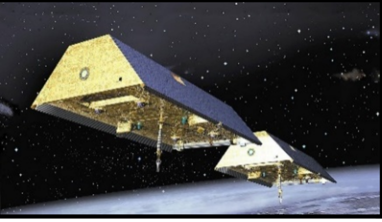

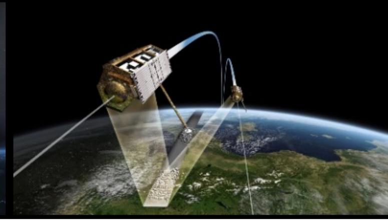
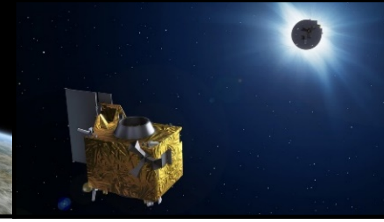
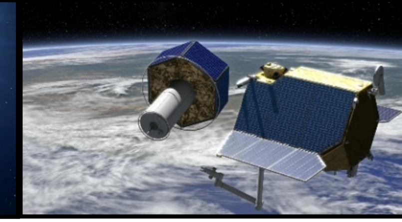

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Spacecraft Formation-Flying and Rendezvous: Flight Demonstrations and Way Forward

Simone D'Amico, PhD
Assist. Prof. of Aeronautics and Astronautics
Director, Space Rendezvous Lab

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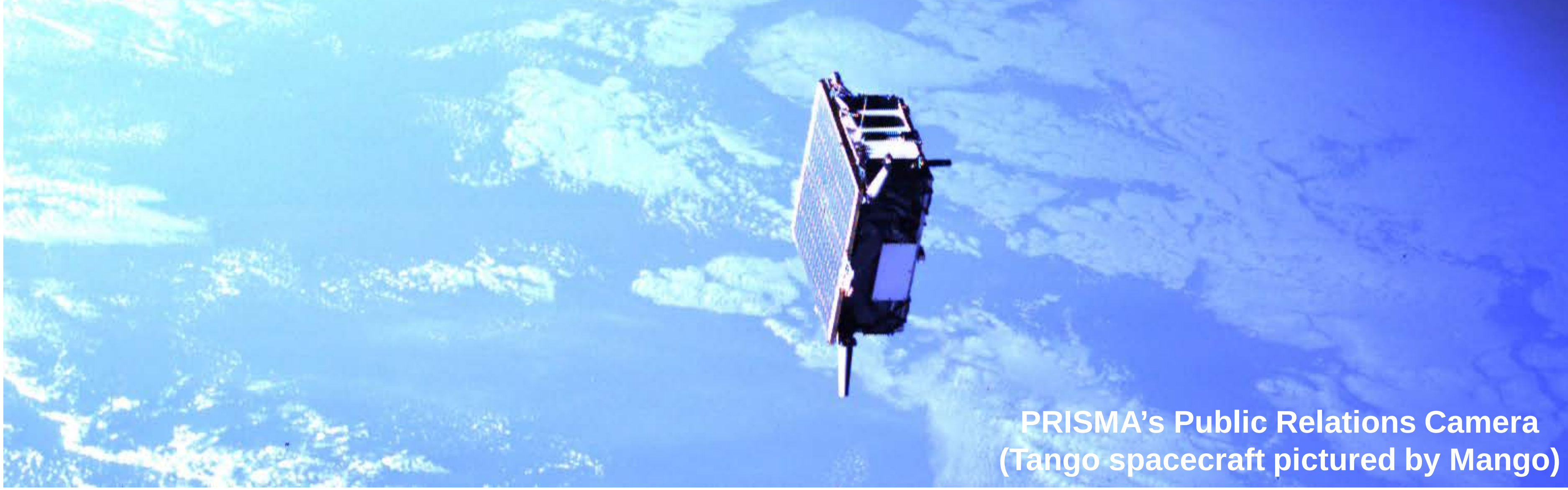
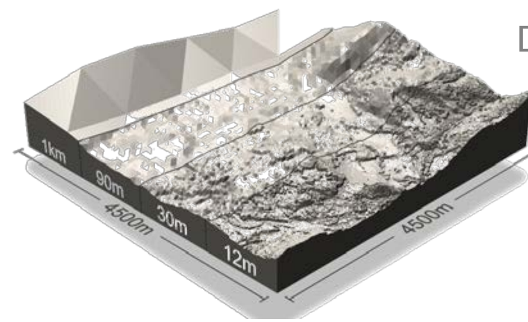


PRISMA's Public Relations Camera (Tango spacecraft pictured by Mango)

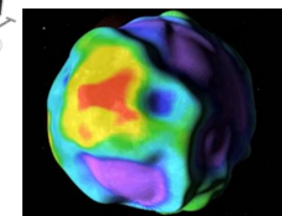
Why Distributed Space Systems?

- Space Science
  - Astronomical search for origins
  - Solar system exploration
  - Structure and evolution of the universe
- Planetary Science
  - Synthetic aperture radar interferometry
  - Gravity mapping
  - Atmosphere characterization
- Technology
  - Human exploration technology
  - On-orbit servicing and assembly
  - Development of space infrastructure

Kepler 186
Solar System



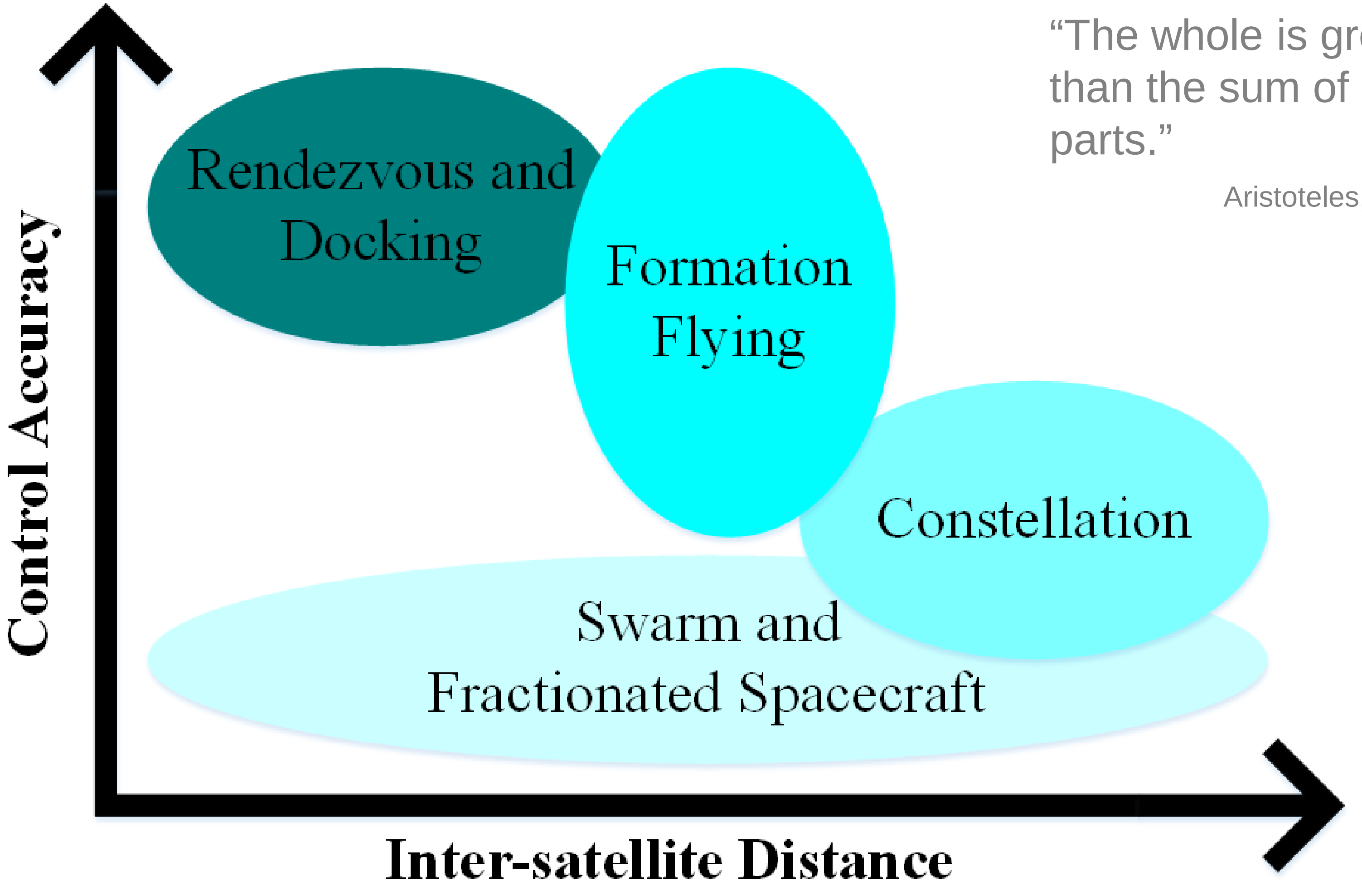
DEM Accuracy
(TanDEM-X)



Moon gravity
(GRAIL)

Autonomous
approach to the ISS
(HTV)

What is a Distributed Space System?



"The whole is greater than the sum of its parts."

Aristoteles, 350 B.C.

Distributed Space Systems Are Not New

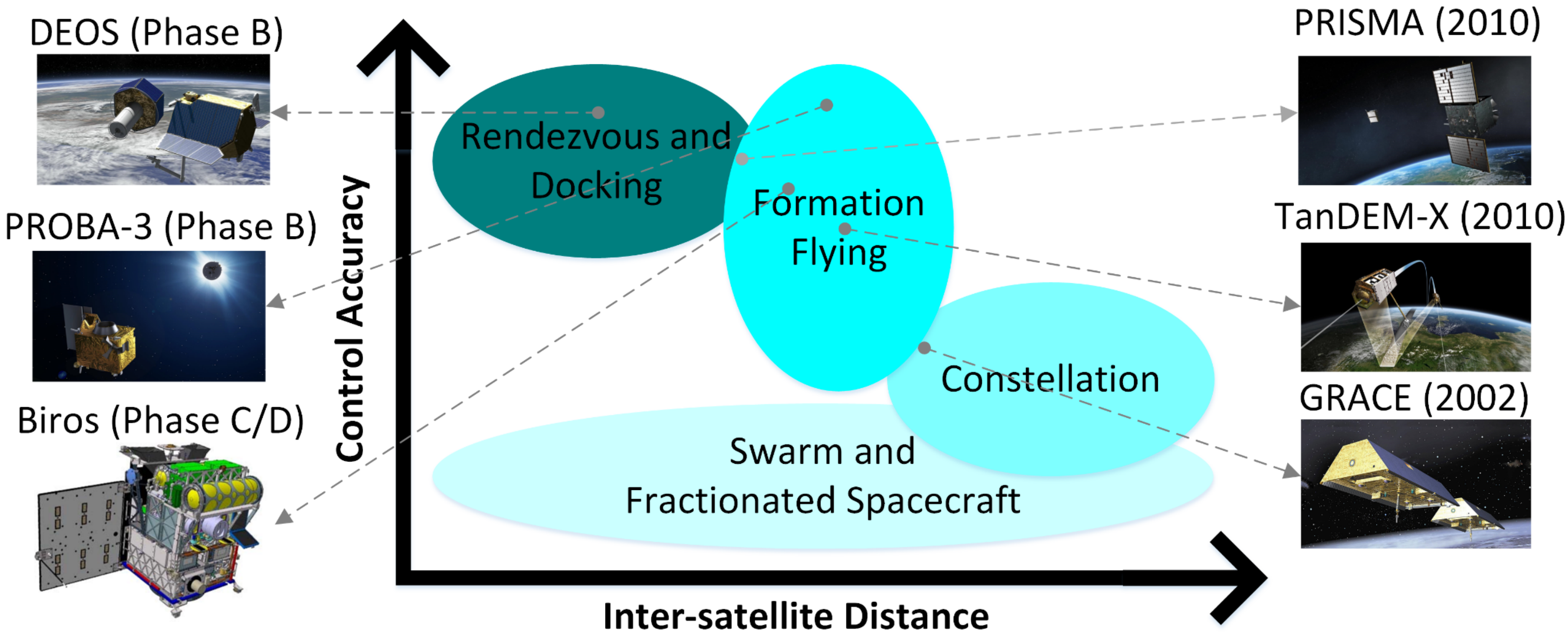
Historic milestones
- Short duration
- Ground-control
- Blank checks

Contemporary
- Long duration
- Autonomy
- Cost constraints

Future
- Miniaturization
- Distribution
- Standardization

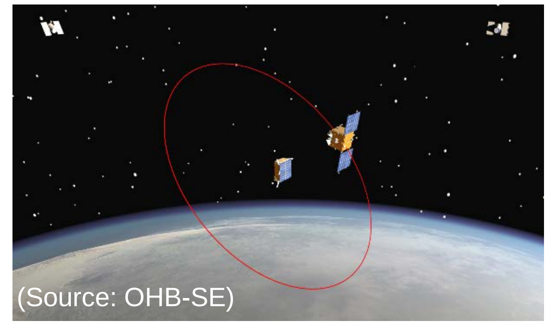
Type	Involved	Year
First FF experiment	Gemini 6A & 7	1965
First automated docking	Kosmos 186 & 188	1967
RvD at other celestial bodies	Columbia & Eagle	1969
RvD with vehicles from 2 nations	Apollo & Soyuz	1975
RvD of 3 “objects”	D.Gardner, Weststar VI, Discovery	1984
Collision due to FF	Progress & MIR	1997
Autonomous FF	ETS-7	1998
Autonomous microsatellite RvD	XSS-11 & Minotaur 4th stage	2005
Collision due to RvD	DART & MUBLCOM	2005
First on-orbit servicing demo	Orbital Express	2007
Fully autonomous docking	ATV & ISS	2008

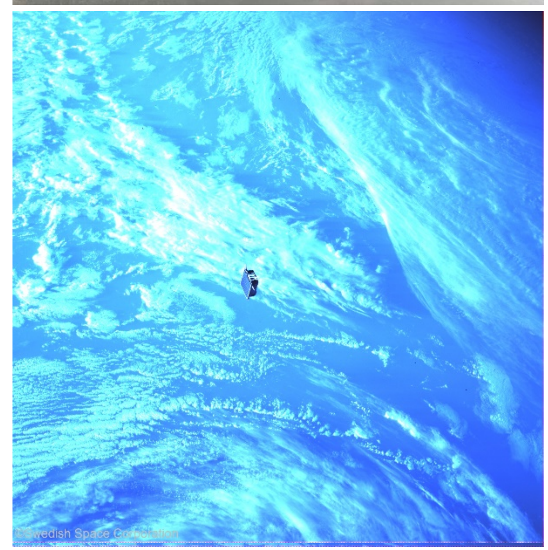
Most Recent Mission Achievements



PRISMA: Prototype Research Instr. & Space Mission Tech. Advancement

- Two microsatellites (Mango, Tango)
  - Launch 2010 (Dnepr from Yasny)
  - Presently in extended mission phase
  - Sun-synch. orbit at 710 km altitude
- GN&C software experiments
  - Autonomous formation flying (5 km – 20 m)
  - Homing and rendezvous (< 50 km)
  - Proximity operations (100 m – 0 m)
- GN&C hardware experiments
  - Green propellant & Micro-propulsion
  - GPS (DLR), FFRF (CNES), VBS (DTU)

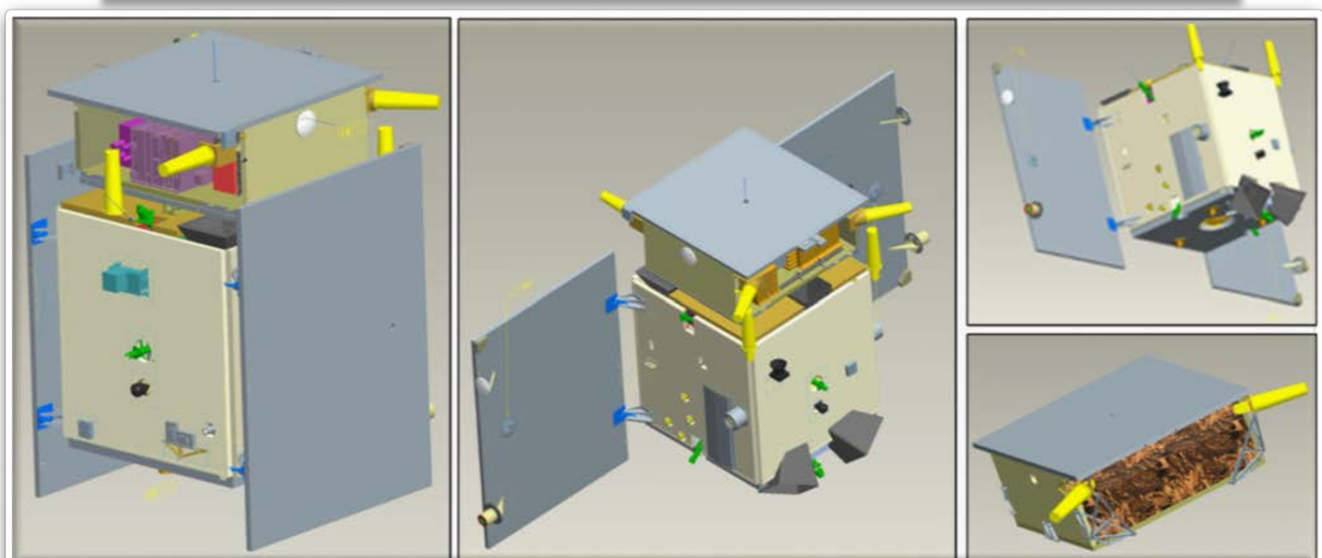




Fly around
March 27, 2011

PRISMA: Spacecraft

AOCS/GN&C		Mango	Tango
Attitude control	Sensors	MM,SS,GYR,SCA	MM,SS
	Actuators	MT,RW	MT
Orbit control	Sensors	GPS,FFRF,VBS	-
	Actuators	6 1N-Hydrazine	-



SAFE: Spaceborne Autonomous Formation Flying Experiment

Key Objectives

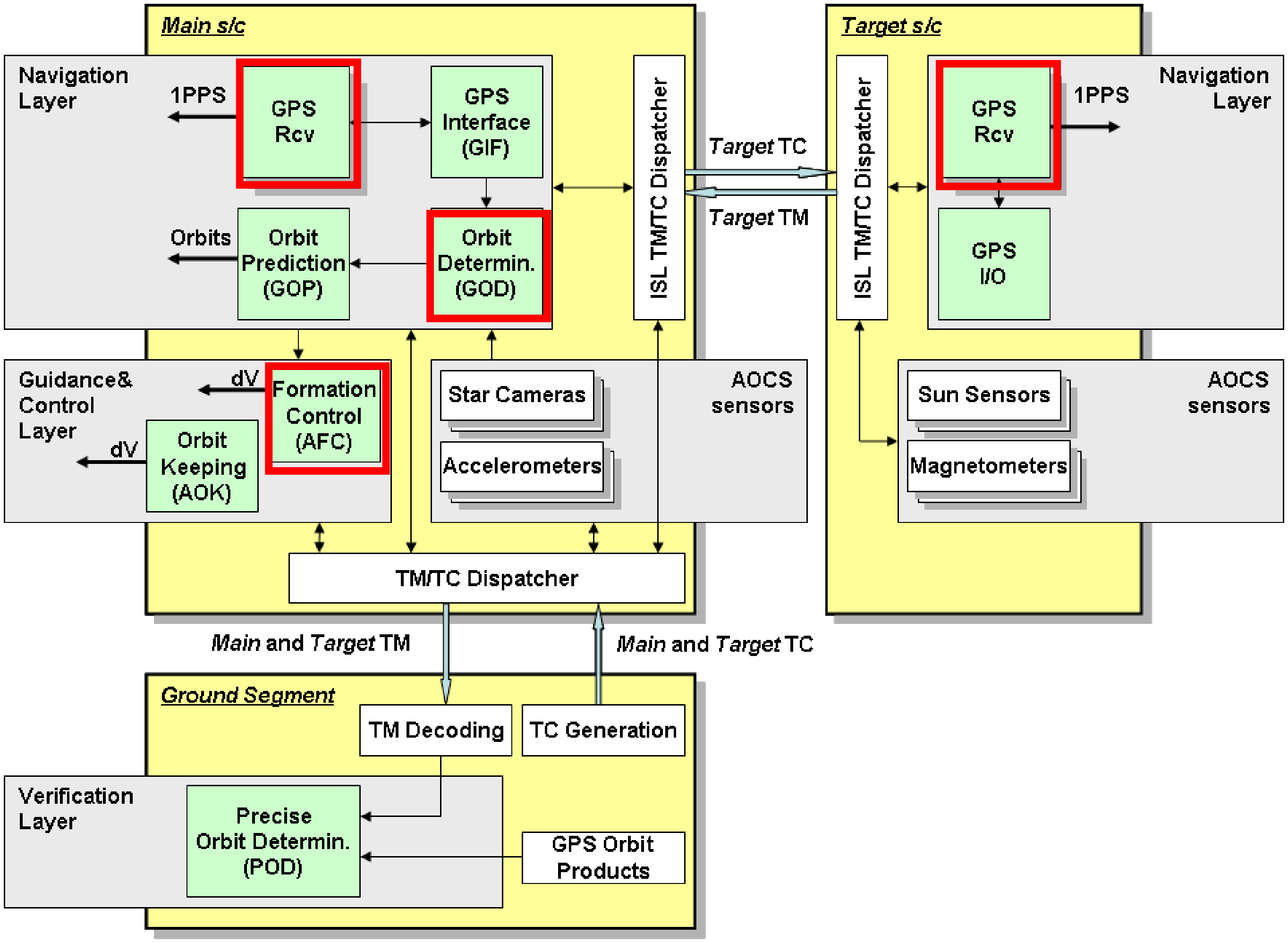
On-Orbit

- **GPS receivers (DLR's Phoenix-S)**
  - High accuracy code and carrier phase measurements
  - Redundant and flexible system architecture
- **GPS-based real-time navigation system (GIF,GOP,GOD)**
  - Absolute position accuracy of 3 m (3D, RMS)
  - Relative position accuracy of 0.2 m (3D, RMS)
- **Impulsive autonomous formation control (AFC)**
  - Guidance based on relative eccentricity/inclination vectors
  - Relative orbit control accuracy of 30 m (3D, RMS)

On-Ground

- **Precise Orbit Determination (POD)**
  - Reduced-dynamic orbit determination from GPS raw data
  - Absolute position accuracy of 0.2 m (3D, RMS)
  - Relative position accuracy of 0.02 m (3D, RMS)

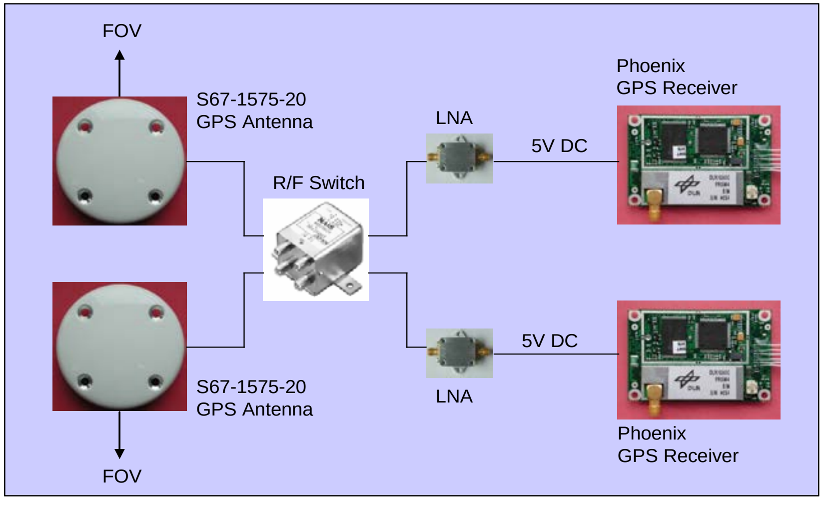
SAFE: Top Level Architecture



Architecture Design

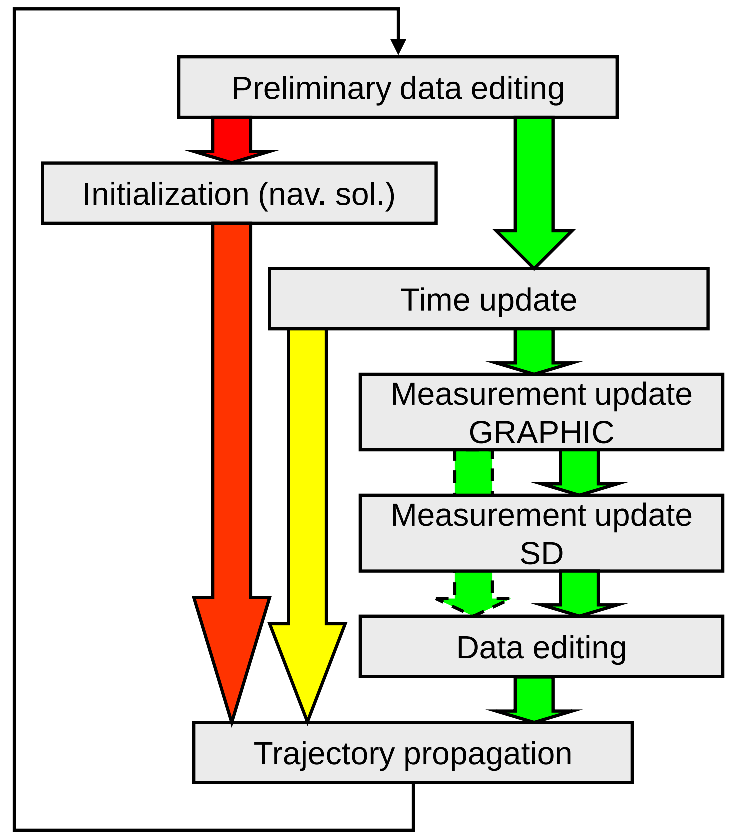
SAFE: GPS Hardware

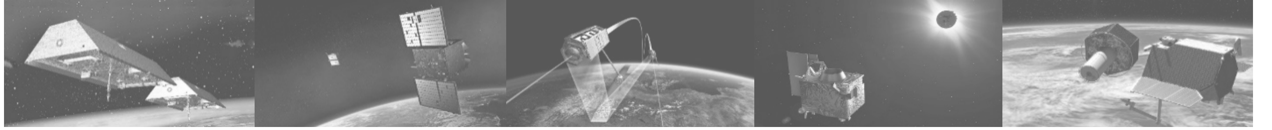
- Phoenix-S GPS Receiver
  - SigTec, COTS
  - DLR software
  - 12 channels L1 C/A tracking
  - Power 0.8 W (BOL) at +5V
  - Latch-up/FDIR protection (SSC)
- Performance
  - C/A code noise 0.5 m @ 45 dB-Hz
  - Carrier tracking 1 mm @ 45 dB-Hz
- Redundancy & Flexibility
  - Two receivers and amplifiers
  - Two passive antennas
  - Automatic switch of branches



SAFE: GPS-based Orbit Determination (GOD)

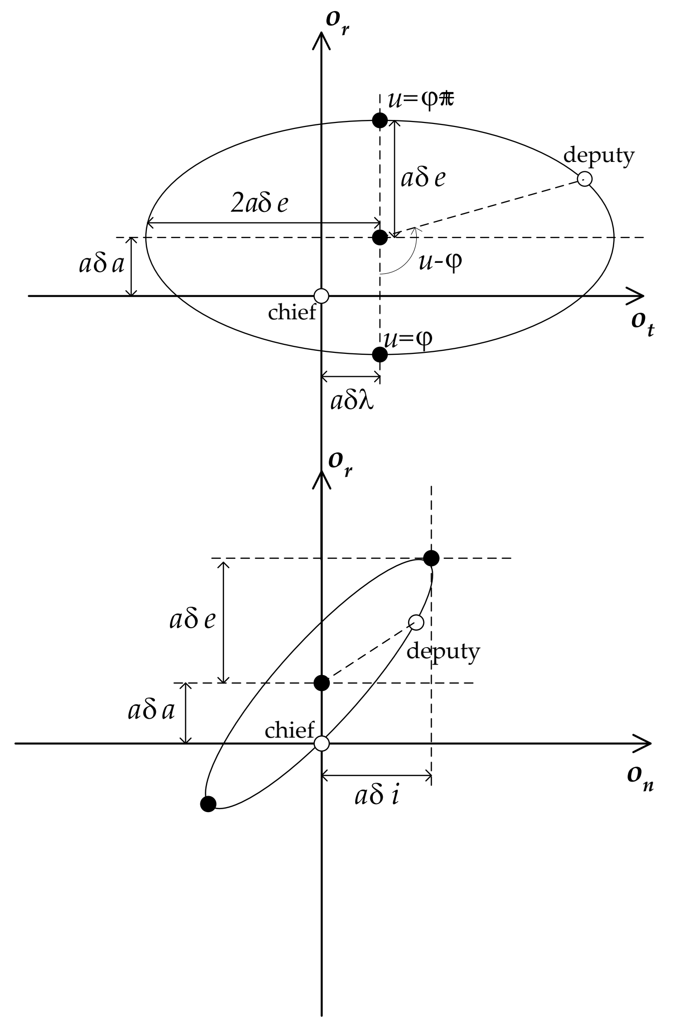
- Extended Kalman Filter with 46+3 states
  - Absolute pos. and vel. (2*6)
  - Aerodynamic drag (2*1)
  - Empirical accelerations (2*3)
  - Clock offsets (2*1)
  - GRAPHIC float biases (2*12)
  - MAIN delta-v maneuver (1*3)
- Measurements Concept
  - Ionosphere free GRAPHIC data (<=2*12)
  - Single-difference Carrier Phase (<=12)
- Dynamics Model
  - 20x20 Earth's geopotential
  - Sun and Moon third-body
  - Jacchia-Gill density model
  - Solar radiation pressure





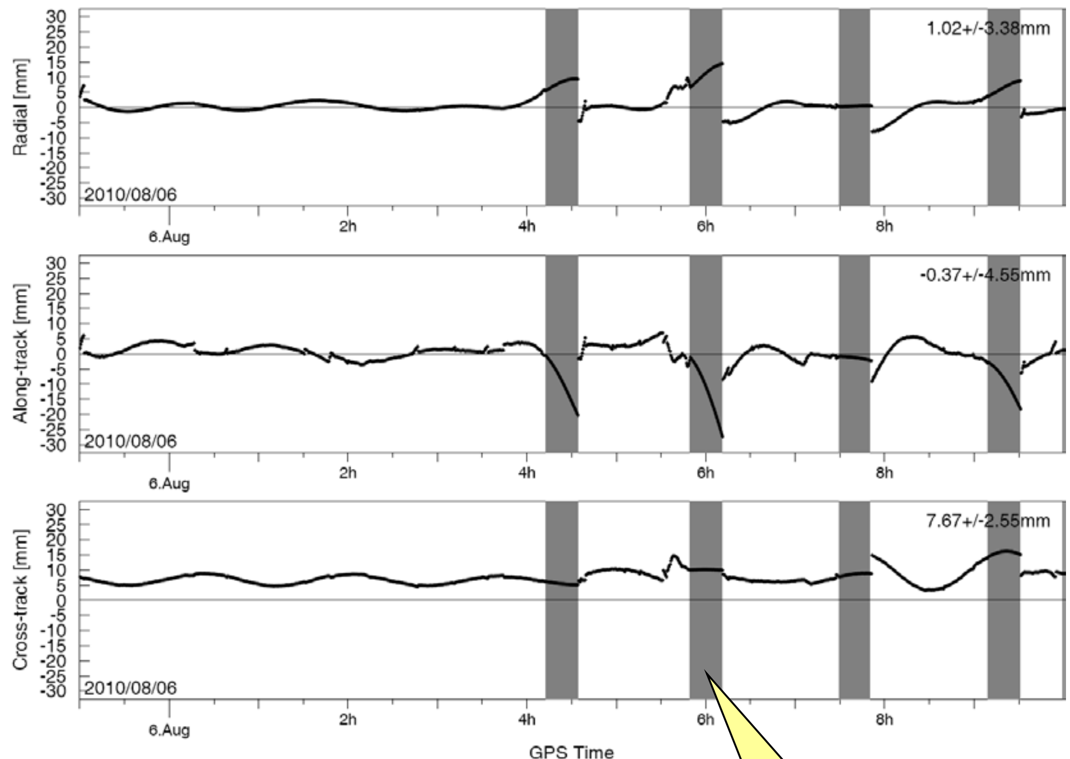
SAFE: Autonomous Formation Control (AFC)

- Relative orbit parameterization
  - Based on relative orbital elements (ROE)
  - δa, δu or $\delta\lambda$, $\delta\boldsymbol{e}$, $\delta\boldsymbol{i}$
- Relative Motion Model
  - HCW + J_2 + Diff. Drag
  - ROE as integration constants of HCW
- In-plane Maneuver Planning
  - Compensation of J_2 induced effects ($\delta\boldsymbol{e}$)
  - Compensation of diff. drag effects (δa)
  - Pairs of along-track (or radial) maneuvers
- Out-of-plane Maneuver Planning
  - Compensation of J_2 induced effects ($\delta\boldsymbol{i}$)
  - Required only if $i_2 \neq i_1$
  - Single cross-track maneuver



SAFE: Precise Orbit Determination (Flight Results)

- Performance
  - ~1 cm with ambiguity fixing
  - Float ambiguity solution sufficient for verification
  - ~2 cm propagation errors during 20 min. data gap
- Combined vs. Free flying
  - High multipath/shadowing
  - Accurate Tango attitude
  - No orbit control maneuvers



South Athlantic Anomaly passages

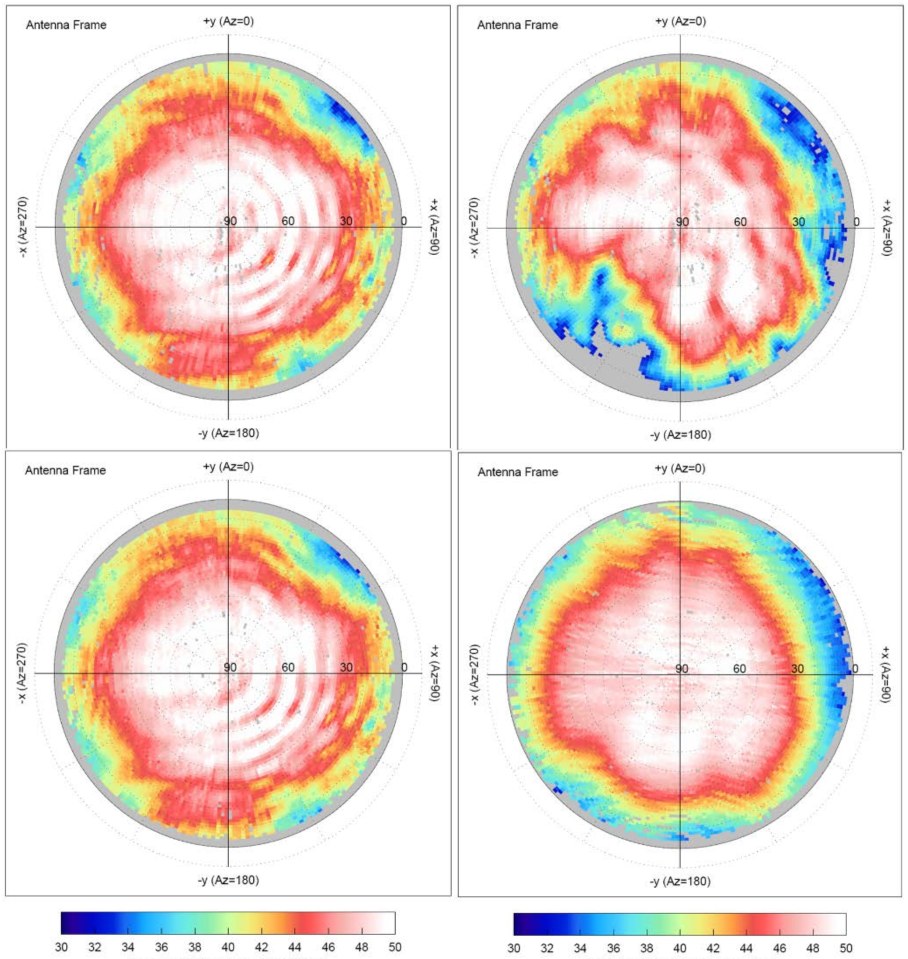
	Relative positioning error [m]		
	Radial	**Tangential**	**Normal**
integer ambiguity	**0.001±0.003**	**0.000±0.005**	**0.007±0.003**
float ambiguity	**0.003±0.022**	**-0.010±0.045**	**-0.015±0.015**

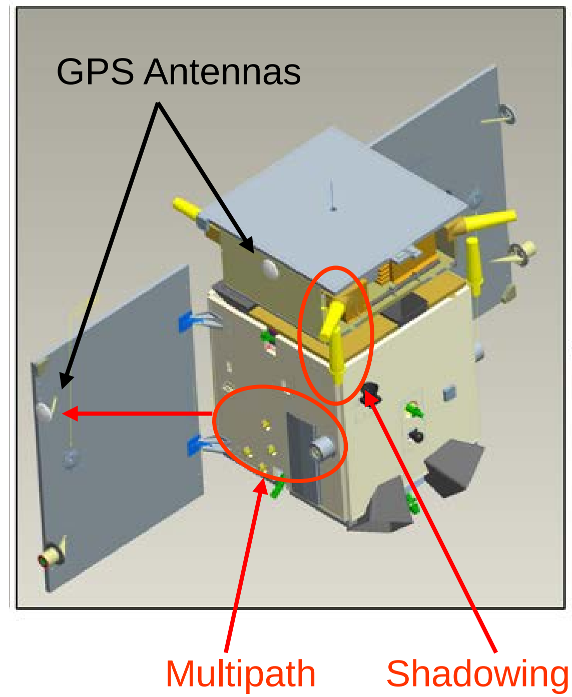
SAFE: GPS Multipath (Flight Results)

Mango | Tango

Before separation
(6-August 2010)

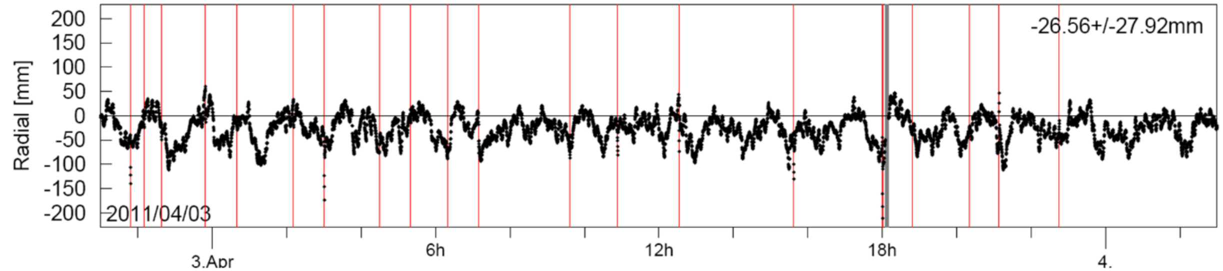
After separation
(22-August 2010)



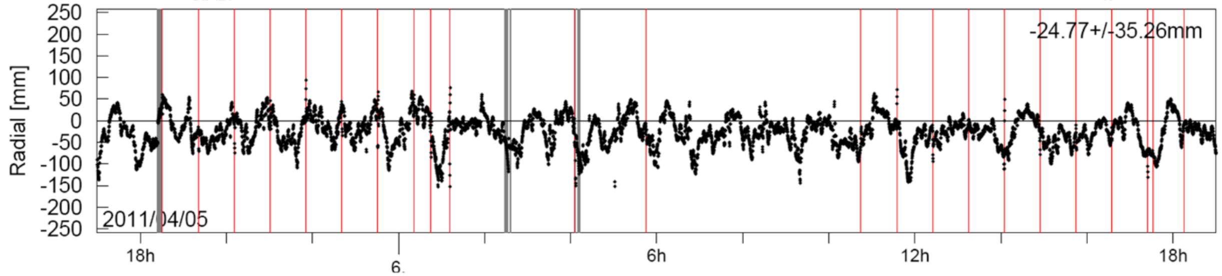


SAFE: GOD Flight Results

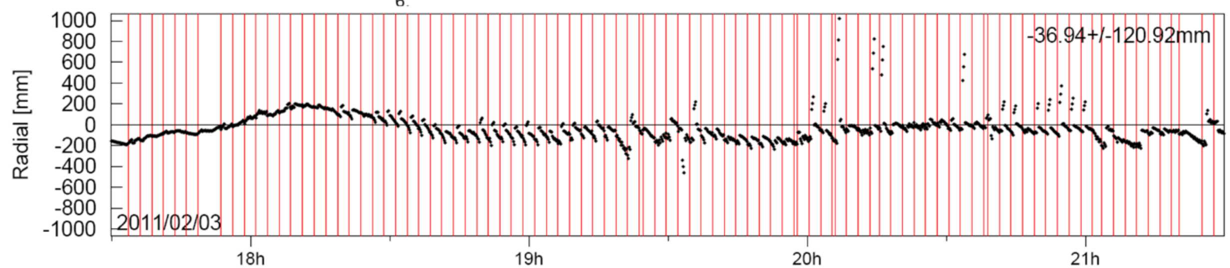
Sparse control/short range [Performance]
Rel. pos. 4.74±1.96 cm (3D)
Rel. vel. 0.12±0.13 mm/s (3D)



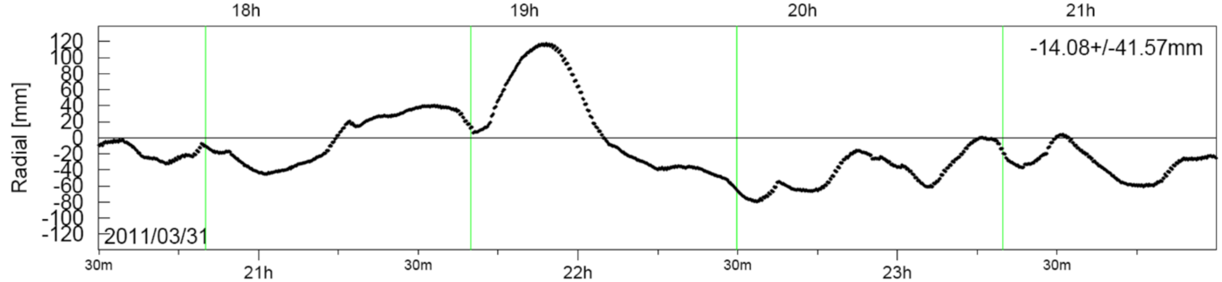
Sparse control/far range [Performance]
Rel. pos. 5.30±2.60 cm (3D)
Rel. vel. 0.20±0.36 mm/s (3D)



Forced motion control [Frequent thrust]
Rel. pos. 14.83±8.01 cm (3D)
Rel. vel. 1.59±1.76 mm/s (3D)

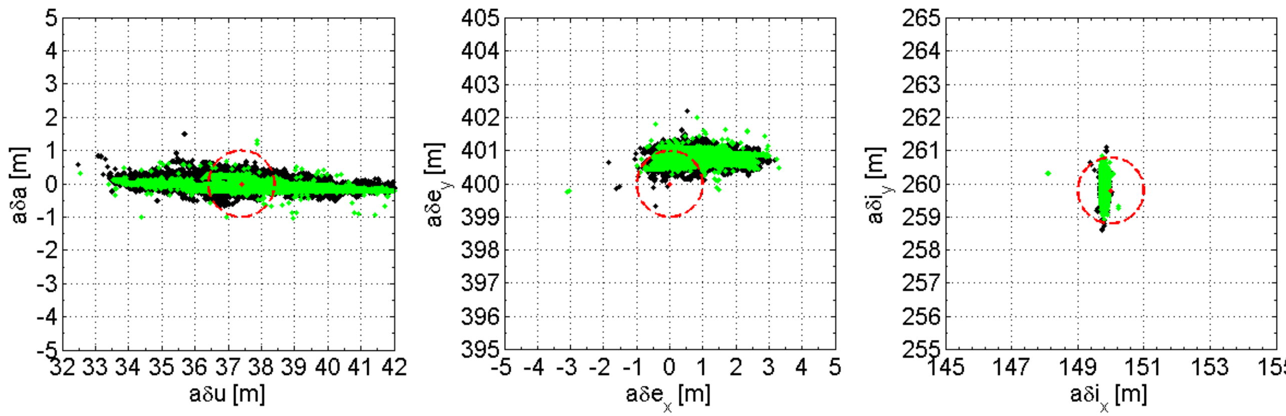


Large attitude rotations [Robust]
Rel. pos. 6.84±2.94 cm (3D)
Rel. vel. 0.08±0.04 mm/s (3D)

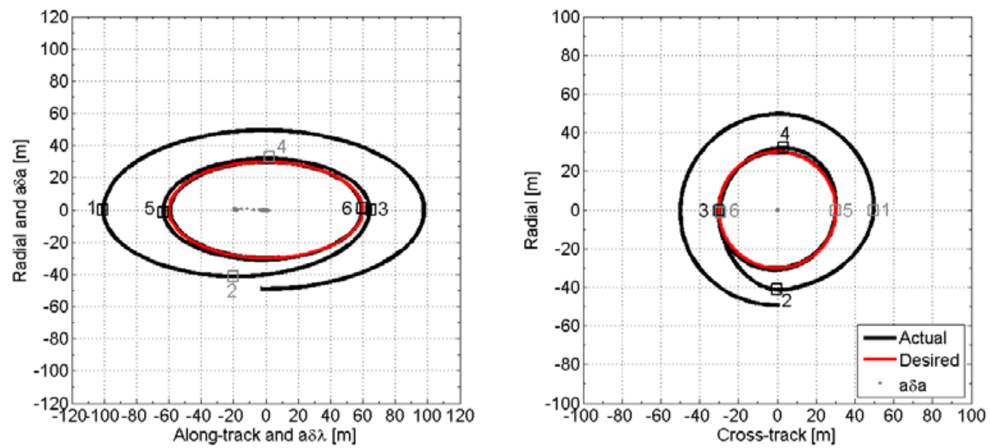


SAFE: AFC Flight Results

AFC1-C (29-30 Sept 2010)
CL-R mode
a$\delta\lambda$=aδa=0
*aδ**e**=(0,400), aδ**i**=(150,259.8)*

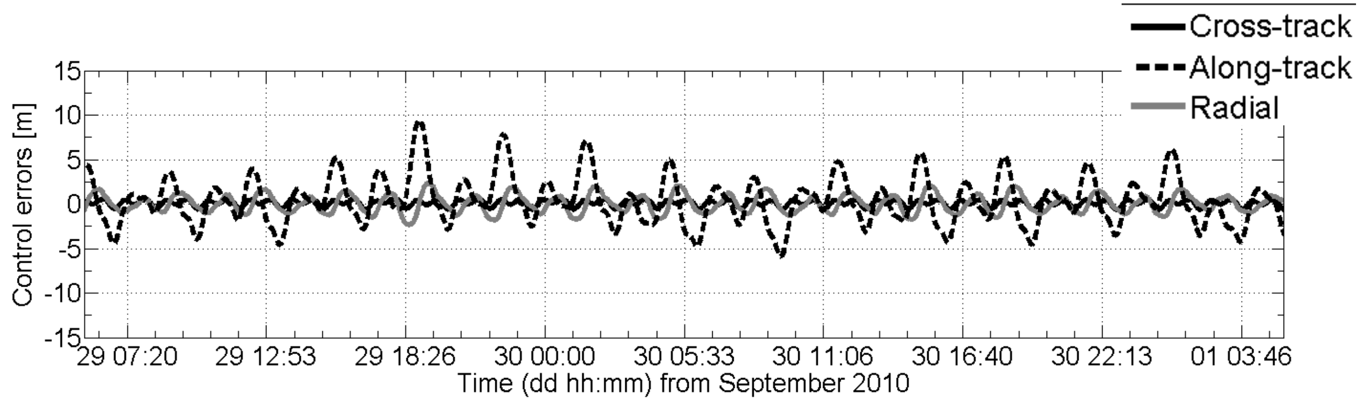


AFC2 H-I (27 March 2011)
CL-R mode
a$\delta\lambda$=aδa=0
*aδ**e**=(0,50 to 30), aδ**i**=(0,-50 to -30)*

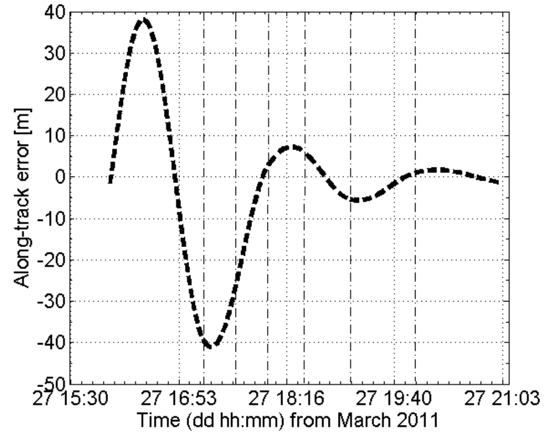


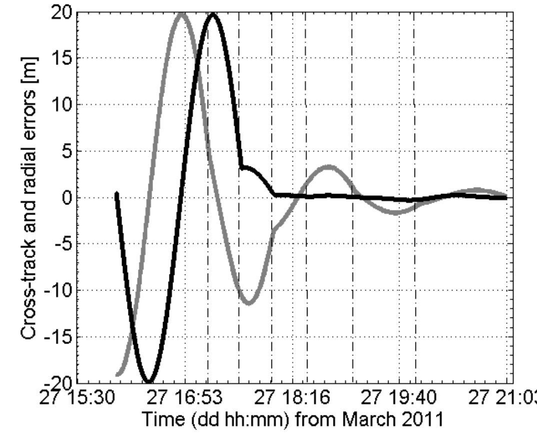
SAFE: AFC Flight Results

AFC1-C (29-30 Sept 2010)
CL-R mode
$a\delta\lambda = a\delta a = 0$
$a\delta\mathbf{e}=(0,400)$, $a\delta\mathbf{i}=(150,259.8)$



AFC2 H-I (27 March 2011)
CL-R mode
$a\delta\lambda = a\delta a = 0$
$a\delta\mathbf{e}=(0,50 \text{ to } 30)$, $a\delta\mathbf{i}=(0,-50 \text{ to } -30)$





ARGON: Advanced Rendezvous using GPS and Optical Navigation

Key Objectives

Functional

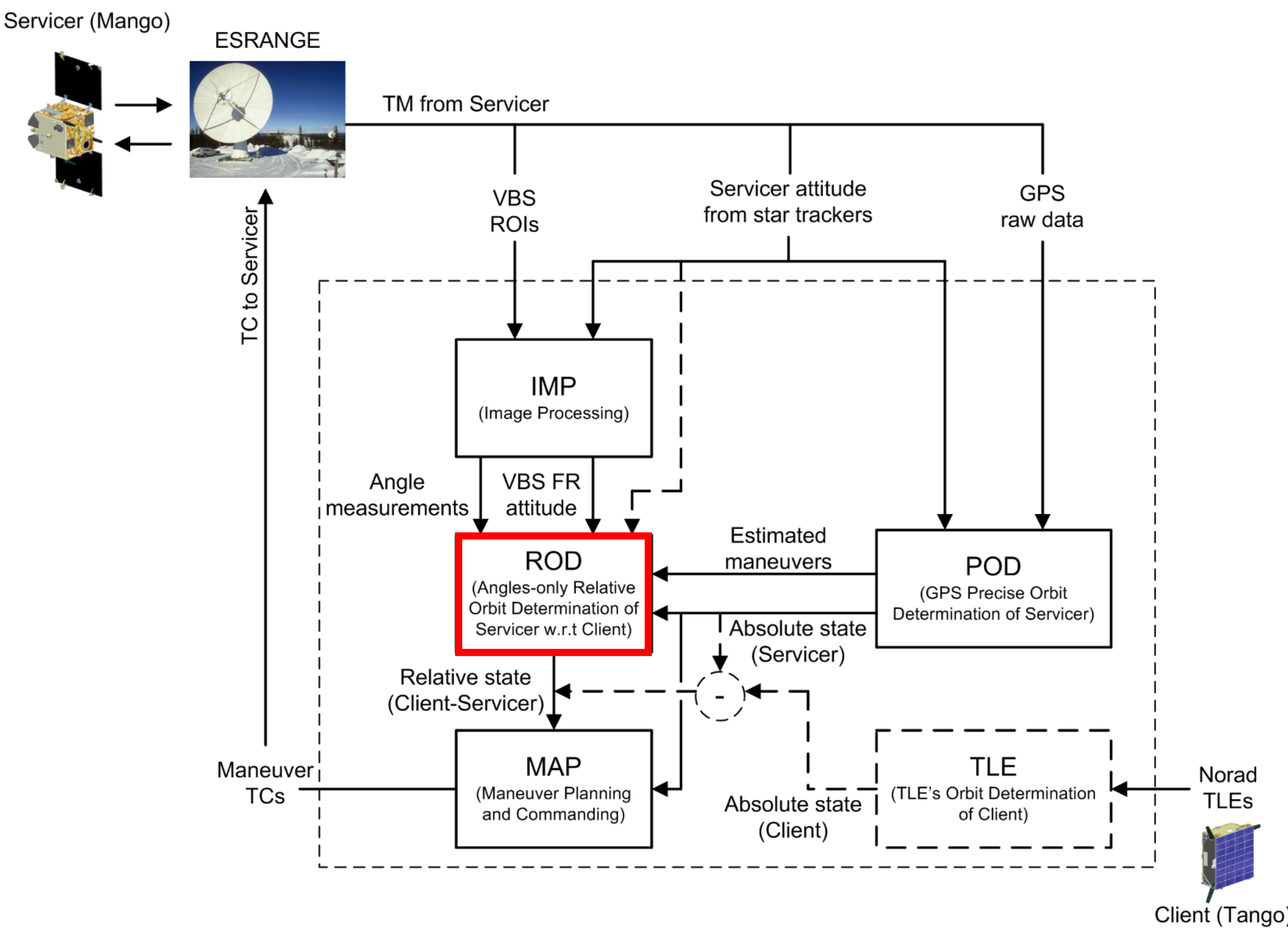
- Handover from Norad TLEs to vision-based navigation and control at 30 km separation
- Planning and execution of safe guidance strategy based on relative eccentricity/inclination vector separation
- Collection and processing of camera images during complete rendezvous
- Accurate relative orbit determination based on angles-only data and ROE linear dynamics model
- Ground-based maneuver planning and execution

Performance

- Range from 30 km to 3 km
- Target identification at 90% hit rate
- Centroiding at sub-pixel accuracy
- Angles-only navigation error <10 m (δa,$\delta \boldsymbol{e}$,$\delta \boldsymbol{i}$) and <300 m ($\delta\lambda$)

ARGON: Top Level Architecture

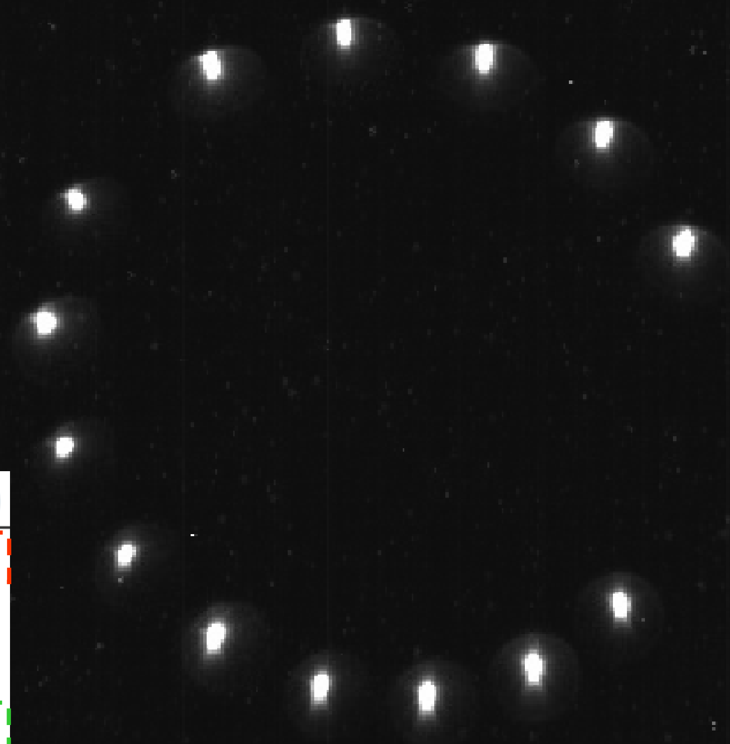
Architecture Design

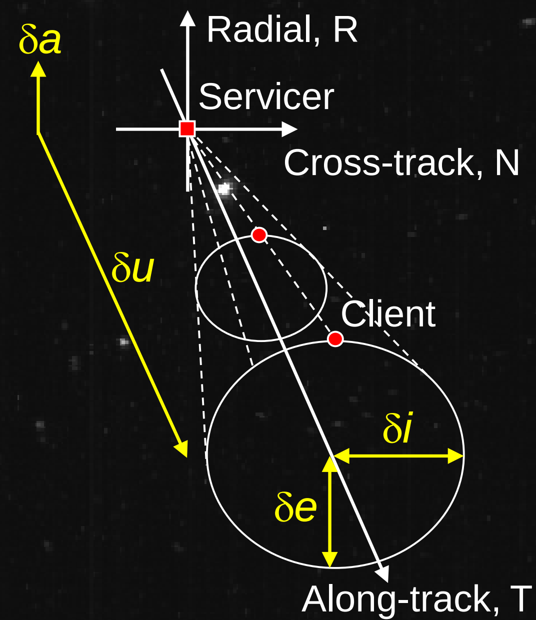


ARGON: Relative Orbit Determination (ROD)

$$\delta\boldsymbol{\alpha} = \begin{pmatrix} \delta a \\ \delta e_x \\ \delta e_y \\ \delta i_x \\ \delta i_y \\ \delta u \end{pmatrix}$$

δa	δu	rank$\mathbf{H}$	cond$(\mathbf{H}^{\mathrm{T}}\mathbf{H})$
x	x	5	1.6^{19}
x	-	5	22.94
-	x	4	1.9^{18}
-	-	4	1.06



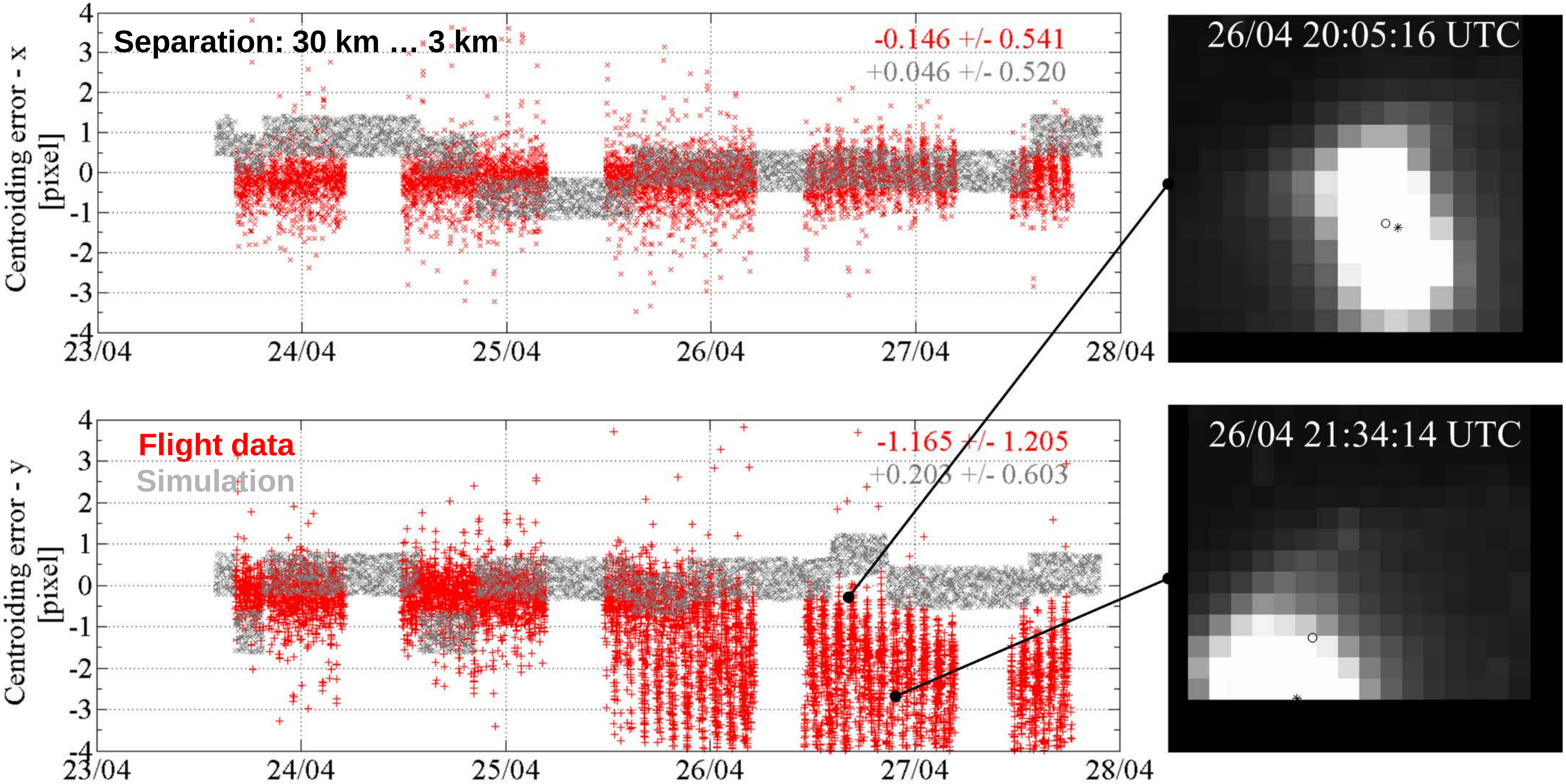


Relative eccentricity and inclination vectors are observable!

Low cost sensors, simplicity, and wide range

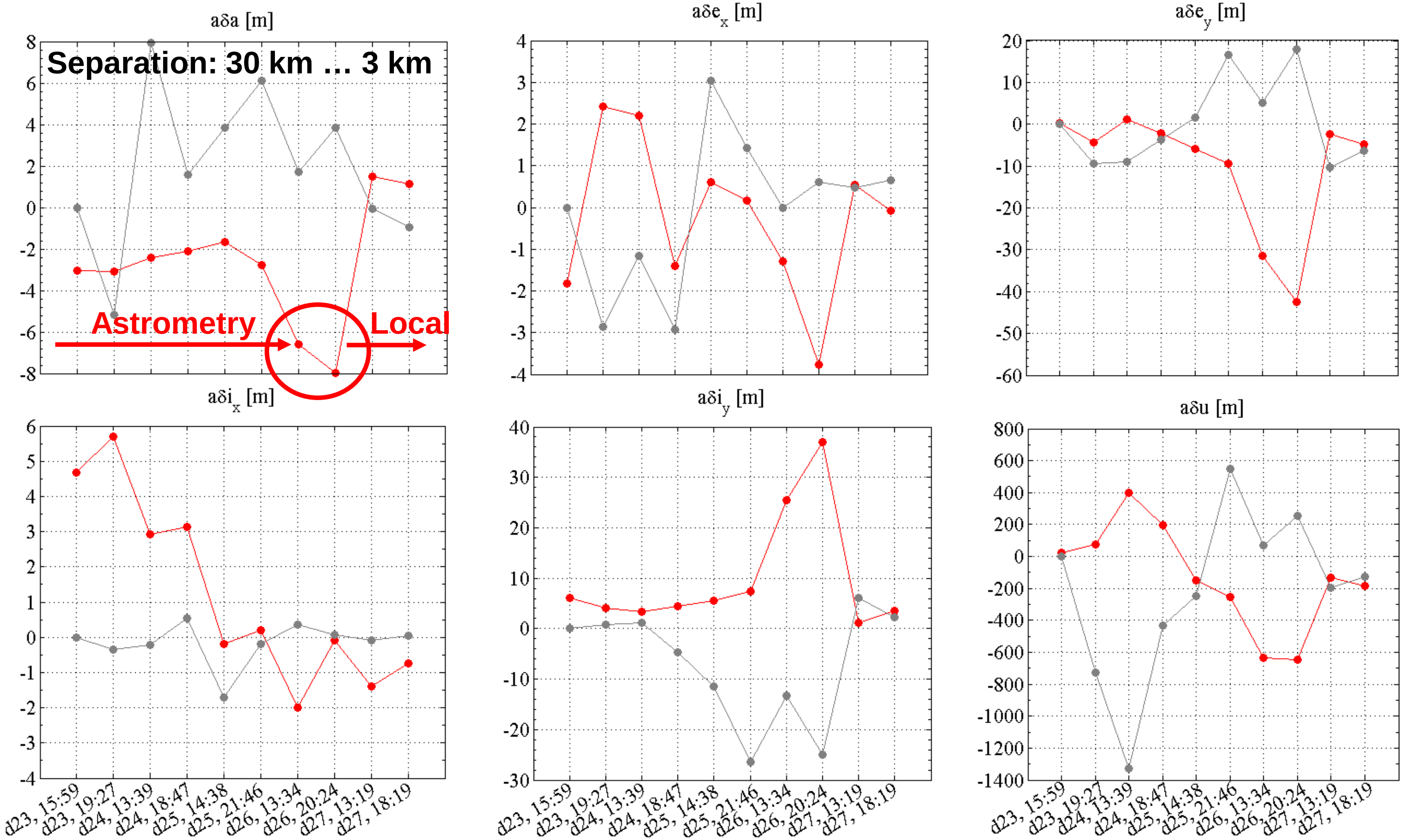
Identical profile of measurements gives an infinite set of possible relative orbits

ARGON: Image Processing Flight Results

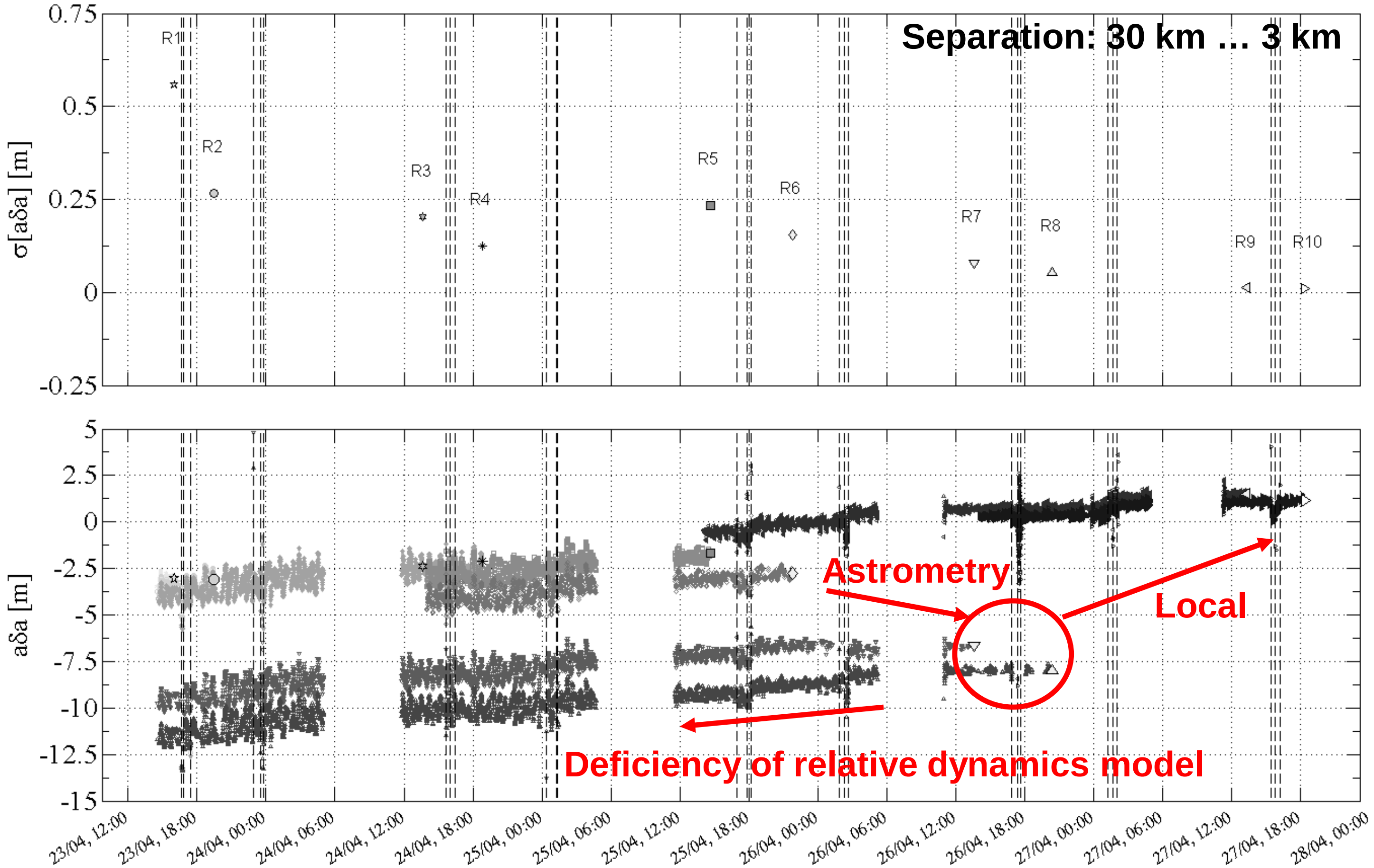


Overexposure of target

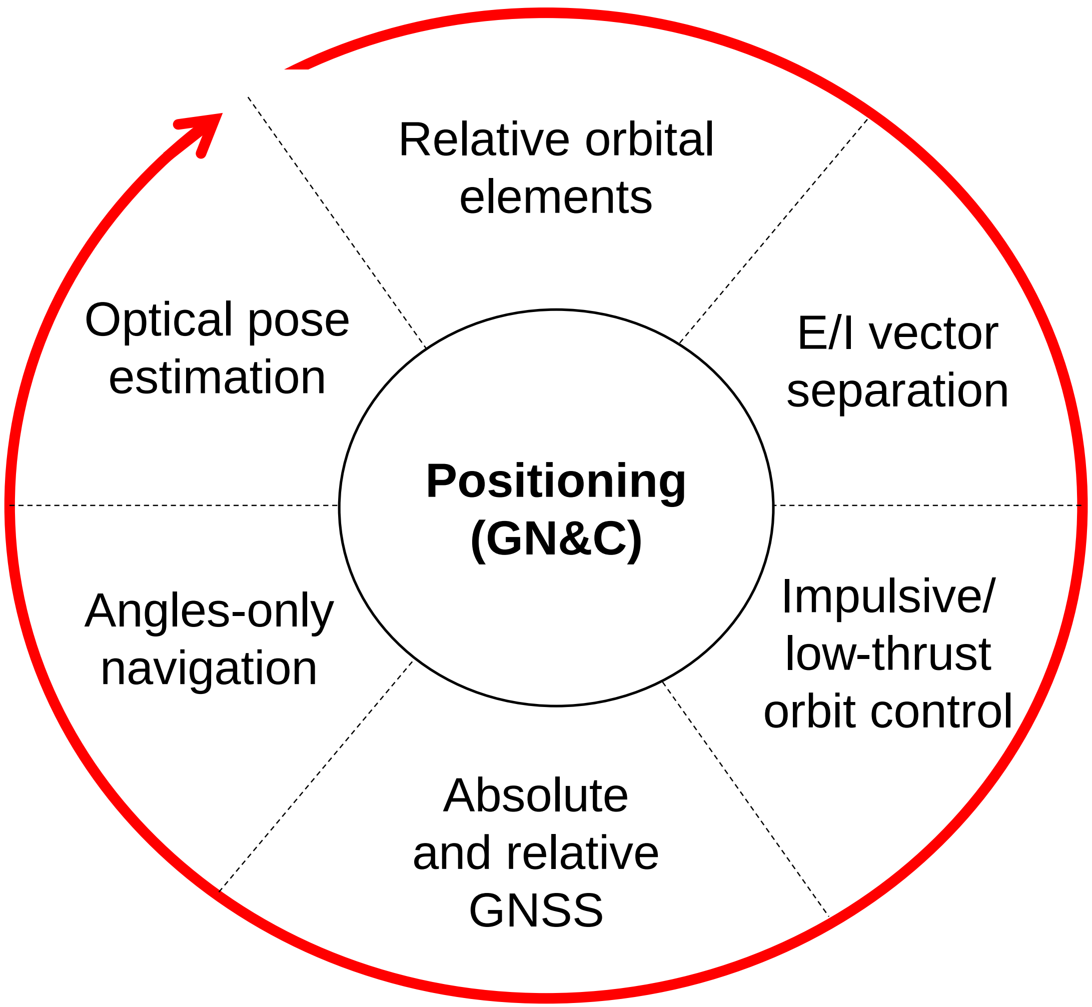
ARGON: ROD Flight Results

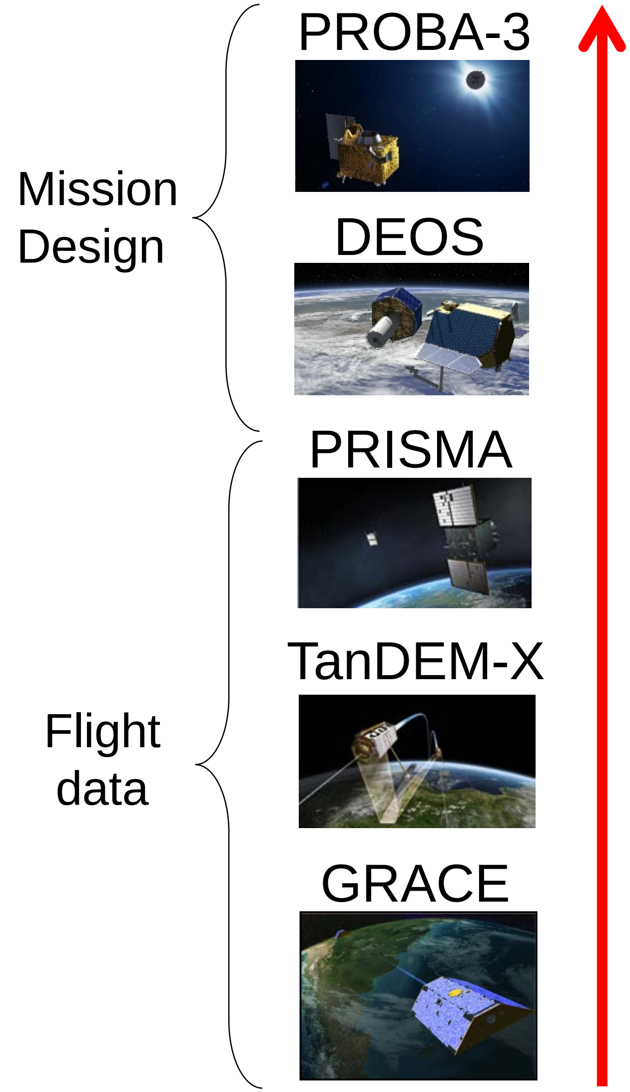


ARGON: ROD Flight Results



Advancing the State of the Art





Stanford's Space Rendezvous Laboratory (SLAB)

Space rendezvous

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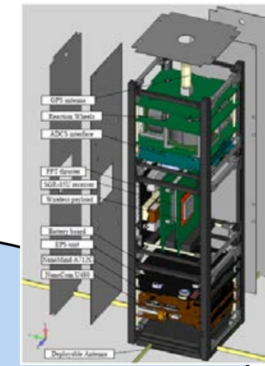
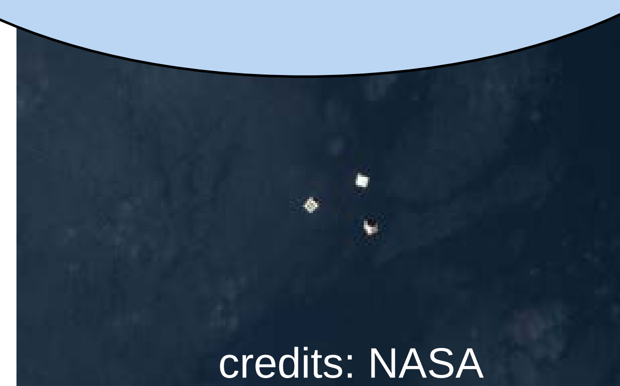


Vision

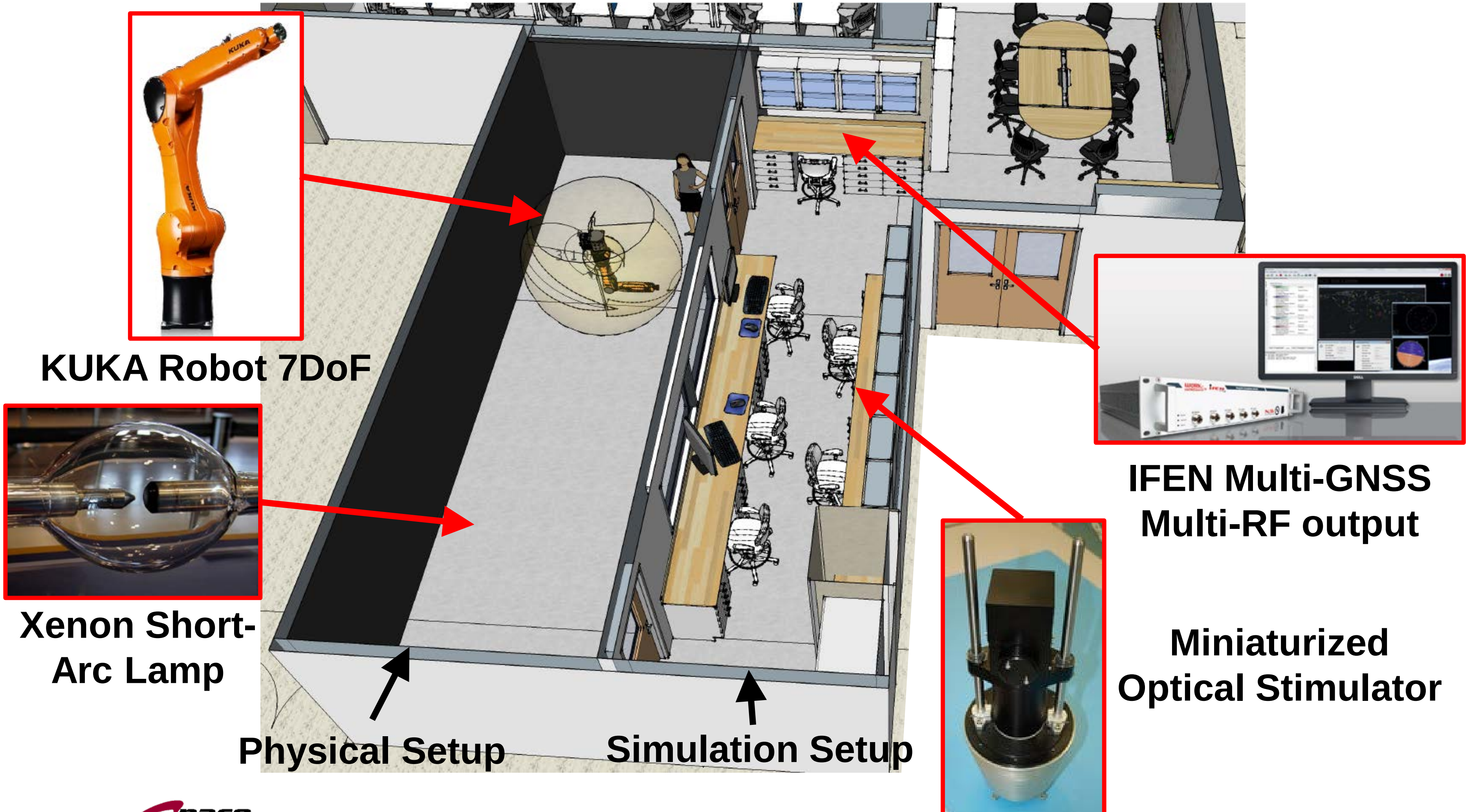
Enabling advanced distributed space systems for unrivaled space science and exploration

Mission

Deploy a **millimetric** accurate formation of three autonomous **nanosatellites** in low Earth orbit before 2020

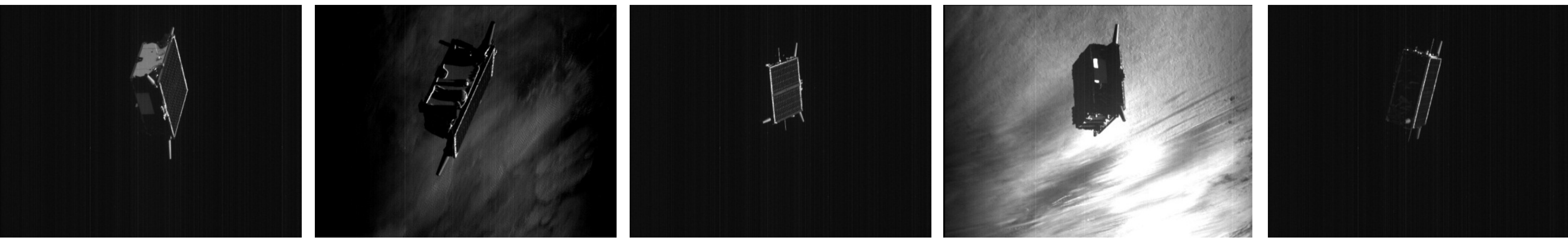


High-Fidelity Hardware-in-the-Loop Testbed



Close-In Inspection of Tango down to 2m based on SAFE

Questions?



PRISMA's Navigation Camera
(Tango spacecraft pictured by Mango)