# AA 279 D – SPACECRAFT FORMATION-FLYING AND RENDEZVOUS: LECTURE 1


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Stanford's Space Rendezvous Laboratory (SLAB)

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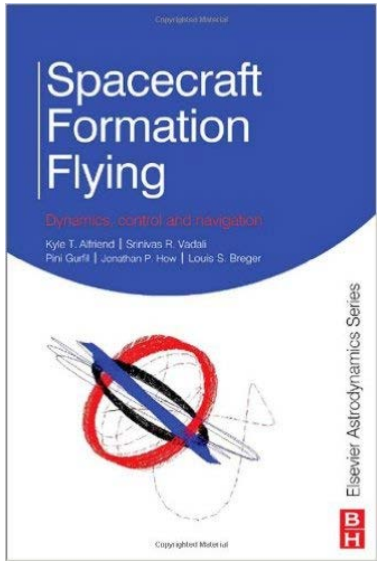


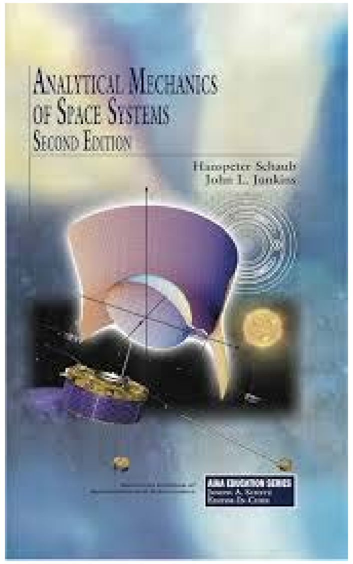



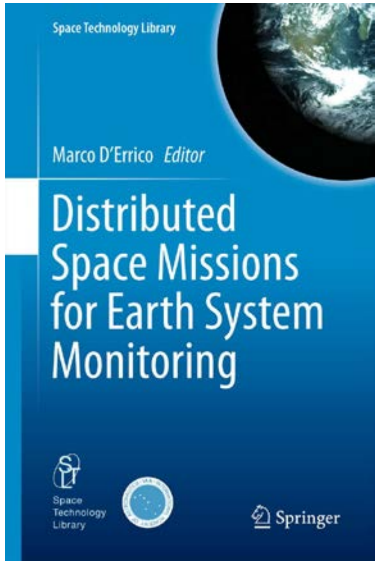

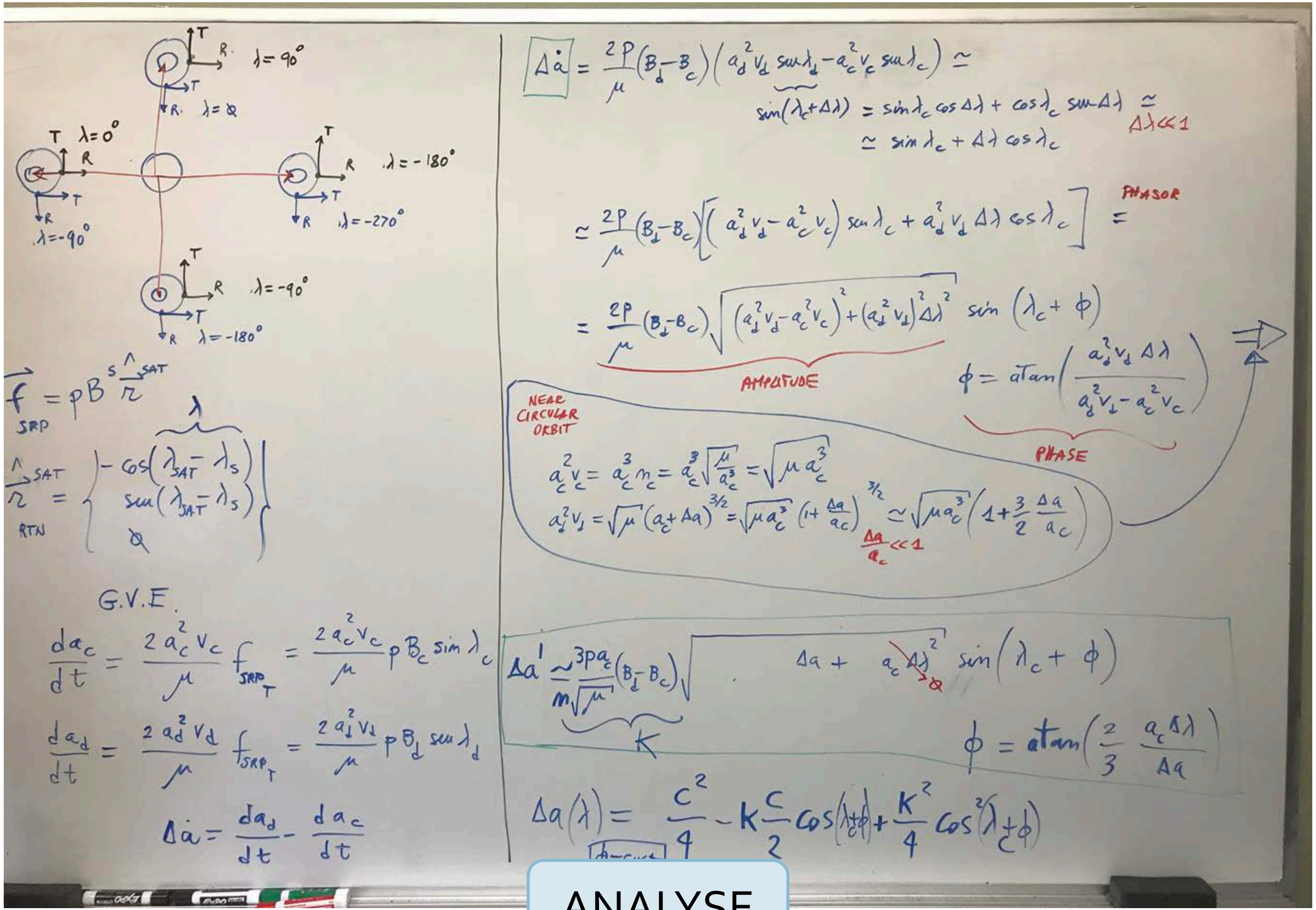


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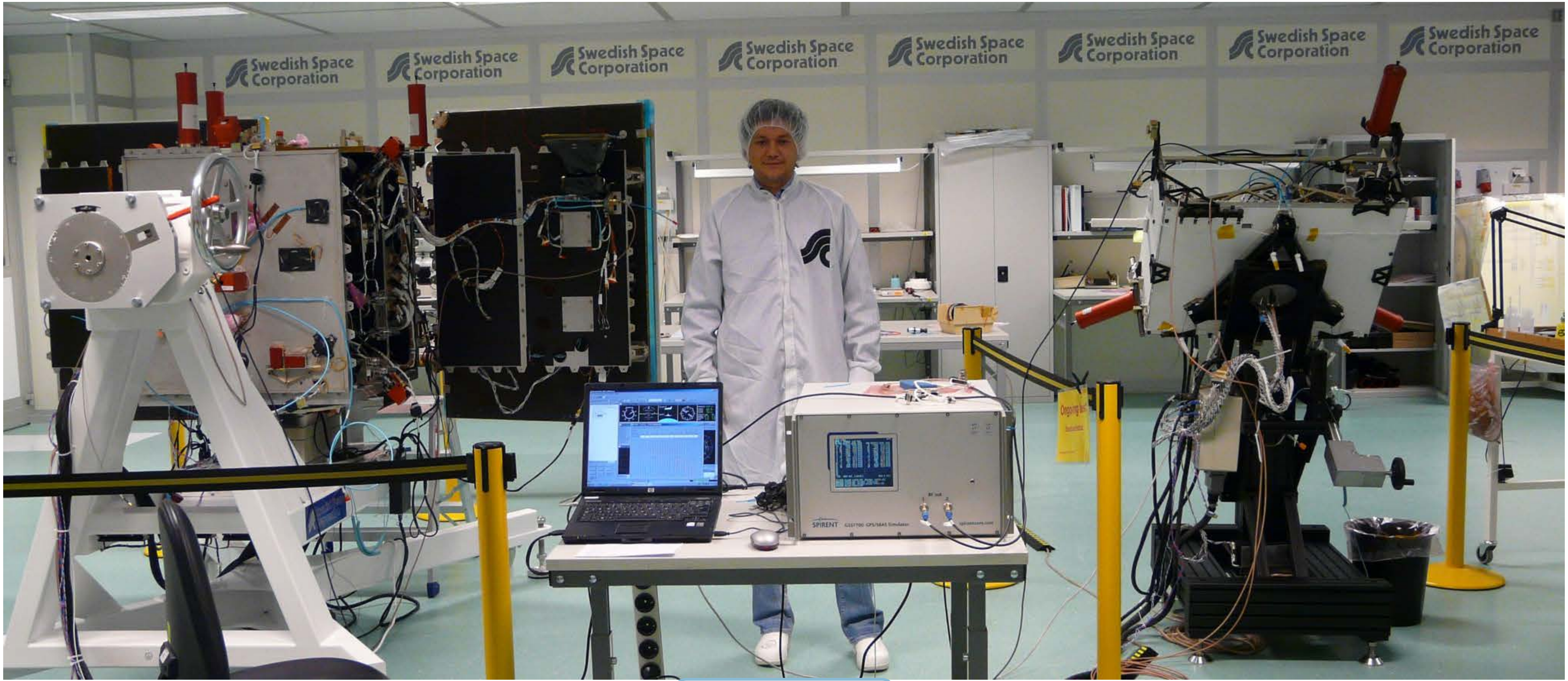


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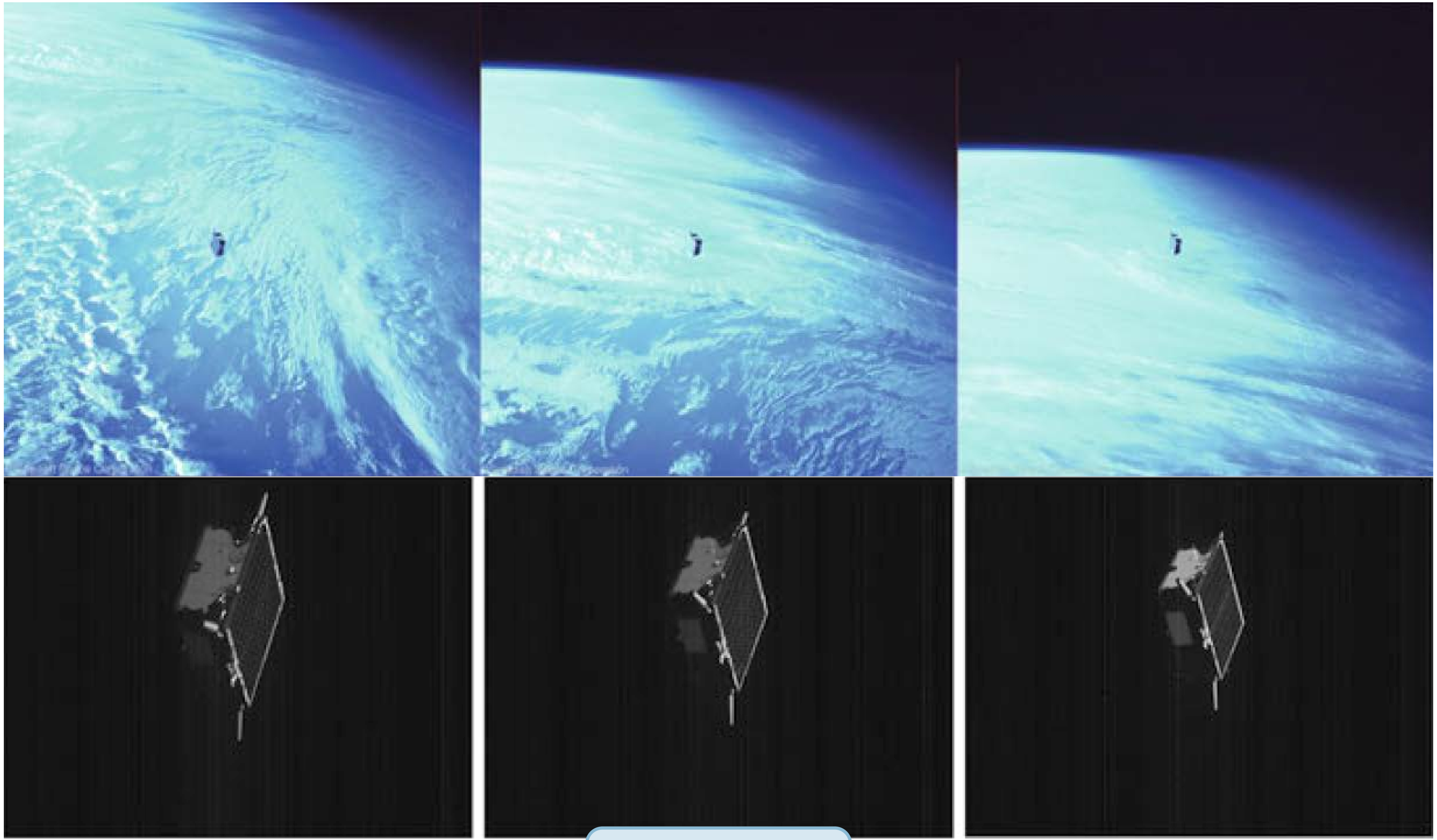
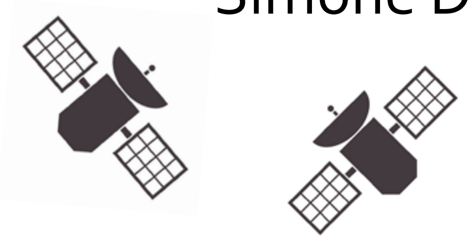


FLY

# Mission Statement

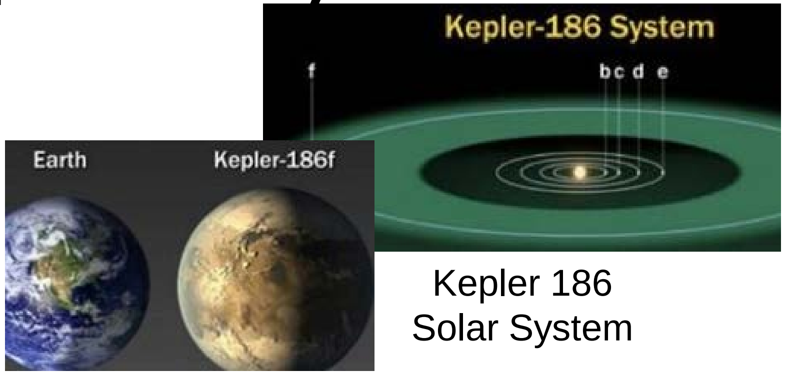
“The goal of SLAB is to enable future (**miniature**) distributed space systems (DSS). DSS are made of two or more spacecraft that **interact** to meet **objectives** otherwise very difficult to achieve”

Simone D'Amico, 12/01/2013

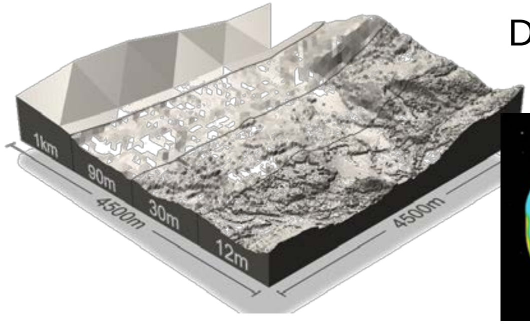


# Objectives of Distributed Space Systems

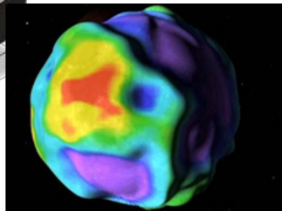
- Space Science
  - Astronomical search for origins (exoplanets)
  - Solar system exploration (asteroids)
  - Structure and evolution of the universe (gravitation)
- Planetary Science
  - Synthetic aperture radar interferometry
  - Gravity and shape mapping
  - Atmosphere and magnetosphere characterization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




Kepler 186
Solar System



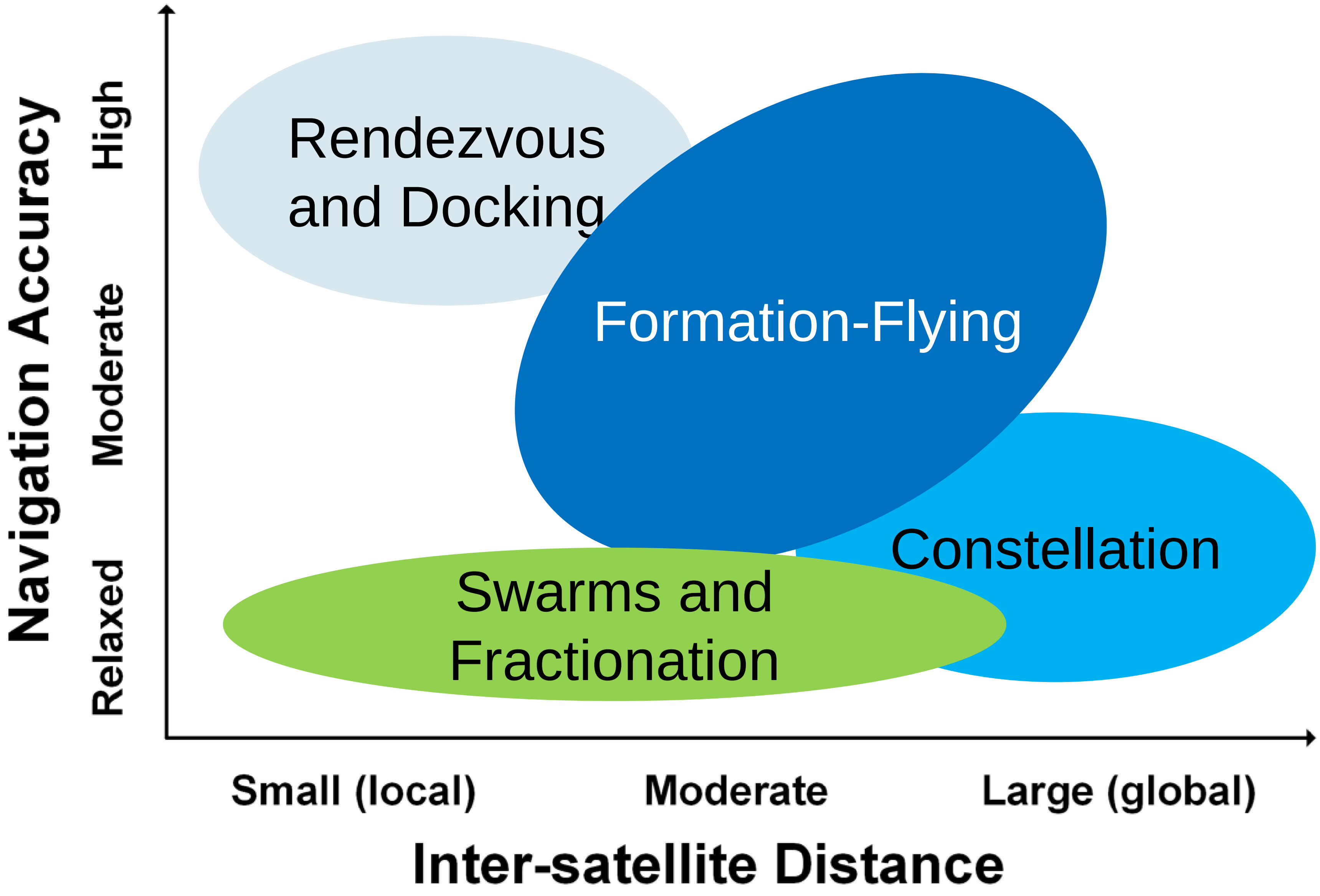

DEM Accuracy
(TanDEM-X)



Moon gravity
(GRAIL)

Autonomous
approach to the ISS
(HTV)

# Interaction of Distributed Space Systems

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# Distributed Space Systems are NOT New

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

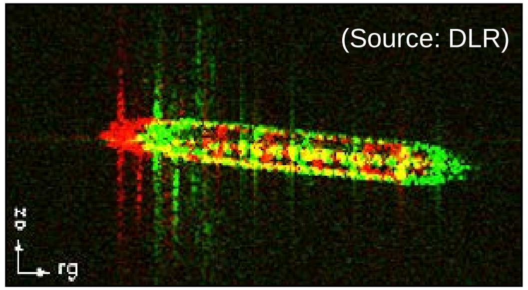
Contemporary
- Long duration
- Autonomy
- Cost constraints

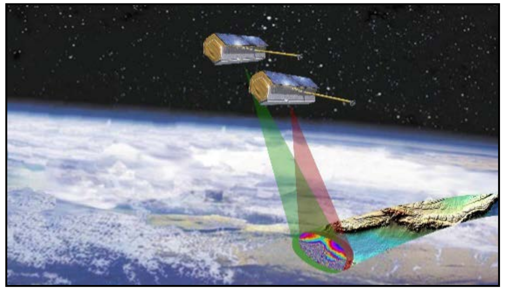
Future
- Miniaturization
- Distribution
- Standardization

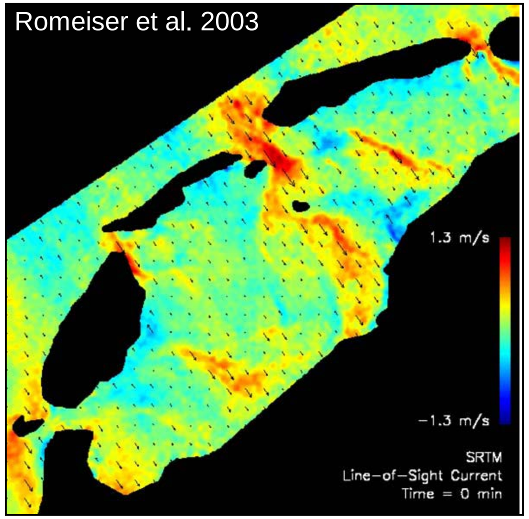
| Type | Involved | Year |
|---|---|---|
| First FF experiment | Gemini 6A & 7 | 1965 |
| First automated docking | Kosmos 186 & 188 | 1967 |
| RvD at other celestial bodies | Columbia & Eagle | 1969 |
| RvD with vehicles from 2 nations | Apollo & Soyuz | 1975 |
| RvD of 3 "objects" | D.Gardner, Weststar 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 |

# TanDEM-X

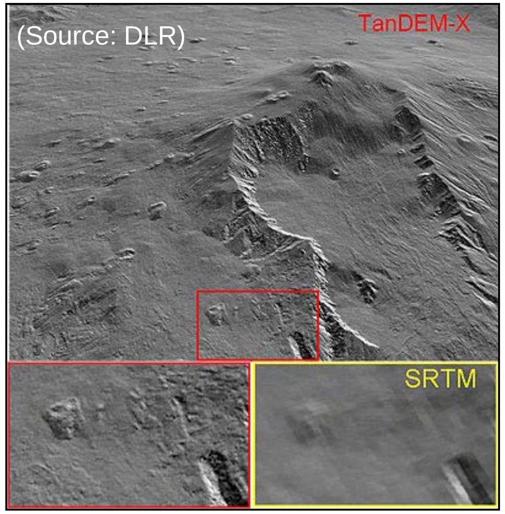
- Scope
  - Global Level-3 DEM (2m height, 12m pixel)
  - Local Level-4 DEMs
  - Innovative SAR techniques
- Mission Profile
  - Dual SAR satellites (TSX&TDX)
  - Formation flying (close&wide)
  - Launch 2007/2010
  - > 3 years overlap





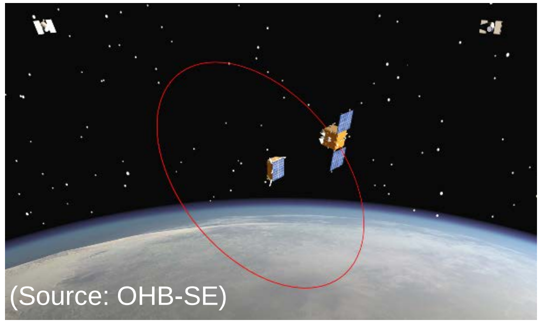

Along-track Interferometry
(Velocity on-ground objects)

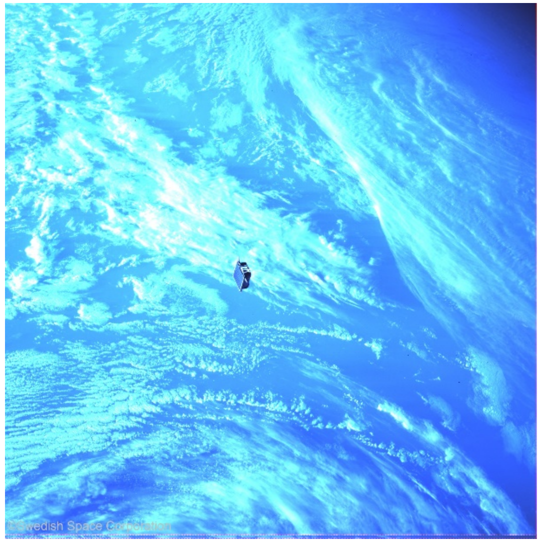



Cross-track Interferometry
(Digital elevation models)

# PRISMA

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

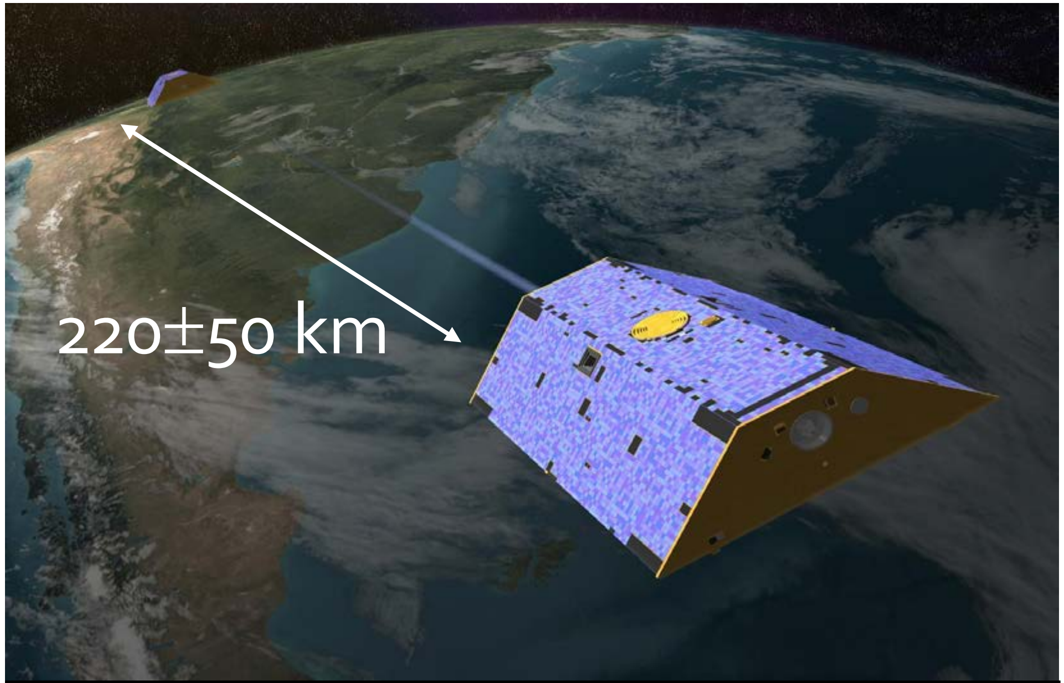

(Source: OHB-SE)

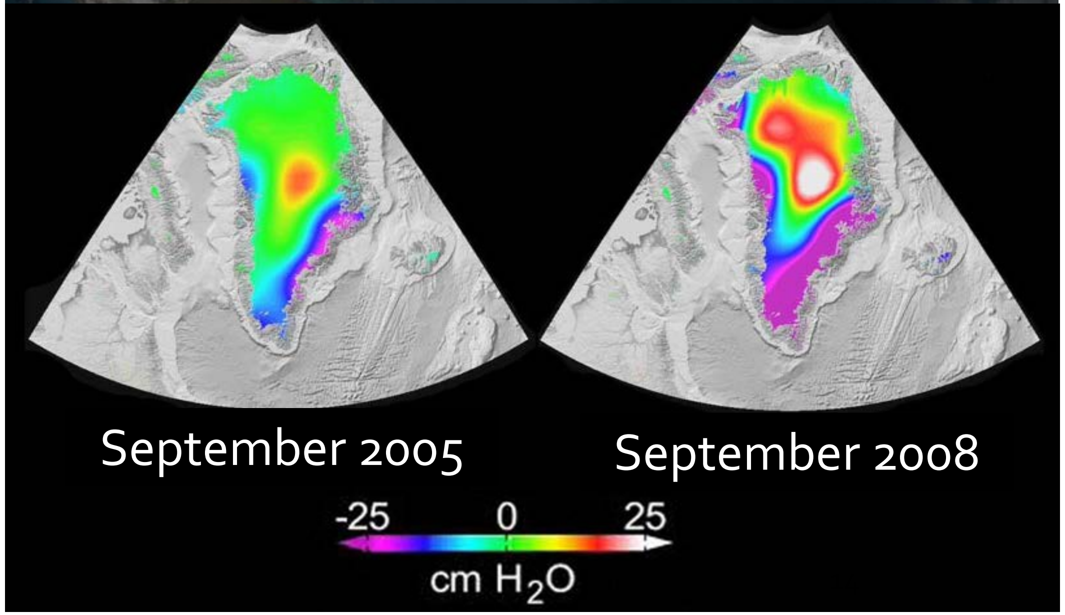

Fly around
March 27, 2011

# PRISMA (Close-In Inspection Experiment – 2 m)

# GRACE

- GRACE twin satellites, Tom and Jerry, launched in 2002, to be replaced by the GRACE-FO
- Relative motion represents the total differential forces acting on the formation (measured by k-band radar)
- Non-conservative forces measured by precision accelerometers
- Besides understanding the planet-dynamics system, GRACE gravity field models are used every day for precise orbit determination and prediction around the world
- Flight dynamics requirements: 220+-50 km separation,  longitude swap maneuver required

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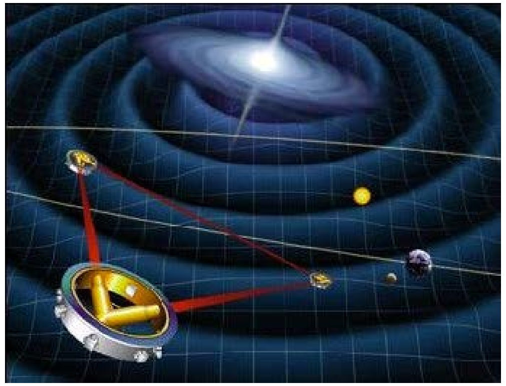
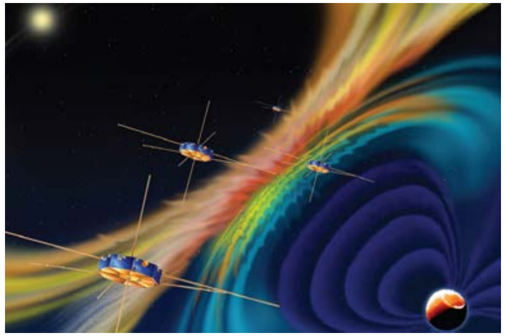
# PROBA-3 (Mission Objectives and Scenario)

# Other Flagship Missions (NASA/ESA)

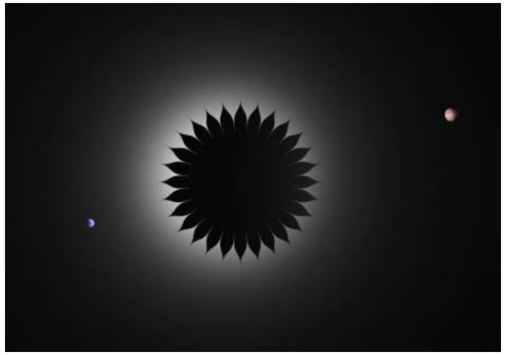
- Laser Interferometer Space Antenna (LISA)
  - Detect and measure gravitational waves
  - Equilateral triangle with arm length of 5M km
  - Precisely tracked free-floating proof masses



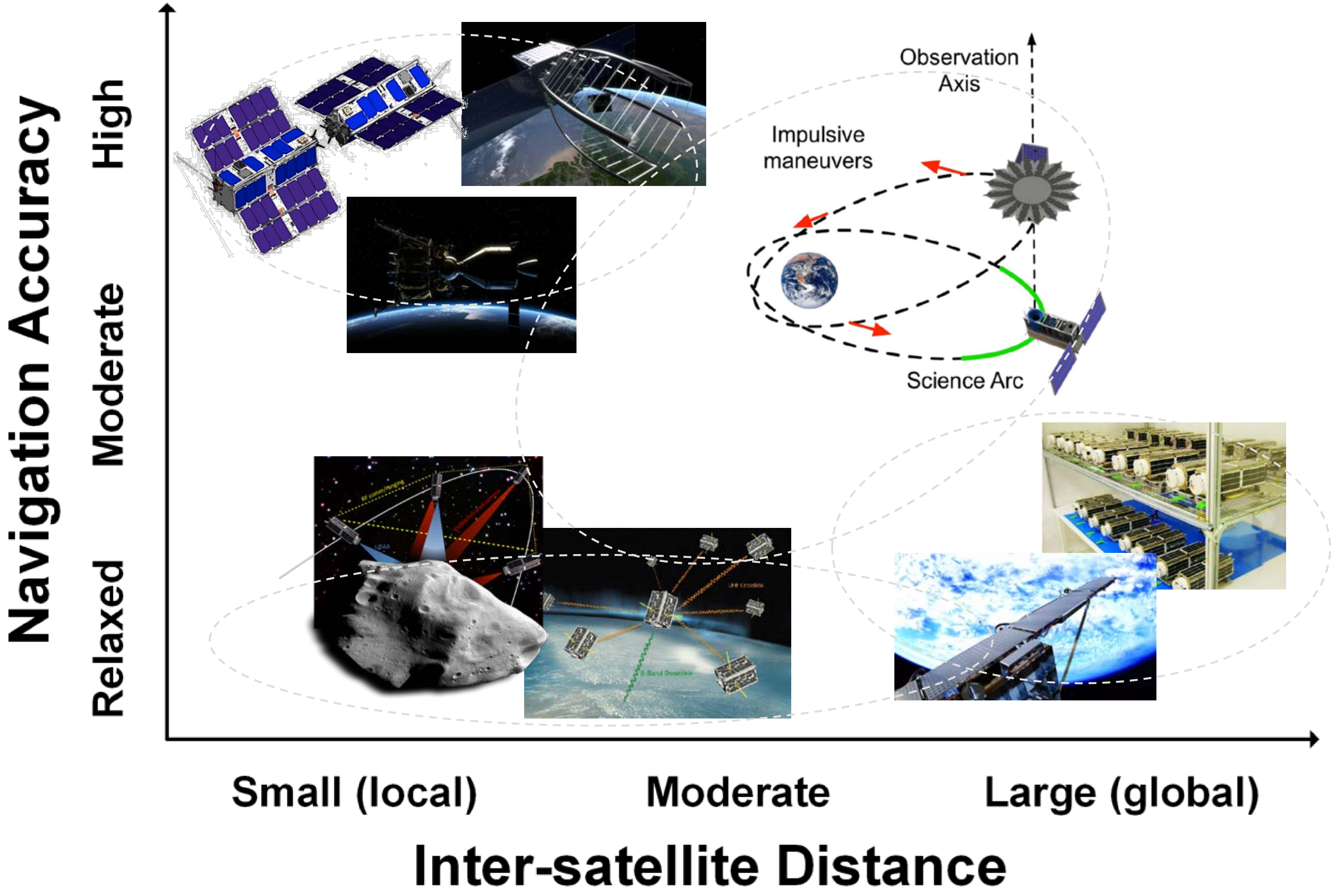
- Magnetospheric Multiscale Mission (MMS)
  - Understand magnetic reconnection
  - Variably spaced tethraedron (1 km to several Earth radii)
  - Electron and ion plasma spectrometers



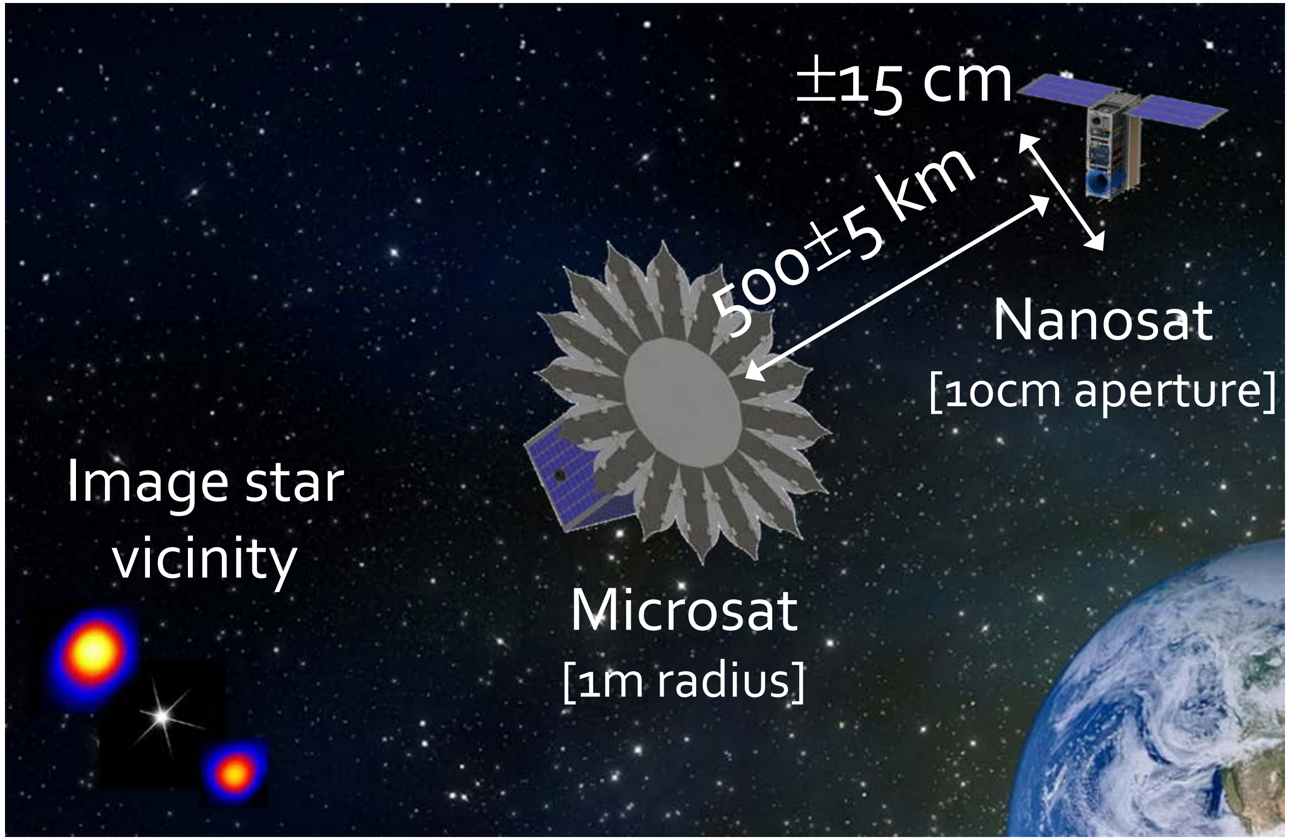
- New Worlds Observer (NWO)
  - Discover and directly image Earth-like planets
  - Telescope+Starshade at 50K km distance
  - Diffraction limited telescope in visible band

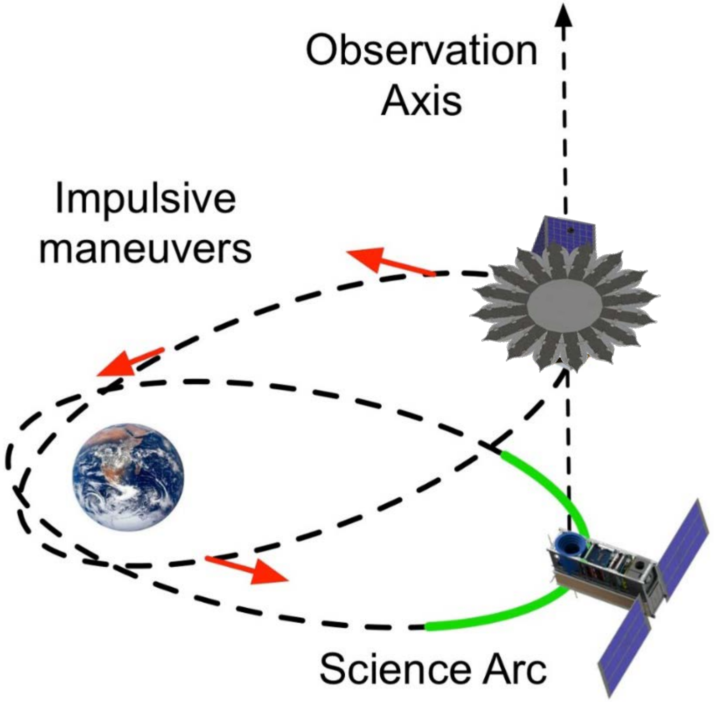


# Miniature Distributed Space Systems



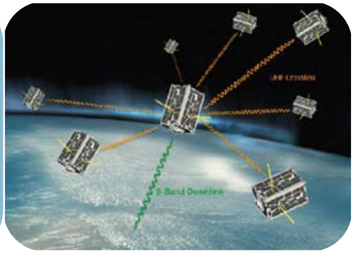
# Can a miniaturized Distributed Occulter/Telescope (mDOT) image exoplanets from Earth's orbit?



# Research Pillars

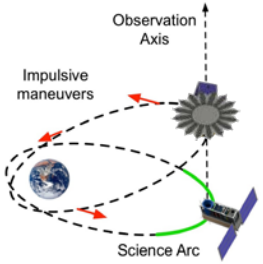
Flight Missions



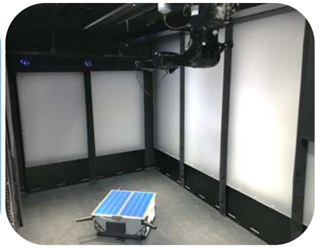
*Lessons learned & Innovation*

*Integration in mission conops*

Advanced Mission Design and Science

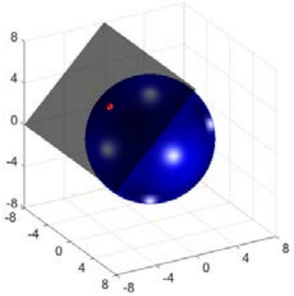



High-Fidelity Validation and Training



*Requirements & Objectives*

DGN&C for Multiple Spacecraft

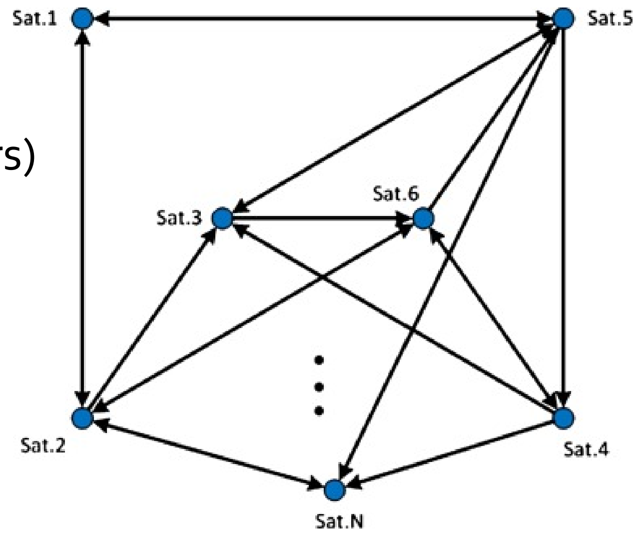


*Prototype Algorithms*

# Coordination Approaches

- Orbit tracking
  - Similar to single satellite missions
  - Each satellite in the formation is controlled to a particular desired orbit
  - No cooperation required, but does not exploit coupled nature (more maneuvers)

- Leader/Follower
  - Leader controlled to reference orbit
  - Follower(s) controlled w.r.t. leader
  - Satellites follow natural dynamics of absolute orbit of leader
  - Fuel usage is not balanced because leader controls its absolute motion only




- Virtual structure
  - Fitting desired states of formation so to minimize overall state error
  - State error pertain all the satellites in the formation
  - Fuel usage can be balanced methodically

- Swarming
  - Simple heuristic laws to arrange many satellites based on local info
  - Easily scale to arbitrary number of vehicles without large computation and communication burdens
  - Typically not fuel optimal and rarely guarantee collision avoidance

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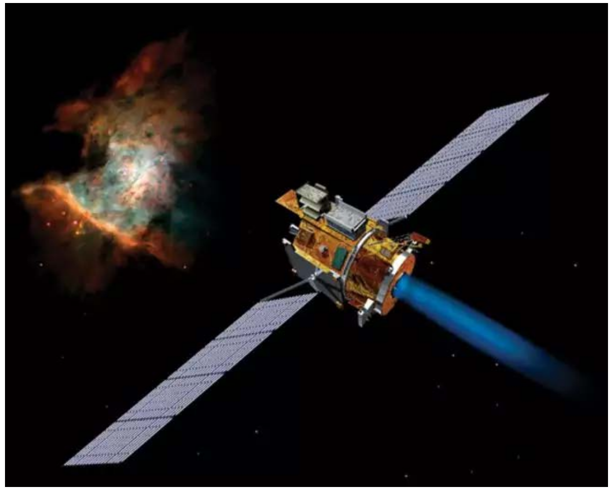
# Fuel-Use Drivers

- Primary concern in the design of any spacecraft controller
- Minimizing fuel use is critical in any space mission, since fuel is expensive to launch and non-replenishable
- Keeping formation from drifting apart and achieving science requirements at the same time is generally more expensive than single spacecraft control
- Typical fuel-use drivers in a spacecraft formation are
  - Mission requirements
  - Initial conditions
  - Navigation uncertainty
  - Actuation errors
  - Dynamical process noise
  - Algorithms



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# Control Approaches

- Although many formation control strategies are proposed in the literature
  - Proportional-derivative (PD)
  - Linear quadratic regulation (LQR)
  - Linear matrix inequalities (LMI)
  - Lyapunov
  - Rapidly exploring random trees (RRT)
  - Model predictive control (MPC)
- Thrusting schemes which exploit the inversion of the state transition matrix remains the most commonly used in practice because of their
  - Impulsive nature
  - Determinism
  - Simplicity
  - Higher technology readiness level

$$\sum_{i=0}^{\infty} \frac{x}{2^i}$$

**Numerical**

$$\sum_{i=0}^{10000} \frac{x}{2^i}$$

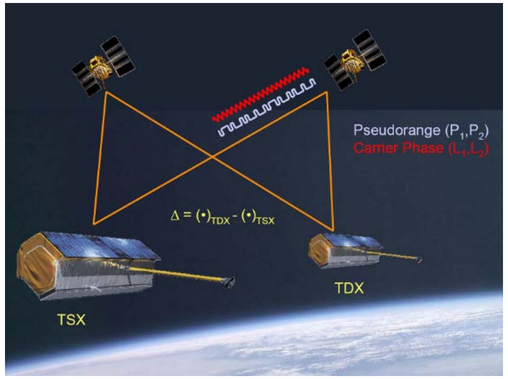
**Closed-form**

2x

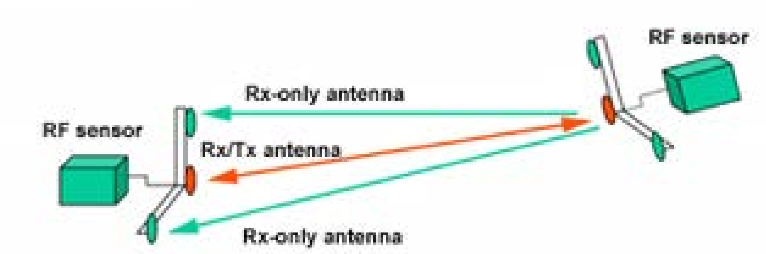
**Solution**

# Navigation Approaches

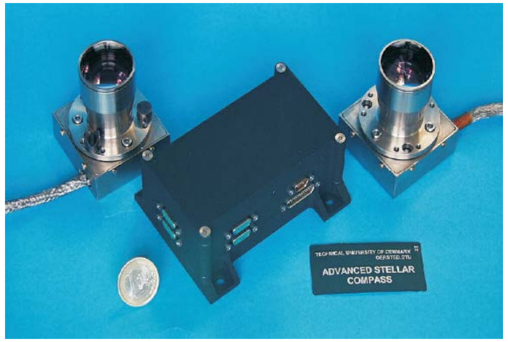
- GPS/GNSS
  - Cooperative, rely on GNSS constellation
  - Phase difference = Projected baseline + bias
  - Ambiguity resolution




- Radio Frequency
  - Cooperative, self-contained
  - Pseudolites provide GPS like signals
  - Applicable for deep space navigation




- Vision-Based
  - (Non-)Cooperative, optical/infrared
  - High dynamics range: far- to short-range
  - Support angles-only to full pose estimation

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