Analyzing Feasibility of Optical Communication Observables for Navigation

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Overview

- Introduction
- Measurement models
- Mars Network Analysis Case
- Near-Earth mission Analysis Case
- Conclusions

Terminology

- Radiometric tracking data
  - Doppler, two-way range, ΔDOR
- Optical navigation
  - On-board image-based radiometric navigation
- Optical tracking data for spacecraft
  - Optical range
  - Ground based astrometric measurements of angular position
- Ground observations of target
  - Optical astrometric measurements of angular position of target body

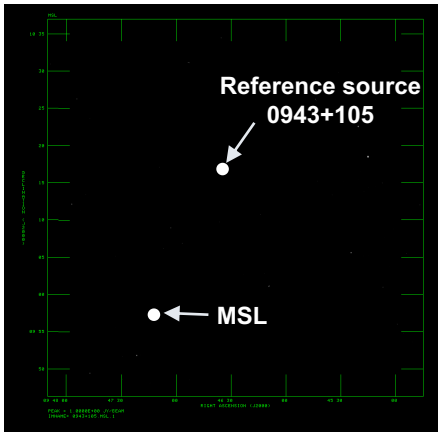


Image: C. Jacobs

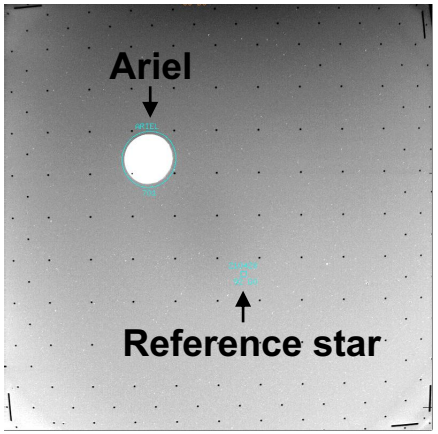


Image: B. Owen

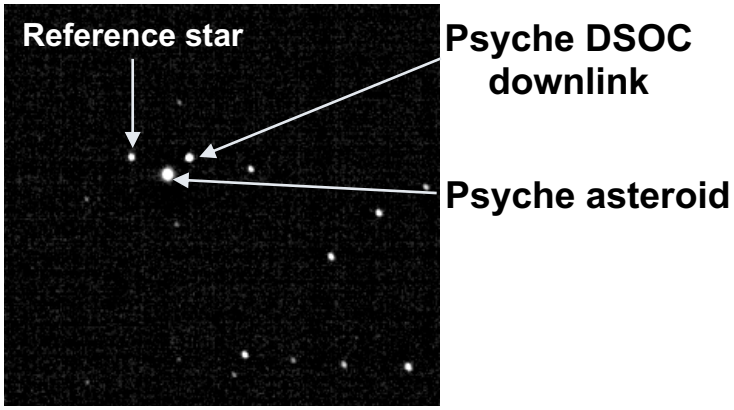
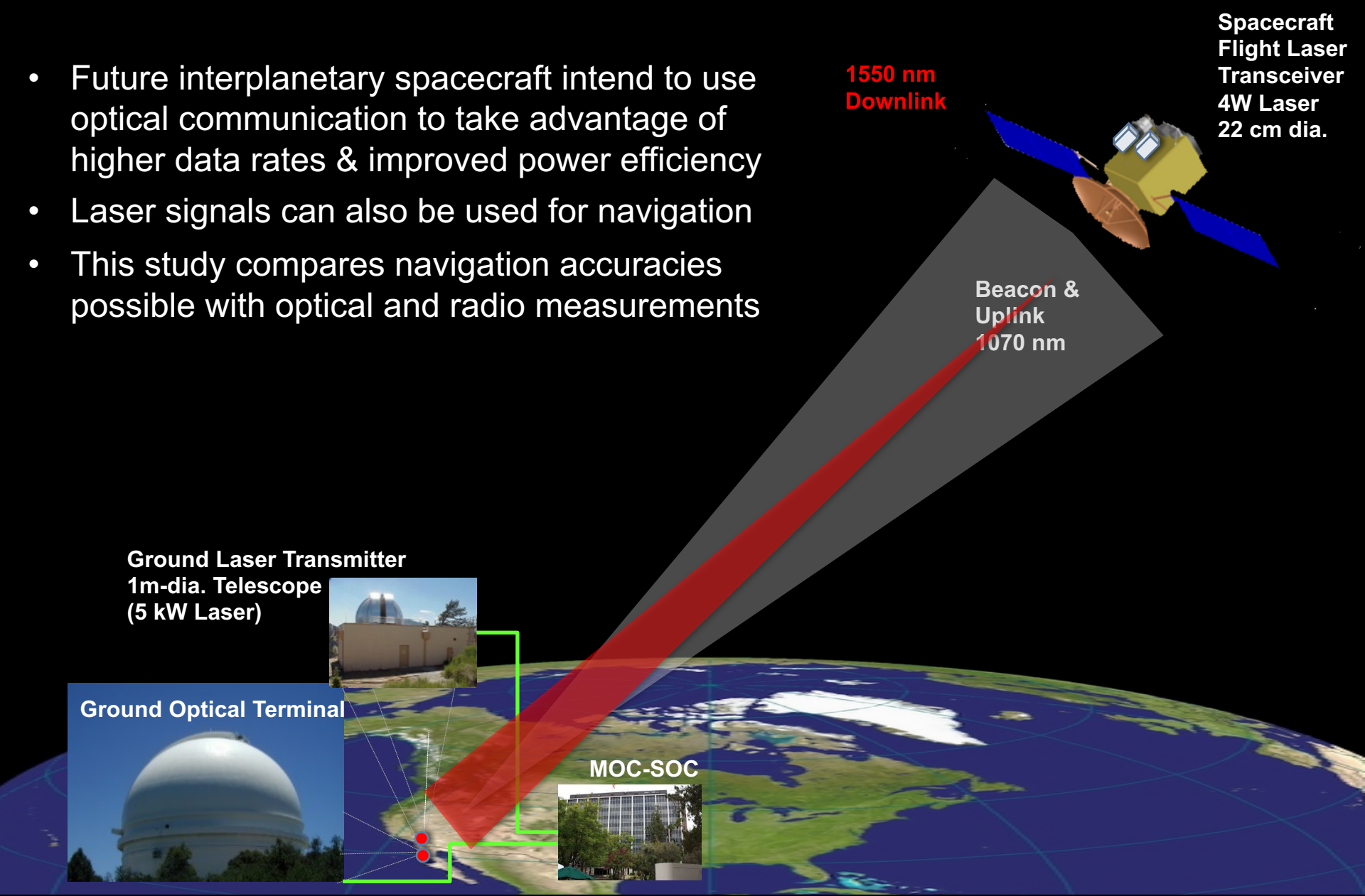


Image: C. Zhai

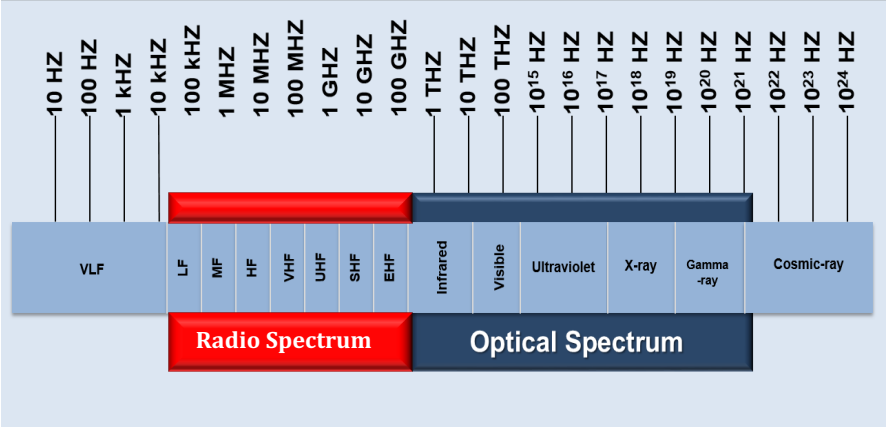
Deep-Space Optical Communication

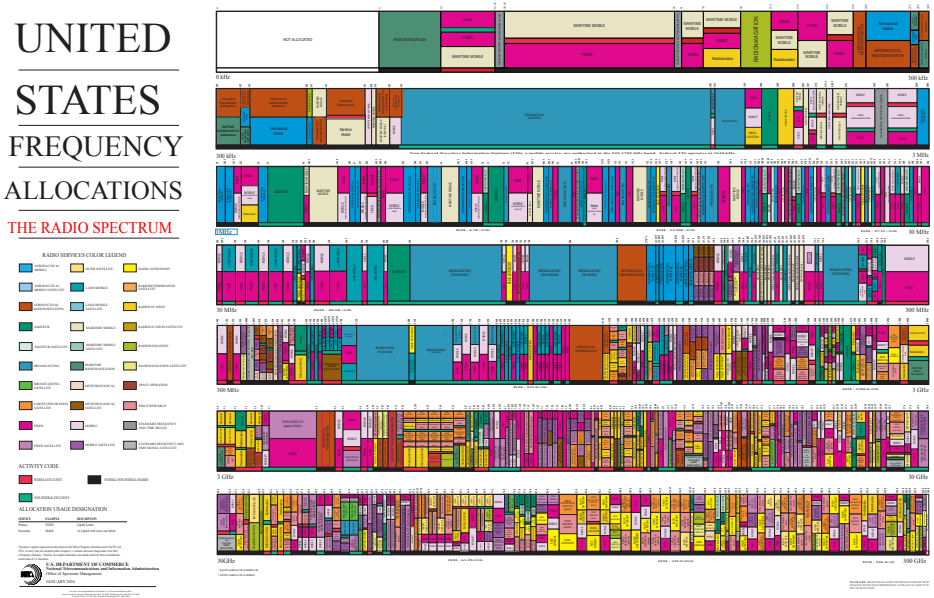
- Future interplanetary spacecraft intend to use optical communication to take advantage of higher data rates & improved power efficiency
- Laser signals can also be used for navigation
- This study compares navigation accuracies possible with optical and radio measurements



Case for Optical Communications

- Higher bandwidth
- No allocation limitations
- Smaller on-board infrastructure





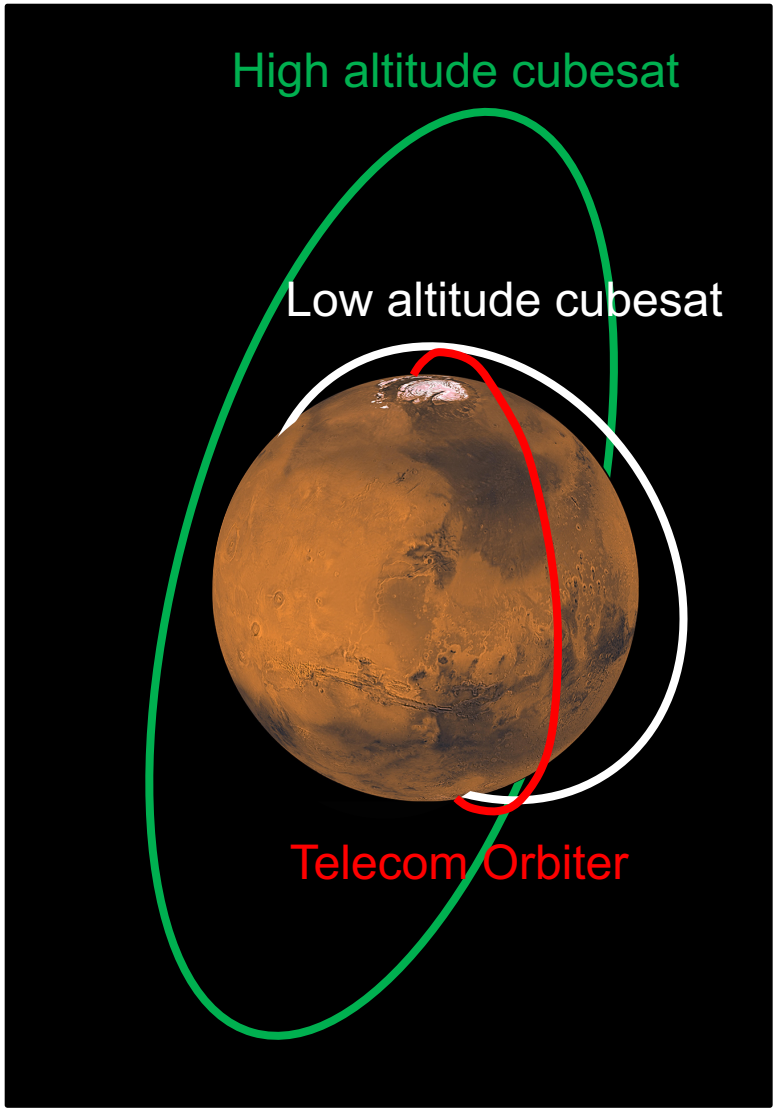
Radio spectrum allocations as of January 2016. Image courtesy of National Telecommunications & Information Administration, U.S. Department of Commerce

Optical Measurement Models

- Optical Range
  - Active system at each end of link
  - Record round-trip light-time
  - Exclude ionospheric group delay
- Optical Astrometry
  - Image active signal on spacecraft against background optical sources
  - One-way right ascension and declination measurements simulated

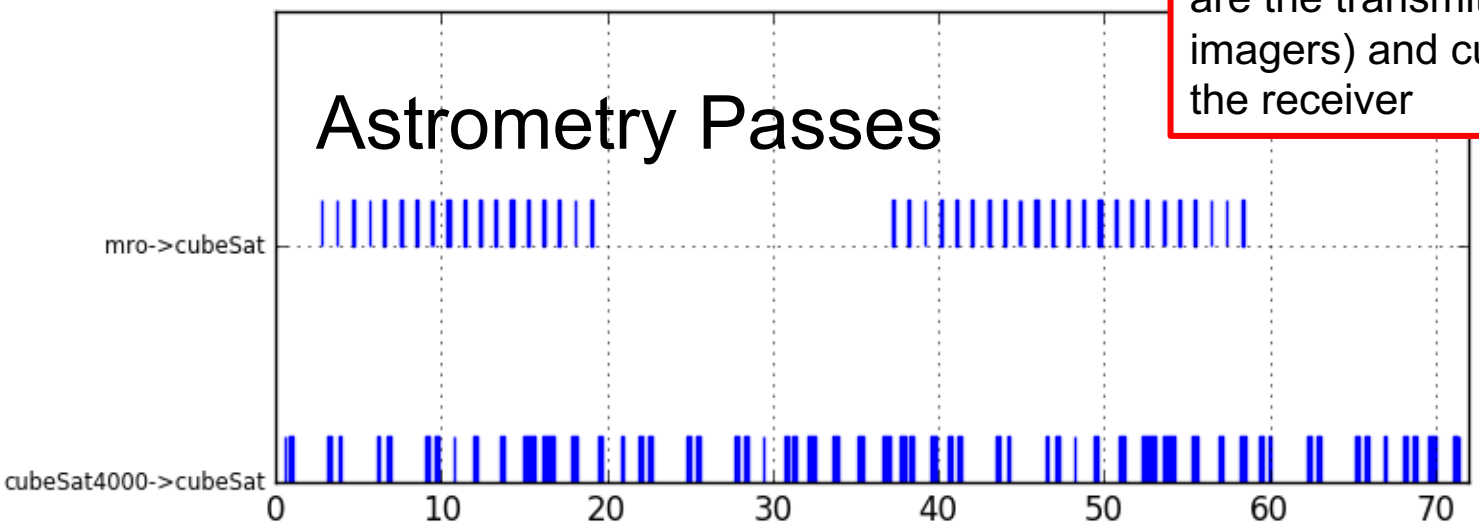
Mars Network of Spacecraft

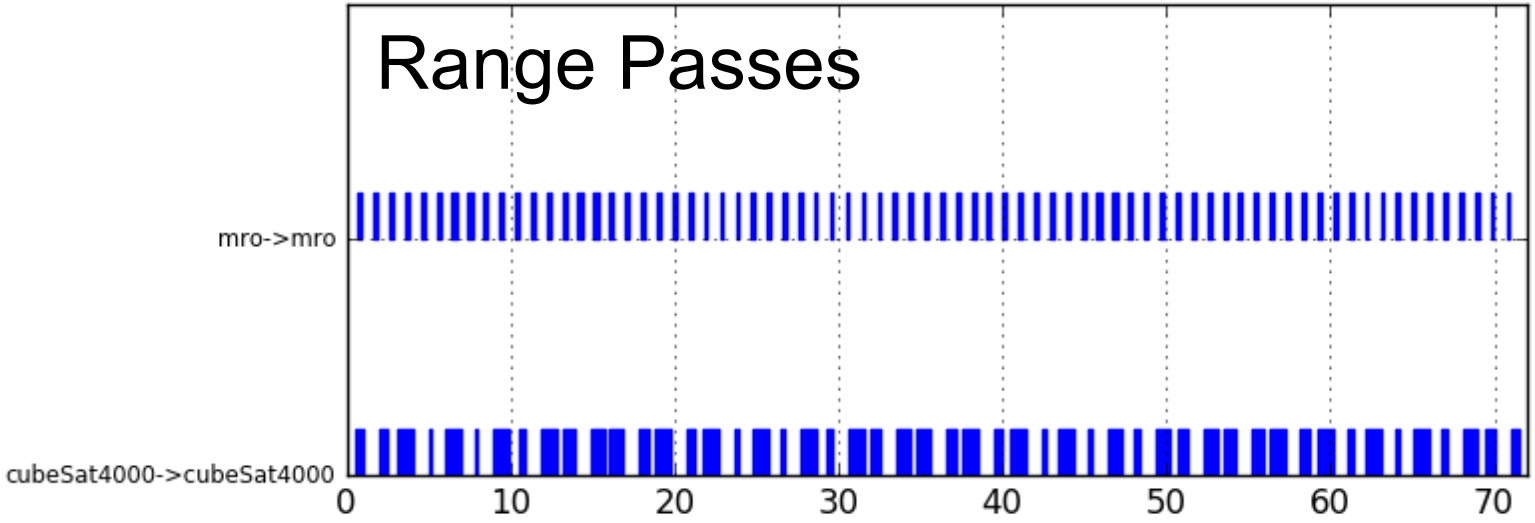
- Simulating spacecraft-to-spacecraft links
  - Astrometry (One-way)
  - Optical Range (Two-way)
- Spacecraft models
  - 2 cubesats in orthogonal orbit planes
  - Telecommunications orbiter
- Three day simulation
  - 2/28/15 5:50 ET – 3/3/15 5:50 ET
- Measurement Constraints
  - Mars exclusion angle
  - Sun exclusion angle



Tracking Data Passes

Note: MRO/cubeSat4000 are the transmitters (e.g. imagers) and cubeSat is the receiver





Measurement Assumptions

- DE 424 ephemeris
- Stochastic: solar radiation pressure, atmospheric density
  - SRP for both cubesats: 0.3 (3-sigma MRO value)
  - Density for low-altitude cubesat: 0.6 (3-sigma MRO value)
- All available contacts between spacecraft are used for navigation
- Uncertainty in MRO orbit (7.5 m, 2.4 mm/sec)
- Uncertainty in cubeSat4000 orbit (100 km, 10 m/sec)
- Desats are modeled for each cubesat as 1x/day impulse burns (0.3 mm/sec in each axis)

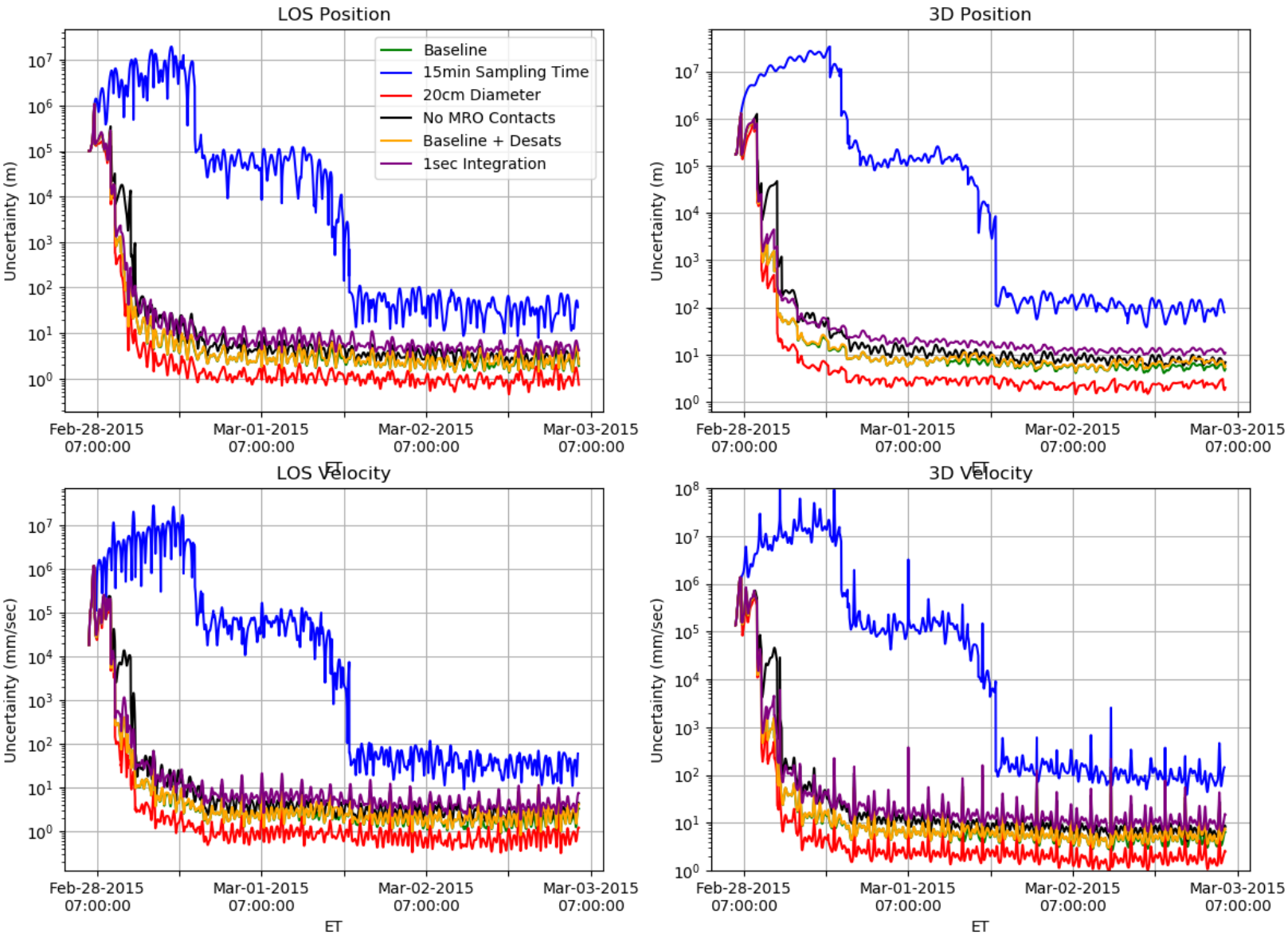
Nominal Values

Parameter	Value
Optical Range Sigma	5 cm
Telescope Diameter	5 cm
Integration Time	10 sec
Observation Time	60 sec
a_{night}	0.75e-6 arcsec^2
b_{night}	0.25e-6 arcsec^2

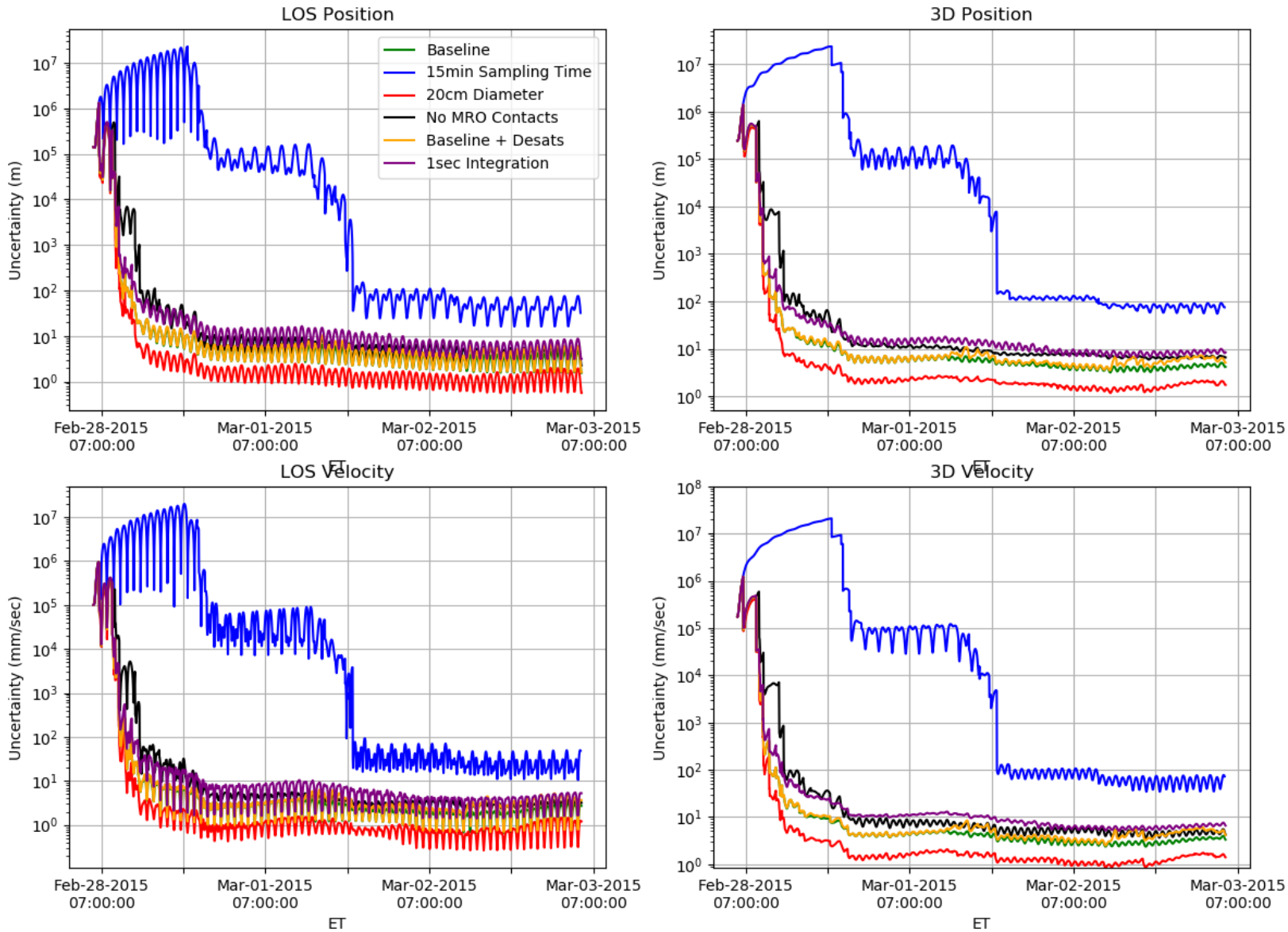
$$\epsilon^2 = a + b$$

$$a \sim 0.75 \left(\frac{1\ \mathrm{m}}{D}\right)^2 \left(\frac{1\ \mathrm{hour}}{T}\right) \mathrm{mas}^2, b \sim 0.25 \left(\frac{1\ \mathrm{m}}{D}\right)^2 \left(\frac{1\ \mathrm{hour}}{T}\right) \mathrm{mas}^2$$

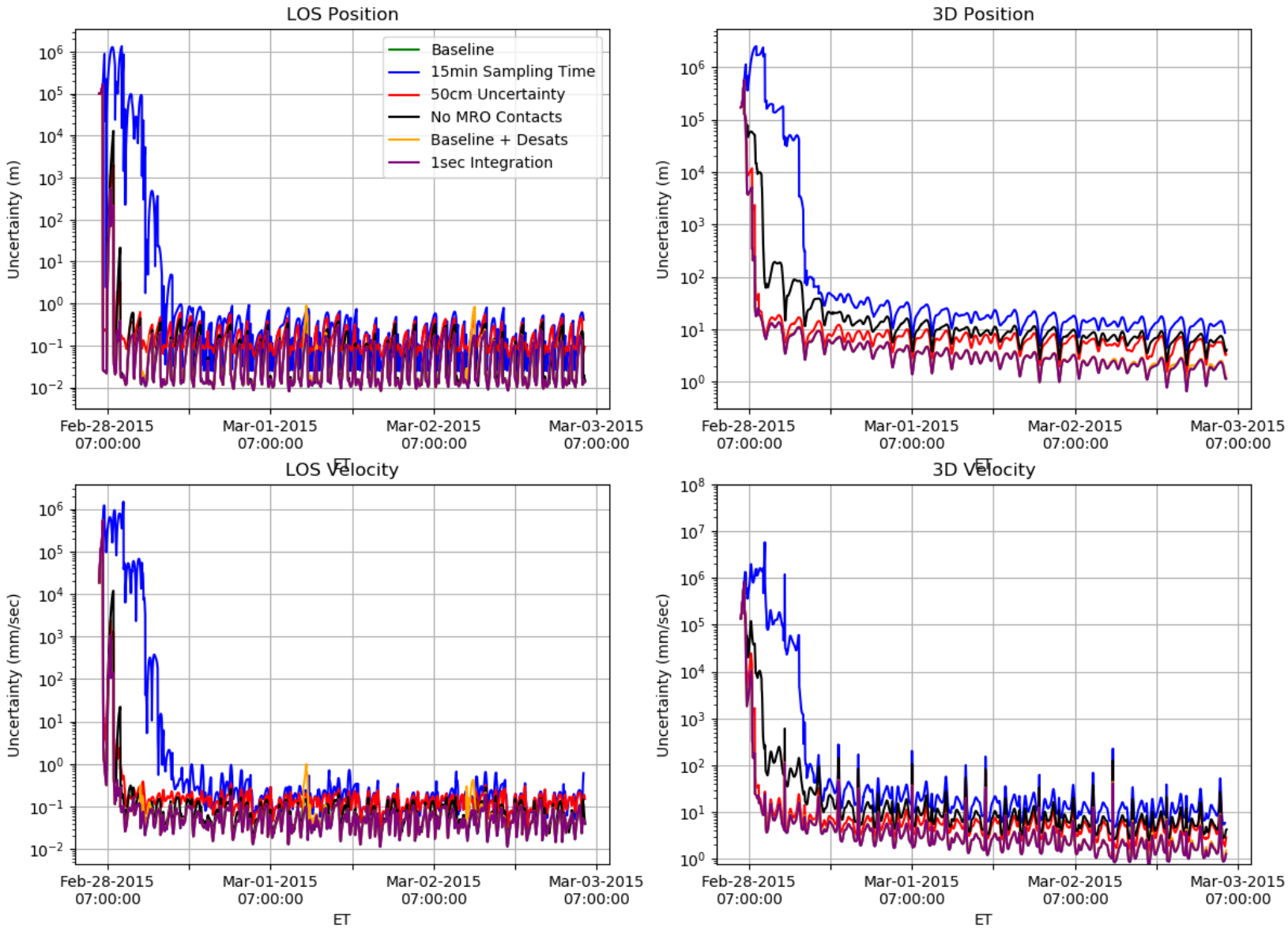
Orthogonal cubesat planes, Astrometric Measurements, 1-Sigma Relative Uncertainties



Orthogonal cubesat planes, Astrometric Measurements, 1-Sigma Absolute Uncertainties



Orthogonal cubesat planes, Range Measurements, 1-Sigma Relative Uncertainties



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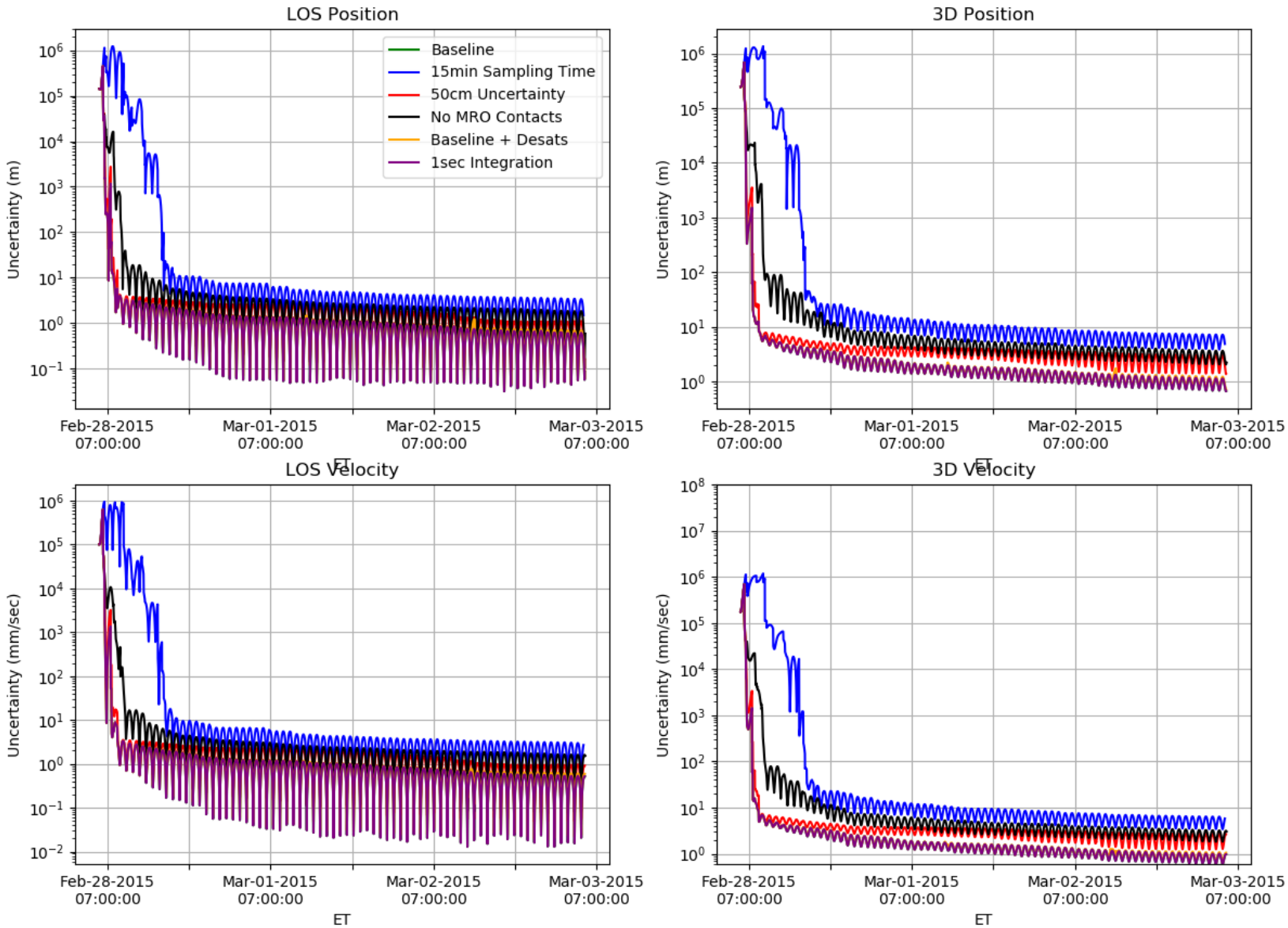


Network Summary Tables

Table 2. Baseline Cubesat State Uncertainties

	LOS Velocity	3D Velocity	LOS Position	3D Position
Relative Radio Range + Doppler	0.050 mm/s	0.26 mm/s	92 mm	28 cm
Relative Astrometry	2.4 mm/s	6.7 mm/s	2.8 m	7.0 m
Absolute Astrometry	2.3 mm/s	3.9 mm/s	3.9 m	5.4 m
Relative Range	0.052 mm/s	2.9 mm/s	5.3 cm	2.9 m
Absolute Range	0.59 mm/s	1.3 mm/s	67 cm	1.5 m

Network Summary Tables

Table 3. Varying Cubesat Line-of-Sight Velocity Uncertainties

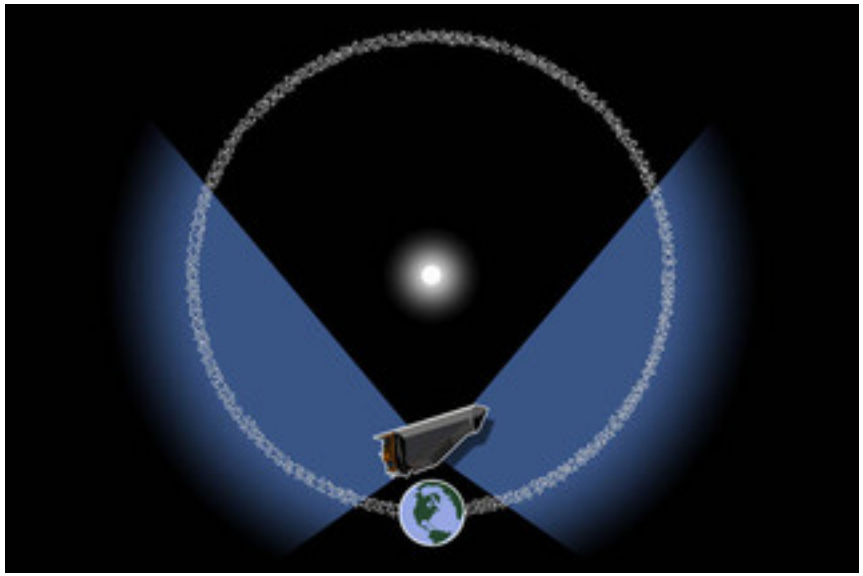
	Baseline	15 Minute Sampling Time	20 cm Diameter	50 cm Uncertainty	No Orbiter Contacts	Baseline + Desats	1 sec Integration
Relative Astrometry	2.4 mm/s	449 m/s	0.91 mm/s	–	4.2 mm/s	2.8 mm/s	5.9 mm/s
Absolute Astrometry	2.3 mm/s	520 m/s	0.88 mm/s	–	4.1 mm/s	2.8 mm/s	5.3 mm/s
Relative Range	0.052 mm/s	0.20 mm/s	–	0.50 mm/s	0.070 mm/s	0.062 mm/s	0.052 mm/s
Absolute Range	0.59 mm/s	2.9 mm/s	–	1.1 mm/s	1.6 mm/s	0.62 mm/s	0.59 mm/s

Mars Network Summary

- Astrometric measurements allow for absolute position determination even when no other measurement types are used
- Ranging measurements allow for position determination when the position of one s/c is well known
- MRO helps tie down non line-of-sight errors for optical range data type

Near-Earth Mission

- Simulating Near-Earth Object Camera (NEOCam) Mission
  - Earth– Sun L1 mission
- Measurements
  - Space-based Astrometry (One-way)
  - Ground-based Optical Range (Two-way)
- Eight month simulation
  - 6/1/21 – 1/31/22



Tracking Data Passes

- Optical Range
  - 5 passes/week for one hour each
  - 5 min sampling time
  - 10° elevation constraint
- Astrometry
  - Using asteroids for space-based optical astrometry
  - Each asteroid is only used once per 12 days
  - Observations are made every 9 hours
  - Using closest asteroids within FOV (defined to be 45° x 110°)
  - Simulating Ra/Dec measurements
  - Using weight of 0.5 arcsec

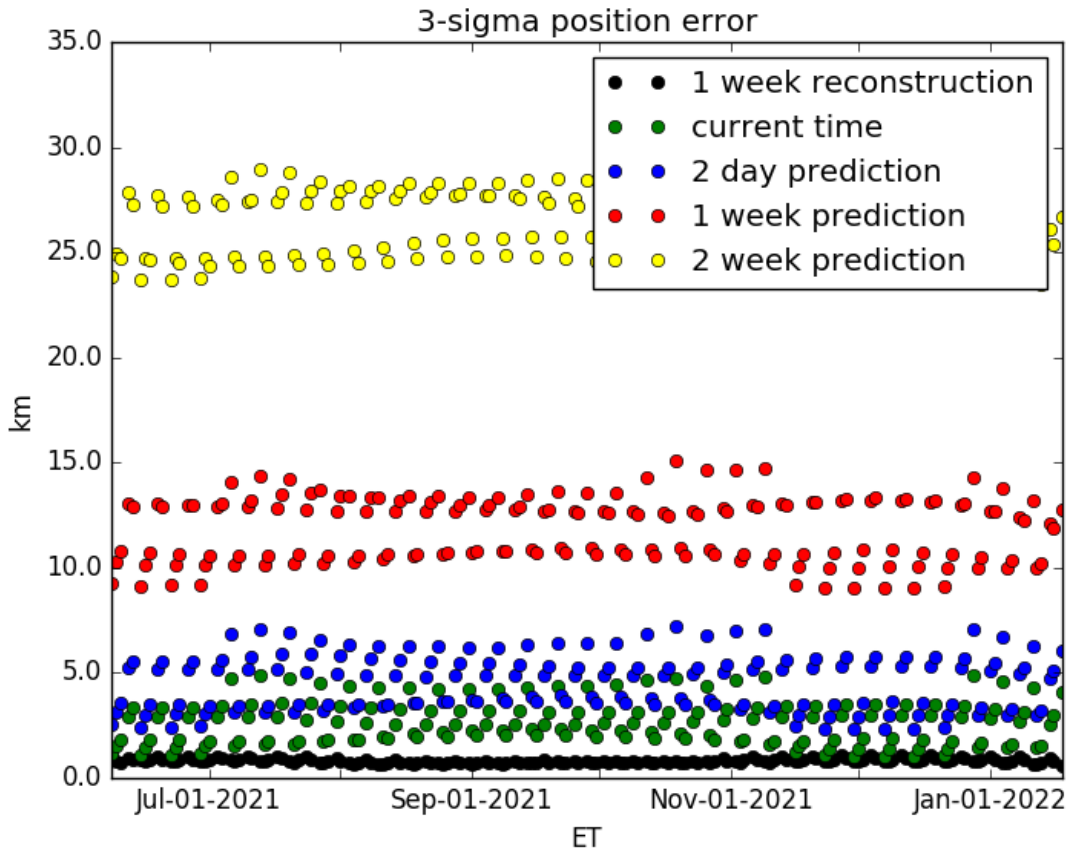
Nominal Values: Optical

Parameter	Value
Optical Range Sigma	5 cm
Optical Range Sampling	5 min
Astrometry Sigma	0.5 arcsec
Asteroid Position Covariance	10 km

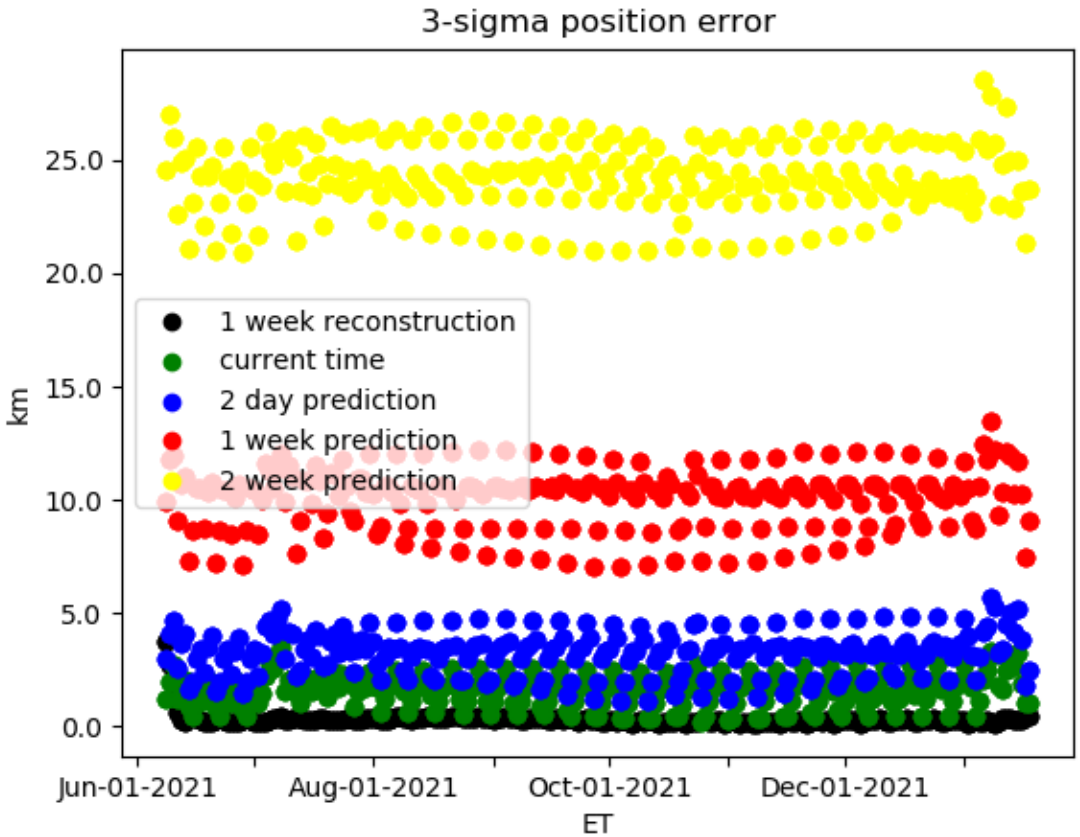
Analysis Cases

- Baseline Optical Range: 5 passes/week, 5 cm sigma, 5 min integration time
- Vary asteroid position covariance
  - 1000km, 100km, 50km, 10km, 1km, 100m
  - 10 – 50km uncertainty is the most realistic. 1km maybe for asteroid very well known (e.g. Ceres), and sub-km not realistic (simulated for sake of comparison)
- Case with range only

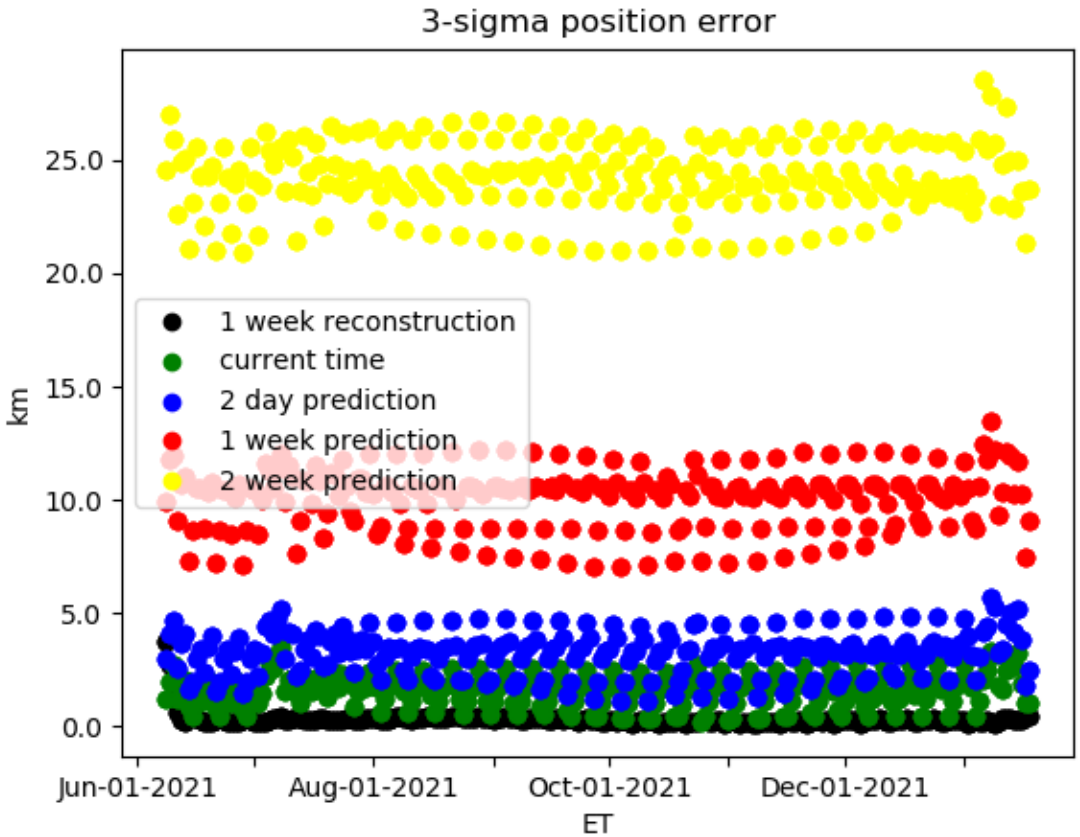
Radiometric Comparison: Radio Range, Doppler



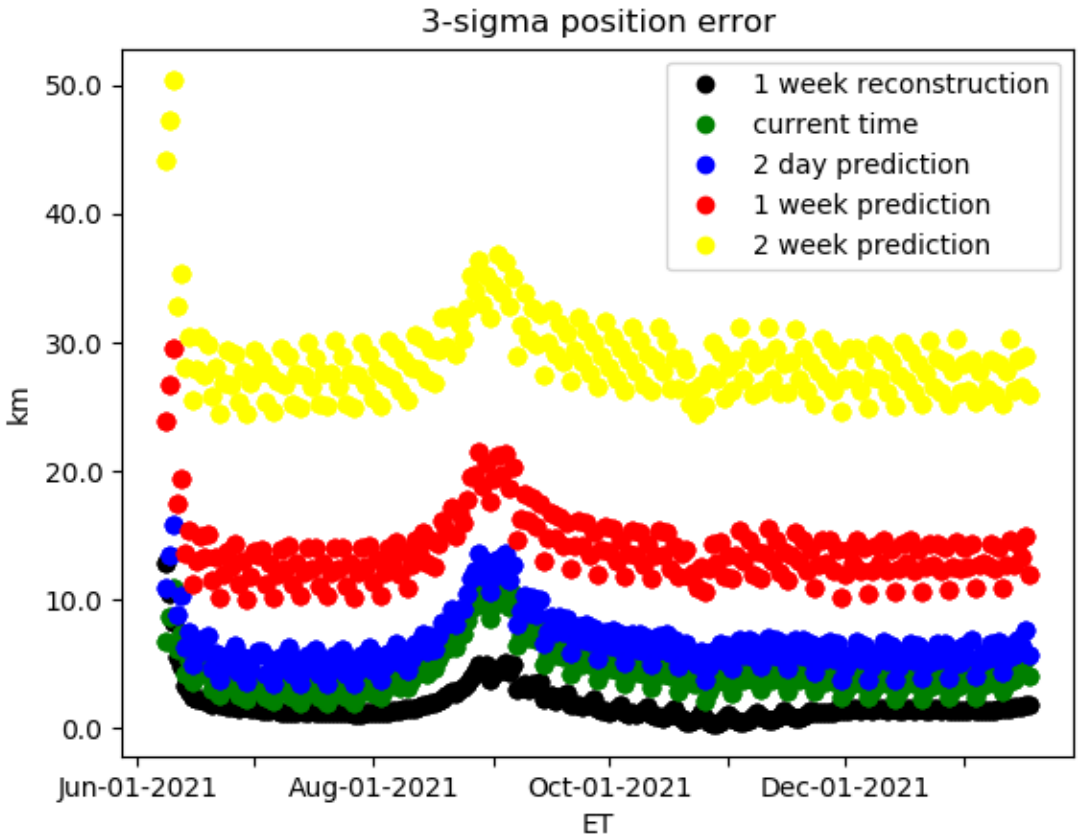
Optical Baseline: Range Only



Optical Baseline (50 km Uncertainty)



Optical Baseline: Range Only, 3 passes/week



NEOCam Summary Tables

Table 4. NEOCam State Uncertainty Means

	Radio Range + Doppler	Optical Range +Astrometry (50 km Asteroid Covariance)	Optical Range Only	Optical Range Only, 3 Passes/Wk
1 Week Reconstruction	0.82 km	0.31 km	0.31 km	1.8 km
Current Time	2.6 km	1.6 km	1.6 km	4.5 km
2 Day Prediction	4.6 km	3.3 km	3.3 km	6.5 km
1 Week Prediction	11.8 km	10.1 km	10.1 km	14.0 km
2 Week Prediction	26.3 km	24.3 km	24.3 km	28.8 km

NEOCam Summary

- Density of range measurements makes a huge difference
  - Some simulations run with less range data and even with good astrometric measurements, mission requirements are not met
- Larger uncertainty in angular measurements negates impact of asteroid covariance
  - Uncertainty increased to 0.5 arcsec, and results for variety of asteroid position covariance values are the same
- Astrometry does not add to the certainty of spacecraft position
- If angular sigmas are tightened, asteroids used for observation very important
  - Blanket position covariance used, but values depend heavily on the asteroids themselves
  - Poorly known asteroids are worse than using no asteroids at all

Conclusions

- Optical observables are viable for a variety of mission scenarios
  - Previous research not presented here analyzed Mars lander, Mars orbiter, asteroid rendezvous, and Europa fly-by cases showing viability
- Considerations must be made for ground stations (e.g. account for weather since optical signals are more heavily affected by clouds, fog, and rain)

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