Angles-Only Absolute and Relative Trajectory Measurement System (ARTMS)

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NASA POC: Dr. Howard Cannon

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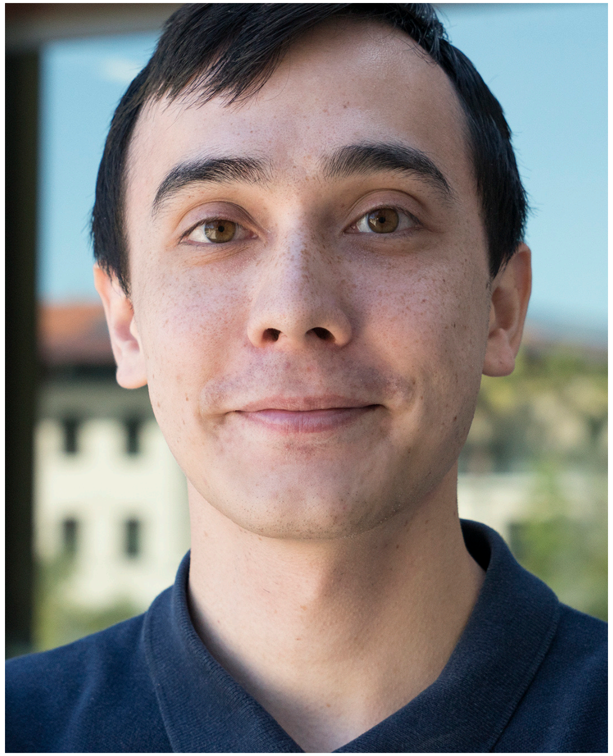
Postdoctoral Scholar



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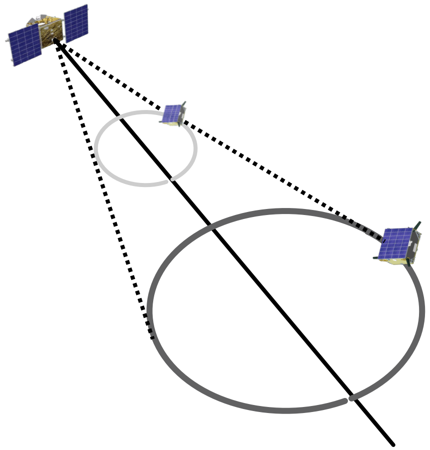
ARTMS Objective and Operating Principles

- **ARTMS is intended to provide autonomous, self-contained navigation for future deep space missions conducted by smallsat swarms**
  - Minimal requirements on ground interaction and data accuracy
- ARTMS is a software payload deployed on each of a team of cooperative observers equipped with low-cost optical sensors and a cross-link radio
  - Estimates absolute and relative orbits of all cooperative spacecraft and noncooperative RSO in a local cluster
  - Target tracking using kinematic constraints on relative motion
  - Nonlinear batch/sequential estimation algorithms that overcome weak observability without translational maneuvers

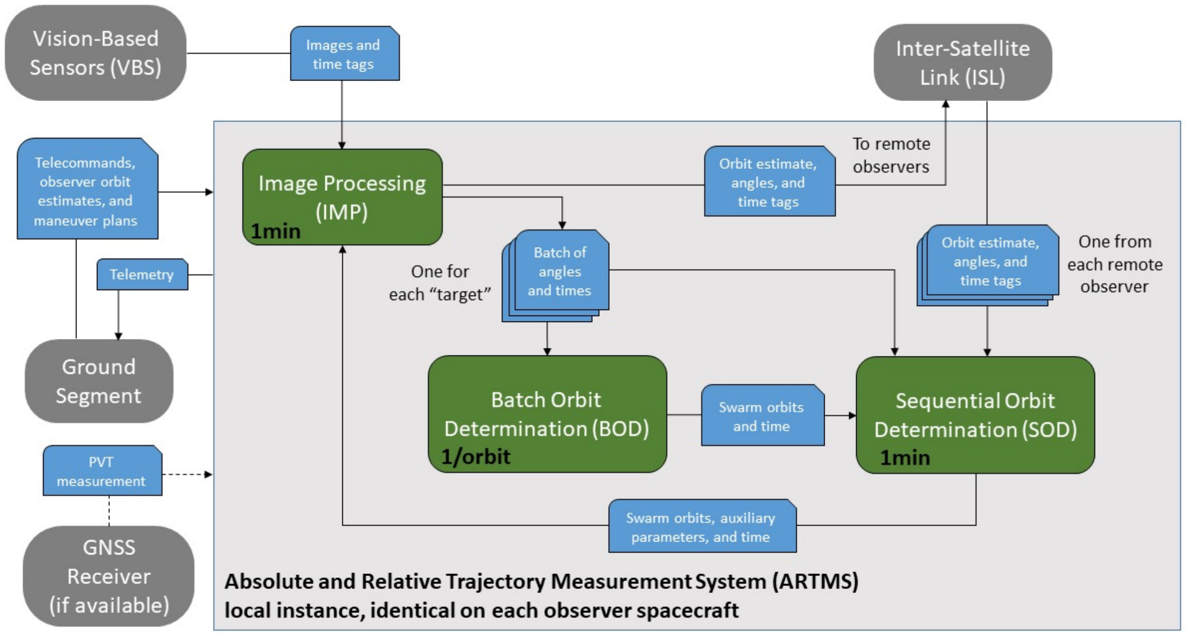
A CubeSat-compatible star tracker.
Credit: BCT



Angles-only range ambiguity.

ARTMS Architecture

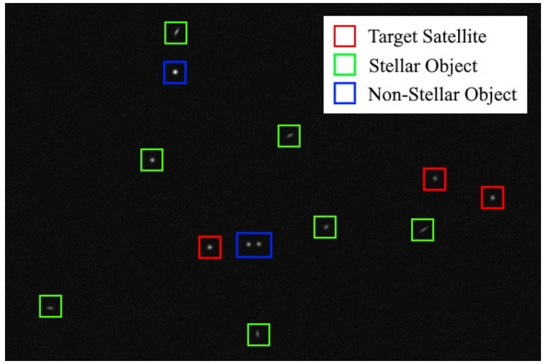
- ARTMS includes three modules:
  - Image Processing (IMP)
  - Batch Orbit Determination (BOD)
  - Sequential Orbit Determination (SOD)
- IMP produces batches of bearing angles to each detected target
- BOD estimates state of local swarm using bearing angles and one orbit estimate
- SOD refines estimate using bearing angles from all observers



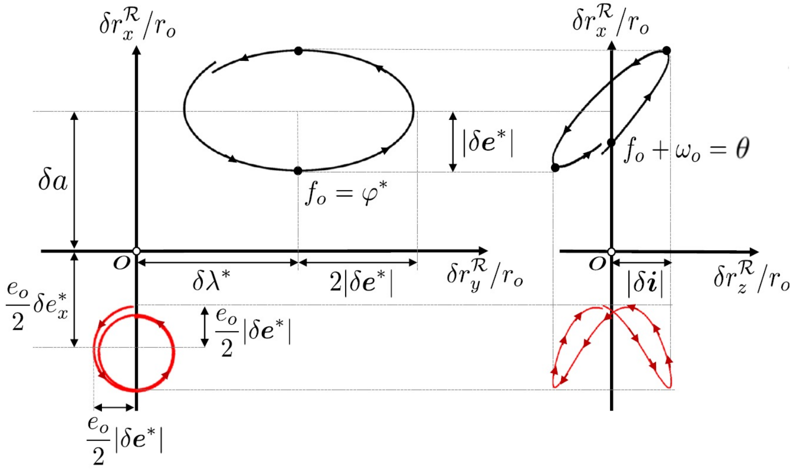
Data flow between ARTMS modules and external systems.

Image Processing (IMP)

- **Goal: produce batches of bearing angles corresponding to each detected target using**
  1) Coarse estimate of observer's orbit and uncertainty
  2) Images from onboard camera
- Approach: MHT with kinematic constraints
  1) Process images to obtain attitude and bearing angles
  2) Enumerate possible target tracks from measurements
  3) Apply domain-specific models of target kinematics to score candidate tracks
     a) Determine if tracks contain a maneuver
  4) Select most likely measurement assignment candidate
  5) Prune lowest scoring tracks to reduce computation cost



Example VBS image.

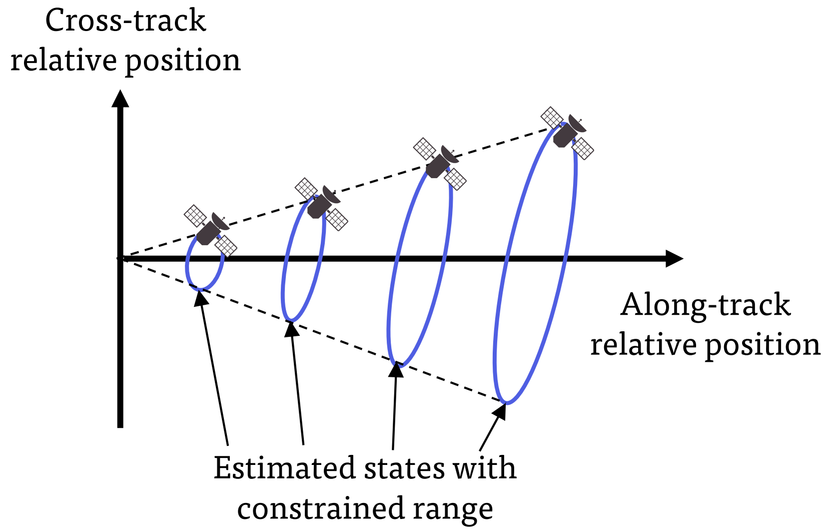


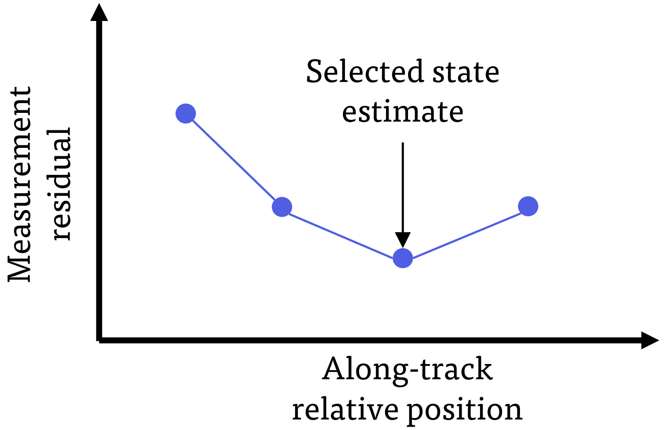
Target kinematics in observer RT (left) and RN (right) planes.

Kruger J. and D'Amico S., "Autonomous Angles-Only Multi-Target Tracking for Spacecraft Swarms", *AAS/AIAA Astrodynamics Specialist Conference* (2020).

Batch Orbit Determination (BOD)

- **Goal: compute orbit estimates for observer and all targets using**
  1) Single estimate of observer's orbit and uncertainty
  2) Batch of bearing angles to each target
- Approach: Sampling-based range estimation
  1) Specify candidate values of mean along-track separation
  2) For each detected target:
     1) Compute one-dimensional family of candidate solutions including observer semimajor axis
     2) Select candidate state with smallest measurement residuals
     3) Compute state uncertainty using measurement residuals
  3) Assemble swarm state estimate



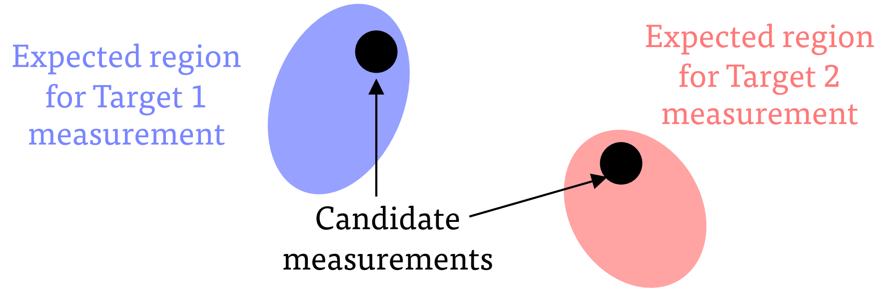


Koenig A. W. and D'Amico S., "Observability-Aware Numerical Algorithm for Angles-Only Initial Relative Orbit Determination", *AAS/AIAA Astrodynamics Specialist Conference* (2020).

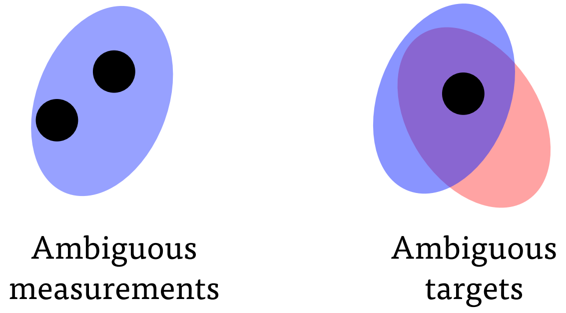
Sequential Orbit Determination (SOD)

- **Goal: continuously refine swarm state estimate provided by BOD using bearing angle measurements from all observers**
  - GNSS solutions used if available
- Approach: Novel unscented Kalman filter (UKF)
  1) Efficient dynamics with integration constants
  2) Exploitation of triangular structure for efficiency
  3) Adaptive process noise tuning
  4) Assignment of ISL measurements using Mahalanobis distance criteria
  5) Fault detection using BOD solutions

Cholesky factorization
$$\begin{bmatrix} L_{11} & 0 & 0 \\ L_{12} & L_{22} & 0 \\ L_{13} & L_{23} & L_{33} \end{bmatrix}$$
Can reuse prior orbit propagation when sigma point data identical to mean



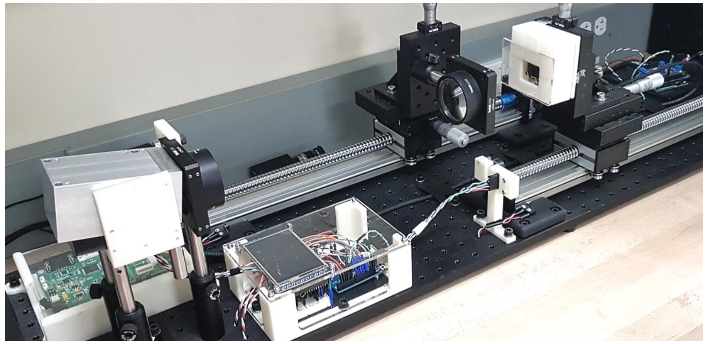
Measurements assigned when correspondence to targets are unique



Sullivan J., Koenig A. W., Kruger J., and D'Amico S., "Generalized Angles-Only Navigation Architecture for Autonomous Distributed Space Systems", *Journal of Guidance, Control, and Dynamics* (2021). Published online.

Status and Current Testing Results

- ARTMS is at TRL 6 after hardware-in-the-loop testing and will advance to TRL 9 on NASA's Starling1 mission
- Software-only Monte Carlo simulations for C++ implementations of each ARTMS module
  - IMP: >99% precision in LEO, eccentric orbits, and Mars orbit
  - BOD: Initial relative orbit estimates with <10km range error in presence of large absolute orbit uncertainty
  - SOD: Steady-state convergence to <1% range error in 5 orbits or less
- High-fidelity hardware-in-the-loop simulations using SLAB's Optical Stimulator (OS) testbed
  - Calibrated point source placement errors of <10arcsec



Optical Stimulator testbed at the Space Rendezvous Laboratory.

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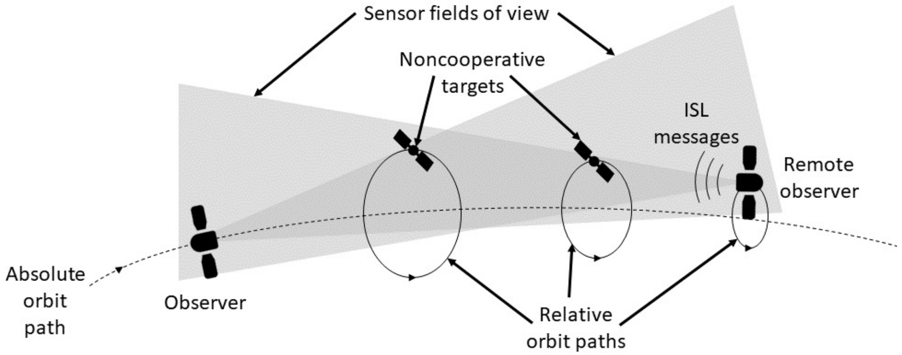
Beierle, C. and D'Amico, S., "Variable-Magnification Optical Stimulator for Training and Validation of Spaceborne Vision-Based Navigation." *Journal of Spacecraft and Rockets*, Vol. 56, No. 4, pp. 1060-1072, (2019).

Example Starling1 Autonomous Navigation Scenario

- ARTMS tested in most challenging experiment configuration planned in Starling1 mission
  - Starling1 includes 4 CubeSats launched into 200km formation in low earth orbit
  - Two observers are provided with a single orbit solution with GNSS-level errors, enabling IMP to start tracking targets
  - Once 2 orbits of measurements are collected, BOD for each observer computes a swarm state estimate using a-priori orbit solution
  - SOD refines swarm state estimate using bearing angles from both observers
- Ground truth data generated by high-fidelity numerical orbit propagator

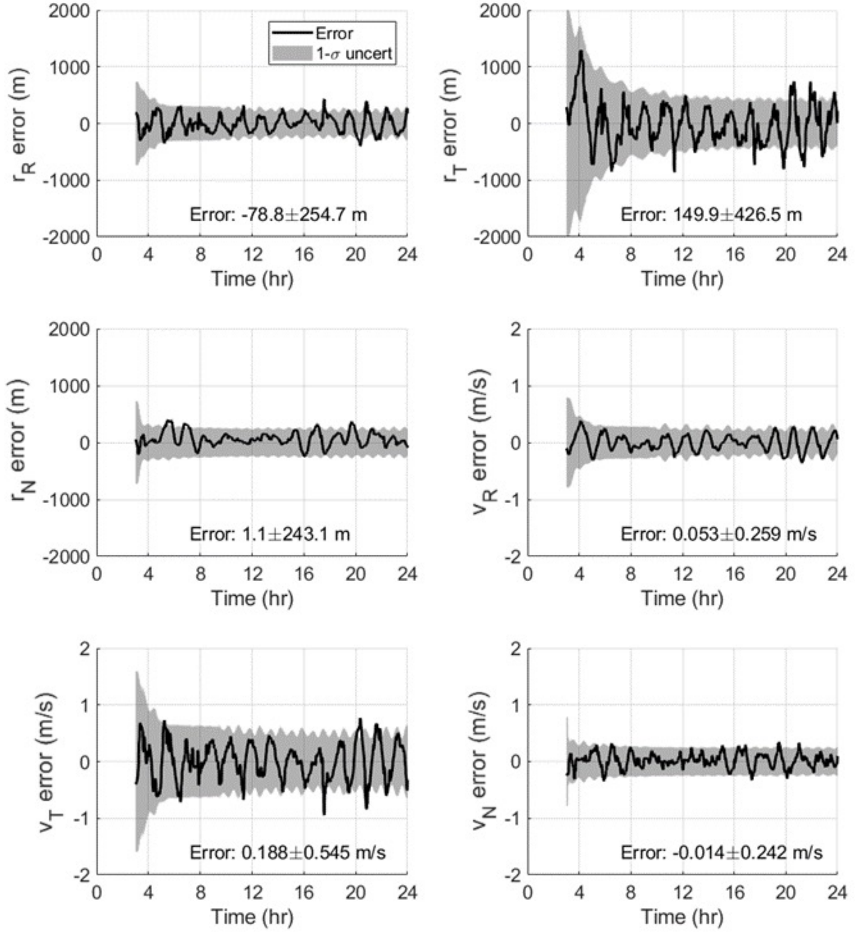


Swarm configuration for test scenario.

	Absolute orbit					
-	a (km)	$e_x(-)$	$e_y(-)$	$i(^o)$	$\Omega(^o)$	$u(^o)$
Observer	6978	0.0014	0.0014	98	40	105
	Relative orbits					
ROE (m)	$a\delta a$	$a\delta\lambda$	$a\delta e_x$	$a\delta e_y$	$a\delta i_x$	$a\delta i_y$
Target 1	0.0	65000	0	3000	0	3000
Target 2	0.0	133000	0	2600	0	2600
Target 3	0.0	200000	0	1200	0	1200

Initial absolute and relative orbits.

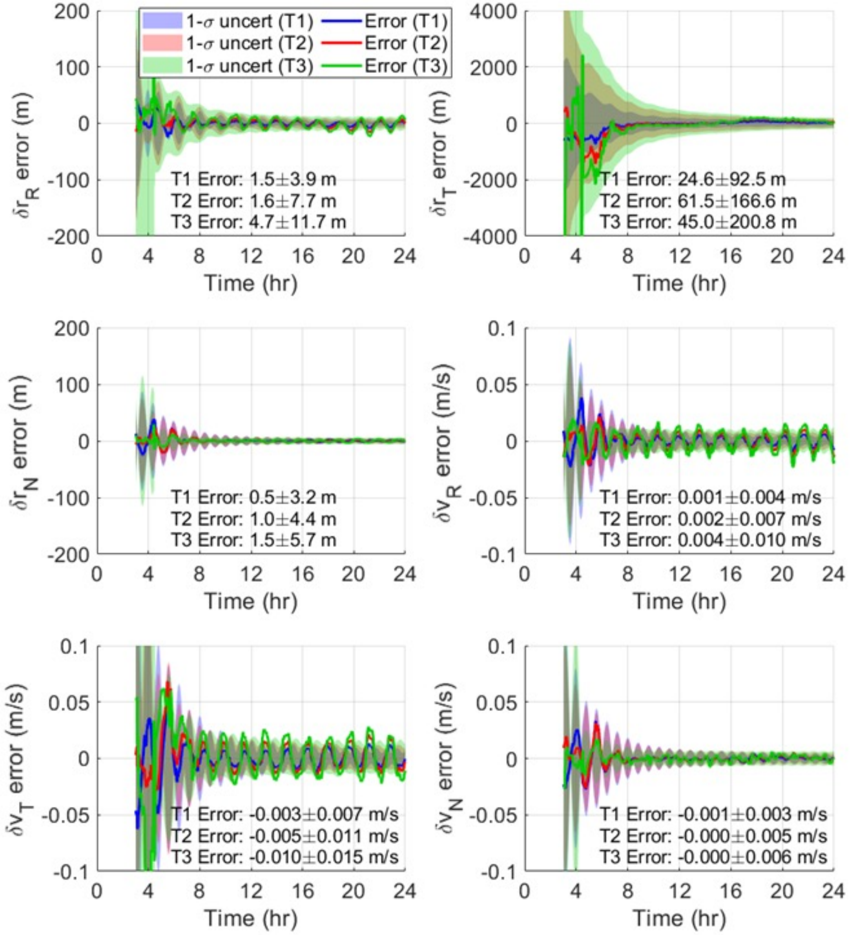
Test Results: Starling1 Autonomous Navigation



Filter converges in 12hr

Steady-state position errors of 300m and velocity errors of 0.3m/s

Absolute navigation errors in local RTN frame.



Initial errors of 2-5km in range

Steady state range errors of 200m or less

Filter able to converge with only a single a-priori orbit estimate for each observer

Relative navigation errors in local RTN frame.

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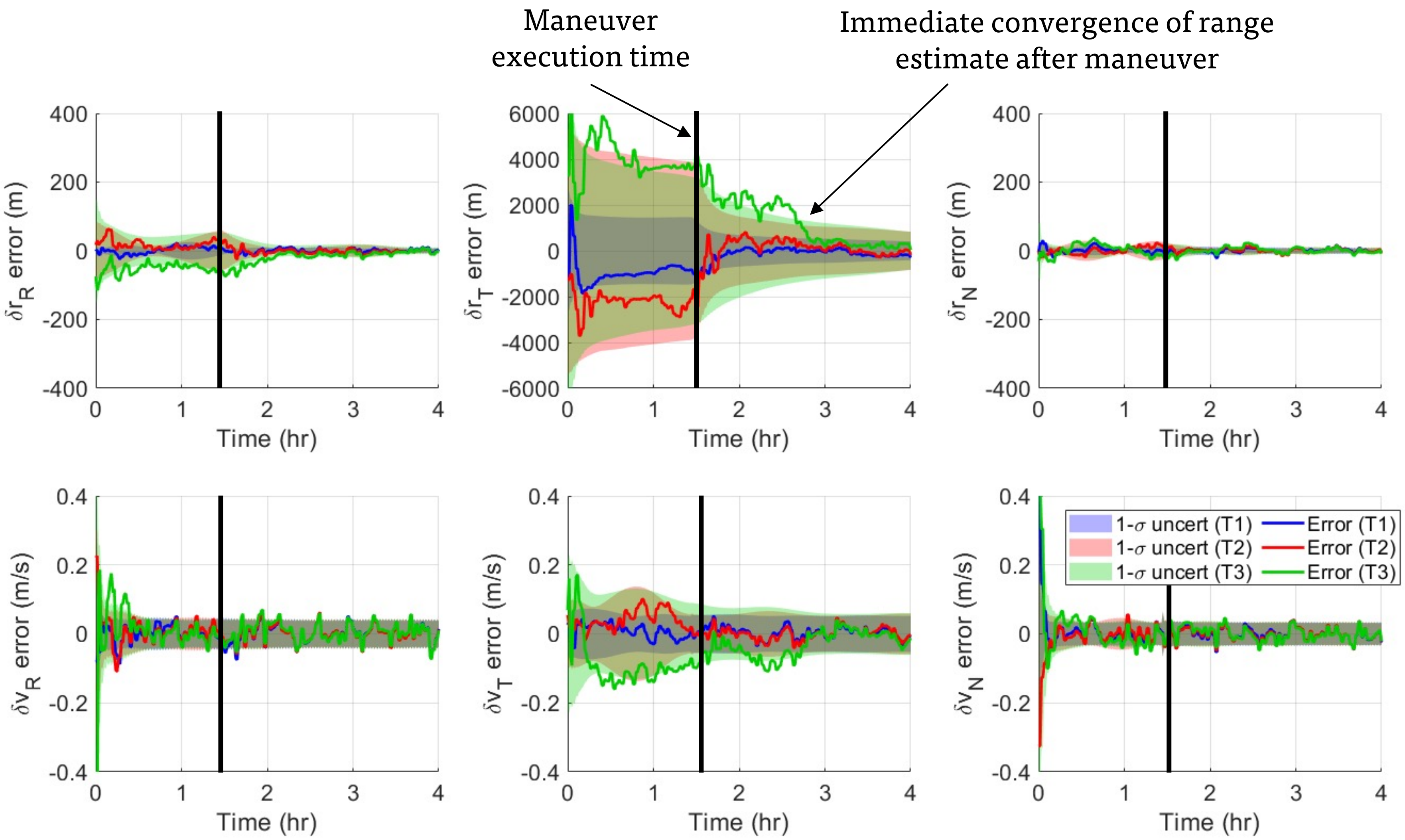
Test Results: Translational Maneuver



Starling1 relative navigation results with 1m/s translational maneuver.

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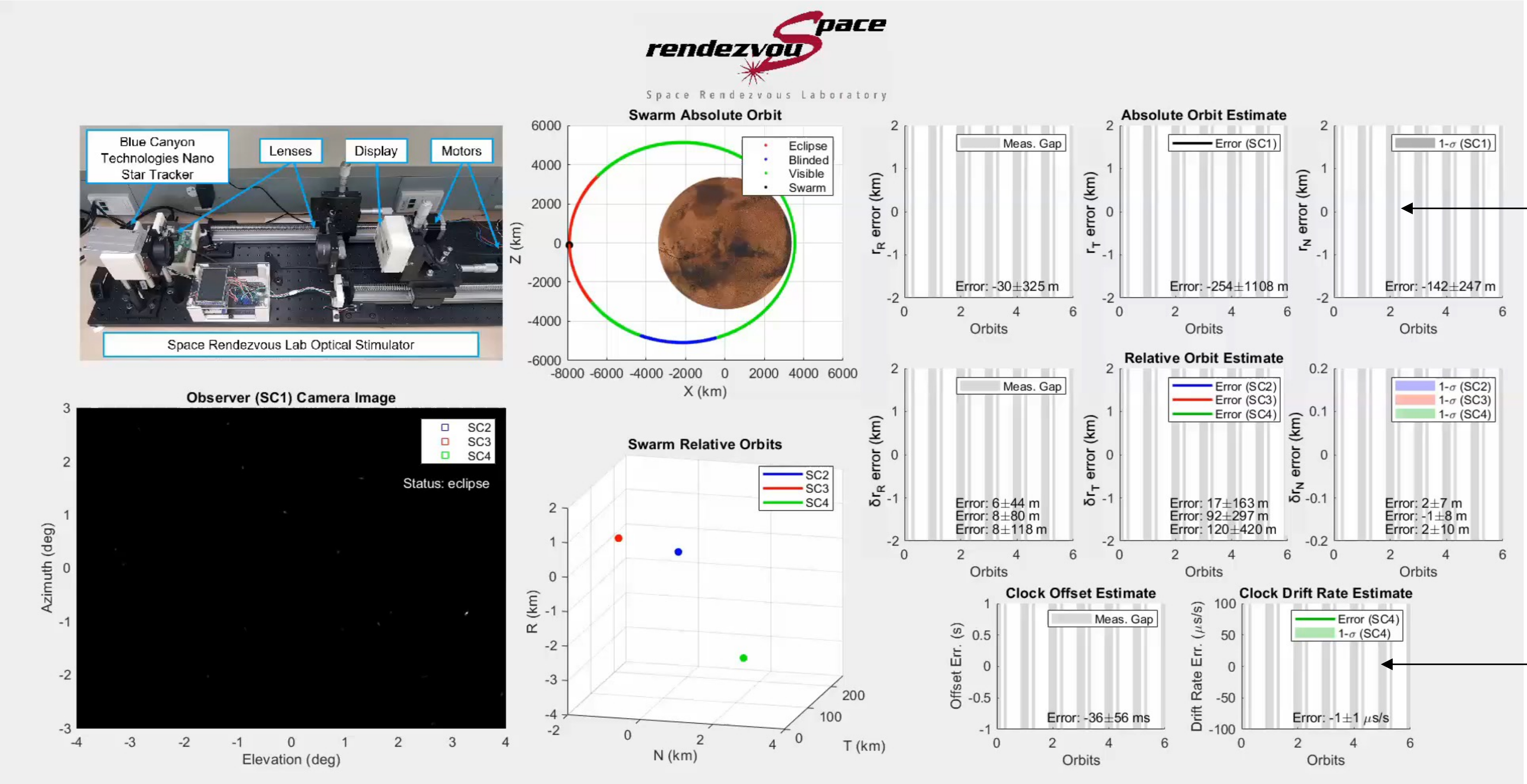
Test Results: Mars Orbit



Convergence robust to data outage from eclipse and blinding

Able to estimate differential clock offset and rate

Autonomous navigation test results in Mars orbit.

Status Summary and Next Steps

- Status
  - ARTMS is a software payload at TRL 6 that provides autonomous, self-contained absolute and relative orbit determination using angles-only measurements
  - ARTMS has been tested in software-only Monte Carlo simulations and high-fidelity sensor-in-the-loop simulations using the Optical Stimulator testbed
  - **Completed first demonstration of fully autonomous angles-only orbit determination using a single orbit estimate for each observer provided by the ground**
- Next steps
  - Comprehensive profiling on flight processor and verification/validation testing
  - Integration into Starling1 flight software and flight demonstration for TRL 9
  - Generalize to more challenging orbit environments (e.g., Mars, cislunar, and deep space)
  - Address more challenging scenarios (e.g., maneuver detection, partial networks)

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