PNT USING TIME-DIFFERENCE OF ARRIVAL (TODA) TECHNIQUES WITH LOW-EARTH ORBITING (LEO) SATELLITES

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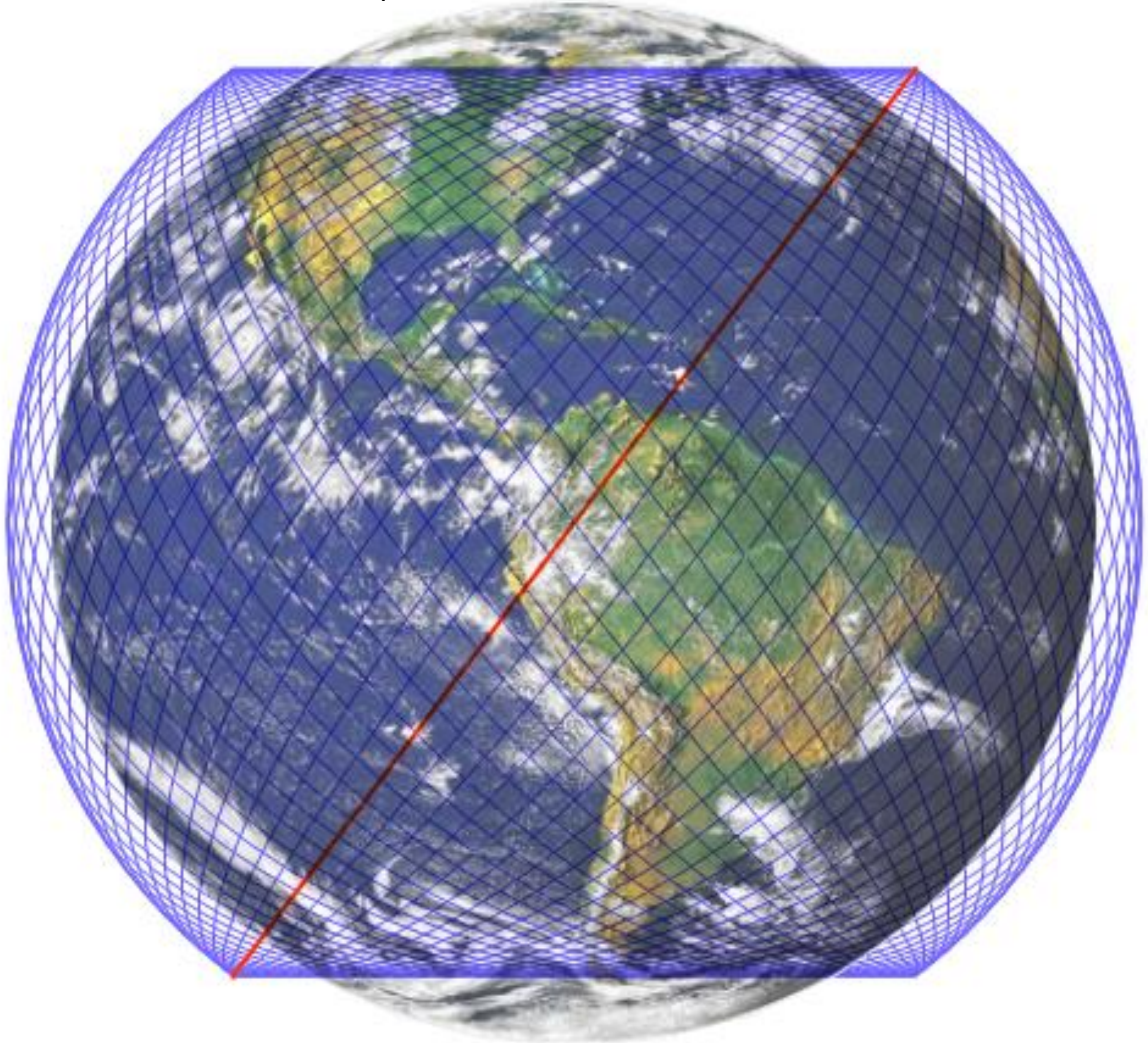
Alternate PNT is Vital to US Security

- Two large categories of signals for navigation
  - Signals of Intent (SOI) – e.g. GPS/GNSS
  - Signals of Opportunity (SOOP)
- Alternatives
  - Satellite – **Low Earth Orbit (LEO)**, Starlink, Kuiper, Iridium, etc.
  - High Altitude Pseudo-Satellites (HAPS) – Balloon, Aircraft
  - GPS rebroadcast
  - Pseudolites (Stationary or Moving; One-Way vs. Two Way)
  - Quantum
  - Sensor Fusion – Inertial Management Units (IMU); Barometers, etc.
  - Multilateration (MLAT)/TDOA/Hyperbolic Positioning

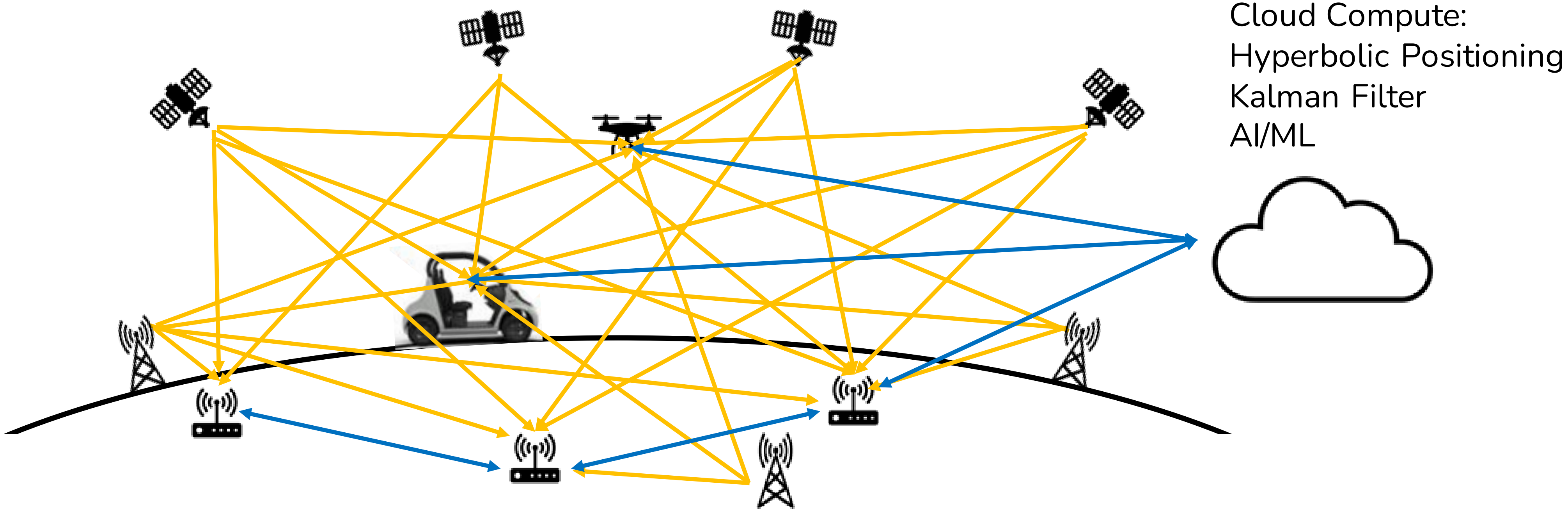
Signals of Opportunity

- RF sources used opportunistically
  - Fixed terrestrial sources
  - Mobile, Airborne, Spaceborne
- For LEO Source (Asset)
  - We assume we know nothing about LEO clock or position
  - Reference sensors receive and timestamp source signal at multiple locations
  - Sensors need to be synchronized and know their positions
  - Other users receive a subset of same signals as the sensors
- Position of asset is computed and can be shared with others for their PNT

SpaceX Starlink LEOS



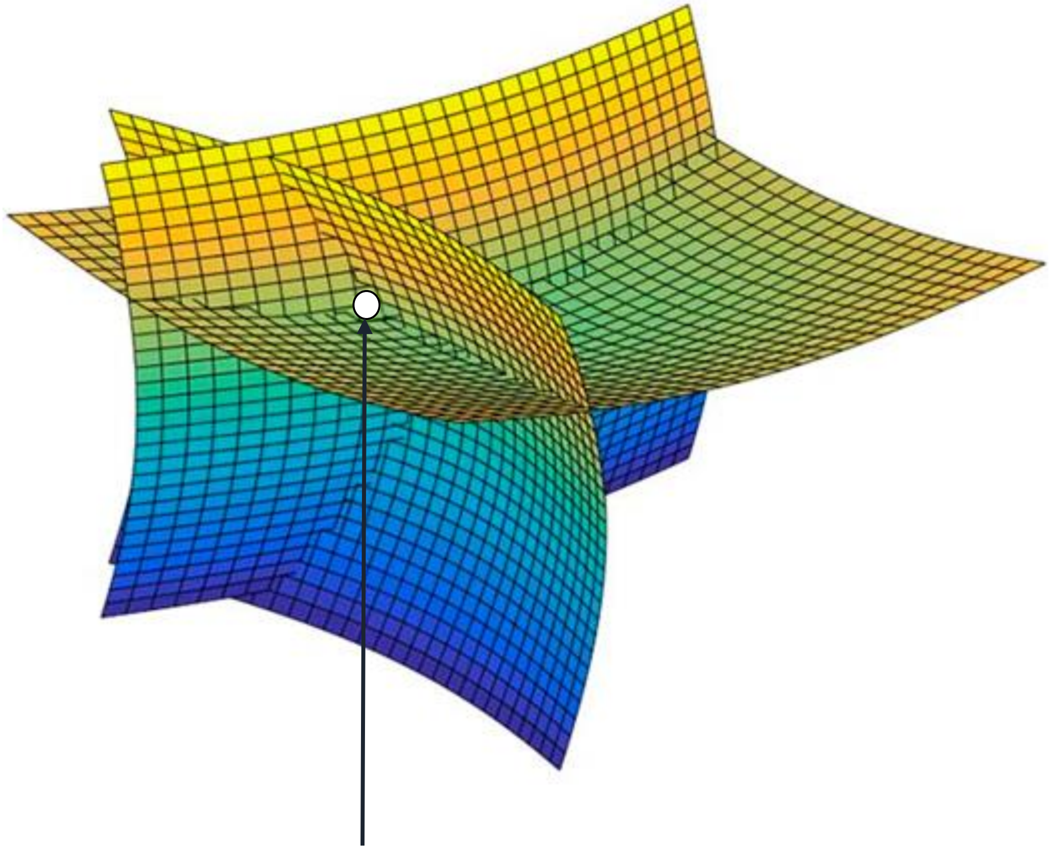
Alternate PNT with SOOP



- Network Multilateration assisted by LEO SOOP:
  - Clients/Assets (ROV, UAV) and Reference Receivers mark TOA of Terrestrial and LEO SOOP
  - TOA streamed to cloud and processed for Time Difference of Arrival (TDOA)
  - Hyperbolic Positioning algorithm, Kalman filter and AI/ML determine PVA
    - References stream LEO SOOP TOA along with known reference position to Cloud (sync required)
    - Client streams LEO SOOP TOA to Cloud (sync not required)
    - Cloud computes LEO PVA, TDOA; streams to assert; Cloud and/or asset determine asset location

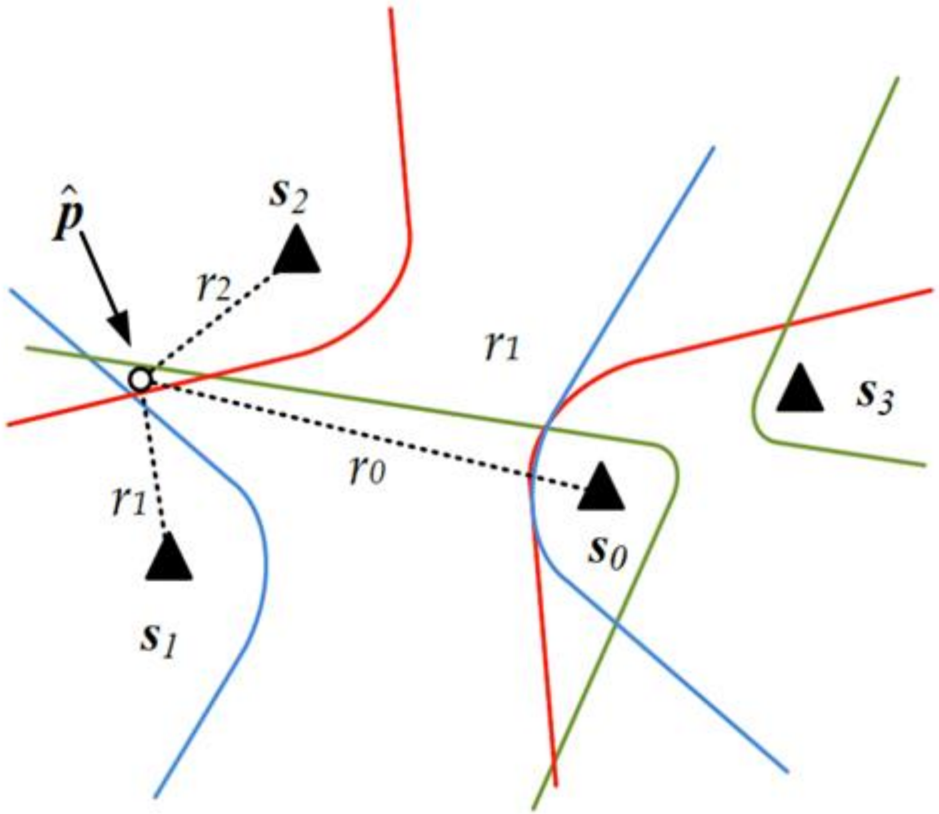
LEO Satellite   Radio, TV, Cell Tower   Reference Receiver   ROV   Drone/UAV   RF SOOP   Wireless Network

TDOA/Hyperbolic Positioning



3D Asset Position is at intersection of hyperboloids formed from Time Difference of Arrival (TDOA)

https://www.gpsworld.com/signals-of-opportunity-holy-grail-or-a-waste-of-time/



2D Asset Position is at intersection of hyperbolas formed from Time Difference of Arrival (TDOA)

https://www.meta.org/papers/robust-time-difference-of-arrival-tdoa/29510539

Advantages/ Disadvantages: TDOA with LEO Satellites

- Previous Studies
  - Doppler results measured: ~ 8 m accuracy
  - Doppler GDOP estimates 1-5 m accuracy
  - Results simulated combining INS and LEO signals ~ 10 m
  - Results measured combining INS and LEO signals ~ 20 m
- We propose Time Difference of Arrival – Hyperbolic positioning with LEOs
- Advantages with LEOs
  - 20 times closer to Earth than GNSS signals ➔ 300 - 2,400 times more RF power than GNSS
  - Many thousands of satellites by One Web, Space X (Starlink), Amazon (Kuiper), and others
  - Diverse Frequency bands and directions
- Disadvantages – and mitigations
  - These being communications satellites, they are unlikely to provide several satellites visible at a given location
  - With high comm data rates, side-lobes may be strong enough for PNT
  - Positioning may require using multiple constellations
  - Ground sensors need sync and position
  - Estimators can assist sensor position and sync

LEO Constellations

TABLE 1 Characteristics of large LEO constellations

Name	No. of Planes	Sats./ Plane	Total No. of Sats.	Inclinations(s) (deg)	Altitude(s) (km)	Min. No. Visible Above 7.5° Elev. Mask
Iridium	6	11	66	86.4	780	1
OneWeb (Initial)	18	40	720	87.9	1200	19
Starlink (Initial)	32	50	1600	53.0	1150	56*
Kuiper	34	34	1156	51.9	630	17#
Starlink (Final)	51	50-75	2825	53.8-81.0	1110-1325	81

*In ± 65° latitude range. #In ± 60° latitude range.

From “Navigation using carrier Doppler shift from a LEO constellation: TRANSIT on steroids”
Mark L.Psiaki
NAVIGATION. 2021;68:621–641.

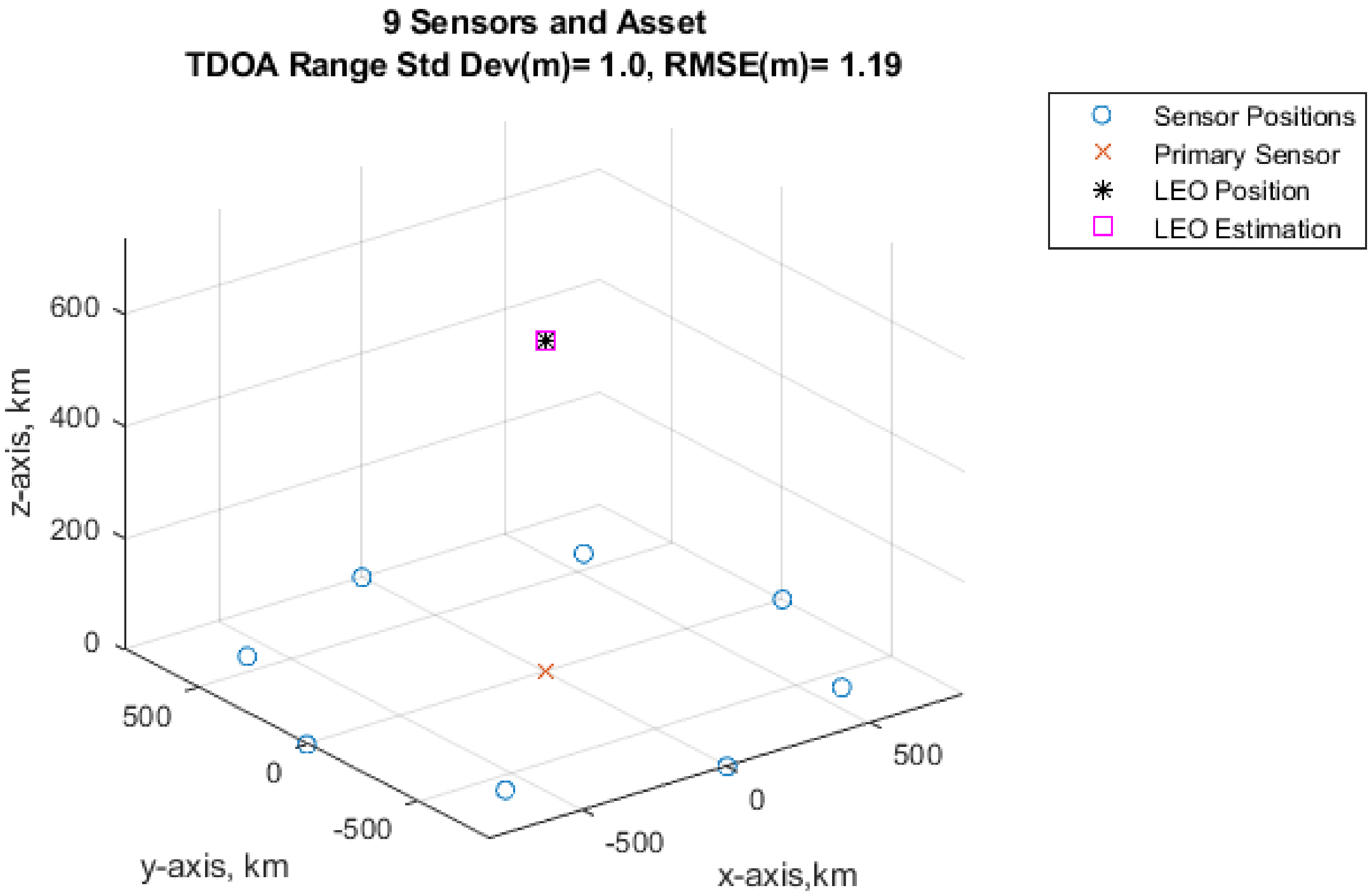
Space X Starlink Signals

- Starlink has permission to transmit in the Ku, Ka, and V-bands
- Channel bandwidths of 50 MHz on the Ku-band and 1 GHz on the V-band
- Potential for range accuracy of 1 ns

LEO TDOA Example 1

9 Sensors at radius 830 km, LEO Asset 590 km high

- 8 Sensors placed equally around a circle of radius 830 km, 1 at center
- LEO asset 590 km above center of circle – the height of some Starlink satellites
- View angle from circle to LEO is 35 degrees above horizon
- 1 ns range accuracy can provide 1.2 ns (40 cm) satellite positions



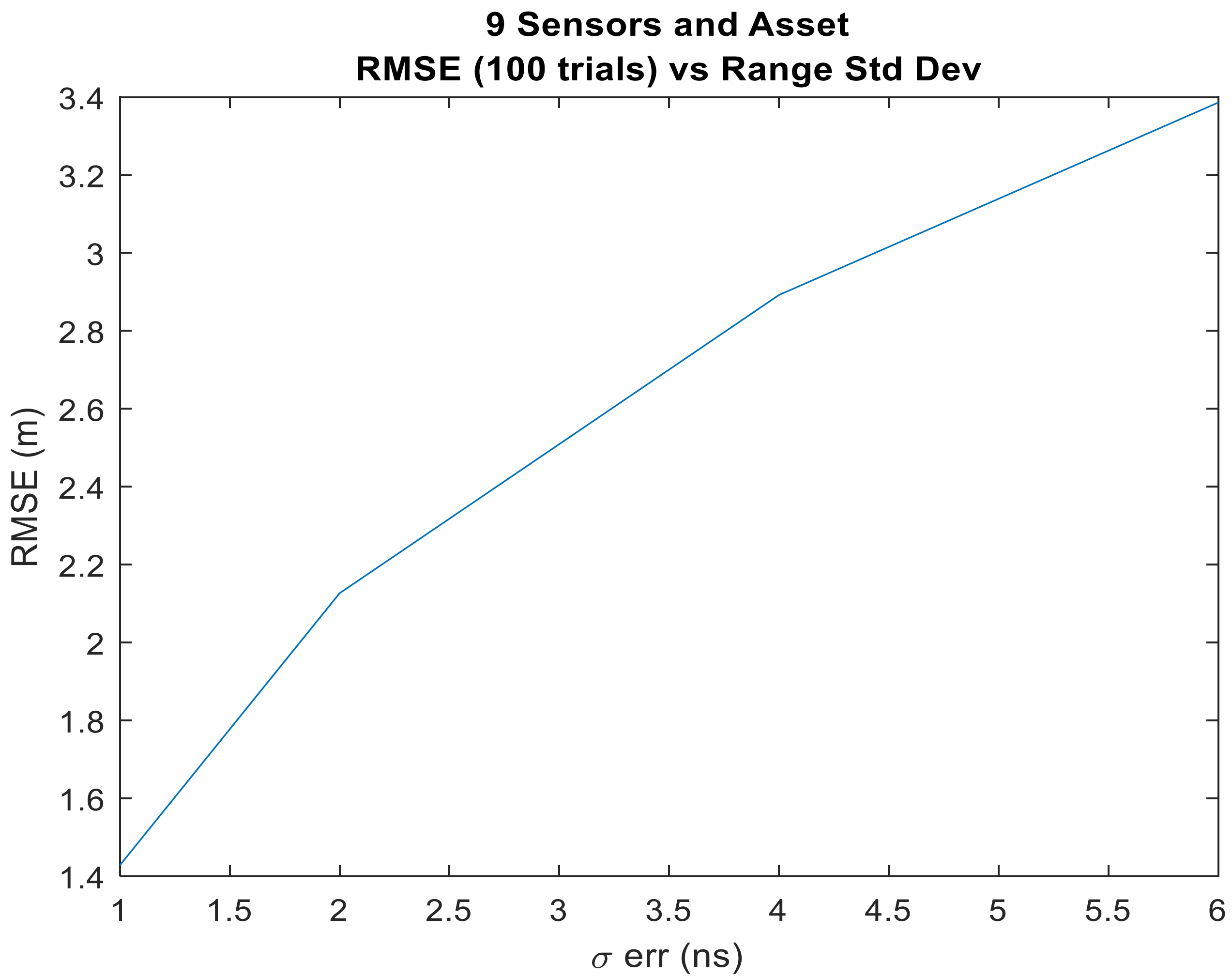
LEO TDOA Example 1

RMS Error over 100 trials

8 Sensors at radius 830 km, Primary Sensor at center

LEO Asset 590 km high

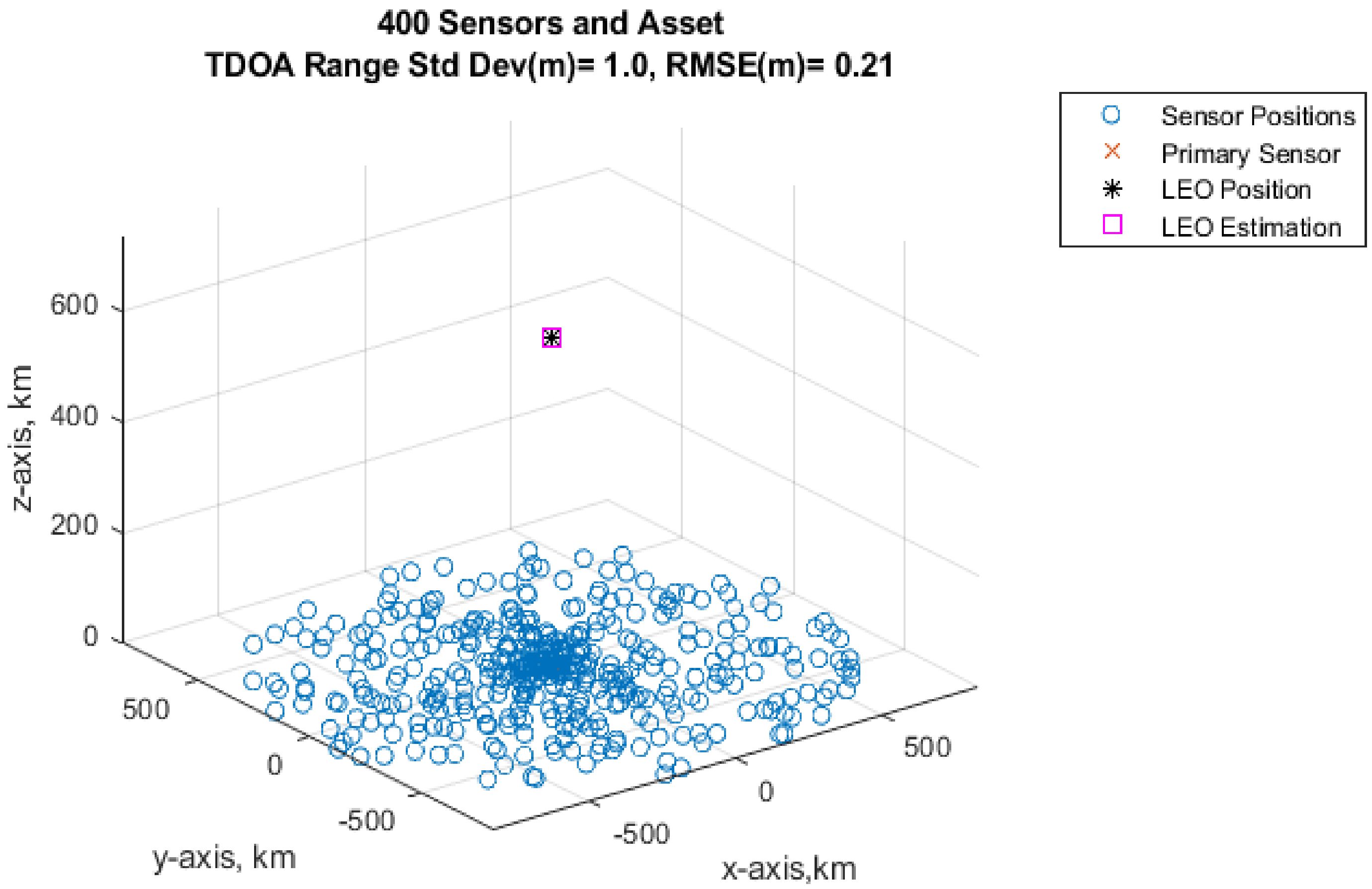
- Root-mean-squared error (RMSE) vs. Range Standard Deviation
- RMSE over 100 trials



LEO TDOA Example 2

400 Sensors within 830 km, LEO Asset 590 km high

- 399 Sensors placed randomly within a circle of radius 830 km with primary sensor at origin, i.e., directly beneath LEO
- This model is for A-PNT users to be estimated simultaneously with being used to help location LEO
- Potential for accuracies comparable to GPS



LEO TDOA Example 2

RMS Error over 100 trials

400 Sensors within 830 km, LEO Asset 590 km high

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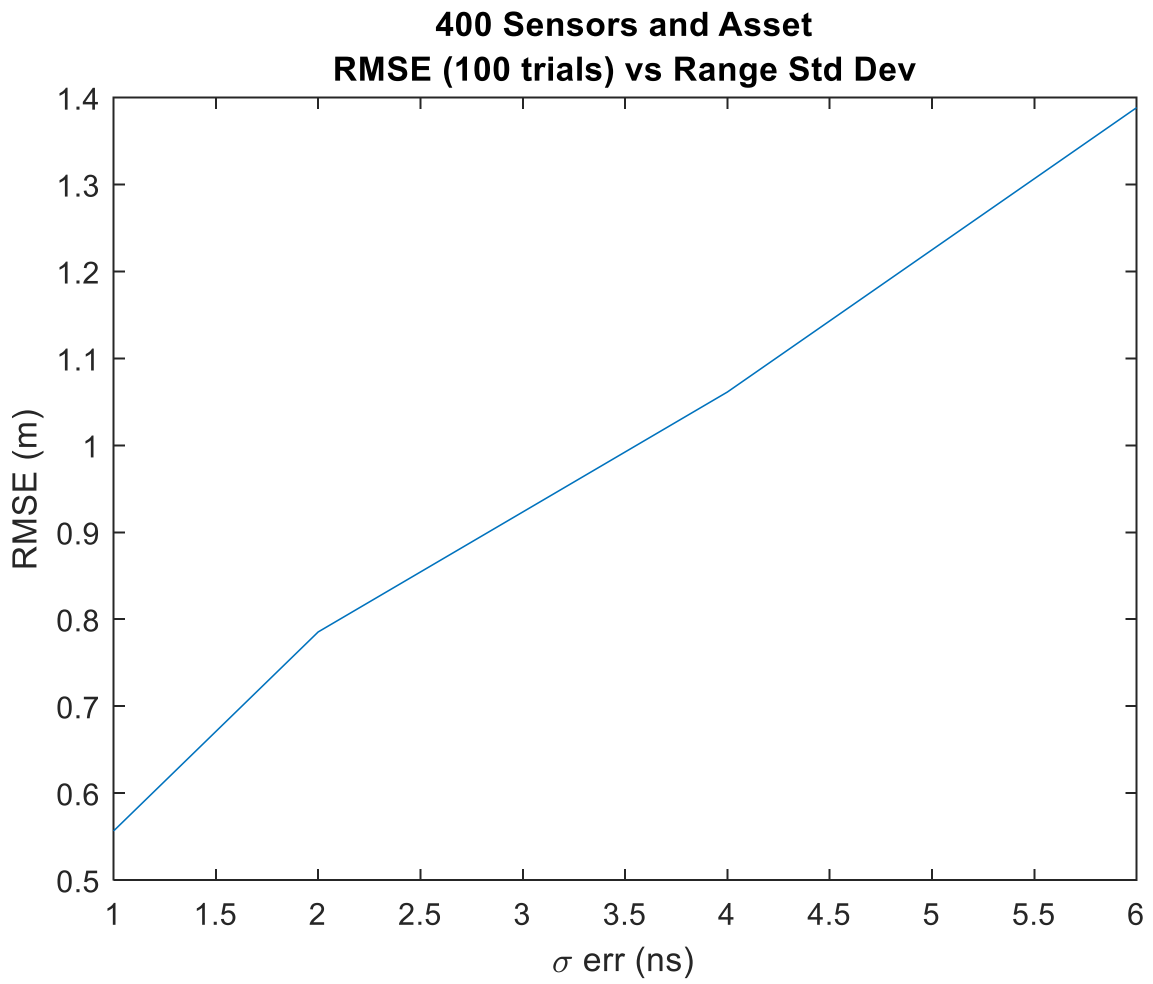
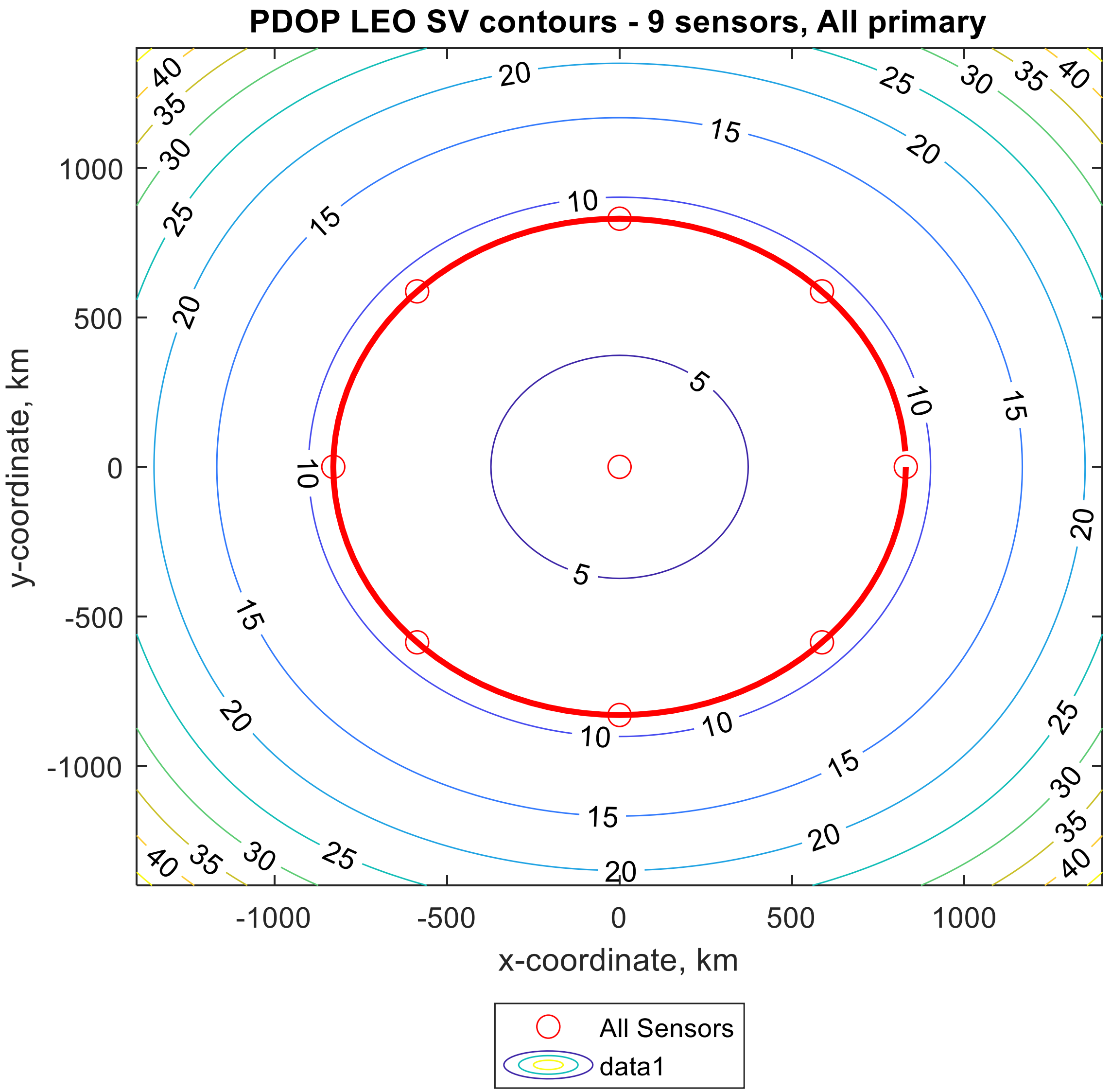


LEO TDOA Total Position Dilution of Precision (PDOP)

- 9 Sensors on the ground, 8 on circle radius 830 km, 1 at Center
- All sensors used as reference
- LEO Sat at 590 km at various locations over sensors
- With 1 ns range error, Positioning LEO can be within a few meters
- Using estimators combining fixed sources and users together with the LEO estimator can result in A-PNT comparable to GPS



Conclusions

- Massive numbers of LEO satellites coming available can provide signal sources for Alternate PNT
- TDOA techniques can be used without any requirements on LEO signals for PNT accuracy
- Potential for user A-PNT accuracies comparable with GPS