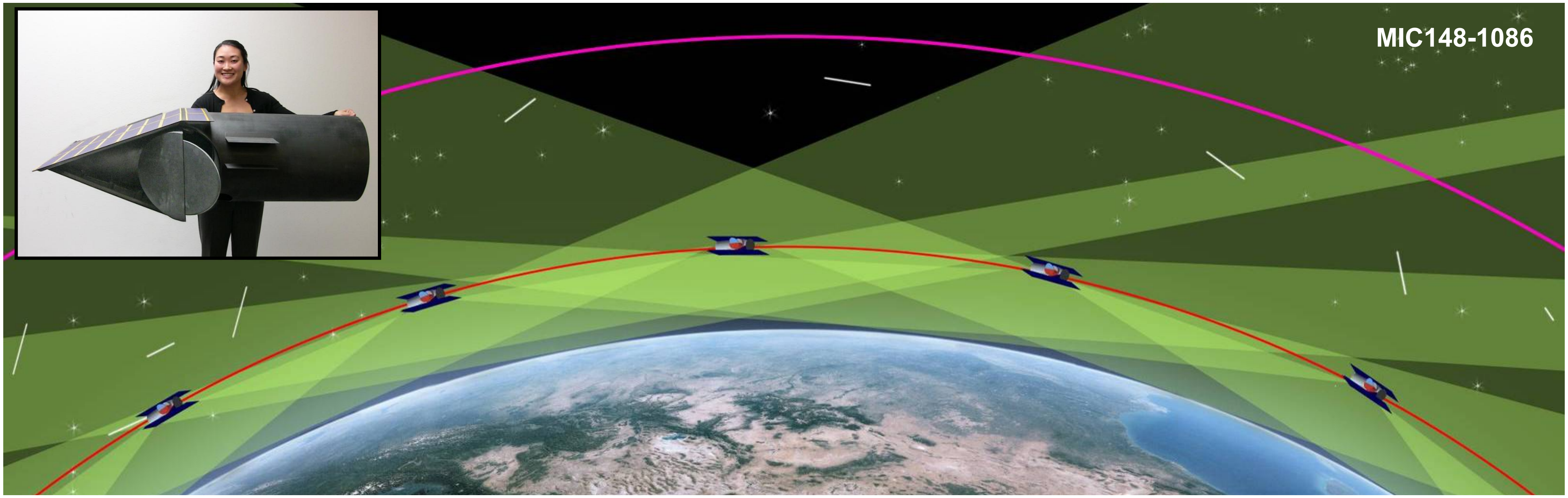

2018 CODER Workshop

DebrisSat: a Low-Cost SmallSat Constellation for both SSA and Debris Monitoring

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Topics

- Summary
- Introduction to Microcosm
- NanoEye and DebrisSat Spacecraft
- SSA in LEO
  - Tracking small particles
  - Coverage every 45-90 min, 24 hrs/day
  - Stereo Tracking
  - Conjunction maneuvers

Summary: What Does It Take to Do Precision Debris Monitoring and SSA?

1. **See faint stuff**
   - DebrisSat can see particles < 1 cm in diameter
2. **See it often**
   - The ***DebrisSat Detection System (DDS)*** constellation sees any given particle every 45 min, every 90 min if the particle is in eclipse
3. **Do high precision tracking**
   - By using simultaneous stereo viewing from 2 different satellites and not using attitude measurements, DebrisSat will provide very high precision position and velocity
4. **Be low cost**
   - A practical requirement to launch a constellation
   - DebrisSat will have a recurring cost/satellite < $5M
5. **Have high delta V**
   - Needed for conjunction maneuvers for close observations
   - DebrisSat has 2,500 m/s of available delta V

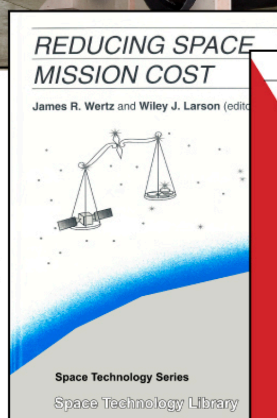
DebrisSat sees particles < 1 cm in diameter every 45 min and provides high precision tracking at low cost. It has high maneuverability for close-up views.

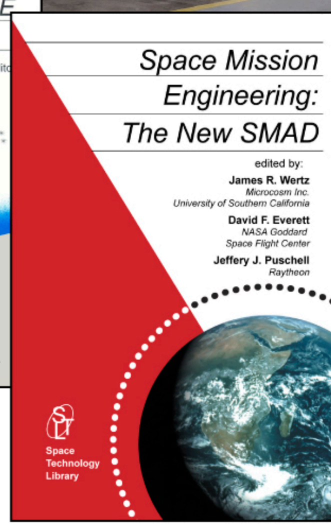
Microcosm Areas of Work

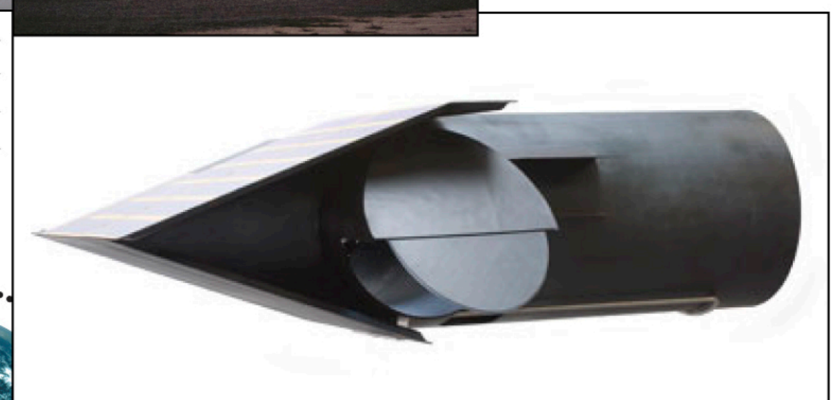
All-composite Cryogenic Tanks
(Nobody else does that)

Low-Cost Launch Vehicles

Space Mission Engineering

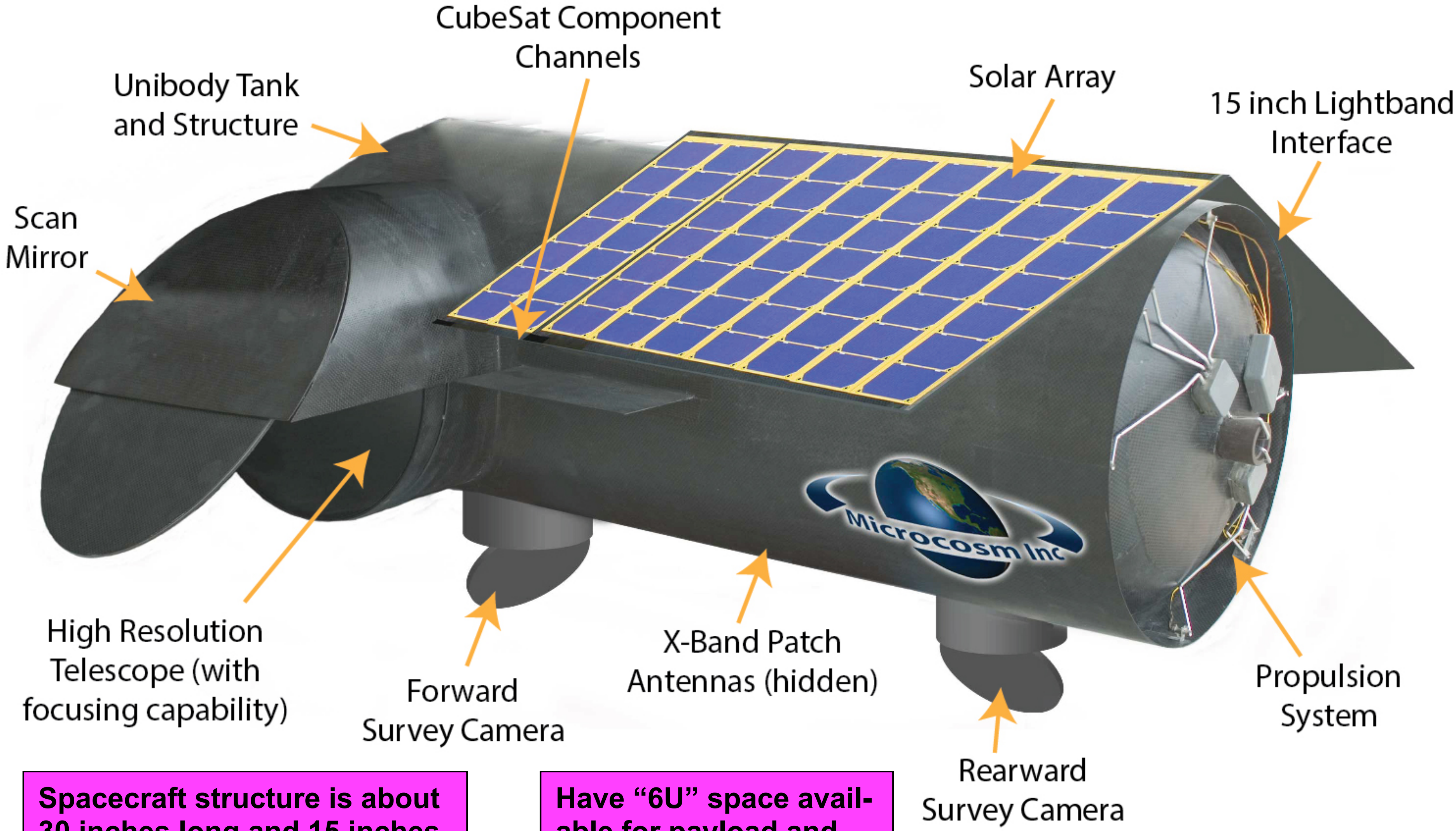






And really, really low-cost spacecraft

DebrisSat is a High-Altitude Variant of the NanoEye Spacecraft



Spacecraft structure is about 30 inches long and 15 inches in diameter. (Cameras extend outside this volume.)

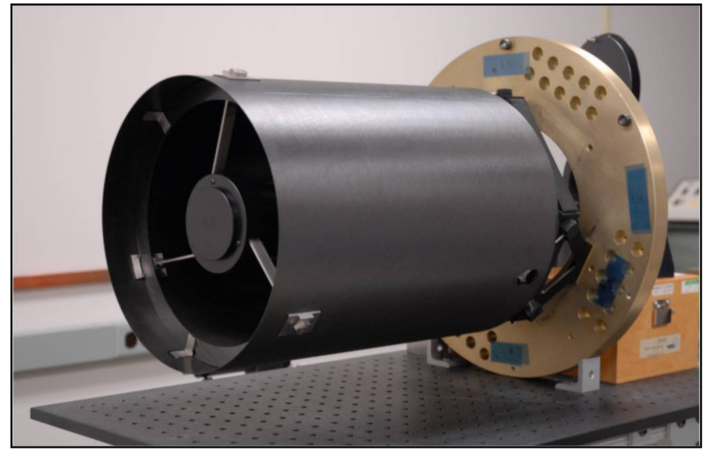
Have "6U" space available for payload and bus electronics. Could easily create more.

NanoEye is a Low-Altitude Spacecraft Concept Using Existing Technology

Structural test model built by Scorpius Space Launch Company and vibration tested to 10g in all 3 axes

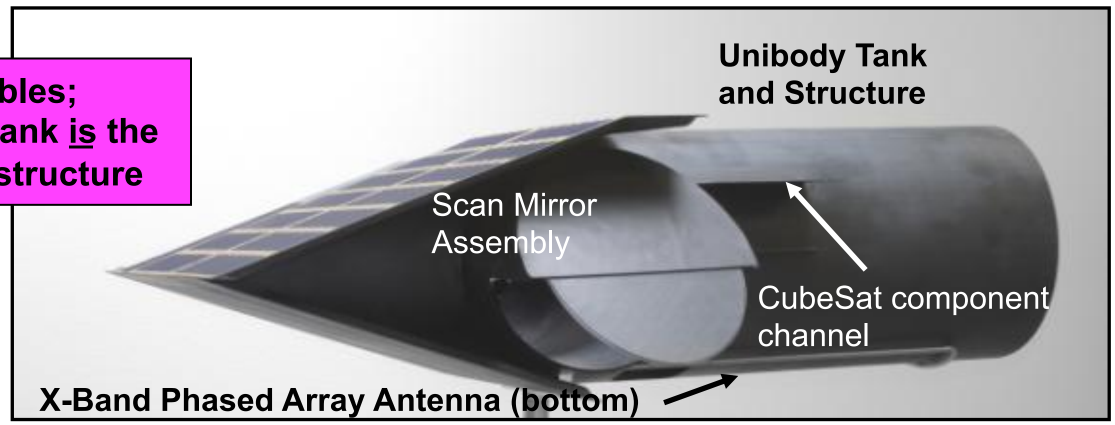
Thruster Nozzle is about twice the size of Washington's nose

1 lbf, 5.4 g thrusters previously flown in space



9.25", 4.5 kg diffraction-limited telescope has flown in space

No deployables; propellant tank is the spacecraft structure



Spacecraft configuration designed to minimize drag and torque, minimize dry mass with large propellant volume, and provide easy access and modular systems for low cost integration and test.

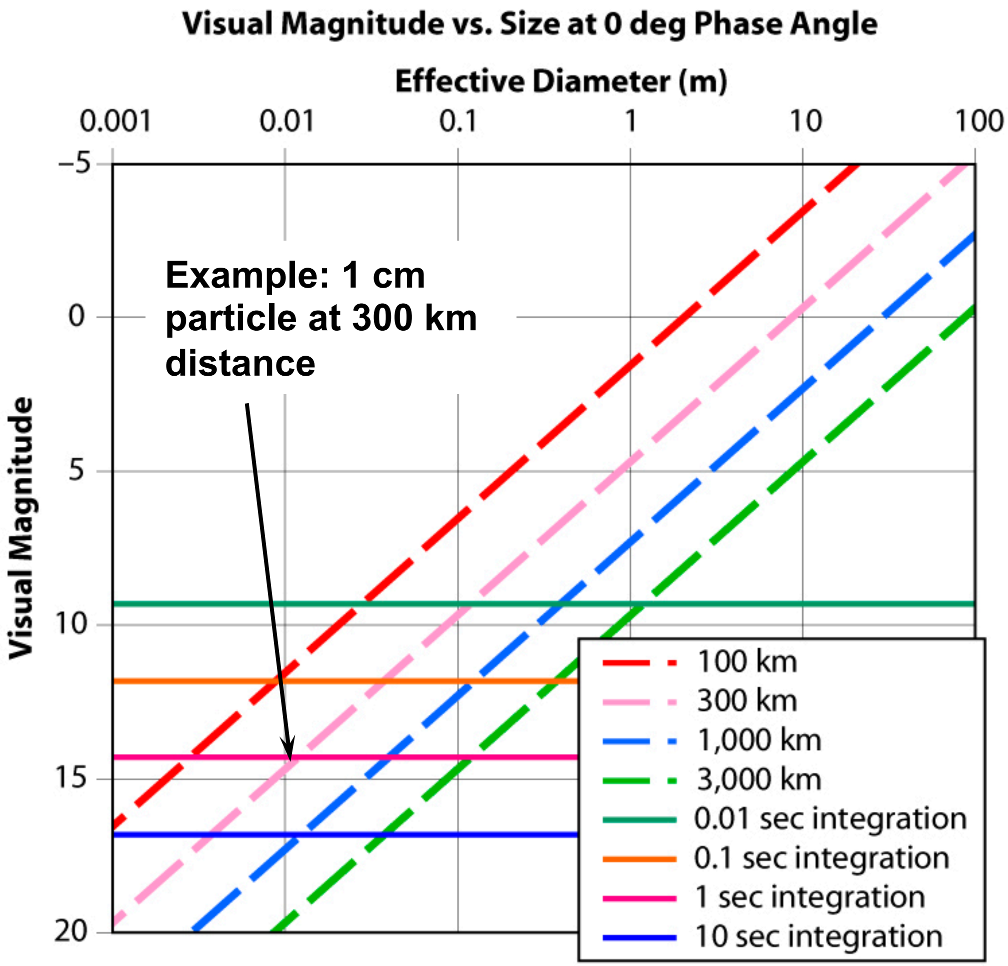
LEO SSA and Satellite Inspection

- A ***DebrisSat Detection System (DDS)*** constellation can provide high accuracy ephemerides for even very small spacecraft and debris, plus satellite inspection

- A 2 LEO DDS demonstration mission could be used to validate SSA, debris monitoring, and inspection capabilities

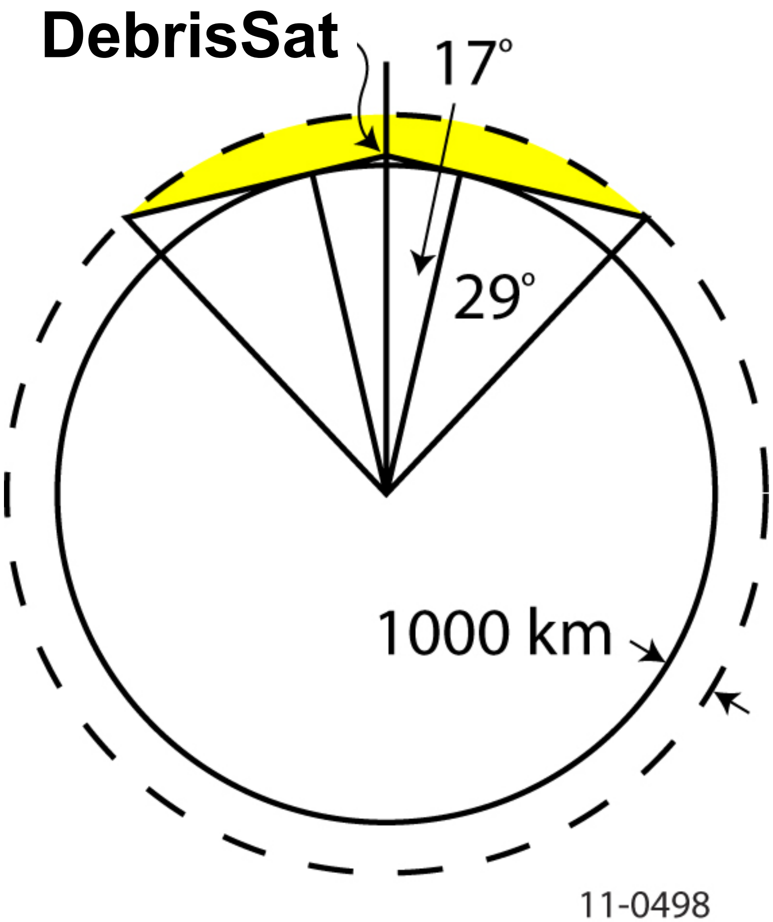
Visibility of Debris and Other Spacecraft as a Function of Size and Distance

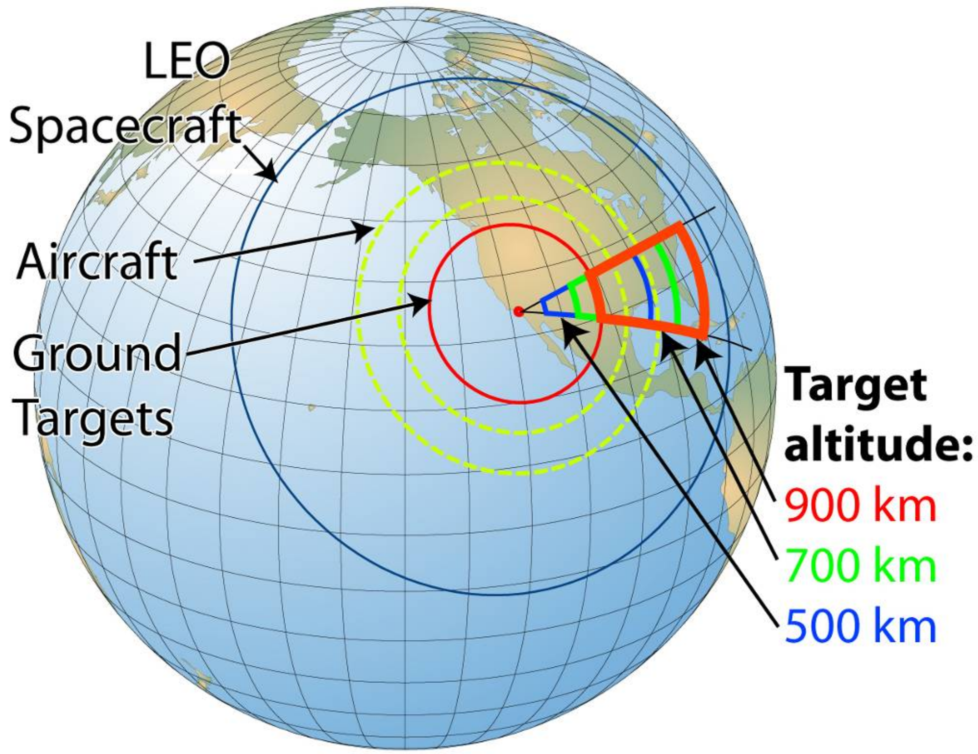
- Wide FoV Survey Camera
  - 7 cm diameter aperture
- Assumptions
  - Albedo 0.2
    - Meteoroids ~0.1
    - Spacecraft ~0.8
  - 0 deg phase angle
    - Relatively little effect out to 90 deg phase angle
  - Distances and integration times per pixel as shown on chart
- Objects and background stars will both appear as tracks in the FoV
  - Very distinguishable from each other



Under good lighting conditions, DebrisSat will be able to see objects less than 1 cm across.

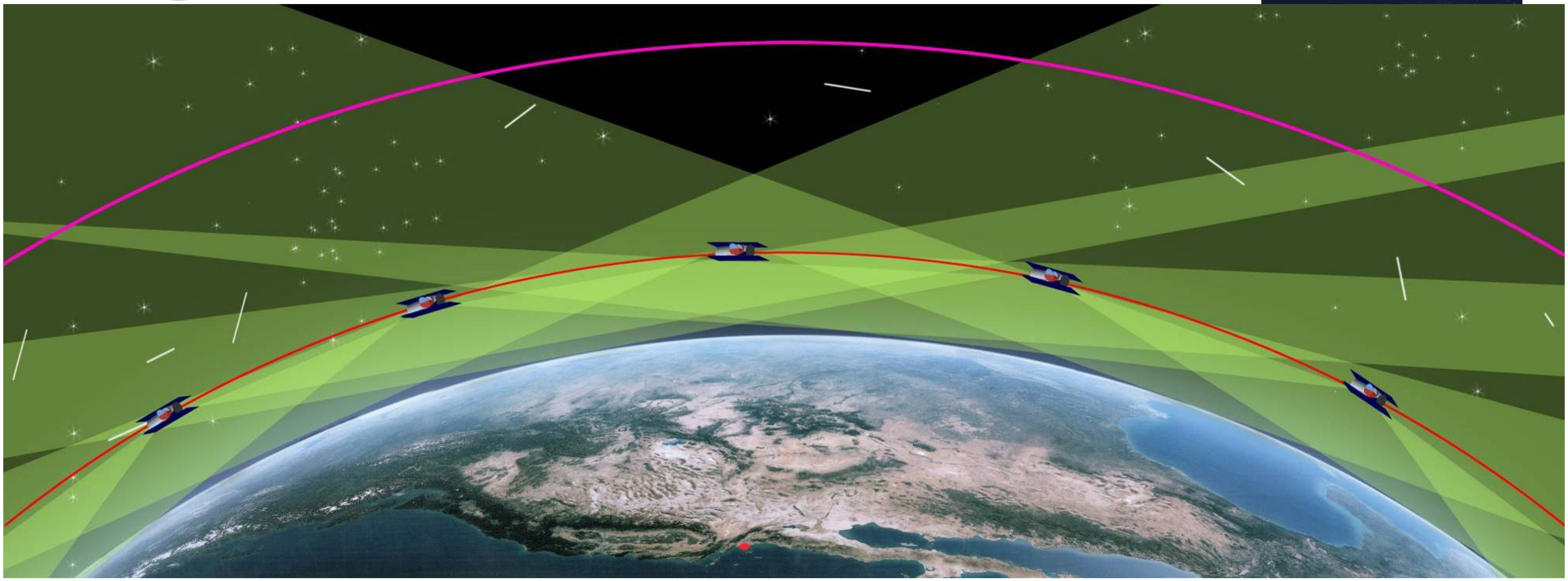
Ground, Air, and Space Viewing Regions from LEO





DebrisSat can see targets in space over more than 200 deg of arc which results in the very large viewing area for close-ups or additional tracking.

DebrisSat Coverage and Resolution in LEO



- **From 500 km, the Field of Regard for spacecraft and orbital debris is 10,000 km across — 3 times the size of North America**
- Imaging Resolution in meters of High-Res camera is D/400, where D is the distance to the target in km **(can see targets that are much smaller)**
  - 5 m resolution at 2000 km
  - 1 m resolution at 400 km
  - 25 cm resolution at 100 km
  - 25 mm resolution at 10 km

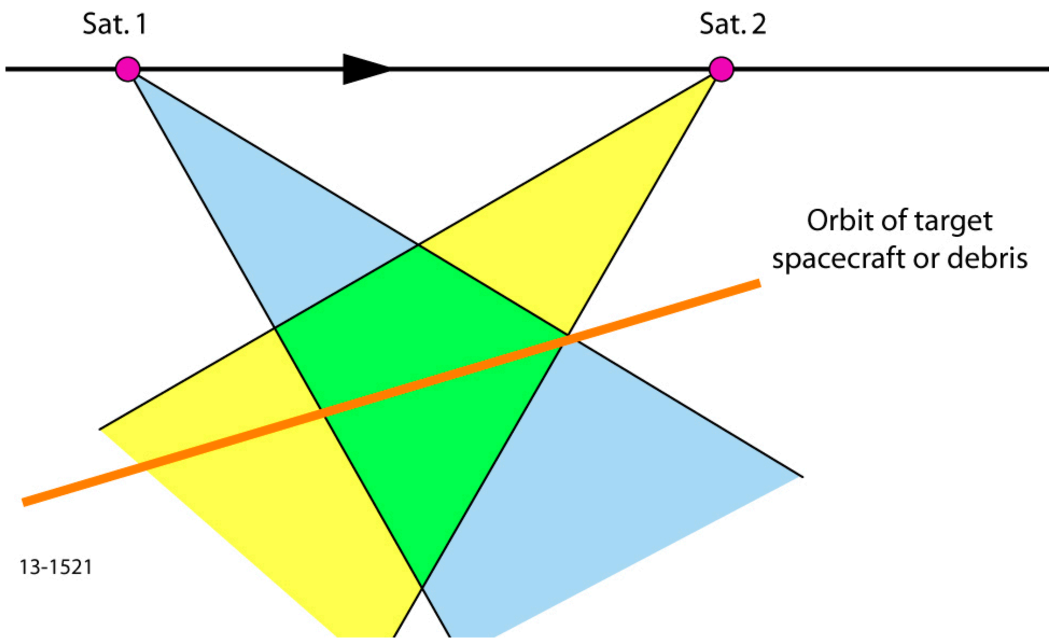
In both LEO and GEO, DebrisSat sees nearly all targets with the best possible viewing — from above the atmosphere, against a dark sky background, looking away from the Sun.

The DDS Constellation Consists of 30 DebrisSat Spacecraft in a 500-600 km Equatorial Orbit

- **Key system characteristics**
  - Creates an equatorial "fence" in space that provides unique tracking data for nearly all debris and spacecraft in low Earth orbit
  - **Sees most objects every 45 min (every 90 min when an object crosses the equator in the Earth's shadow), 24 hours/day — means almost no debris gets "lost"**
  - **Can detect debris and provide good tracking data down to about 1 cm in size**
  - **Viewing of each object by 2 spacecraft simultaneously provides instantaneous 3-dimensional precision position and velocity not available by other approaches**
  - Nearly all previously flown or space-qualified hardware; 5+ year operational life
  - **System can be ready for a demonstration mission in 18 to 24 months**
- **Baseline DebrisSat payload + bus total recurring cost less than $5M**
  - 30 ***DebrisSat*** spacecraft in equatorial LEO orbit provide a complete fence
  - Provides excellent supplement to more traditional approaches

Instantaneous 3-dimensional position data not normally available by other means.
$5 million spacecraft recurring cost enables a multi-spacecraft solution.

Stereo Tracking from 2 Satellites Provides High-Accuracy Position + Velocity



Low-cost Stereo tracking from 2 spacecraft can be used for:

- **LEO space fence (debris and spacecraft)**
- **Missile tracking**

- Simultaneous observations from two spacecraft provides much higher accuracy ephemeris than alternatives (see next chart)
  - Can dramatically reduce the error ellipsoid for missiles, spacecraft, and debris
  - **Example: Would have prevented the Iridium 33/Cosmos 2251 collision by providing much higher accuracy prediction and allowing Iridium to move out of the way**

Simultaneous observations from two satellites provides very precise tracking (position and velocity) not available from any other approach.

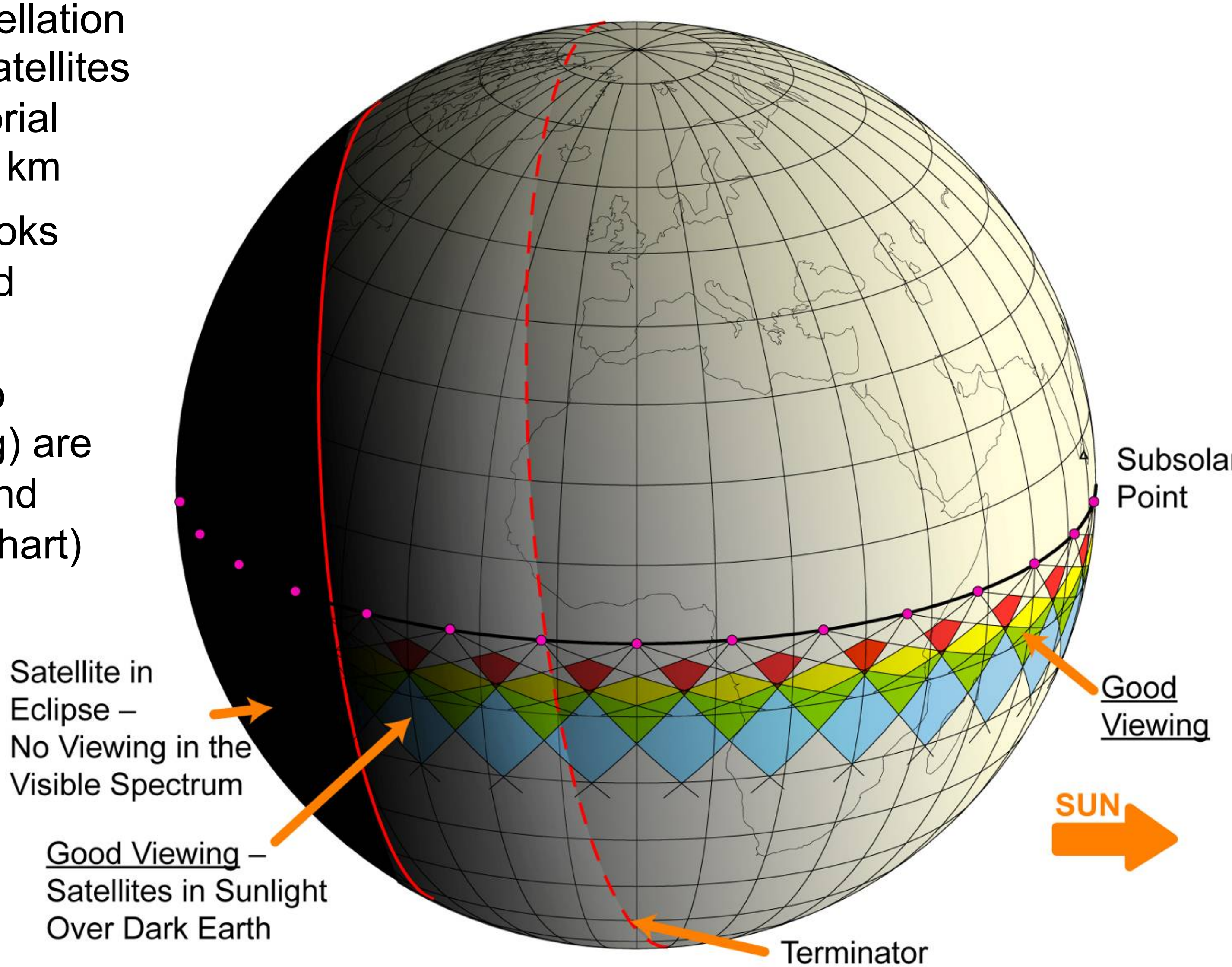
Stereo Tracking for High Accuracy 3-Dimensional Position and Velocity

- Traditional optical tracking
  - Requires 3 or more observations separated in time in order to establish a track
  - Linear motion of tracked object does not give information on distance (could be slow object nearby or fast object further away)
    - Requires observing the non-linearity of the motion to determine the orbit
    - Accuracy is poor and makes calculating the orbit and future positions difficult
- **Space-Based 3-Dimensional Tracking**
  - **Observing a target with respect to the background stars from a single spacecraft puts the target on a line or narrow cone extending out into space**
  - **Observing the same target simultaneously from two spacecraft puts the target at the intersection of these two rays from the two spacecraft**
    - **Highest accuracy when the two observing spacecraft are about at right angles as seen from the target**
    - **<u>If they're not observing the same target, the two cones won't intersect -- use this for target verification</u>**
  - **Observations over even a short interval (say 200 km), will give accurate position <u>and</u> velocity and, therefore, allow a full solution for the trajectory**

Simultaneous observing from 2 spacecraft several thousand km's apart is a new, high precision observing mode not previously available for tracking most objects in space.

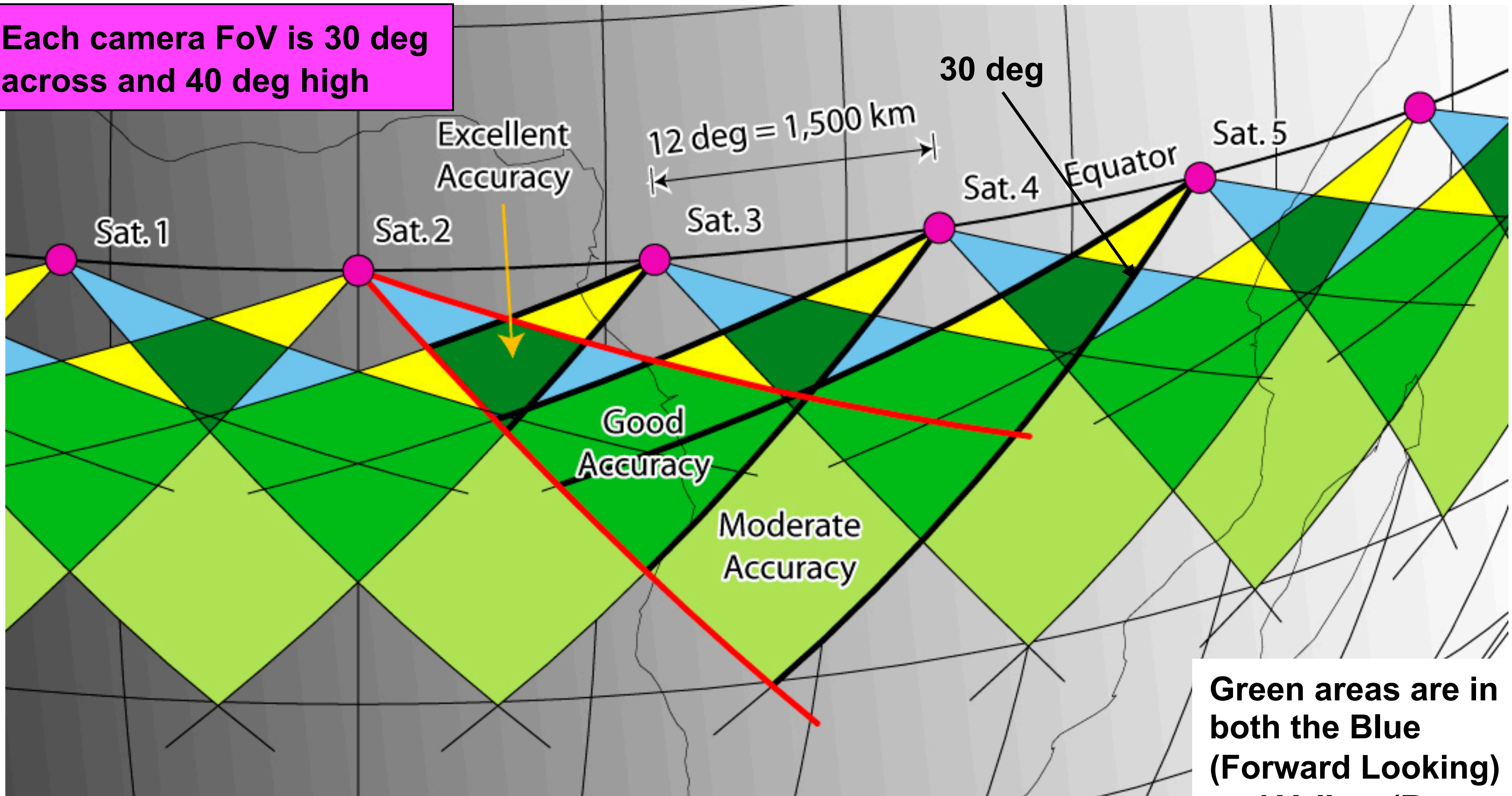
The DDS Constellation

- The DDS Constellation consists of 30 satellites in a LEO equatorial orbit at 500-600 km
- Each satellite looks both forward and rearward
- Areas of overlap (=stereo viewing) are in red, yellow, and blue (see next chart)



The DDS Constellation Provides High-Precision Stereo Tracking

Each camera FoV is 30 deg across and 40 deg high

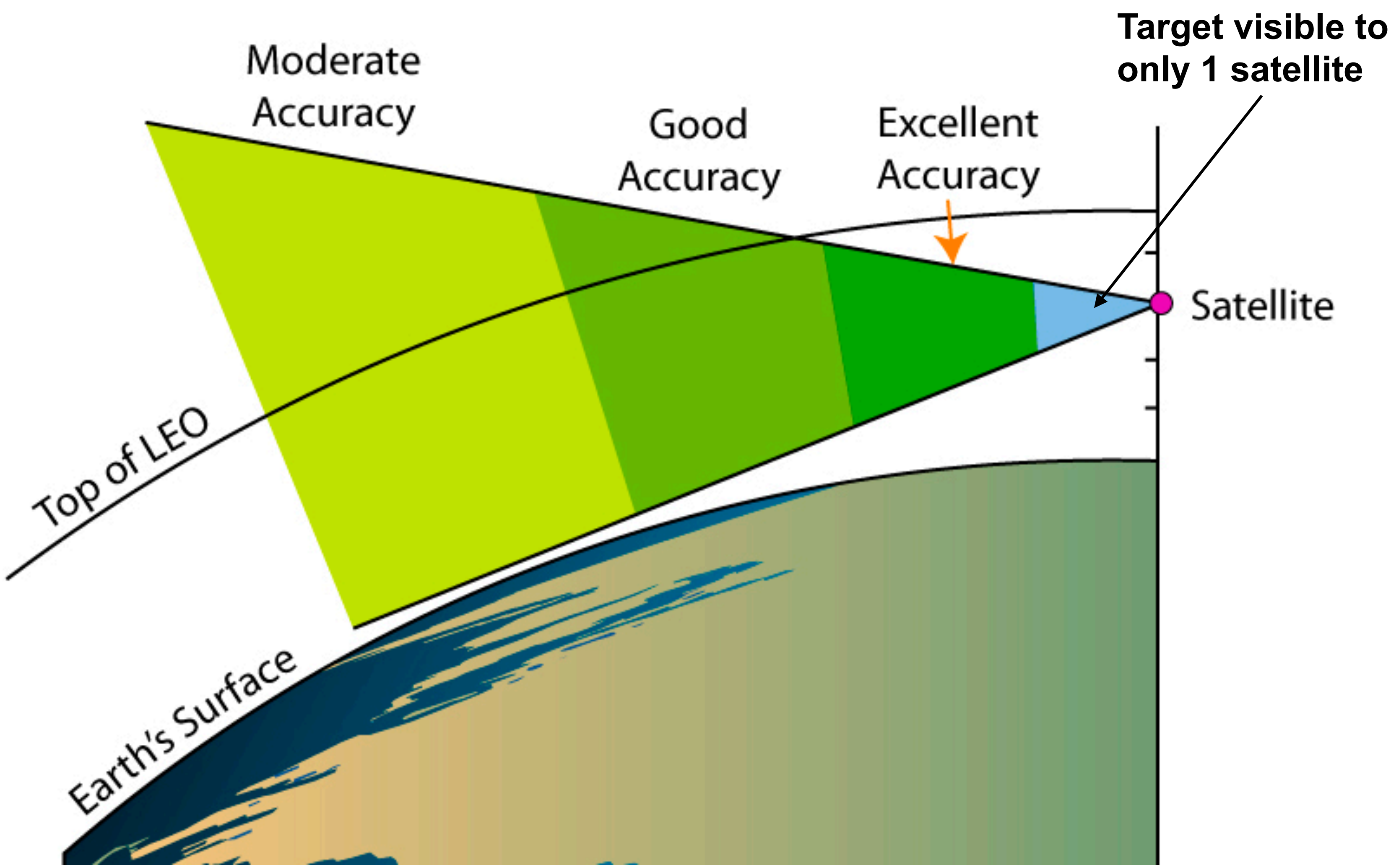


Fence faces south when the Sun is north of the equator and faces north when the Sun is south of the equator.

Green areas are in both the Blue (Forward Looking) <u>and</u> Yellow (Rearward Looking) areas.

Each satellite cooperates with 3 satellites on either side (7 satellites working together) to provide <u>both</u> wide coverage and high precision position and velocity observations.

Vertical Cut of the Field of View



Conjunction Maneuvers

- There is a continuing and ongoing need to image and evaluate space debris or damaged satellites on orbit
- Because of its large delta V, high scanning agility, and good resolution telescope, DebrisSat has a unique capability to get high resolution images at low cost
  - Basic technique is to perform a conjunction maneuver to allow DebrisSat to fly close to an object of interest and use the Scan Mirror Assembly (SMA) to create a series of images spanning the time of closest approach
  - This is a 1-time fly-by of the object; no orbit matching is done
- The principal source of image blur is the inability to accurately track the space object at very high angular velocities
  - This can be resolved by having a separate High-Speed Tracking Sensor (HSTS) fed by a beam-splitter from the main NanoEye telescope
  - HSTS then drives the SMA to maintain optical lock on the space object during the conjunction
- Can do an Earth-based validation test of the full tracking and imaging system

Imaging resolution of 3 to 5 cm should be possible for most objects in LEO.

Can Also Use DebrisSat in Multiple Spacecraft/Debris Inspection Modes

- ***Conjunction modes*** are delta V burns done so as to create one or more future conjunctions for Inspection of targets of interest (involves adding a focusing capability)
- **Single conjunction, long range**
  - Very low delta V, no change in DebrisSat altitude
  - Allows a single conjunction at a range approx. equal to the altitude difference
- **Single conjunction, short range**
  - Same as above, but with elliptical orbit to bring DebrisSat close to the target for a single inspection with good lighting
  - Moderate delta V
- **Repeated conjunctions, short range**
  - This puts DebrisSat into a harmonic period with the target, i.e., DebrisSat does 14 orbits in the same time that the target does 15 orbits
  - Allows new conjunction opportunity on an approximately daily basis
  - Moderate delta V
- **Repeated conjunctions, period matching**
  - Could create conjunctions once or twice per orbit for extended imaging
  - High delta V requirement
  - In general will not be able to match the target inclination, so DebrisSat and the target will not be in the same orbit

Because of the large delta V, DebrisSat provides exceptional versatility in terms of inspection opportunities.

Operations

- **LEO 3-D DDS Constellation**
  - Form a continuous fence for seeing debris and spacecraft crossing the equator
  - Identification and tracking can occur on-board or on the ground
- **Can capture most objects on every orbit, sometimes twice an orbit - high observation rate/high observation accuracy means that very little ever gets "lost" and allows precision tracking of debris and spacecraft**
- **One or more RoverSats for close inspection will be in a short-range conjunction orbit — an elliptical orbit with apogee near or above the target**
  - Timing adjusted to provide good viewing geometry and proper lighting conditions
  - Can either stay there for multiple conjunctions or return to circular orbit
- **Operating modes**
  - **Full Coverage — use wide FOV survey cameras to provide continuous coverage of the complete Fence**
  - **High Accuracy Stereo Tracking — use high resolution telescope from two satellites to provide high accuracy tracking of objects of interest or potential collision candidates**
  - **Small Object Search — adjust telescope scan parameters to see very small objects in specific orbits by tracking the velocity and, therefore, reducing the length of the image trail**
  - **Inspection mode — use RoverSats to image a target and its surroundings**
    - **Can also use RoverSats to fill in for outages that occur due to satellite failures**

DDS provides high level of operational utility at very low operational cost.

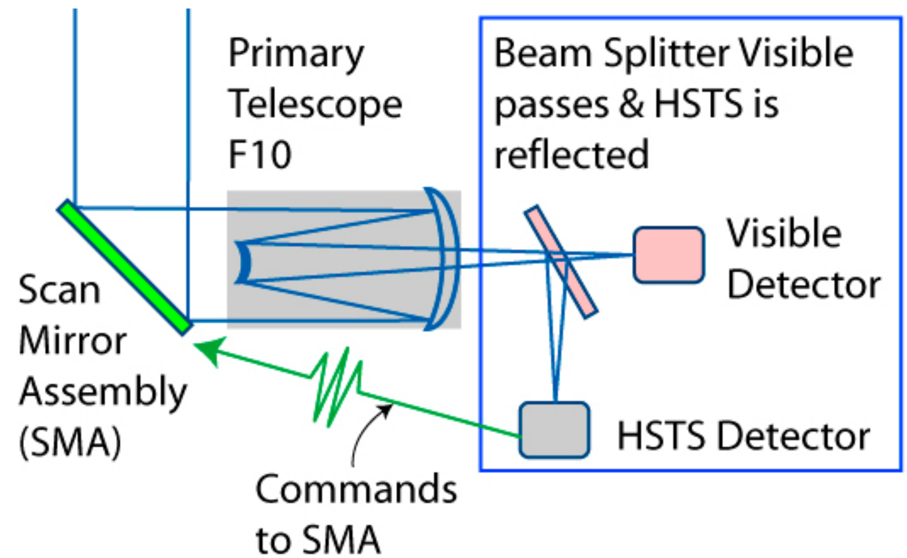
Baseline Conjunction Scenario

- In general DebrisSat and the target (debris or spacecraft to be examined) will not be at the same altitude or inclination
- DebrisSat first does a conjunction maneuver such that its orbit passes within a few km of the target orbit and then adjusts the in-track phase to be there when the target is there
  - Changing apogee or perigee by 300 km requires a delta V of ~90 m/sec
  - Changing the in-orbit phase will depend on the time allotted, but could typically be done for ~50 m/sec
  - DebrisSat total available delta V is >2,500 m/sec -- this enables 1-time fly-bys of many targets
- Principal source of image blur is the inability to accurately track the space object at a very high angular velocity
  - Two spacecraft in LEO will have a relative velocity of ~10 km/sec (either one in a prograde orbit and one in Sun synchronous orbit or two at 45 deg inclination, but 90 deg out of phase in node)
  - Implies an angular velocity of >~50 deg/sec at a closest approach of 10 km
  - Will still be a tracking problem addressed in a later chart

Want to image a space target that is moving at 10 km/sec with a closest approach of ~10 km.

Tracking Near-By, Rapidly Moving Objects

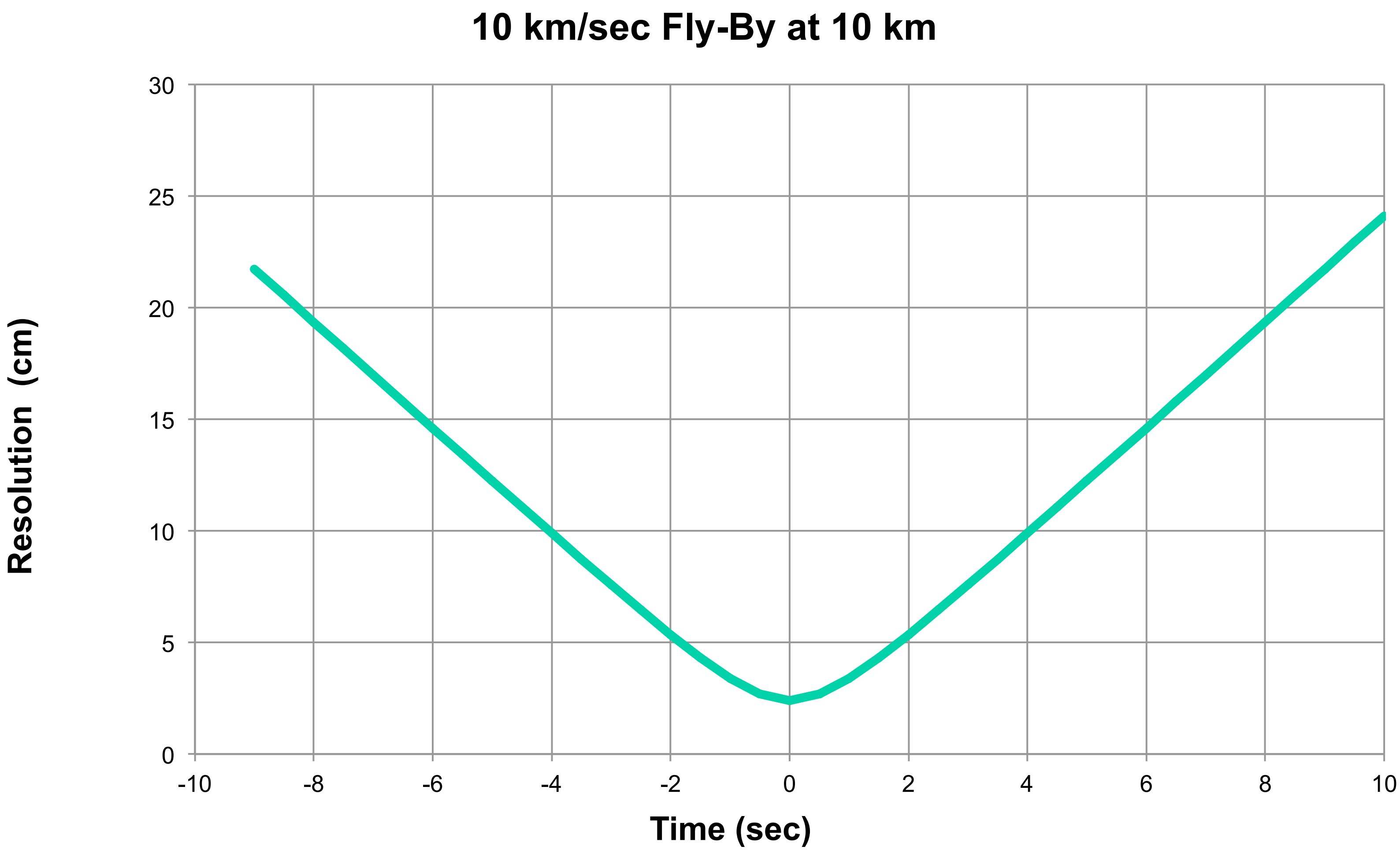
- DebrisSat SMA can rotate at up to 60 deg/sec
  - Could go to 120 deg/sec with 2 motors -- will use this for margin
  - Will add cross-track scan mirror motion to allow for flight path misalignment
- The LEO target ephemeris is uncertain
  - Biggest source of image blur will be inaccuracy in target tracking
  - Like tracking a car coming toward you -- never clear from watching it just how close it will get -- and you want images when it's whizzing by right next to you
- A candidate solution is a beam splitter going to an analog HSTS
  - HSTS drives the SMA motor to maintain precision target tracking



The High-Speed Tracking Sensor (HSTS) drives the Scan Mirror Assembly (SMA)

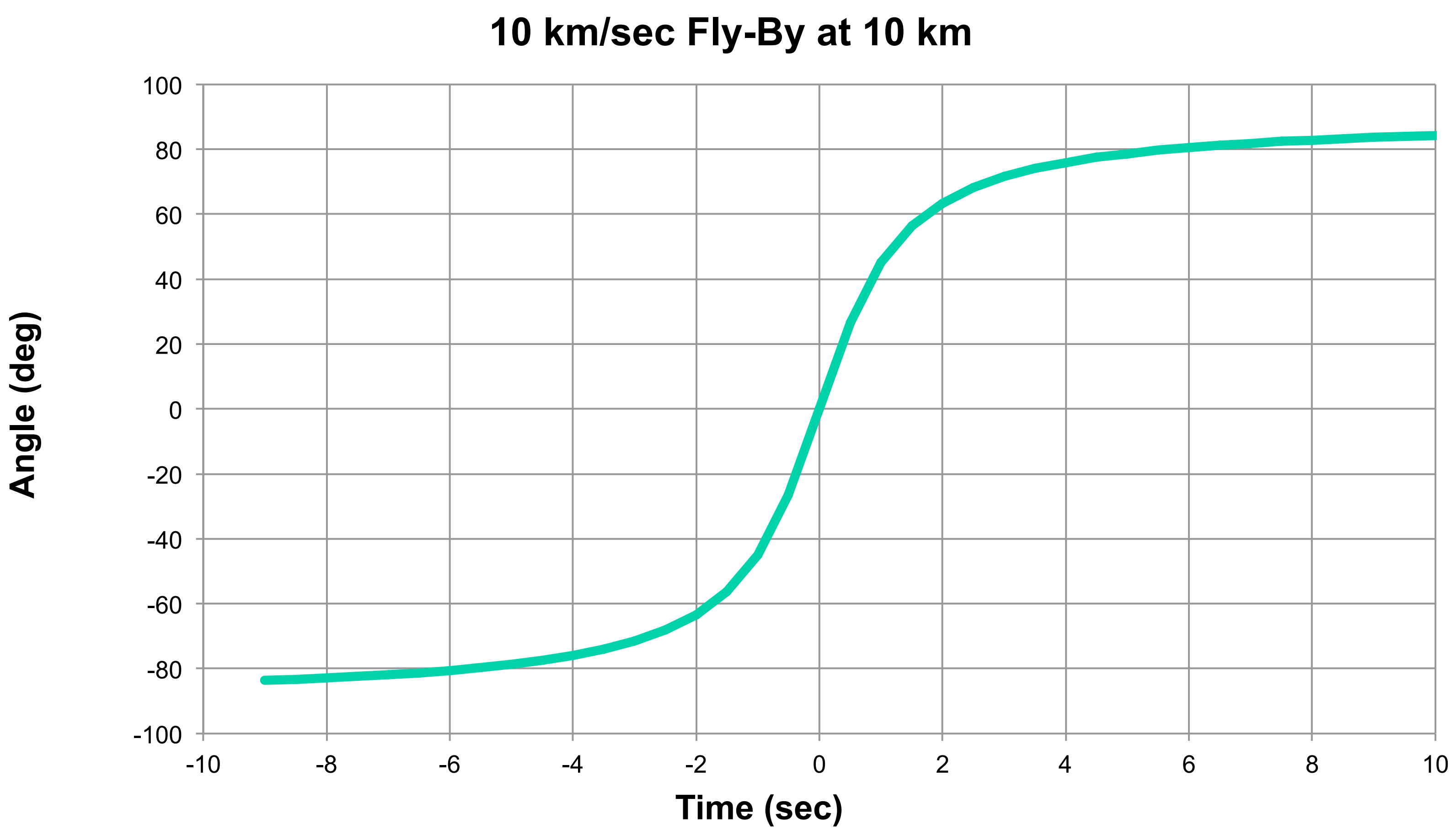
Using HSTS to maintain image stability, we anticipate being able to achieve 3 to 5 cm resolution. We can build, test, and validate both the SMA and HSTS on Earth.

Resolution vs. Time



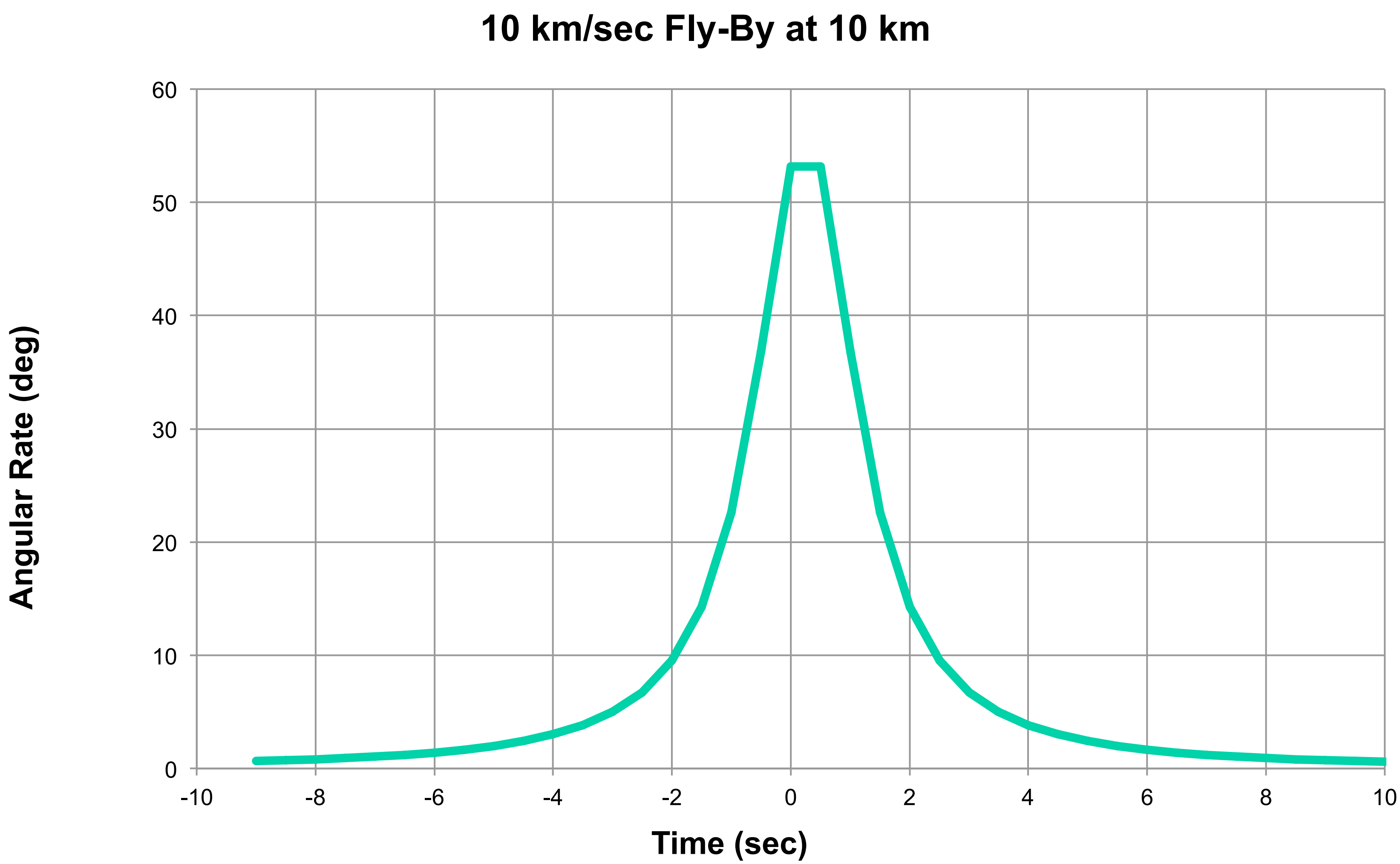
Best images occur within ~2 seconds of closest approach.

Angle vs. Time



Angular position goes through 120 deg in the 4 seconds surrounding closest approach.

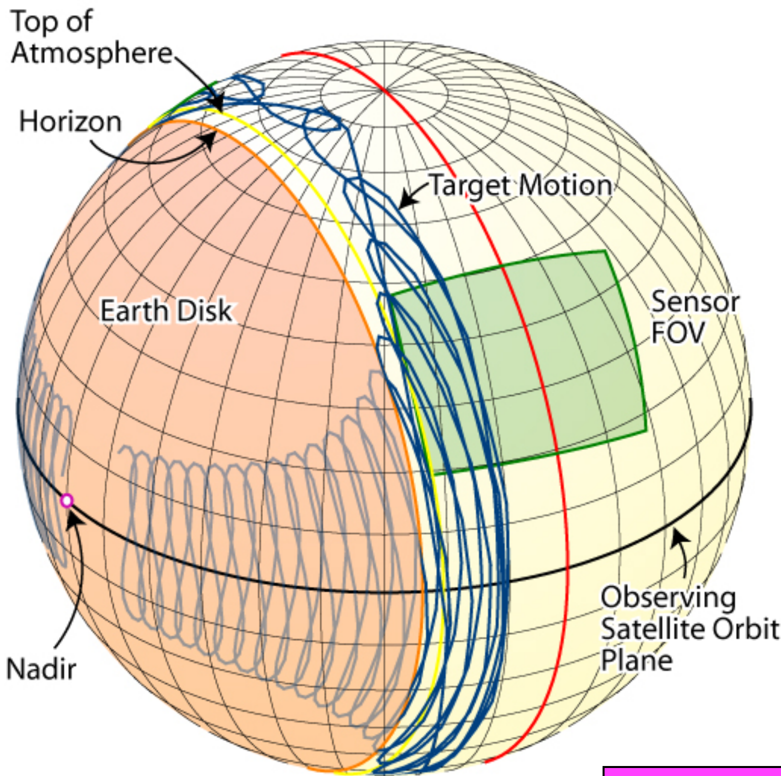
Angular Rate vs. Time



Maximum angular rate is 50 – 60 deg/sec. SMA can go to 120 deg/sec.

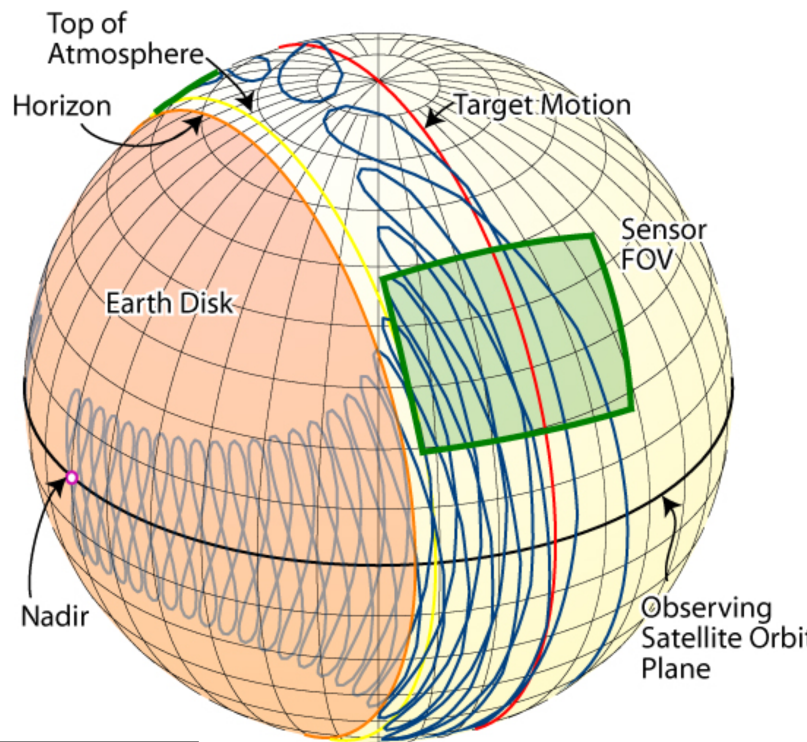
Additional Details

Path of Debris and Other Spacecraft as Seen from the Observing Spacecraft



Observer at 600 km,
Target at 500 km

This is the celestial sphere with the observing spacecraft at the center.



Observer at 600 km,
Target at 700 km

- Nearly all targets (spacecraft or debris) will appear to move back and forth nearly parallel to the horizon with a slow drift either prograde (for lower targets) or retrograde (for higher targets)

Typical LEO Delta V Budget (per spacecraft)

Activity	Delta V/maneuver	Expected Amount or No.	Lifetime Delta V	Notes
Stationkeeping (LEO Fence Maintenance)				
400 km Circular	65 m/s/year	**4 years**	260 m/s	Solar Max
600 km Circular	5 m/s/year	**1 year**	5 m/s	Solar Max
Phase shift	4.6 m/s	**20**	92 m/s	each at 10 deg/day
Conjunction Maneuvers (Inspection mode)				
Phase shift	4.6 m/s	**100**	457 m/s	each at 10 deg/day
400 km Circ -> 400x700	83 m/s	**5**	415 m/s	
400x700 -> 400 km Circ	83 m/s	**5**	415 m/s	
1 deg Plane Change	133 m/s			
Combined maneuver	157 m/s	**2**	314 m/s	Change plane & altitude
End-of-Life Deorbit				
From 400x700	101 m/s			
From 400 Circ	102 m/s	**1**	102 m/s	
Attitude Maneuvers (delta V equivalent to mass used)				
Scanning Step	0.0044 m/s	**20,000**	89 m/s	0.33 deg in 0.4 sec
Slow Large Maneuver	0.0133 m/s	**1,500**	20 m/s	45 deg in 16 sec
Fast Large Maneuver	0.0750 m/s	**1000**	75 m/s	90 deg in 6.5 sec
Total Delta V			**2,244 m/s**	**> 250 m/s remaining**

There is over 2,500 m/s of available Delta V.
There are many options on how to make use of it.