Distributed multi-GNSS Timing and Localization (DiGiTaL)

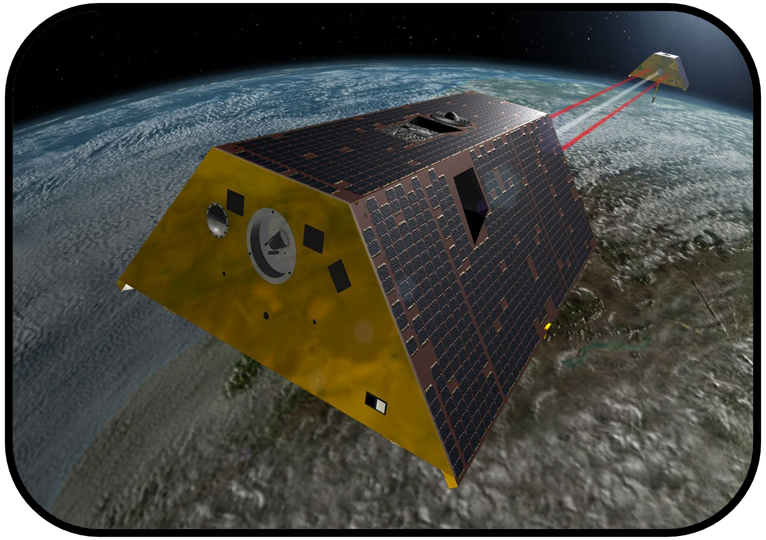
Vince Giralo, and PI: Prof. Simone D'Amico, damicos@stanford.edu

Stanford's Space Rendezvous Laboratory (SLAB)

NASA POC: Neerav Shah

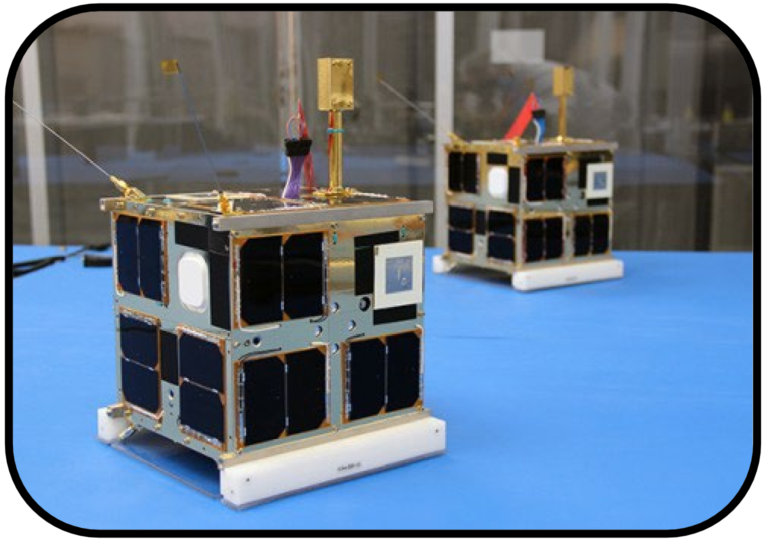
Distributed Space Systems

GRACE

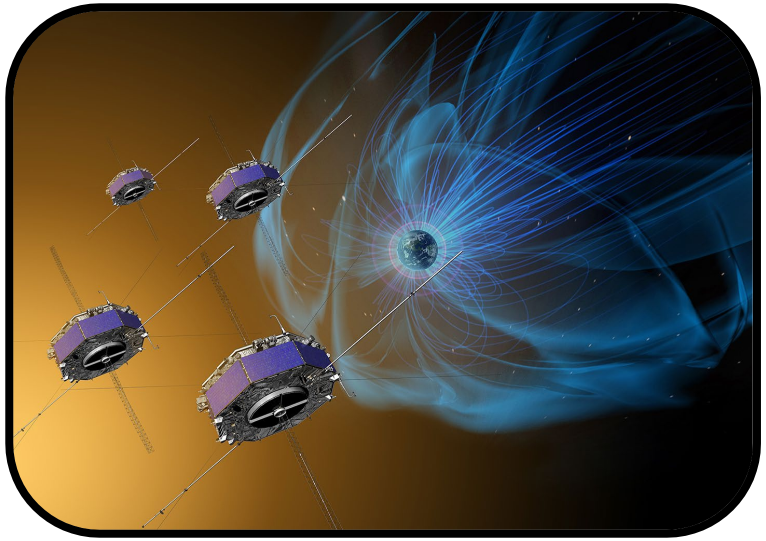


PRISMA

CanX-4/5



MMS



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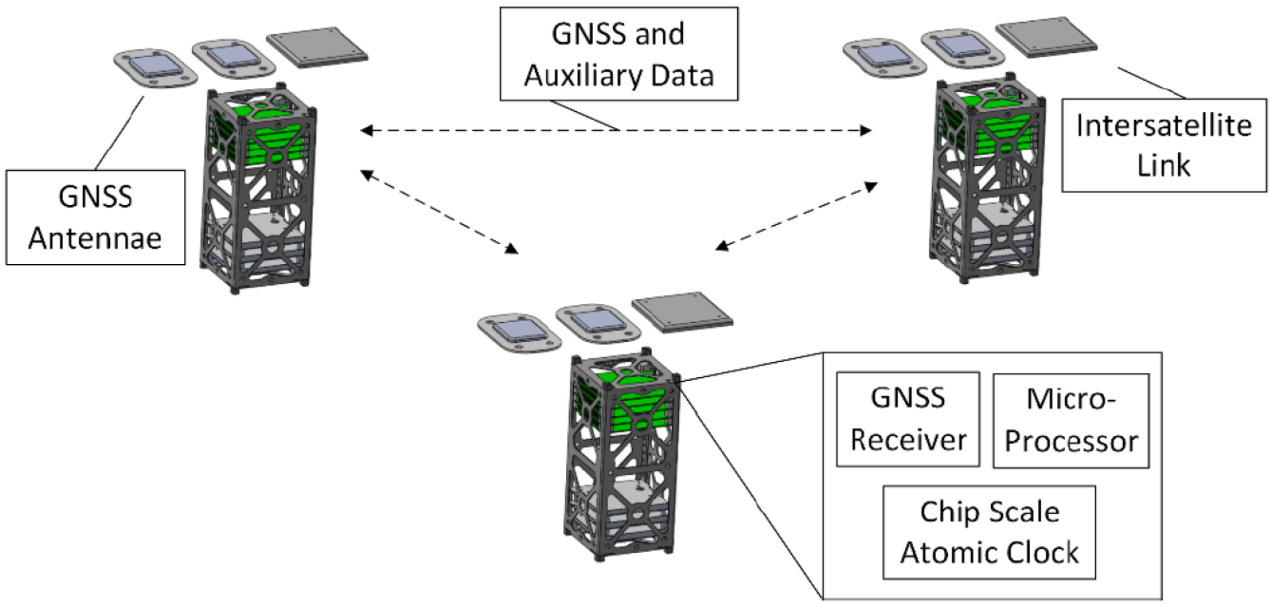
Distributed Multi-GNSS Timing and Localization



DiGiTaL

- Navigation payload for swarms of *N* nanosatellites
- **0.5U** form factor for CubeSats
- Commercial-off-the-shelf hardware with "partial" flight heritage
- Decentralized architecture
- Cm-level **real-time** relative positioning through differential GNSS
  - In-flight integer ambiguity resolution
- Demonstrate on **CubeSat avionics**

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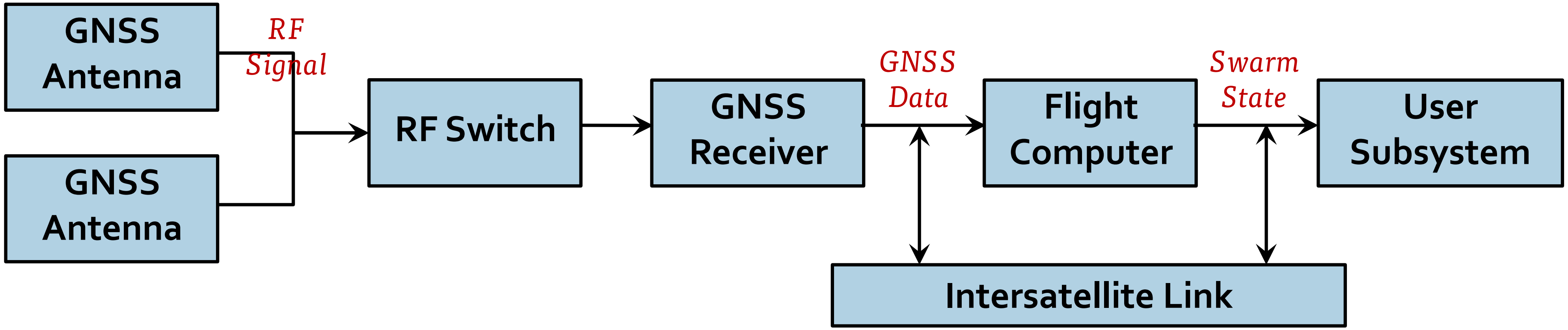
Hardware Architecture



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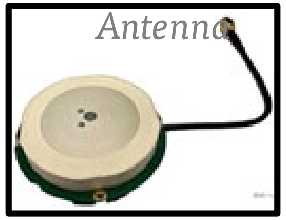
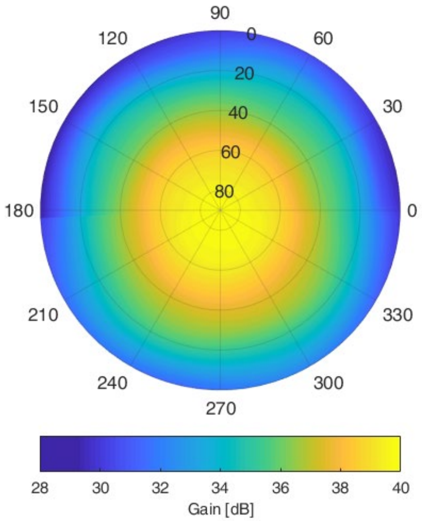
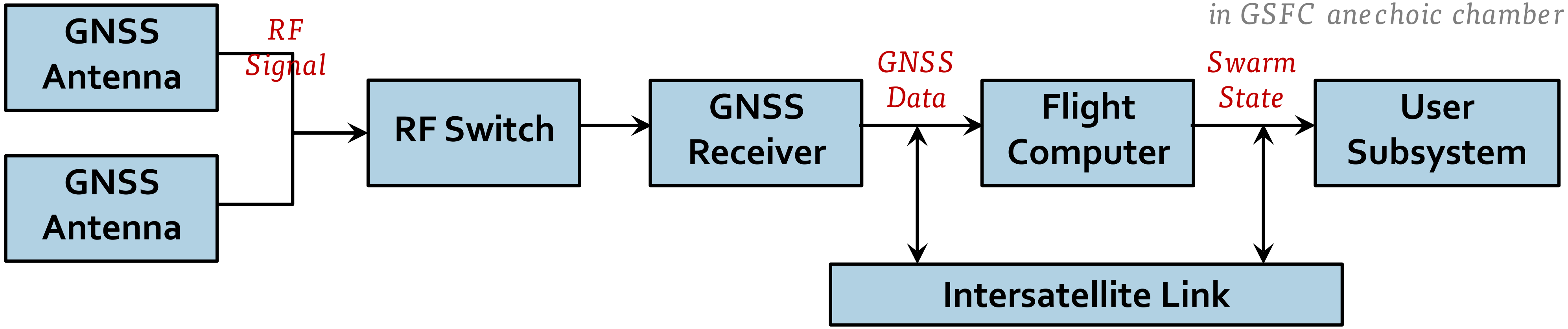
Hardware Architecture

Tallysman Triple Band GNSS Antenna





Gain pattern characterized in GSFC anechoic chamber



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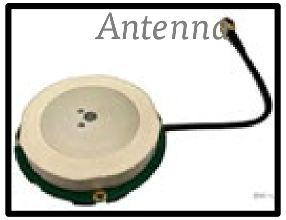
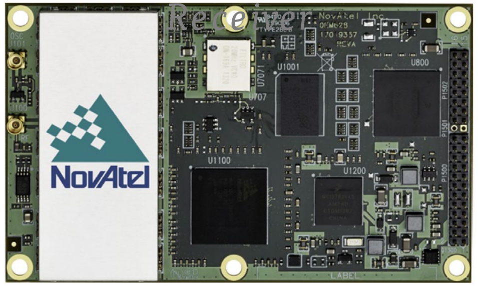
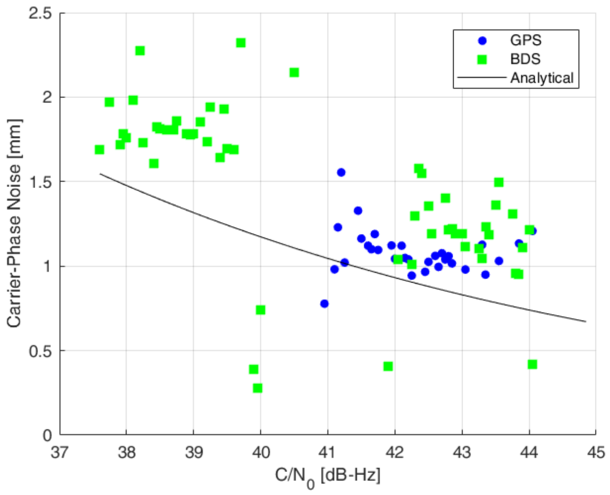
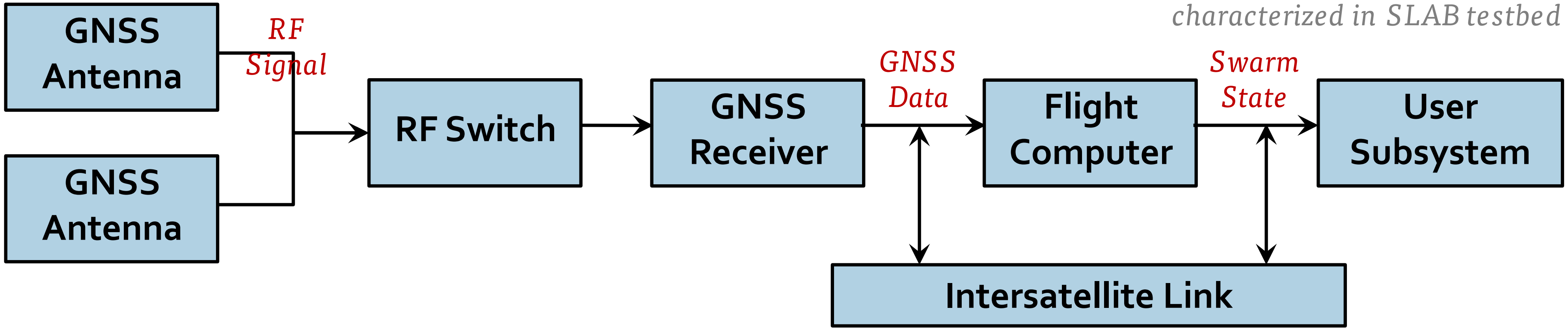


NovAtel OEM628 Multi-Frequency GNSS



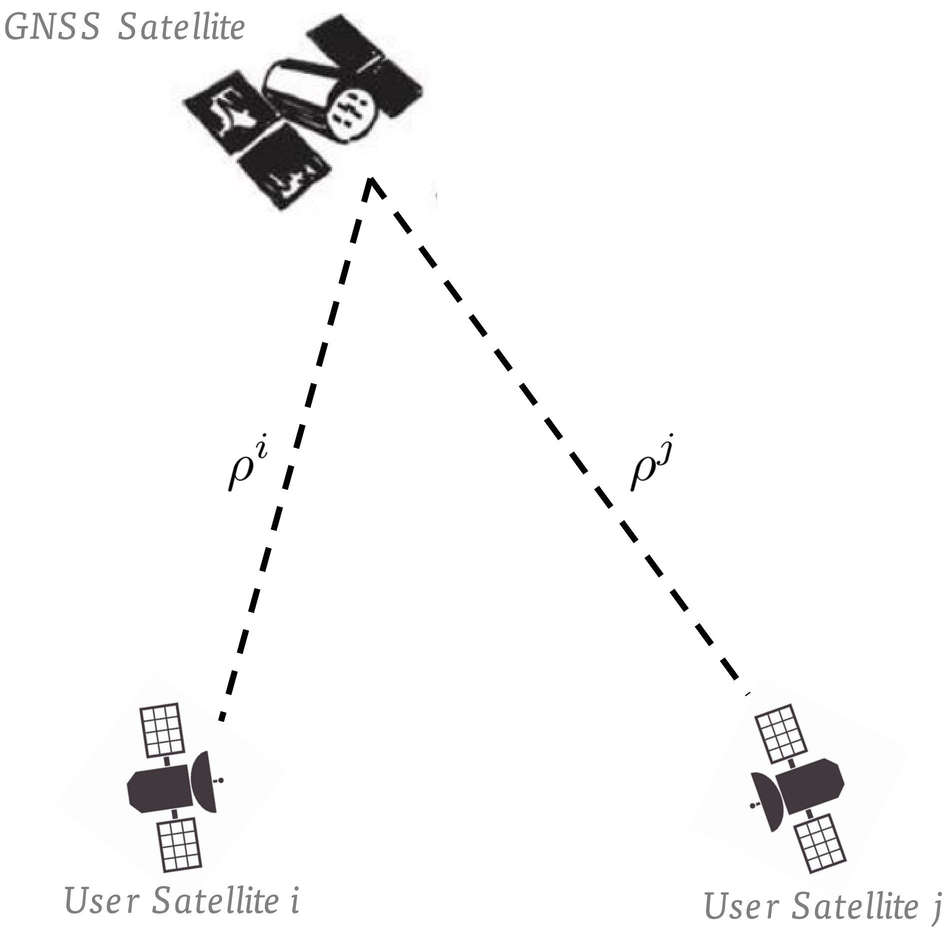


Carrier-phase noise characterized in SLAB testbed



Swarm Navigation Strategy

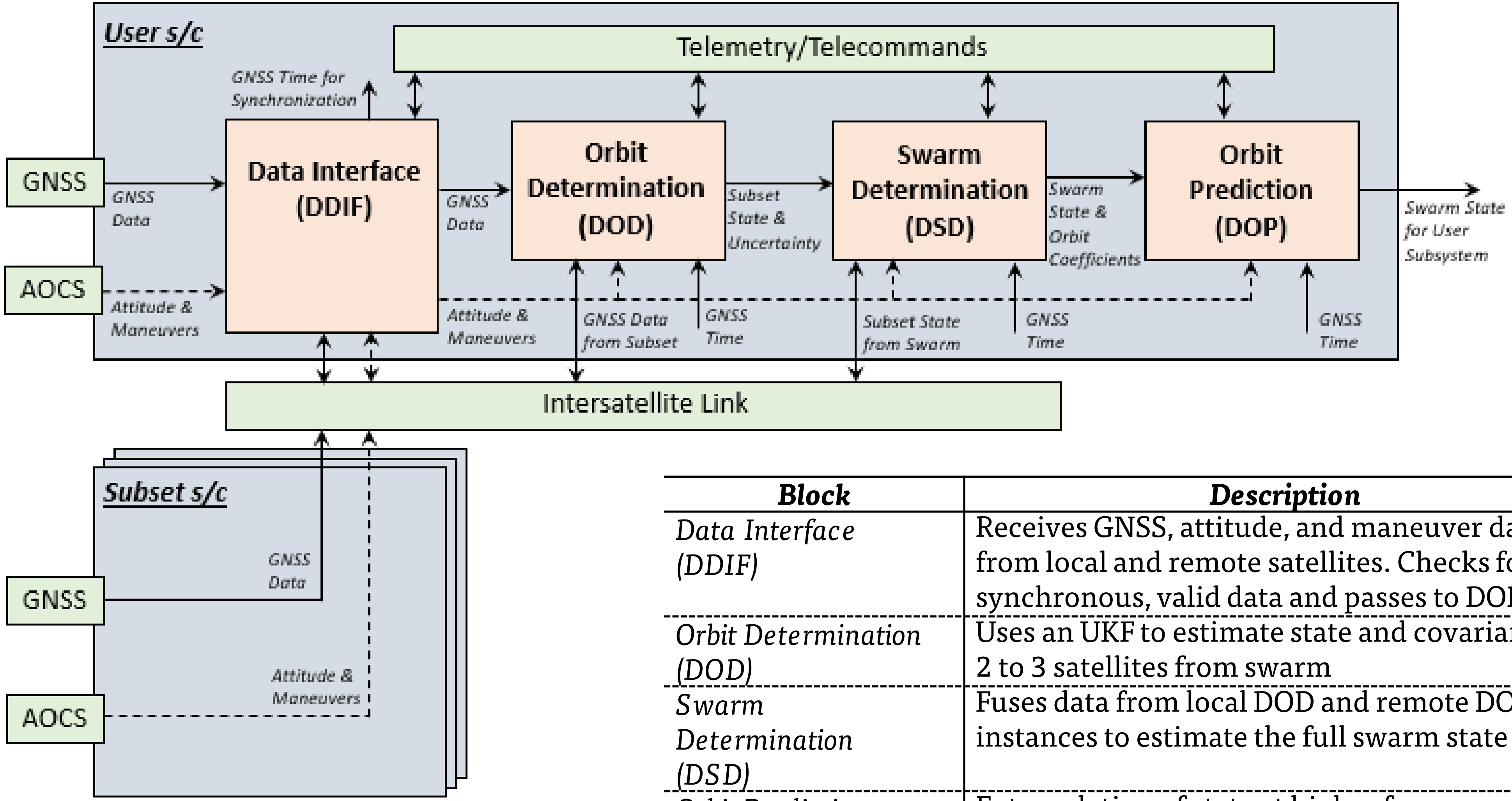
- Differential GNSS
  - Share measurements between spacecraft
  - Singe-difference carrier-phase
  - **Cancel common errors**
- Computational cost grows with size of swarm
  - Based on Kalman filter measurement update
  - Grows with N^2
  - Large swarms become **too expensive**
- **Divide** swarm into smaller "local" pods
  - Perform **orbit determination** in pod
  - Fuse together in **swarm determination**



Single-Difference Measurements

$$\rho^{ij} = \rho^i - \rho^j$$

Software Architecture



Block	Description
Data Interface (DDIF)	Receives GNSS, attitude, and maneuver data from local and remote satellites. Checks for synchronous, valid data and passes to DOD
Orbit Determination (DOD)	Uses an UKF to estimate state and covariance of 2 to 3 satellites from swarm
Swarm Determination (DSD)	Fuses data from local DOD and remote DOD instances to estimate the full swarm state
Orbit Prediction (DOP)	Extrapolation of state at higher frequency than DOD

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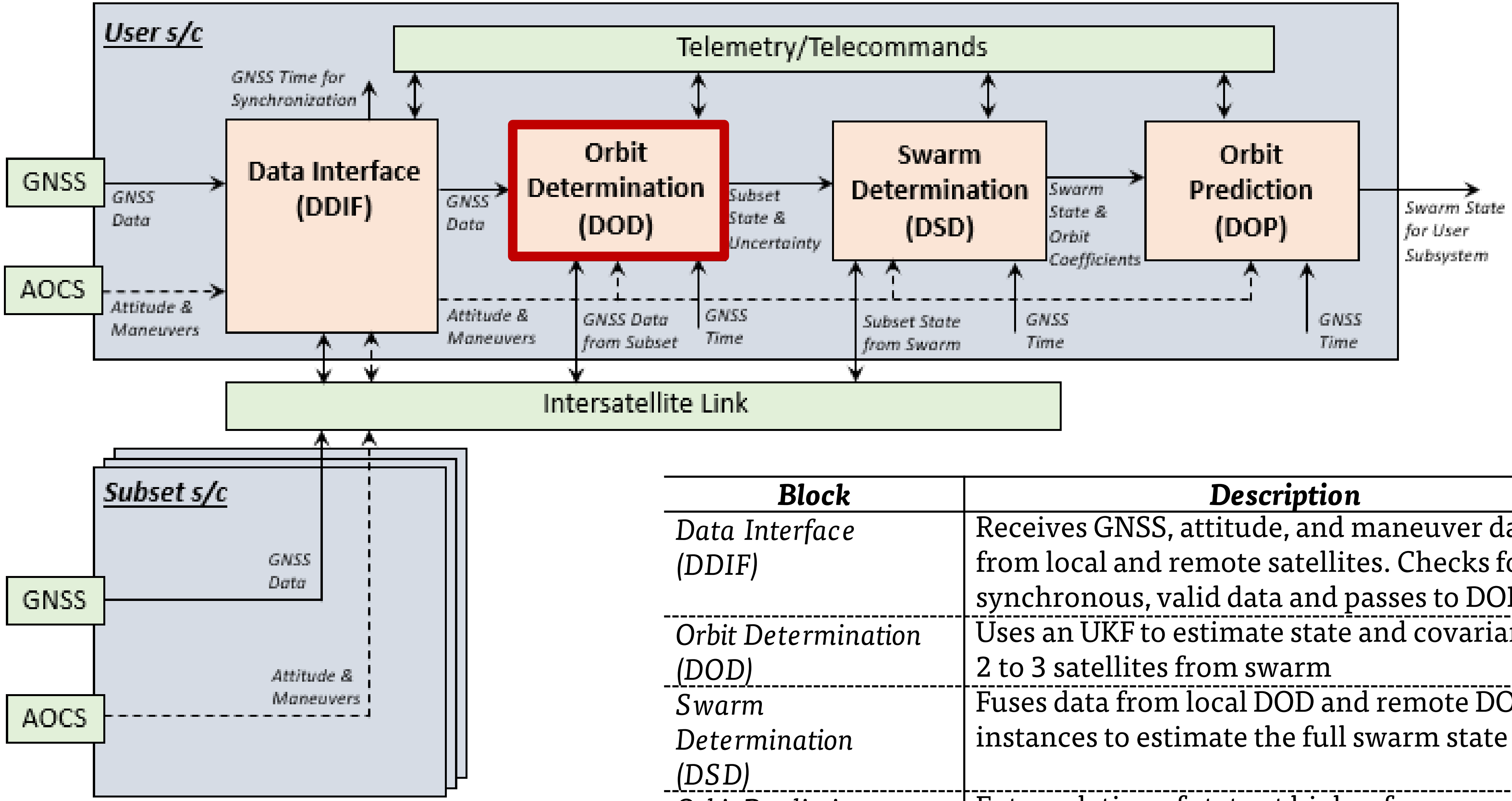
Software Architecture



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DiGiTaL Orbit Determination

- Multi-inertial estimation state
  - Incorporates interdependency of states
  - No need for explicit relative state
  - Extendable to at most 3 states

$$\vec{x} = \begin{bmatrix} \vec{r}^1 & \vec{v}^1 & \vec{a}^1_{emp} & \overrightarrow{c\delta t}^1 & \vec{N}^1 \ldots \\ \vec{r}^2 & \vec{v}^2 & \vec{a}^2_{emp} & \overrightarrow{c\delta t}^2 & \vec{N}^2 \end{bmatrix}^T$$

- Reduced-dynamics estimation approach
  - Extended Kalman Filter
  - First-order Gauss-Markov process

Force Model Setting	Value
Spherical Harmonic Gravity	20 x 20 GGM01S
Empirical Acceleration	Yes

- Multi-GNSS measurement concept
  - Group and phase ionospheric correction
  - Single difference carrier-phase data types

$$\vec{y} = [\rho^1_{GR} \quad \rho^2_{GR} \quad \rho^{21}_{SDCP}]^T$$

- Integer ambiguity resolution
  - mLAMBDA method
  - Discrimination Test, Success Rate Test, Residual Test

$$\min_{\mathbf{N}\in\mathbb{Z}^p} (\mathbf{N} - \hat{\mathbf{N}})^T \mathbf{P}^{-1}_{dd} (\mathbf{N} - \hat{\mathbf{N}})$$

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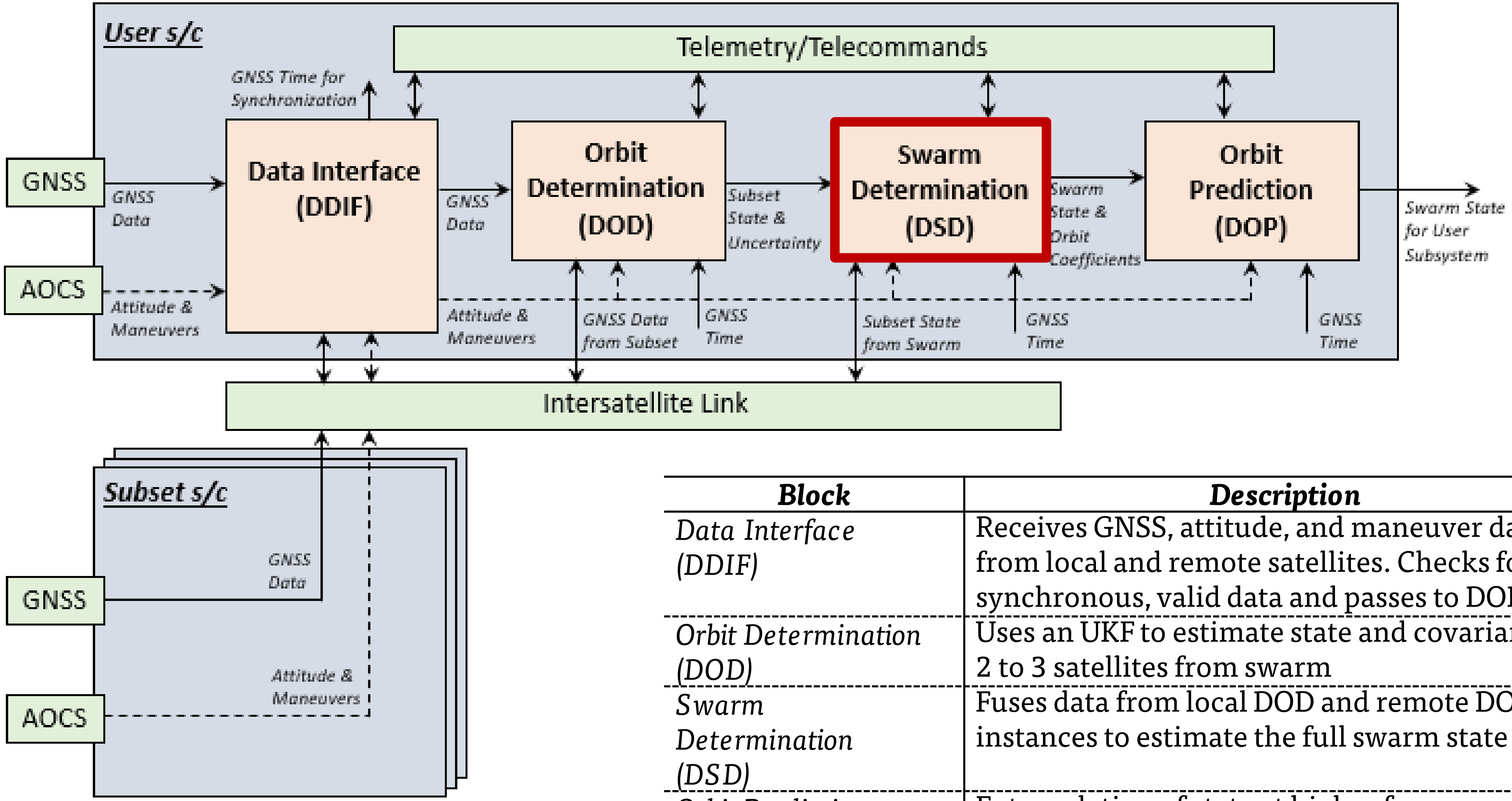
Software Architecture



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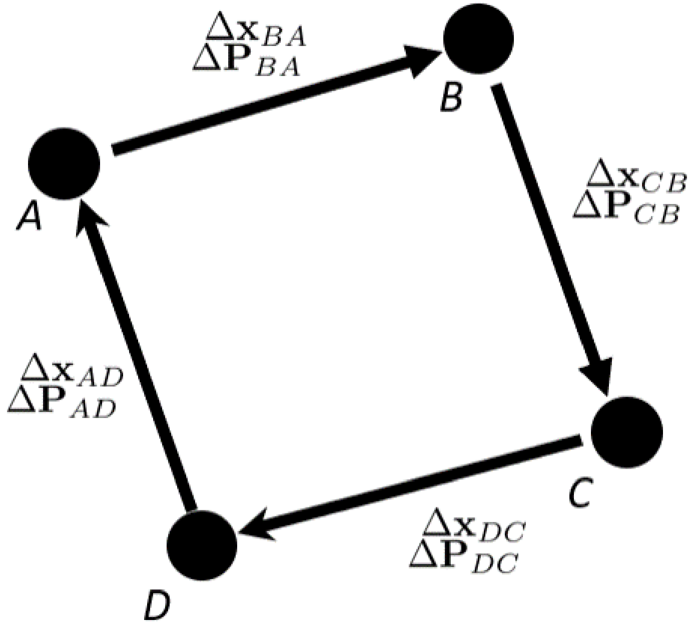
DiGiTaL Swarm Determination



User Spacecraft	Partner Spacecraft	DOD Output by User
A	B	$\Delta\mathbf{x}_{BA}, \Delta\mathbf{P}_{BA}$
B	C	$\Delta\mathbf{x}_{CB}, \Delta\mathbf{P}_{CB}$
C	D	$\Delta\mathbf{x}_{DC}, \Delta\mathbf{P}_{DC}$
D	A	$\Delta\mathbf{x}_{AD}, \Delta\mathbf{P}_{AD}$

$$\boxed{\begin{aligned}\Delta\mathbf{x}_{BA} &= \mathbf{x}_B - \mathbf{x}_A \\ \Delta\mathbf{P}_{BA} &= \mathbf{P}_A + \mathbf{P}_B - \mathbf{P}_{AB} - \mathbf{P}_{BA}\end{aligned}}$$

Vector Algebra

$$\Delta\mathbf{x}_{CA} = \Delta\mathbf{x}_{CB} + \Delta\mathbf{x}_{BA}$$
$$\Delta\mathbf{P}_{CA} = \Delta\mathbf{P}_{CB} + \Delta\mathbf{P}_{BA}$$

Kinematic Kalman Filter

$$\mathbf{x}(k+1) = \mathbf{F}\mathbf{x}(k) + \mathbf{v}(k)$$

$$\mathbf{F} = \begin{bmatrix} 1 & \Delta t & \frac{\Delta t^2}{2} \\ 0 & 1 & \Delta t \\ 0 & 0 & 1 \end{bmatrix}$$

$$\mathbf{Q} = \begin{bmatrix} \frac{\Delta t^5}{20} & \frac{\Delta t^4}{8} & \frac{\Delta t^3}{6} \\ \frac{\Delta t^4}{8} & \frac{\Delta t^3}{6} & \frac{\Delta t^2}{2} \\ \frac{\Delta t^3}{6} & \frac{\Delta t^2}{2} & \Delta t \end{bmatrix}$$

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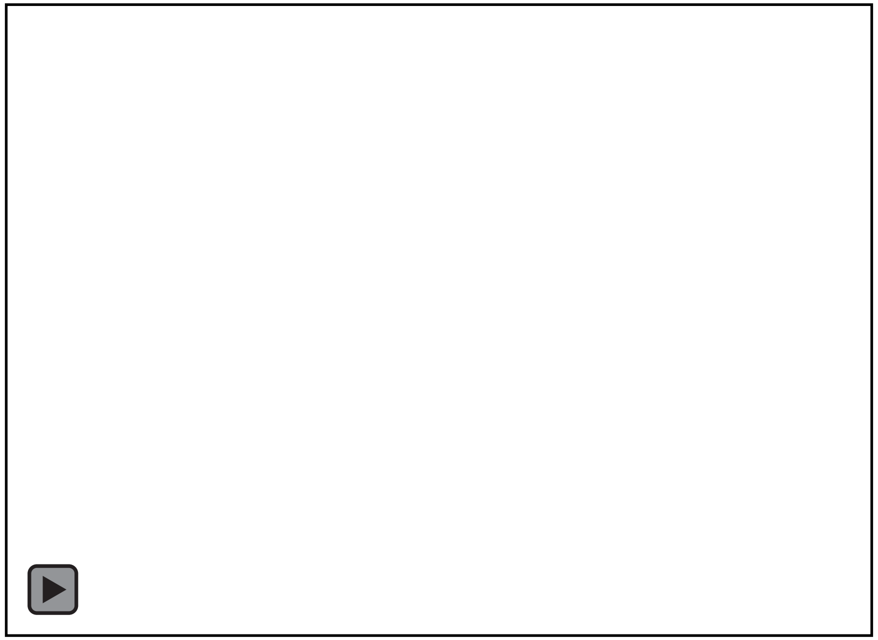
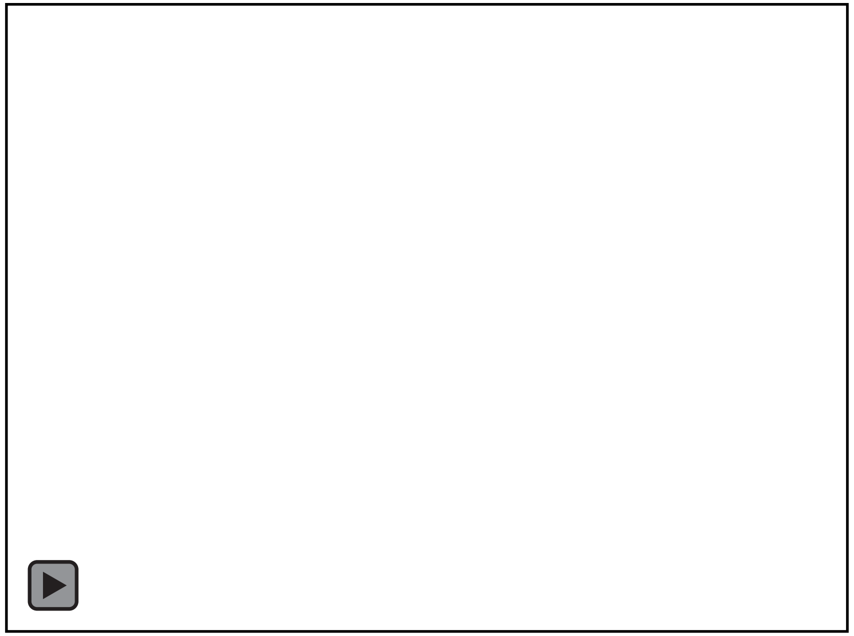
Swarm Test Scenario

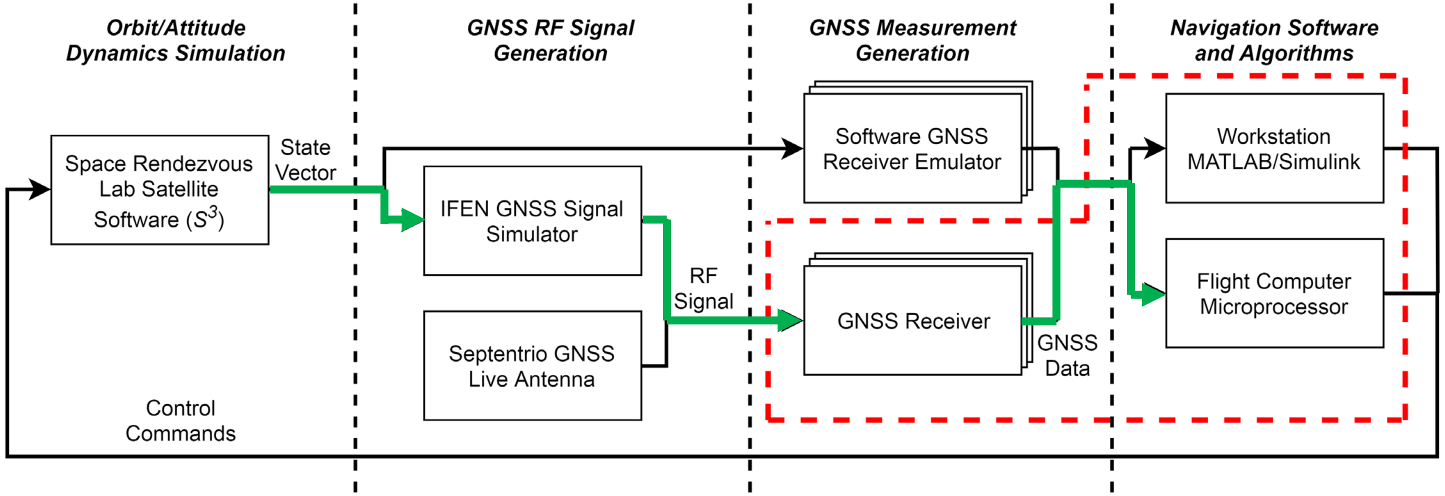
Scenario Parameter	***Value***
Start Epoch (GPST)	September 21, 2019, 00:00:00
Simulation Time [hr]	6
Simulation Rate [Hz]	20
Numerical Integrator	Fixed-Step 4th Order Runge-Kutta
GNSS Constellations	GPS L1

Absolute Orbital Elements	***Satellite 1***
Semi-Major Axis (a) [km]	6969.63
Eccentricity (e) [-]	0.0026
Inclination (i) [°]	97.98
Longitude of Ascending Node (Ω) [°]	25.85
Argument of Perigee (ω) [°]	252.38
Mean Anomaly (M) [°]	330.52





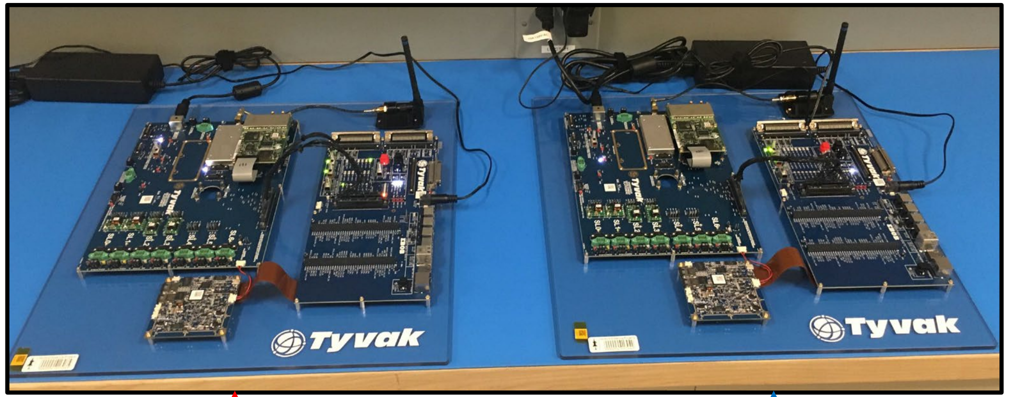
HIL Testbed Setup



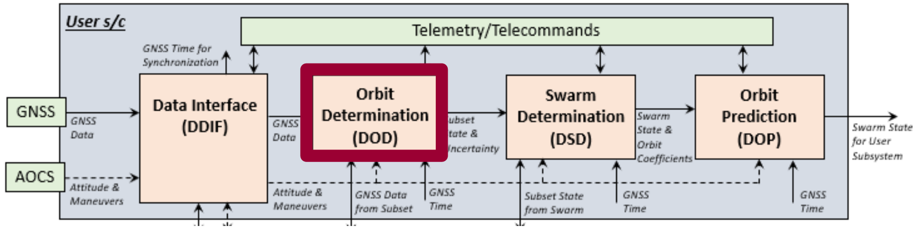
GNSS and Radiofrequency Autonomous Navigation Testbed for Distributed Space Systems (GRAND)

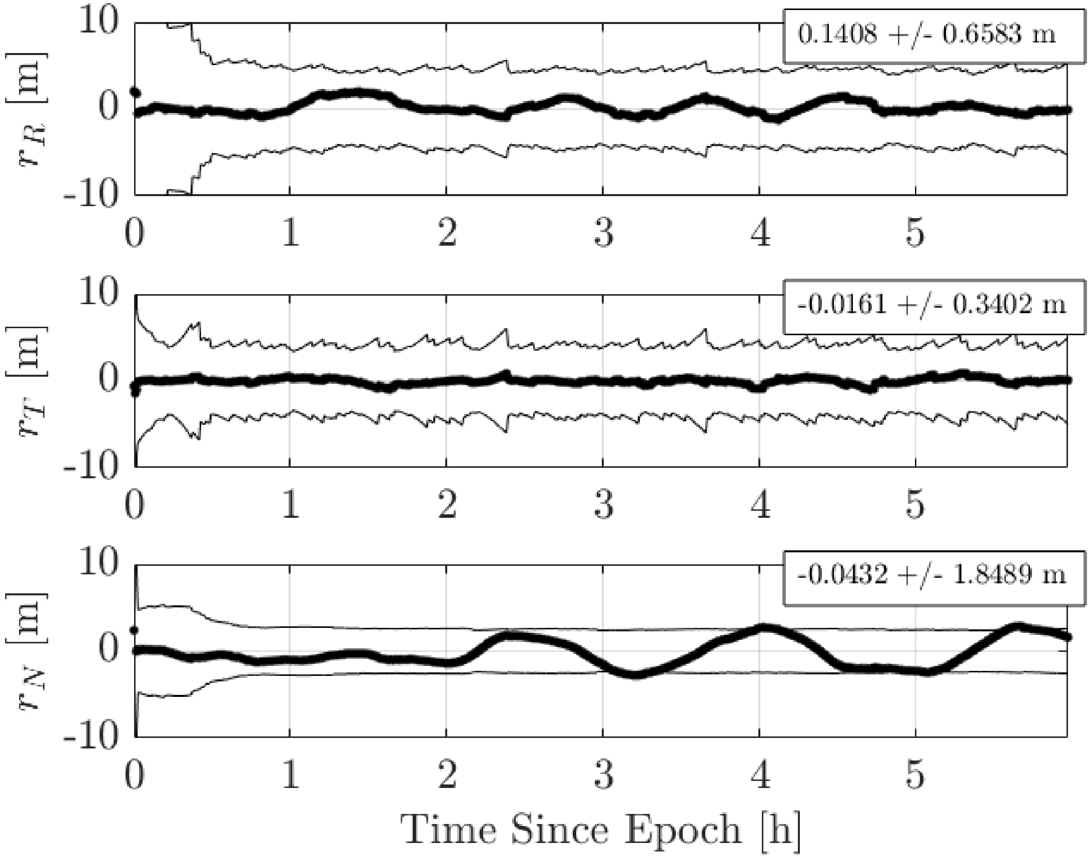
IFEN NavX Professional Multi-GNSS Signal Simulator

Tyvak Flatsat Development Platform with NovAtel 628 GNSS Receiver and UHF ISL

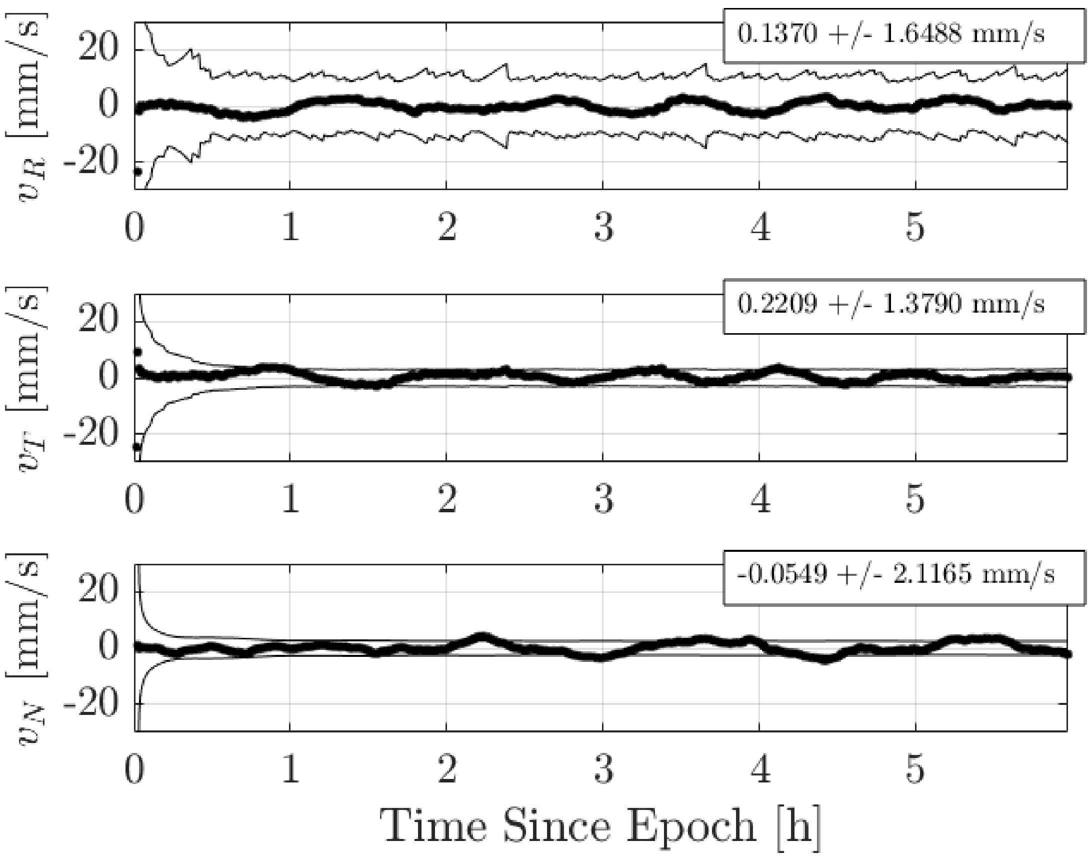


Orbit Determination



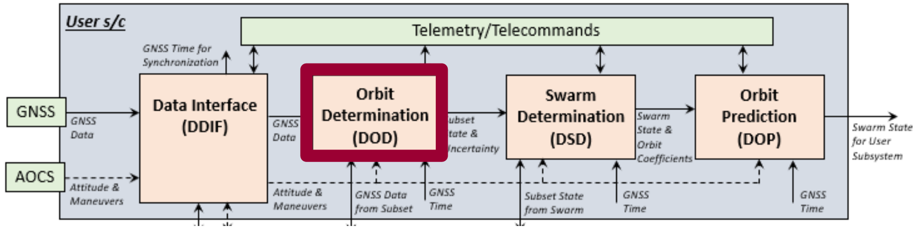


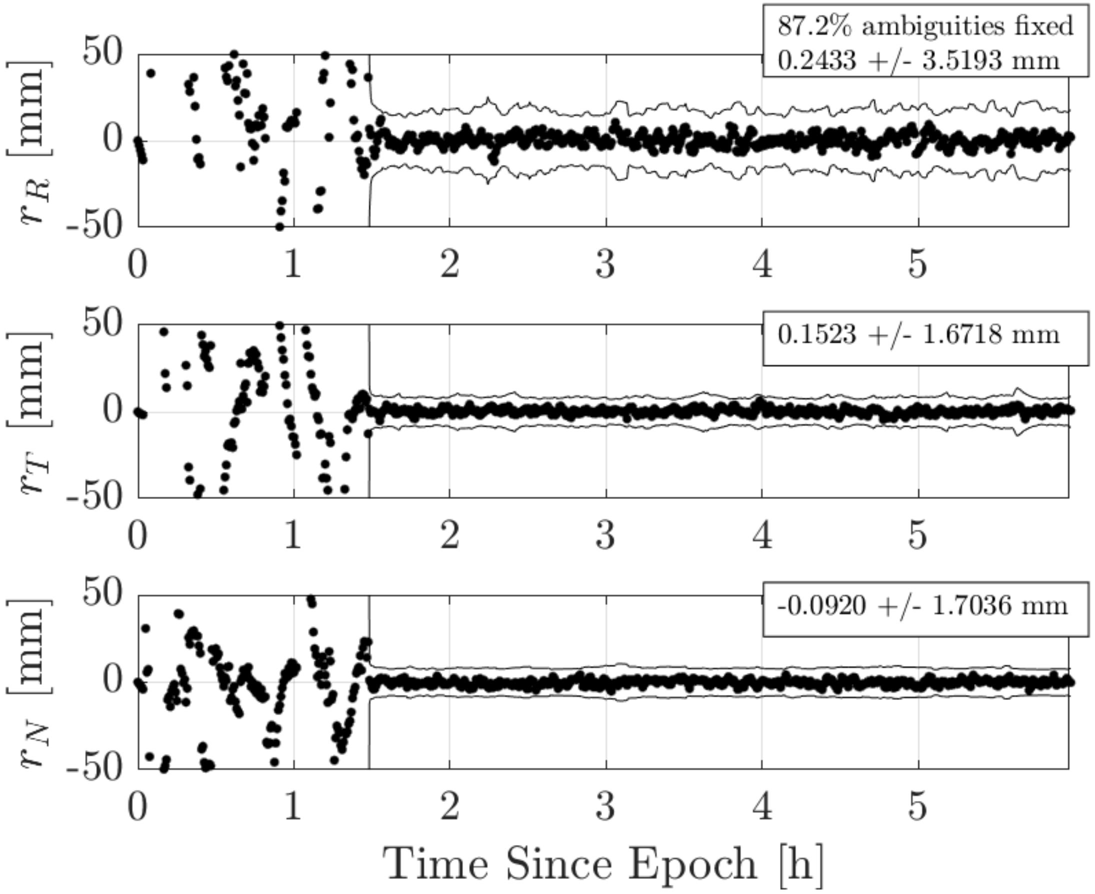
Absolute Position



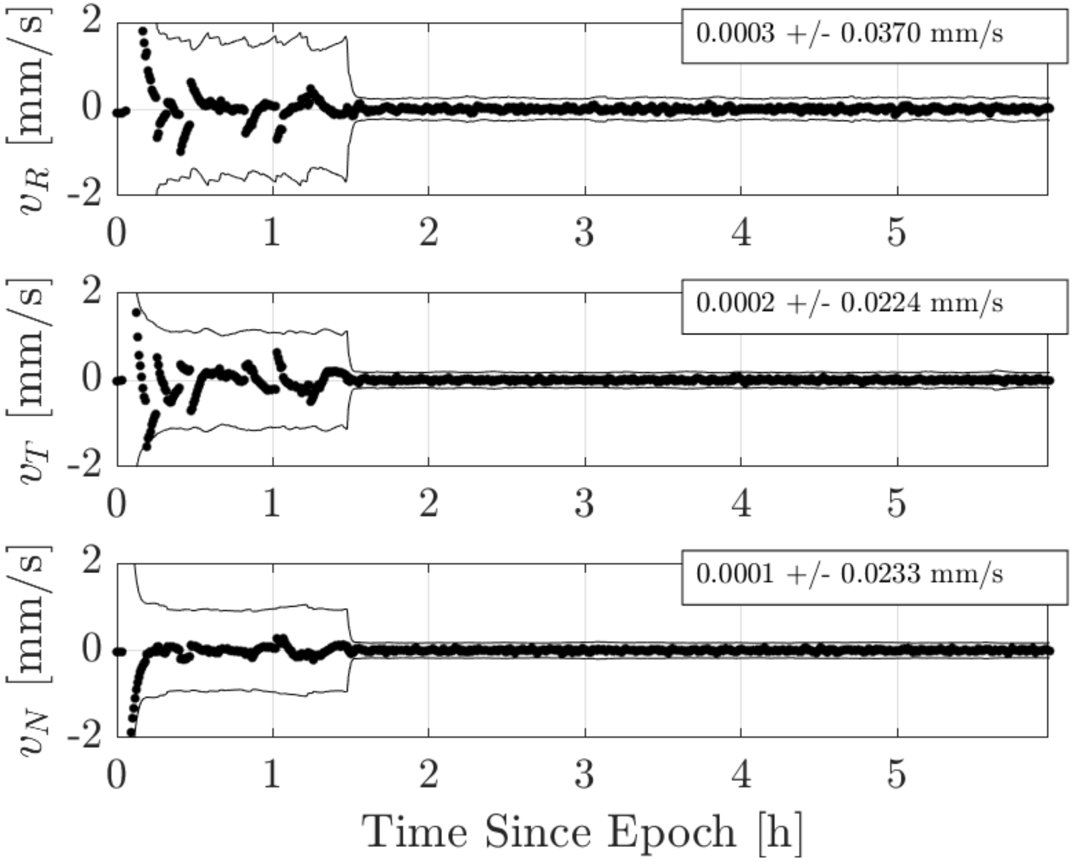
Absolute Velocity

Orbit Determination





Sat 2 Relative Position wrt Sat 1



Sat 2 Relative Velocity wrt Sat 1

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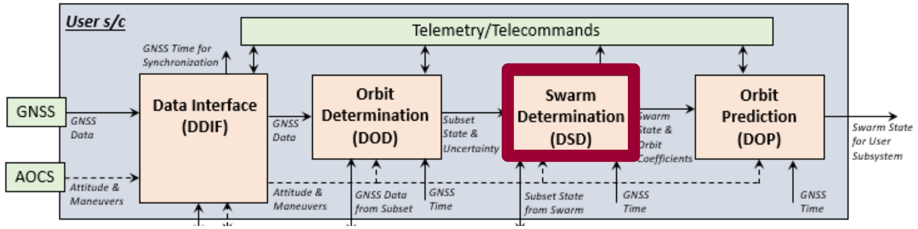
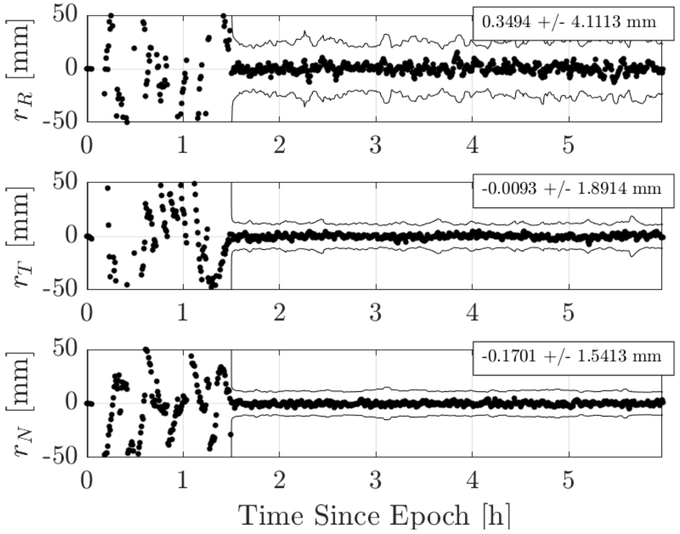
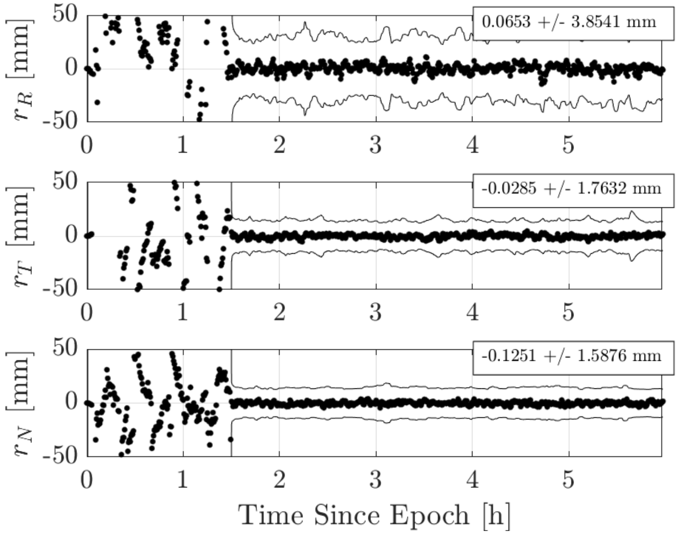
Swarm Determination



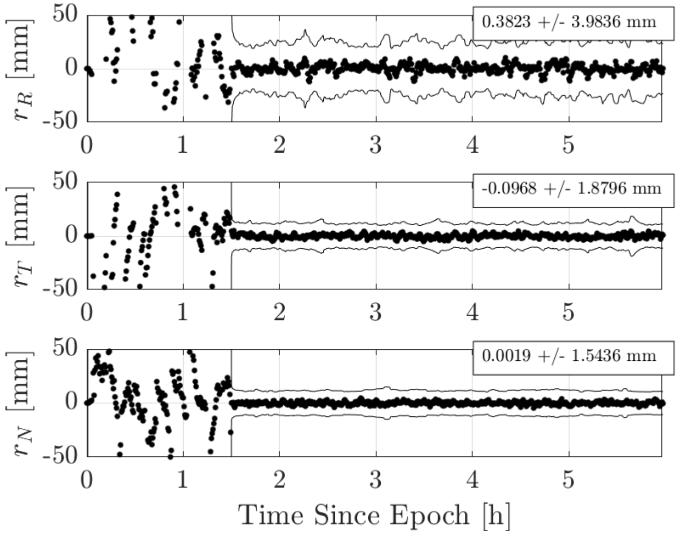
Sat 3 wrt Sat 1



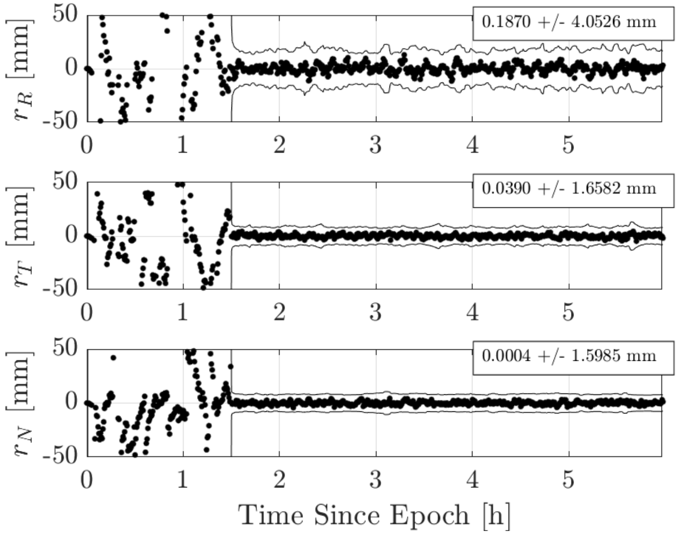
Sat 4 wrt Sat 1



Sat 5 wrt Sat 1



Sat 6 wrt Sat 1



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Large-Baseline Orbit Determination

- Miniaturized Distributed Occulter/Telescope
- Observe extrasolar debris disks
- Binary Formation
  - LEO
  - **~500 km max separations**
- **2 cm relative navigation** requirement
- Large inter-spacecraft separations
  - **Differential GNSS assumptions breakdown**

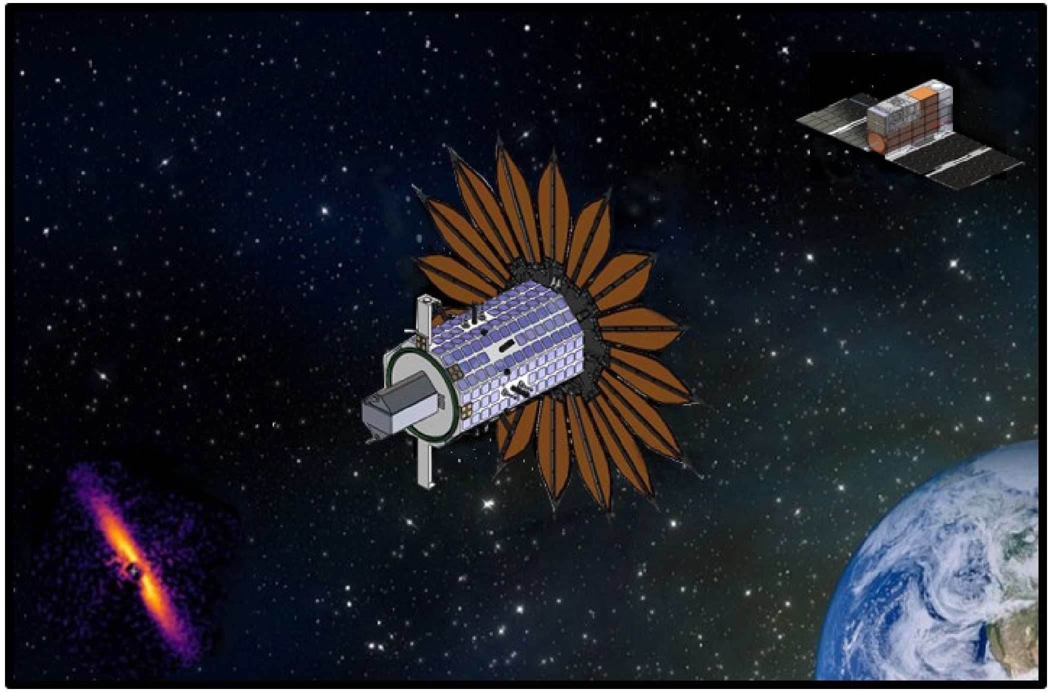

Illustration of nominal operations of mDOT

Navigation Filter Extensions

1. State Augmentation with Ionospheric Path Delay

$$\rho_{uw,cp}(t) = \rho_u(t) - \rho_w(t) = ||\mathbf{r}(t) - \mathbf{r}_s(t_{tr})||_{uw} + c\delta t_{uw}(t) - I_{uw}(t) + \lambda N_{uw} + \epsilon_{uw}$$

$$I_{L1,uw} = I_{K,uw} + \Delta I_{uw}$$

Estimated differential ionospheric correction

2. Hybrid Extended/Unscented Kalman Filter
   - Leverage **nonlinear UKF** filter variant
   - Reduce computational load by **Exploiting Triangular Structure**
   - Further reduce computation by **only using UKF measurement update**

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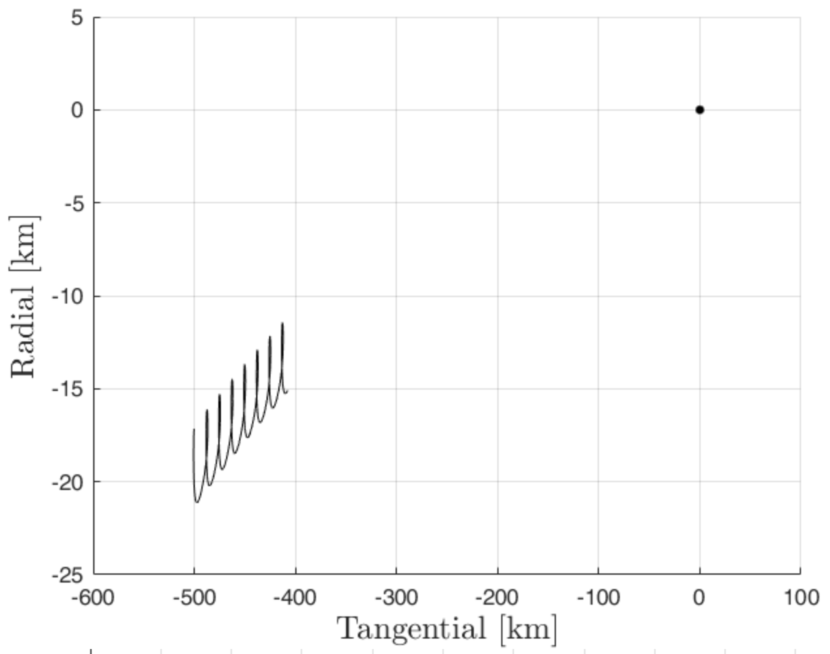
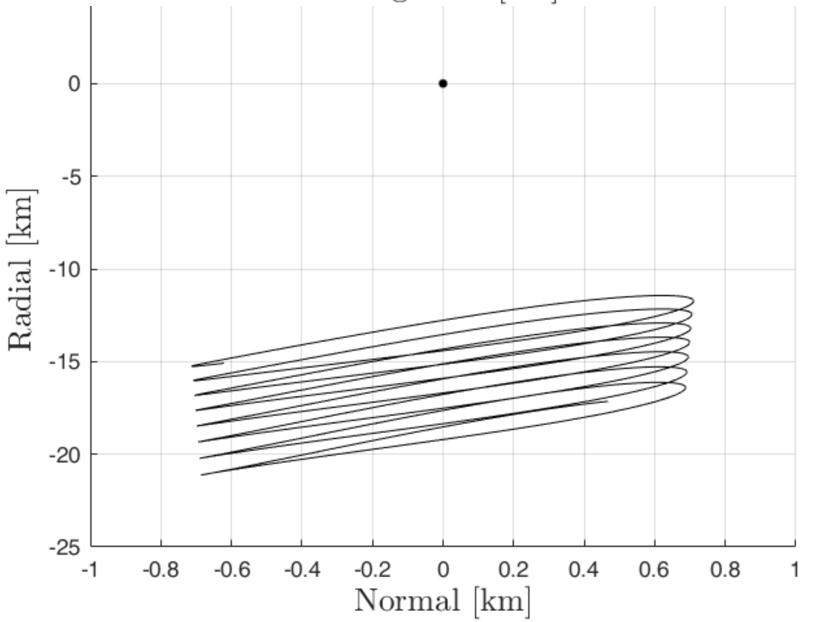
mDOT Test Case

Scenario Parameter	Value
Start Epoch (GPST)	March 1, 2018, 00:00:00
Simulation Time [hr]	12
Simulation Rate [Hz]	20
Numerical Integrator	Fixed-Step 4th Order Runge-Kutta
GNSS Constellations	GPS L1, L2
Orbit Regime	LEO, sun-synchronous
Altitude	600km
Eccentricity	0.003
Nominal Separation	500km





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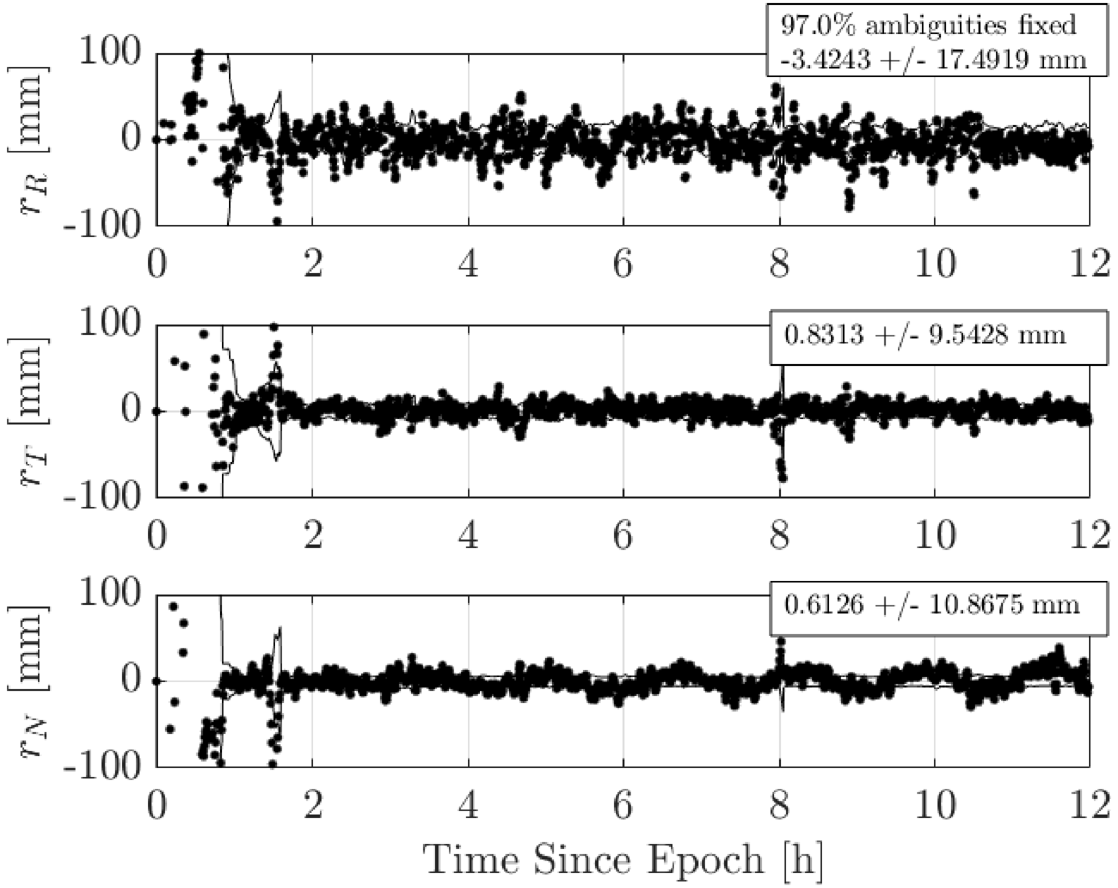
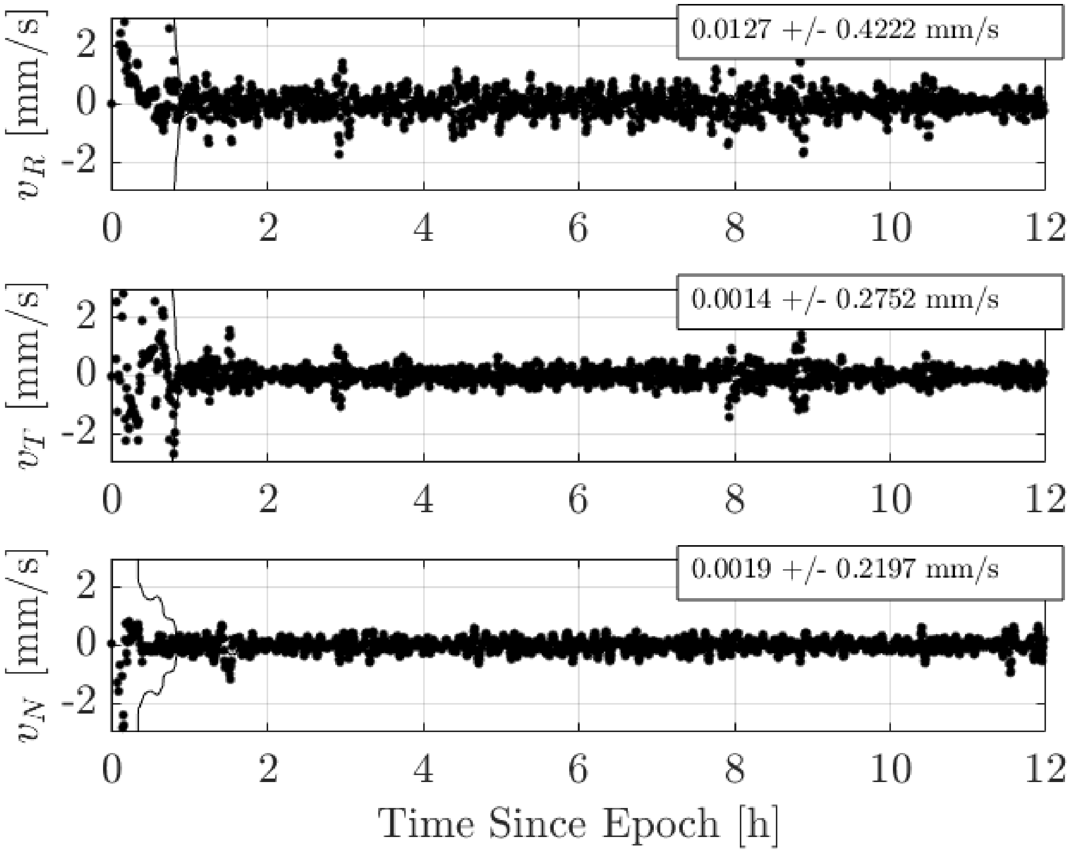
Orbit Determination



Relative Position Error



Relative Velocity Error

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Conclusions

- Developed a navigation payload for nanosatellite swarms
  - COTS hardware
  - Differential GNSS with **IAR in real-time**
  - **Centimeter-level** relative positioning accuracy
- Demonstrated on **CubeSat avionics** in HIL testbed
- Extended algorithms to account for differential ionospheric delay
  - Accurate up to **hundreds of kilometers**

Stanford GNSS Testbed with newly acquired third flatsat

Ways Forward

- Expand swarm determination algorithms
  - **Kinematic Kalman filter**
  - Covariance intersection
  - Data fusion
- Expand hardware capabilities
  - **To GEO and Cislunar**
  - Full integration with Chip-Scale Atomic Clock
- Selected for following missions:
  - **DWARF** (2022)
  - **VISORS** (2024)
  - **SWARM-EX (offline)** (2024)
  - **mDOT** (Pre-Phase A)

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