Massachusetts
Institute of
Technology

Department of
Aeronautics & Astronautics

Laser Communication Crosslinks for Satellite Autonomous Navigation

Pratik K. Davé | Kerri Cahoy
pdave@mit.edu | kcahoy@mit.edu

MIT STAR Lab
MIT Space Systems Lab
MIT Lincoln Laboratory

Motivation

Leverage the inter-satellite connectivity potential of constellations for precise orbit determination

Satellite Autonomous Navigation

Satellite autonomous navigation means performing orbit determination on-board the spacecraft without external intervention, which would:

- Reduce reliance on Earth-based resources (ground sensors, beacons, GNSS) for precise orbit determination and dissemination[1]
- Enable on-board autonomy for location-based operations and data processing (i.e. reducing data volume to downlink)[2]
- Minimize operations cost and propellant utilization for satellite station-keeping and constellation maintenance[3]

On-board sensors used to estimate satellite position and velocity using time-series measurements of relative range or bearing to known bodies/objects:

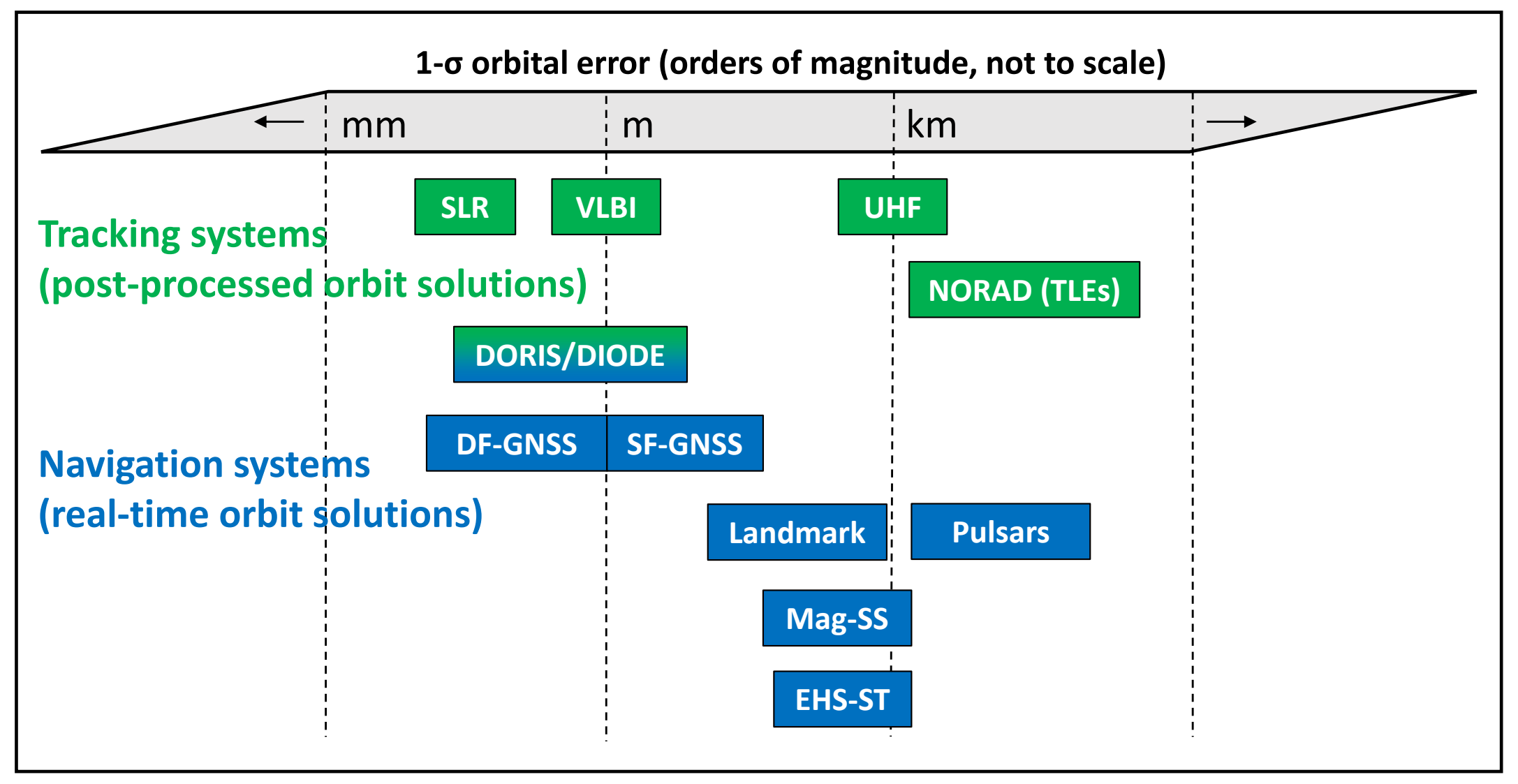
Sensor	Measurement	Reference
Rangefinder (e.g. altimeter)	Range	Objects (e.g. Earth surface)
Visible/IR camera (e.g. star-tracker)	Range, Bearing	Landmarks, Objects (e.g. stars)
Magnetometer	Range, Bearing	Magnetic field
Beacon receiver (e.g. GNSS)	Range	Beacon source (e.g. GNSS satellite)
X-ray detector	Range	Pulsars

Inter-satellite Method

- Utilizes inter-satellite measurements of the relative position vector (range and bearing) between two satellites[4]
- Simultaneously estimates the orbital states of both spacecraft to meter-level accuracy given precise inter-satellite measurements[5]
- Full satellite states observable in most orbit cases using J_2 Earth gravity model, except when satellites have equal a, e, θ at zero inclination[5]

Accuracy

The figure below illustrates the best orbit estimation error achieved using ground-based tracking and autonomous navigation techniques:

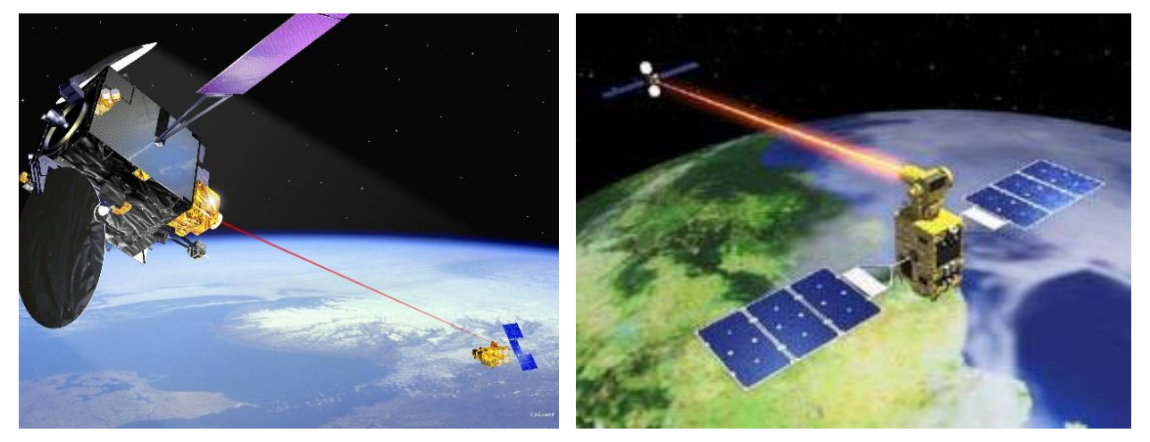


SLR	Satellite Laser Ranging (Zhao, G., et al., 2013)
VLBI	Very-Long Baseline Interferometry (Ulvestad, J.S., 1992)
UHF	Ultra-High Frequency ranging (Foster, C., et al., 2015)
NORAD (TLEs)	North American Aerospace Defense Command Two-line Element Sets (Greene, M.R., et al., 2009)
DORIS	Doppler Orbitography and Radiopositioning Integrated by Satellite (Brunet, M., et al. 1995)
DORIS/ DIODE	DORIS on-board OD software (Jayles, C., et al., 2015)
SF-GNSS	Single-Frequency GNSS (Sun, X., et al., 2017)
DF-GNSS	Dual-Frequency GNSS (Hauschild, A., et al., 2017)
Landmarks	Earth Landmark Sensor (Markley, F.L., 1984)
Pulsars	X-Ray Pulsars (Sheikh, S., et al., 2006)
Mag-SS	Magnetometer & Sun-Sensors (Psiaki, M., 1999)
EHS-ST	Earth Horizon Sensors & Star-Trackers (Hicks, K., Wiesel, W., 1992)

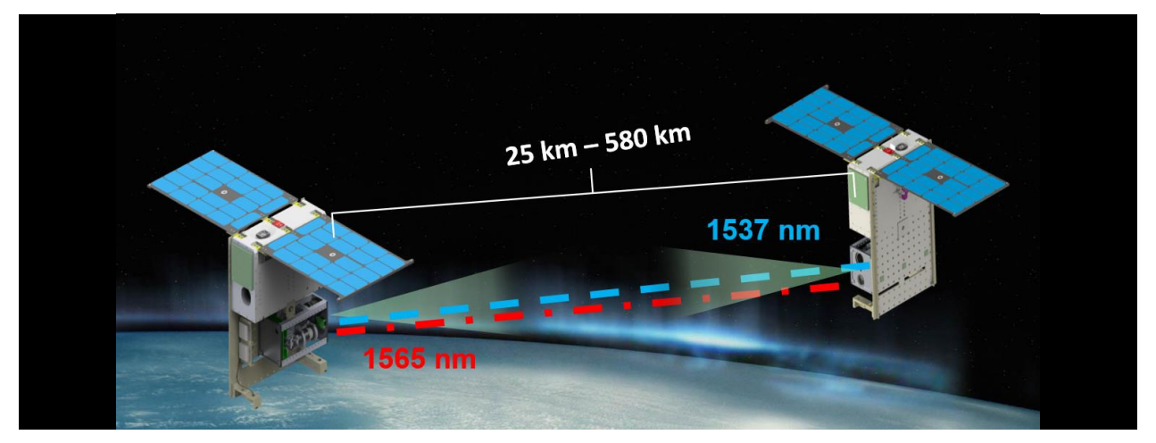
Laser Communication Crosslinks

Laser communication (lasercom) systems offer improved energy efficiency, data rates, and security over traditional radio-frequency (RF) communications systems.[6] Lasercom crosslinks reduce latency in data and command routing in distributed constellations,[7] and can obtain inter-satellite measurements for autonomous navigation.[8]

Notable Demonstration Missions



Past: ESA's ARTEMIS geosynch. satellite demonstrated the first one-way lasercom crosslink with SPOT-4 in 2001 (left), and first two-way link with OICETS in 2005 (right). Both SPOT-4 and OICETS operated from low Earth orbits.[9]

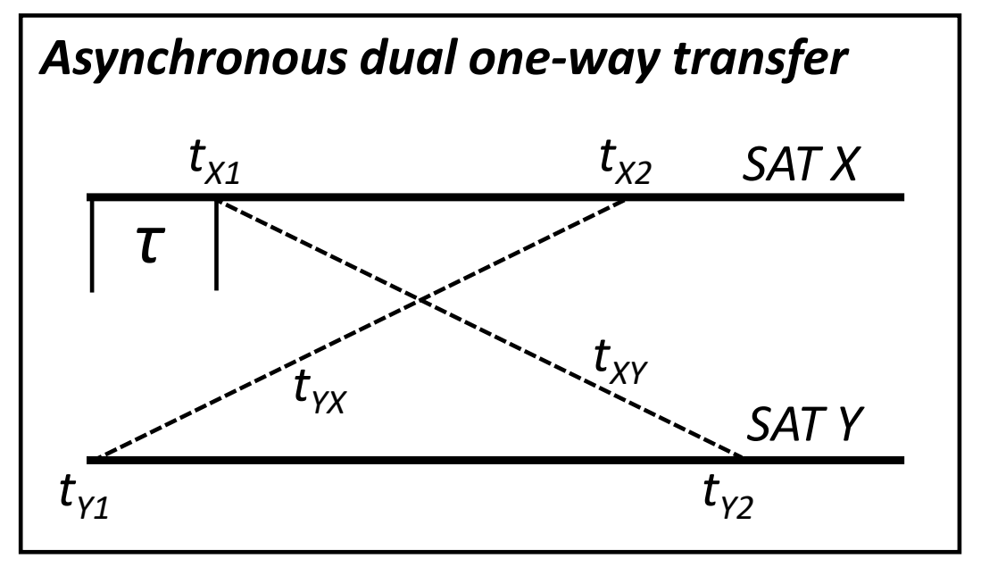


Future: The MIT STAR Lab and Univ. of Florida are co-developing the Cubesat Laser Infrared CrosslinK (CLICK) mission to demonstrate full duplex lasercom crosslinks between two identical 6U CubeSats with 2U transceivers.

Inter-satellite Measurements

Range – derive from time-encoded signal transfers between satellites

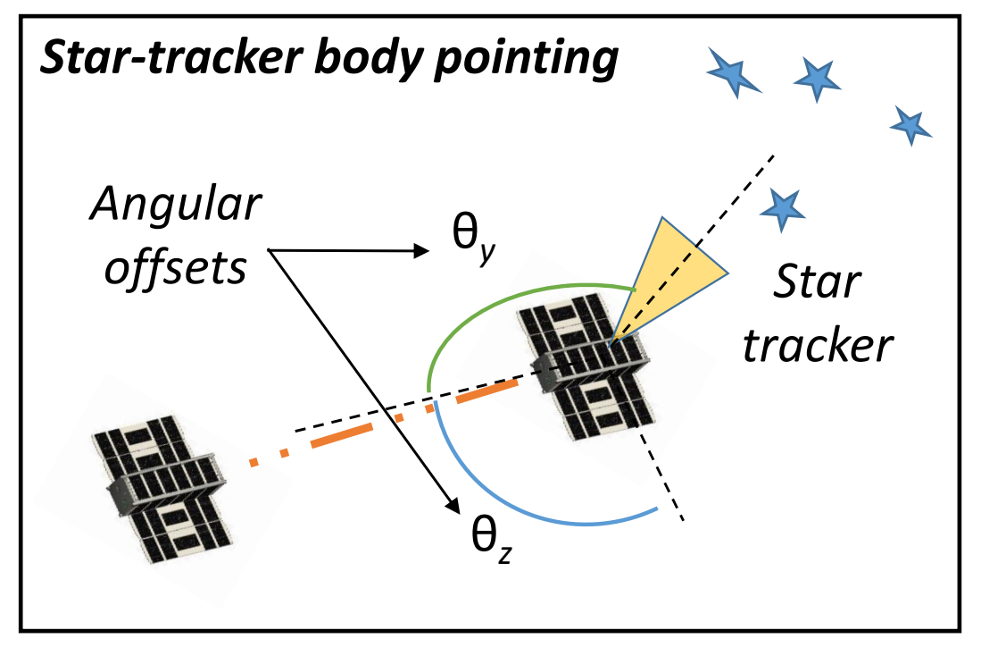
- Optical frequency = greater bandwidth vs. RF systems
- Time transfers on the order of picoseconds[10] → cm-level ranging
- Multiple transfer methods: one-way, dual one-way, or two-way



Above image adapted from [11]

Bearing – derive from on-board star-tracker and pointing offsets

- Higher carrier frequency vs. RF systems = narrower beamwidth
- Leverage accurate body-pointing knowledge from star-tracker, along with known, fixed offsets between star-tracker and transceiver
- Assumes fine-pointing control is achieved, crosslink is established
- Improve with filters/estimators, feedback from fine-pointing system



Approach

In this work, a Cramer-Rao Lower Bound (CRLB) analysis is performed to compare the impact of using crosslink measurements from RF and lasercom systems. CRLB provides the theoretical lower limit of an estimator mean-square error primarily based on measurement uncertainty. The CRLB equations for an Extended Kalman Filter (EKF) estimator are:

$$\boldsymbol{J}_k = \left(\overline{\boldsymbol{F}}_{k-1}\boldsymbol{J}_{k-1}^{-1}\overline{\boldsymbol{F}}_{k-1}^{T}\right)^{-1} + \overline{\boldsymbol{H}}_k^T\boldsymbol{R}_k{}^{-1}\overline{\boldsymbol{H}}_k \qquad \overline{\boldsymbol{F}}_{k-1} = (\partial f/\partial \boldsymbol{x})_{\boldsymbol{x}=\boldsymbol{x}_{k-1}}$$

$$CRLB\left(\boldsymbol{x}_k(j)\right) = \boldsymbol{J}_{k-1}^{-1}(j,j) \quad \text{where} \quad \overline{\boldsymbol{H}}_k = (\partial h/\partial \boldsymbol{x})_{\boldsymbol{x}=\boldsymbol{x}_k}$$

Equations adapted from [12]

Measurements were modeled using the following uncertainties:

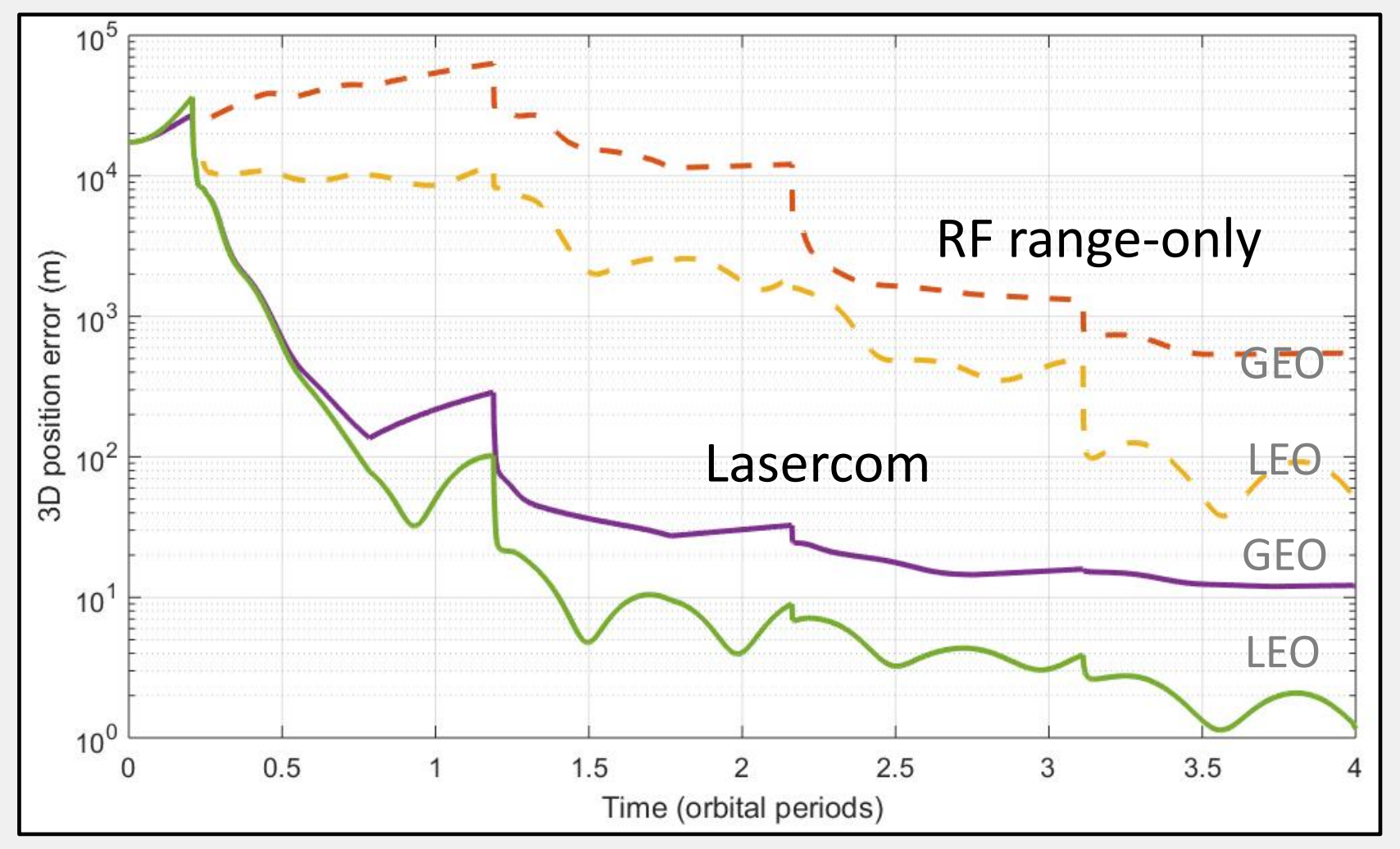
Crosslink Comms	Measurement	RMS Error Model
Radio-frequency (RF)	Range	3 m
	Bearing	N/A
Free-space optical (lasercom)	Range	10 cm
	Bearing	2 arcsec

Bearing not available for RF systems without additional hardware (e.g. camera, beacon).

Three scenarios representing different orbit configurations selected based on existing or proposed satellite mission architectures:

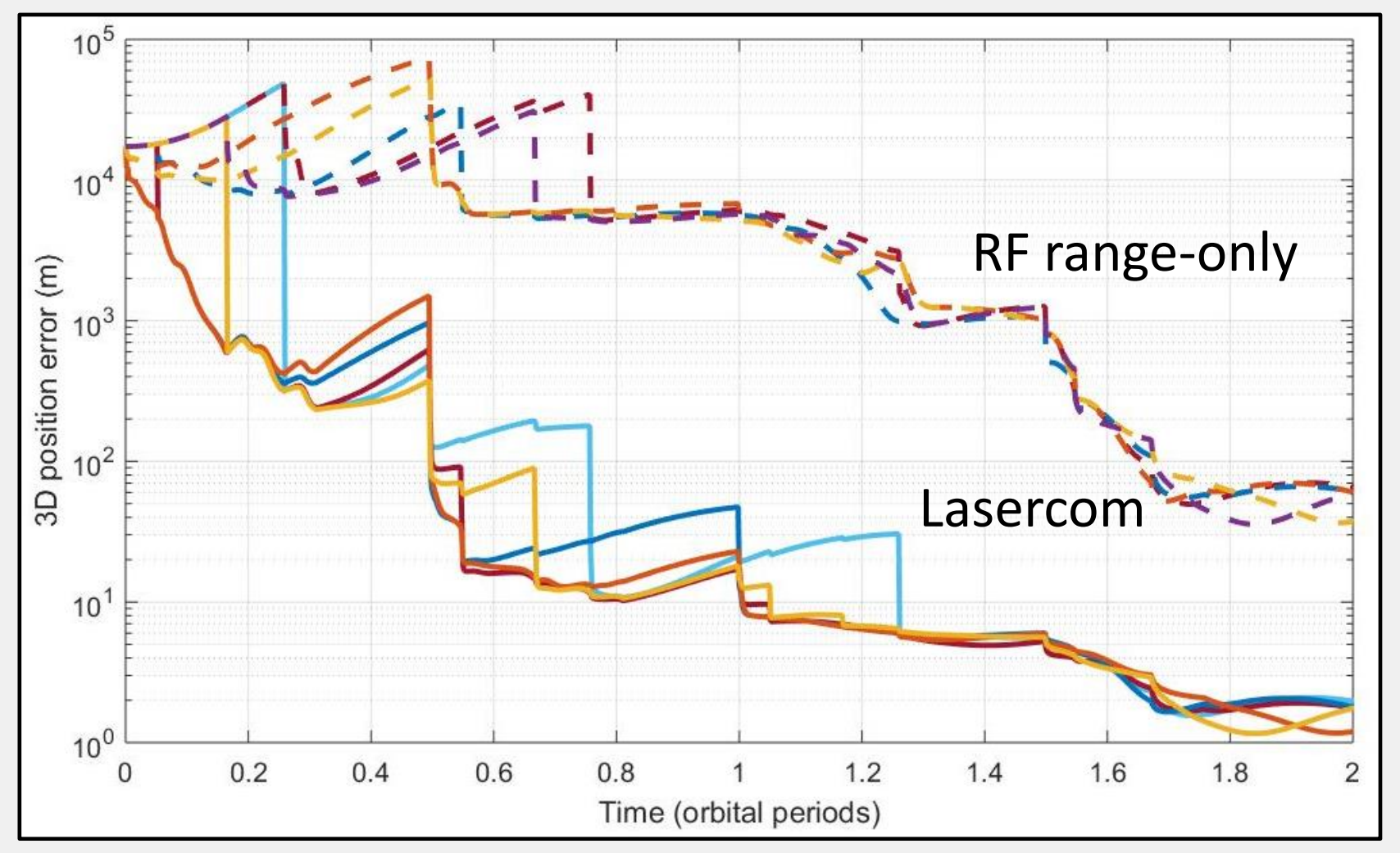
- 2-satellite case – GEO-LEO (existing, based on ARTEMIS-OICETS demo)
- Constellation cases – SAR-Lupe (existing), 9/3/2 Walker (proposed)

Results

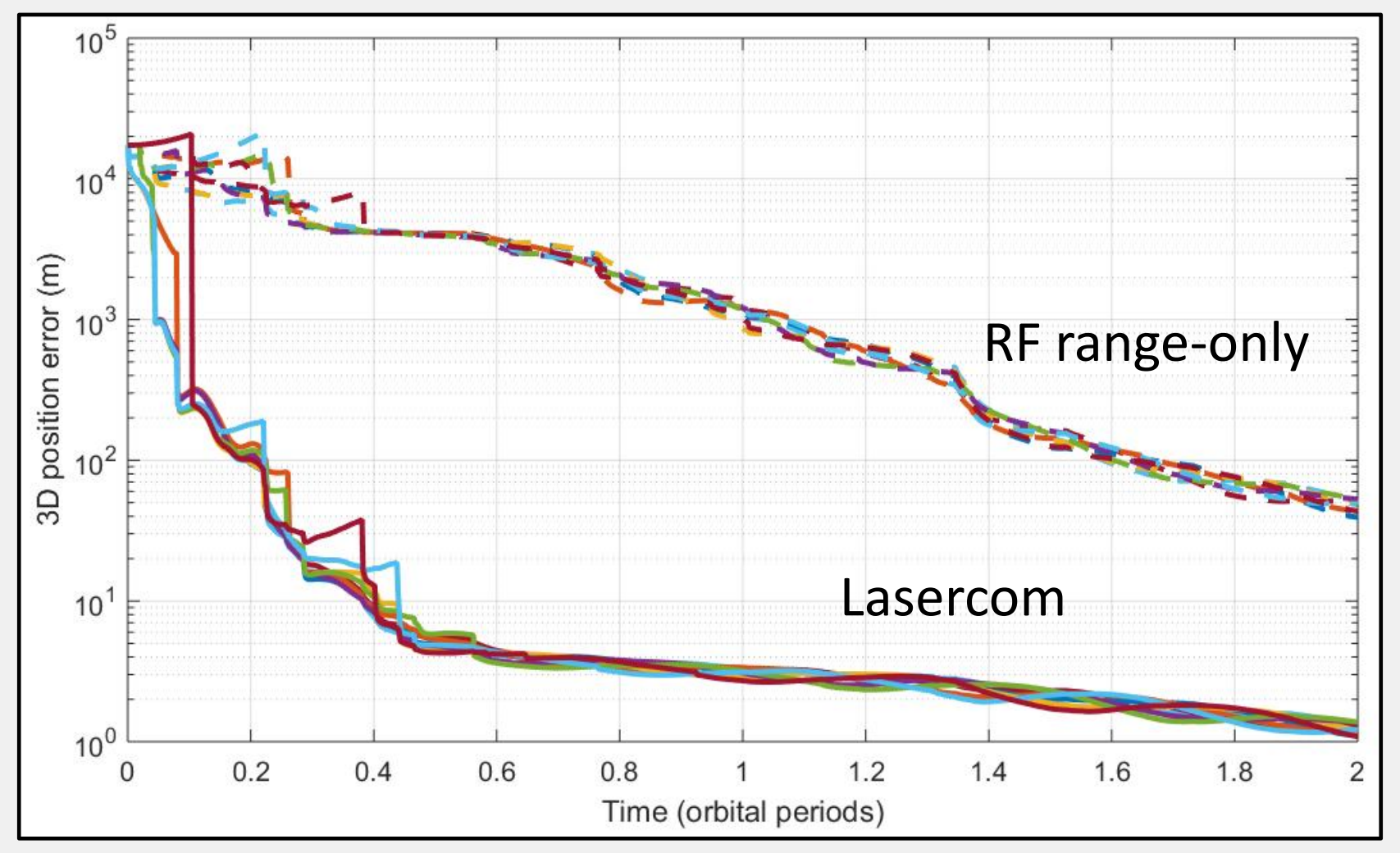


GEO-LEO (e.g. ARTEMIS-OICETS)
GEO: longitude = 10.0° W, i = 10.0°
LEO: a = 7007.14 km, e = 0.00, i = 97.9°

- Orbit position error reduced by more than one order-of-magnitude (30-40x) using lasercom crosslink range and bearing measurements vs. RF range-only
- Faster orbit solutions obtained by more distributed constellations, due to greater number of crosslinks/measurements
- Shows potential to achieve meter-level position errors, consistent with GNSS single-frequency receiver performance



SAR-Lupe 5-sat Constellation
a = 6864.6 km, e = 0.03, i = 98.2°



9/3/2 Walker Constellation
a = 7378.14 km, e = 0.00, i = 57.1°

Future Work

- Incorporate additional input data for potential sub-meter positioning (e.g. GNSS receiver data, downlink measurements, ground updates, fine-pointing system feedback)
- Expand EKF algorithm to estimate satellite clock biases/offsets and spacecraft attitude
- Perform full EKF estimation using simulated measurements

References

1. Chory, M.A., et al., "Autonomous Navigation - - Where we are in 1984", Fluid Dynamics, Plasma Dynamics, and Lasers Conference, 1984.
2. Hauschild, A., et al., "Innovation: Orbit determination of LEO satellites with real-time corrections", GPS World, 2017.
3. Wertz, J.R., et al., "Autonomous Constellation Maintenance", IAF Workshop on Satellite Constellations, 1997.
4. Markley, F.L., "Autonomous Navigation Using Landmark and Intersatellite Data", AIAA/AAS Astrodynamics Conference, 1984.
5. Psiaki, M., "Autonomous Orbit Determination for Two Spacecraft from Relative Position Measurements", Journal of Guidance, Control, and Dynamics, 1999.
6. Kingsbury, R., "Optical Communications for Small Satellites", MIT Thesis, 2015.
7. Kennedy, A.K., Cahoy, K., "Initial Results from ACCESS: An Autonomous CubeSat Constellation Scheduling System for Earth Observation", SmallSat Conf., 2017.
8. Yong, K., et al., "Autonomous Navigation for Satellites Using Lasercom Systems", AIAA Aerospace Sciences Meeting, 1983.
9. Muri, P., McNair, J., "A Survey of Communication Sub-systems for Intersatellite Linked Systems and CubeSat Missions", Journal of Communications, 2012.
10. Serra, P., et al., "Integrated, Software-Defined Pulse Modulator and Laser System for Small Satellite Optical Communication", SmallSat Conf., 2017.
11. Degnan, J., "Asynchronous laser transponders for precise interplanetary ranging and time transfer", Journal of Geodynamics, 2002.
12. Kai, X., et al., "Autonomous Navigation for a Group of Satellites with Star Sensors and Inter-satellite Links", Acta Astronautica, 2013.

SSC18-PII-33

Acknowledgements: This material is based upon work supported by the United States Air Force under Air Force Contract No. FA8721-05-C-0002 and/or FA8702-15-D0001. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author and do not necessarily reflect the views of the United States Air Force.