From Vision to Mission – The PRISMA and TanDEM-X Formation Flying Missions

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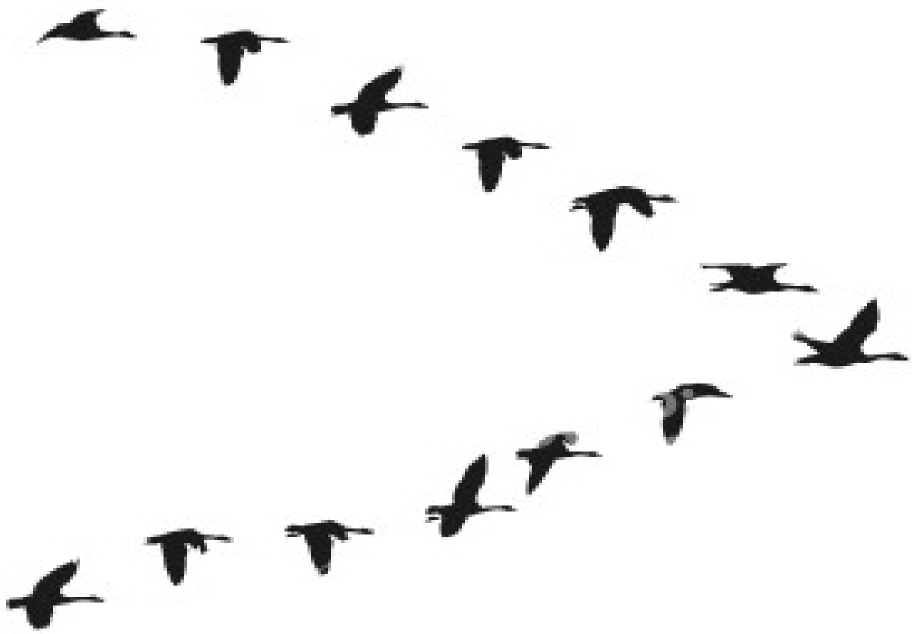
Formation Flying

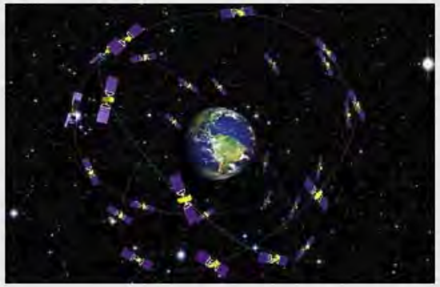


Formation Flying of Spacecraft

Rendezvous & Docking
Temporary
Physical Contact

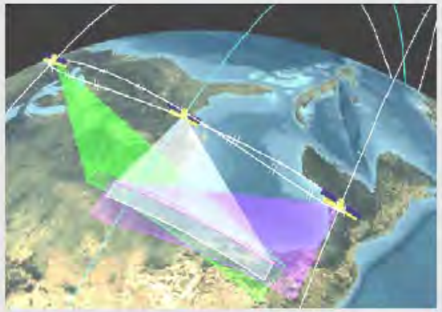
Formation
Few Satellites
Regional
Distributed Systems*

Constellation
Many Satellites
Global Coverage



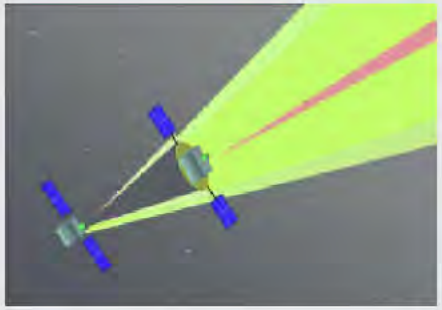
* The whole is more than the sum of ist parts.
Aristoteles

Formation Flying – Mission Concepts



SAR Interferometry

- Low Earth orbit (500 km)
- 2-4 satellites
- 50 – 1000 m separation
- 10 – 100 m control
- 1 mm navigation (post-facto)
- TanDEM-X, (Cartwheel, Techsat-21)



Distributed Telescopes

- High altitude Earth orbit (or Lagrange point)
- Typically 2 satellites
- 30 – 100 m separation
- 0.1 – 10 cm control
- (XEUS, SIMBOL-X, MAX, ASPICS)

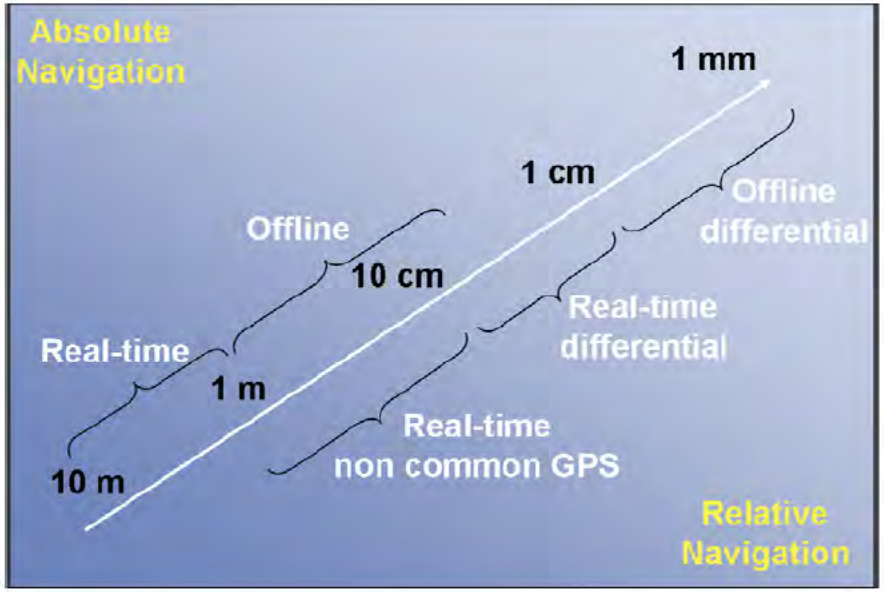
Virtual Apertures

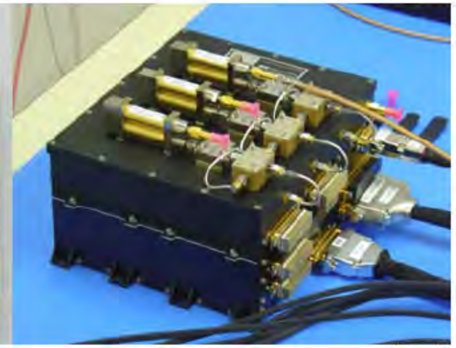
- Lagrangepoint (or high altitude Earth orbit)
- 3++ satellites
- 50 – 500 m separation
- ~1 mm control
- DARWIN, TPF, PEGASE, (LISA)

2010 → 2020

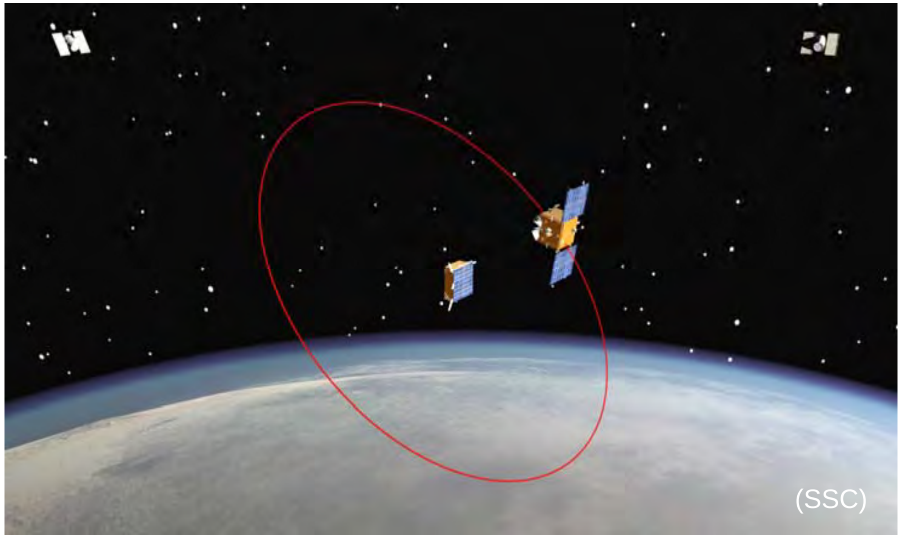
GPS – Key to Success

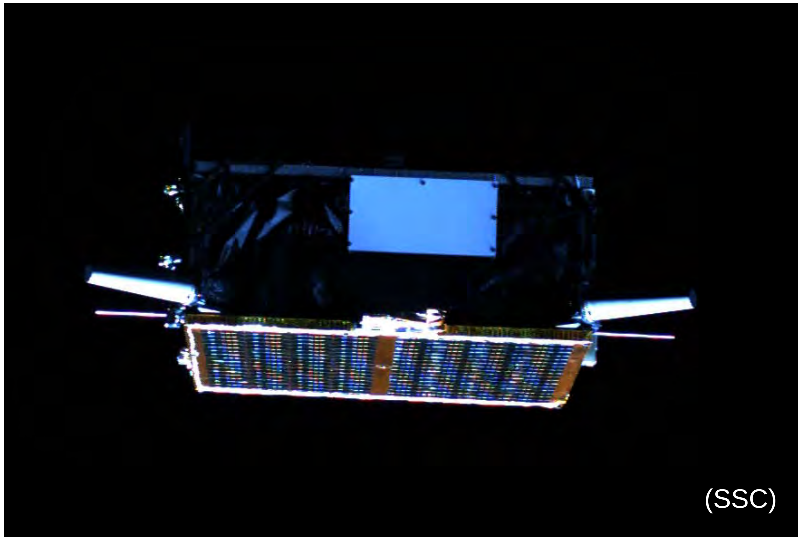
- 3D position, velocity, time
  - On-board availability: autonomy!
- Broad spectrum of receivers
  - Miniaturised, COTS, 1-frequency
  - Space-qualified, 2-frequency
- International GNSS Service (IGS)
  - Worldwide infrastructure
  - Geodetic precision
- On-board navigation systems
  - Dynamic filtering
  - Increased accuracy, robustness
- Precise Orbit Determination





PRISMA

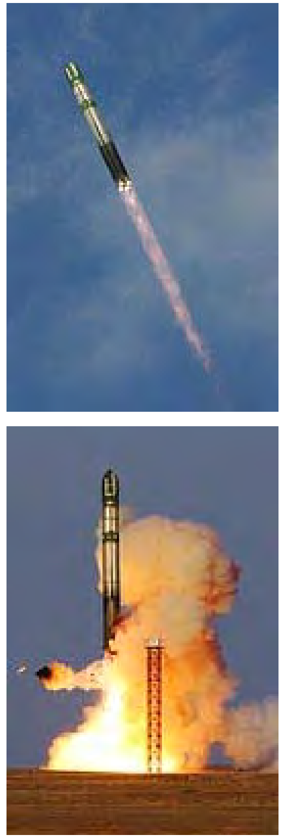




- Swedish technology demonstration mission
- Two micro-satellites (MANGO, TANGO)
- Qualification of sensors (GPS, FFRF, VBS), actuators and control concepts
- Autonomous formation flying, rendezvous and proximity operations

PRISMA Mission: Overview

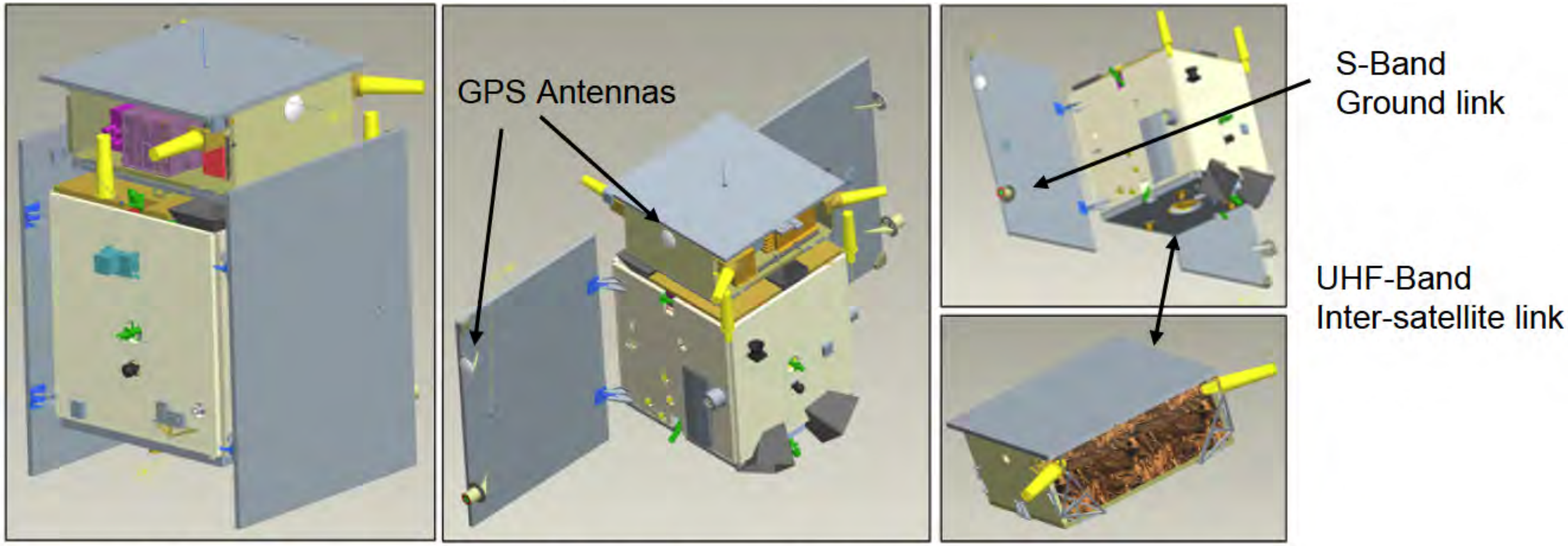
- Launch from Yasni on June 15th 2010 at 14.42 UTC
- Sun-synchronous dawn-dusk orbit at 757 km altitude
- Space Segment
  - Active MANGO spacecraft (150 kg, 400 W, 6 DoF)
  - Passive TANGO spacecraft (40 kg, 100 W, 3 DoF)
- Operations
  - Mission control center in Solna (Sweden) and, temporarily, Oberpfaffenhofen (Germany)
  - Esrange ground station in Kiruna (Sweden)
  - Experiment control centers hosted by partners (DLR, CNES)
  - Mission life time >10 months
  - TANGO operations using MANGO as relay



DNEPR launch

PRISMA Mission: Spacecraft Design

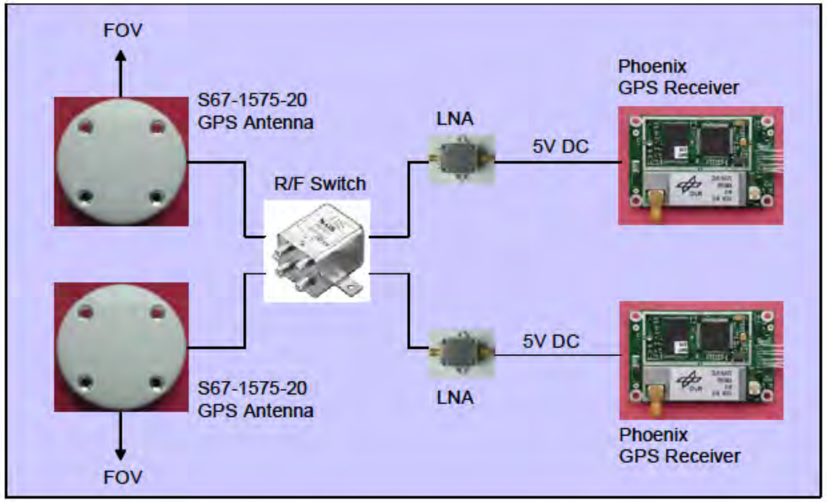
AOCS		MANGO	TANGO
Attitude Control	Sensors	MM,SS,GYR,SCA	MM,SS
	Actuators	MT,RW	MT
Orbit Control	Sensors	GPS_{DLR}, $FFRF_{CNES}$, VBS_{DTU}	-
	Actuators	6 1N-Hydrazine (MIB 0.7mm/s)	-

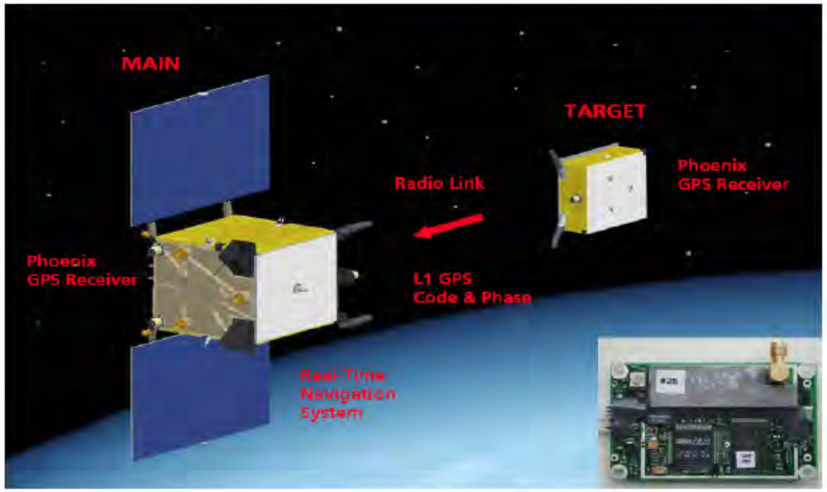


Clamped after launch | Clamped; solar panels deployed | Separated spacecraft

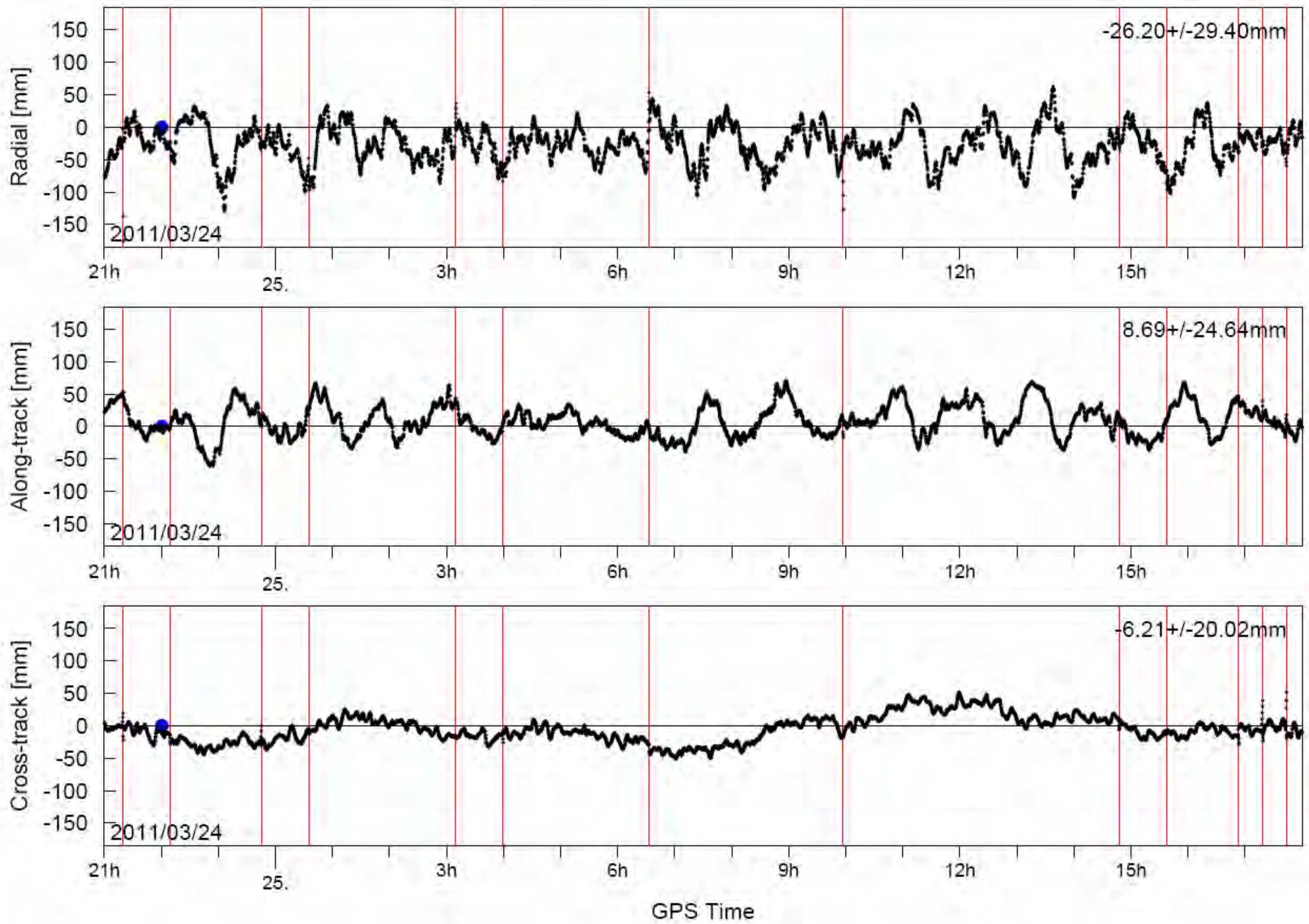
GPS Hardware

- Phoenix-S GPS Receiver
  - Commercial-off-the-shelf hardware platform
  - DLR software
  - 12 channels L1 C/A code tracking
  - Power 0.8 W (BOL) at +5V
  - Latch-up protection (SSC)
- Performance
  - C/A code noise 0.5 m @ 45 dB-Hz
  - Carrier tracking 1 mm @ 45 dB-Hz
  - Integer ambiguities
- Redundancy & Flexibility
  - Two receivers and amplifiers
  - Two passive antennas
  - Switch branches via TC





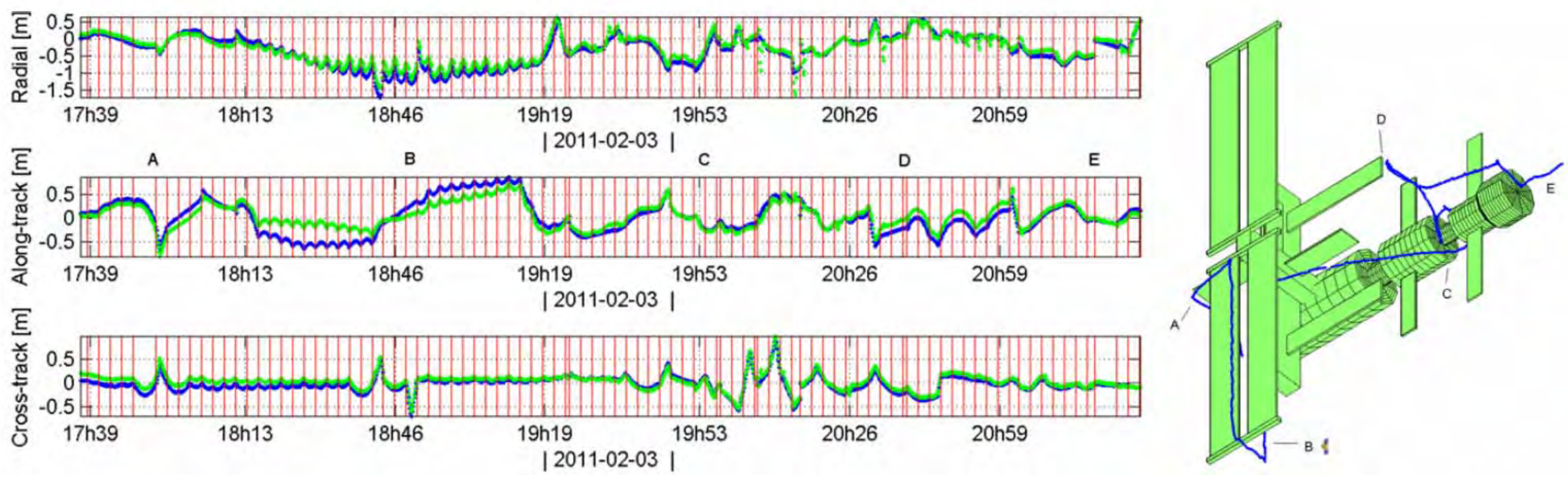
PRISMA GPS-Based Relative Real-Time Navigation



5.1 cm
3D rms

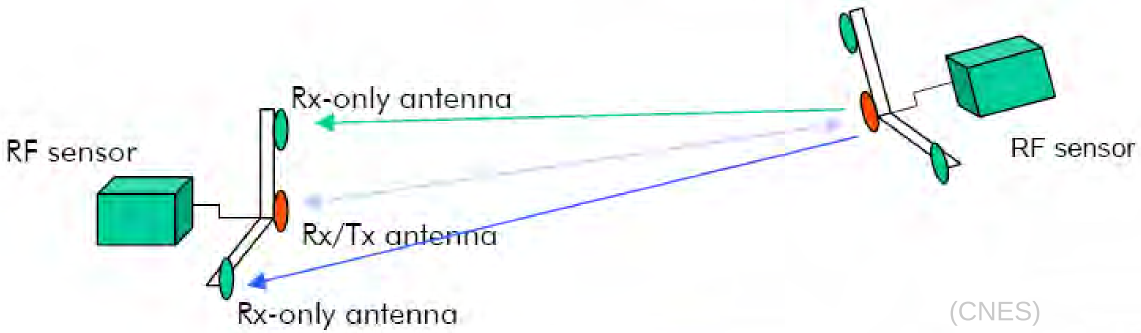
PRISMA GPS-Based Autonomous Orbit Control

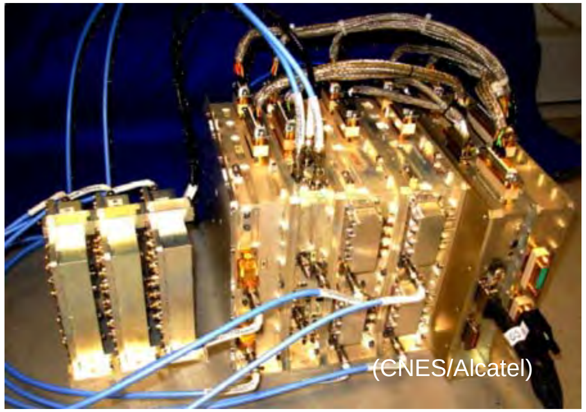
- Inspection flight around virtual structure (PROX/FARM experiment, OHB-SE)
- ~0.5 m 3D rms control error
- Onboard navigation accuracy limited by maneuver frequency (~50 man/rev)



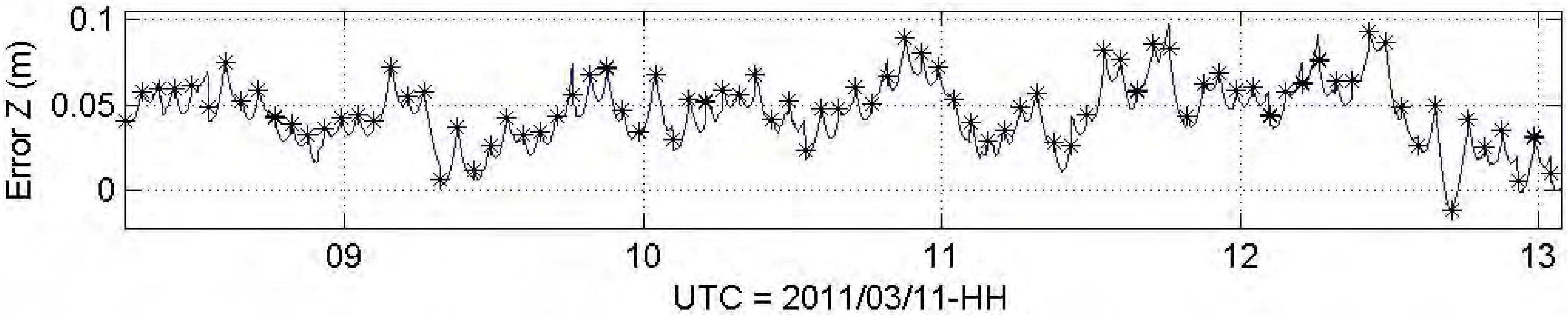
Larsson R., Noteborn R., Bodin P., D'Amico S., Karlsson T., Carlsson A.: Autonomous Formation Flying in LEO - Seven months of routine formation flying with frequent reconfigurations. 4th International Conference on Spacecraft Formation Flying Missions & Technologies, St-Hubert, Quebec, 18-20 May 2011

Formation Flying Radio Frequency (FFRF) Instrument





Error of FFRF-based autonomous formation keeping (reference GPS)

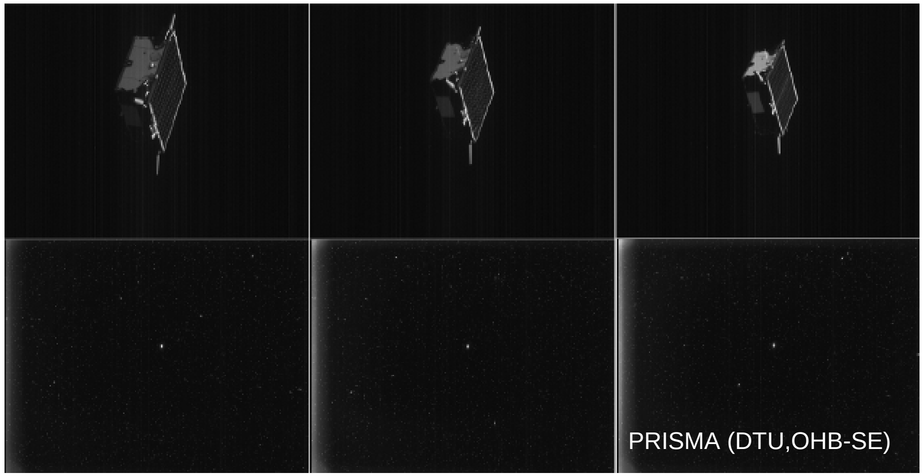


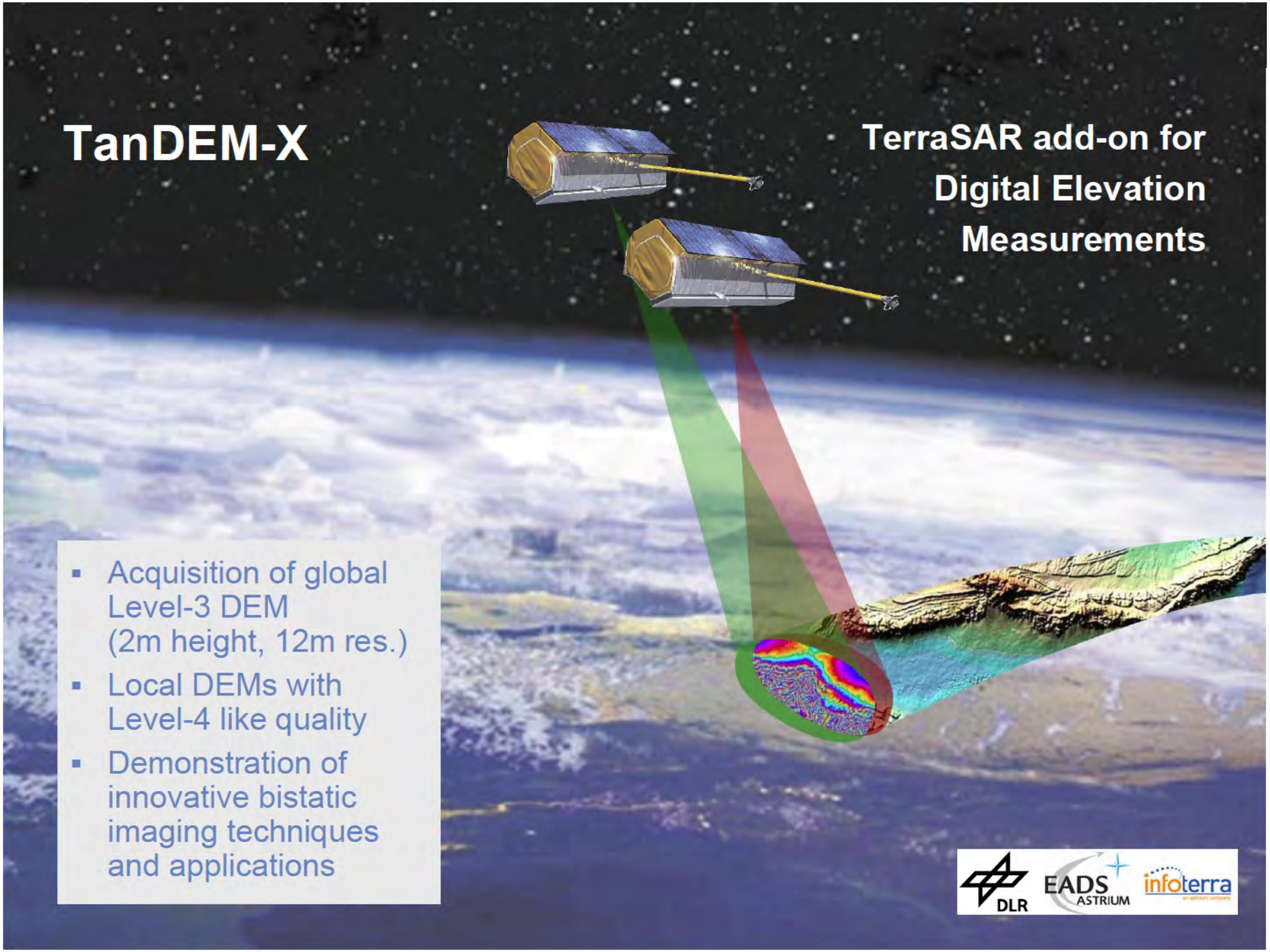
Grelier T., Guidotti P.-Y., Delpech M., Harr J., Thevenet J.-B., Leyre X.; *Formation Flying RadioFrequency Instrument: First Flight Results from the PRISMA Mission*; NAVITEC'2010, 8-10 Dec. 2010, Noordwijk, The Netherlands (2010)

Vision Based System (VBS)

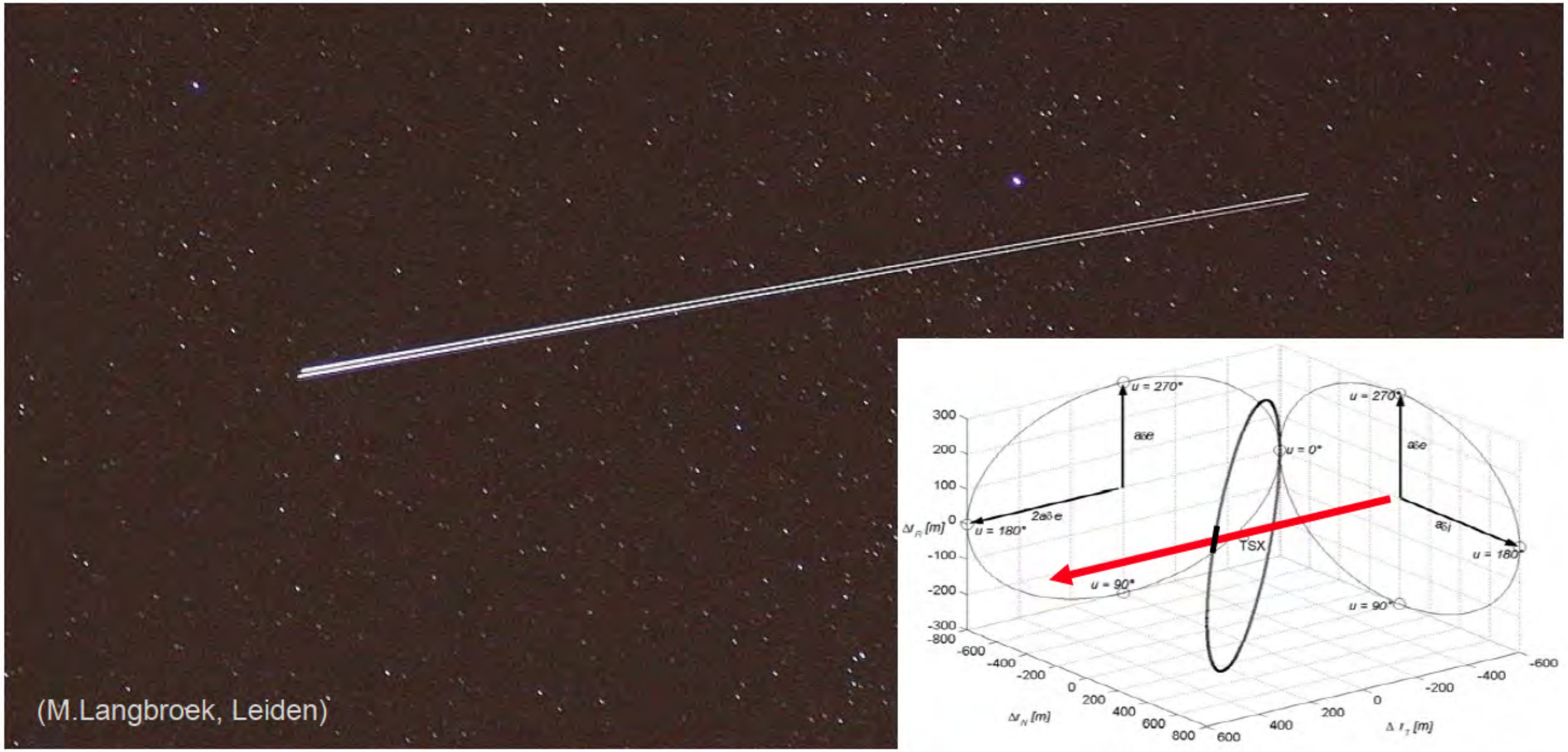
- Flight demo on PRISMA
- Based on DTU‘s „Advanced Stellar Compass“
- Near and far range camera heads
- Non-stellar object identification and line-of-sight vector computation
- Pose estimation and cooperative tracking mode for target with LEDs

(DTU)


PRISMA (DTU,OHB-SE)


TanDEM-X
TerraSAR add-on for Digital Elevation Measurements
▪ Acquisition of global Level-3 DEM (2m height, 12m res.)
▪ Local DEMs with Level-4 like quality
▪ Demonstration of innovative bistatic imaging techniques and applications
DLR
EADS ASTRIUM
infoterra

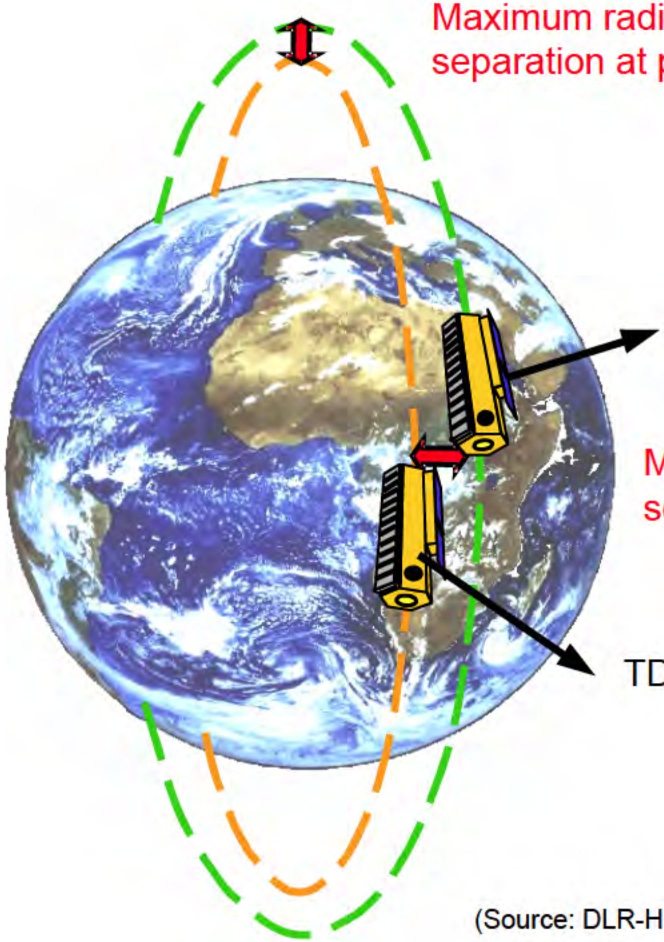
Safe Formation Flying (Δe/Δi-Vector Separation)



[1] Montenbruck O., Kirschner M., D'Amico S., Bettadpur S.; *E/I-Vector Separation for Safe Switching of the GRACE Formation*; Aerospace Science and Technology 10/7:628-635 (2006).

[2] D'Amico S., Montenbruck O.; *Proximity Operations of Formation Flying Spacecraft using an Eccentricity/Inclination Vector Separation*; Journal of Guidance, Control and Dynamics, 29/3:554-563 (2006).

TerraSAR-X / TanDEM-X „Helix-Orbit“

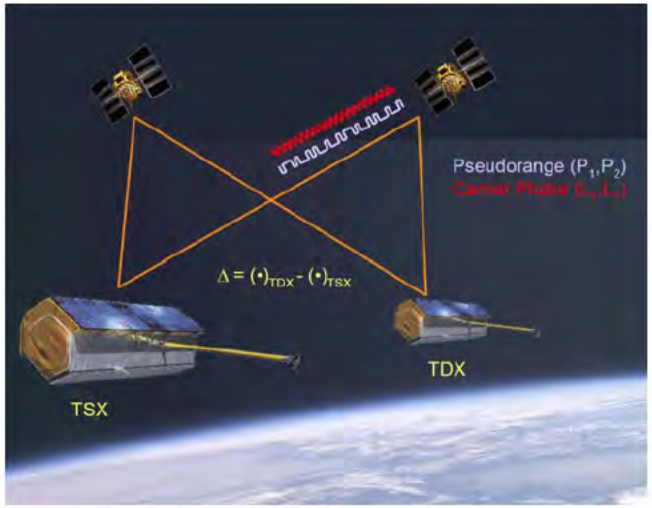


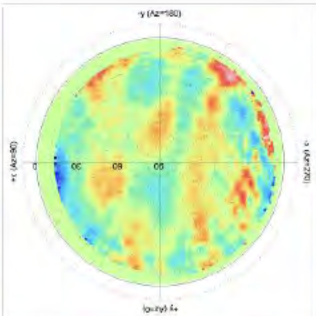
(Source: DLR-HR)

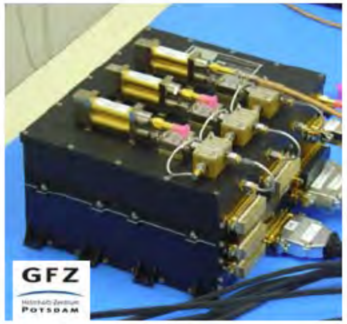
- Parallel $\Delta e/\Delta i$-vector configuration minimizes collision risk
- Equal inclination avoids relative drift of orbital planes
- Planned separation
  $a\delta e$ ~ 240 - 740 m
  $a\delta i$ ~ 400 - 1240 m
- Latitude dependent baseline

Precise Baseline Determination

- X-Band SAR interferometry needs relative position knowledge with utmost accuracy
- Cutting-edge sensor systems, algorithms, and calibration techniques
- Close to 1 mm relative navigation achieved through differential GPS





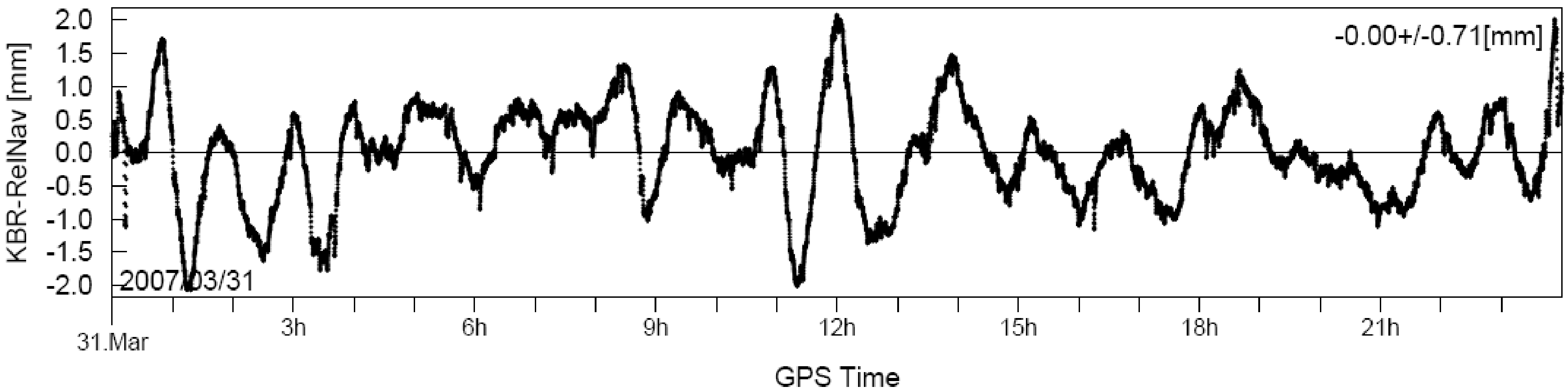


Relative Navigation Filter (Offline)

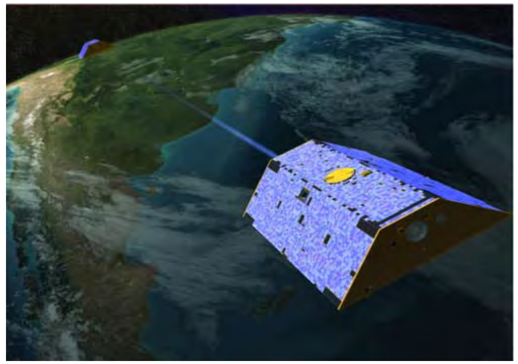
- Extended Kalman filter/smoother
- States (dual-frequency ~48, single frequency ~25)
  - Relative position and velocity (Δr, Δv)
  - Force model parameters (ΔC_R, ΔC_D, Δa_{emp})
  - Relative clock offset ($\Delta\delta t$)
  - Differential ionosphere for each channel (ΔI), zenith ionosphere delay (ZID)
  - Single-difference phase float ambiguities for each channel (ΔA_1 ,ΔA_2)
    Single-difference phase float ambiguties for each (ΔA_1)
- Measurement models
  - Single-difference code and phase
  - Antenna location and orientation (incl. switching)
  - Phase center offsets and variations, phase wind-up
- Ambiguity resolution using LAMBDA method and incorporation of integer constraints as pseudo-observations with zero variance

Kroes R., Montenbruck O., Bertiger W., Visser P.; *Precise GRACE baseline determination using GPS;* GPS Solutions 9, 21-31 (2005).

GRACE – Gravity Recovery and Climate Experiment



- Gradiometer with length of 200 km
- K-band ranging system (10 μm precision)
- First demonstration of GPS-based relative navigation with ~1 mm precision[1]
- Systematic biases at 2 mm-level[2]

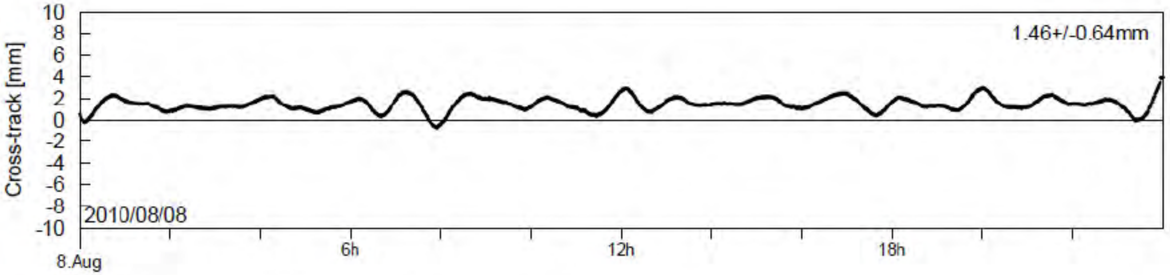


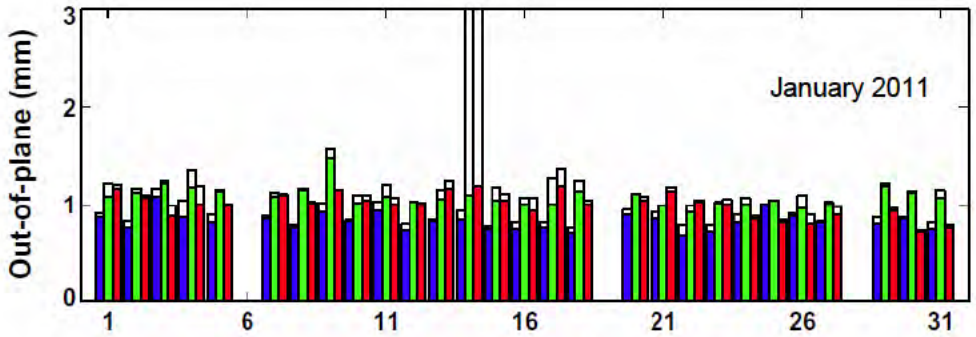
[1] Kroes R., Montenbruck O., Bertiger W., Visser P.; *Precise GRACE baseline determination using GPS;* GPS Solutions 9:21-31 (2005).

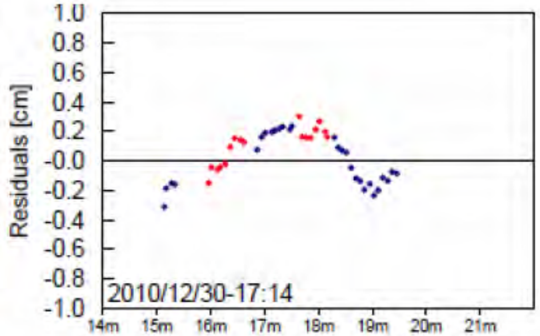
[2] Jäggi A., Dach R., Montenbruck O., Hugentobler U., Bock H., Beutler G.; *Phase center modeling for LEO GPS receiver antennas and its impact on precise orbit determination*; Journal of Geodesy 83(12):1145-1162 (2009).

Precise Baseline Determination – Accuracy Assessment

- Single-/Dual-Frequency[1]
- DLR / GFZ / AIUB[2]
- Calibration Data Takes[3]
- Satellite Laser Ranging







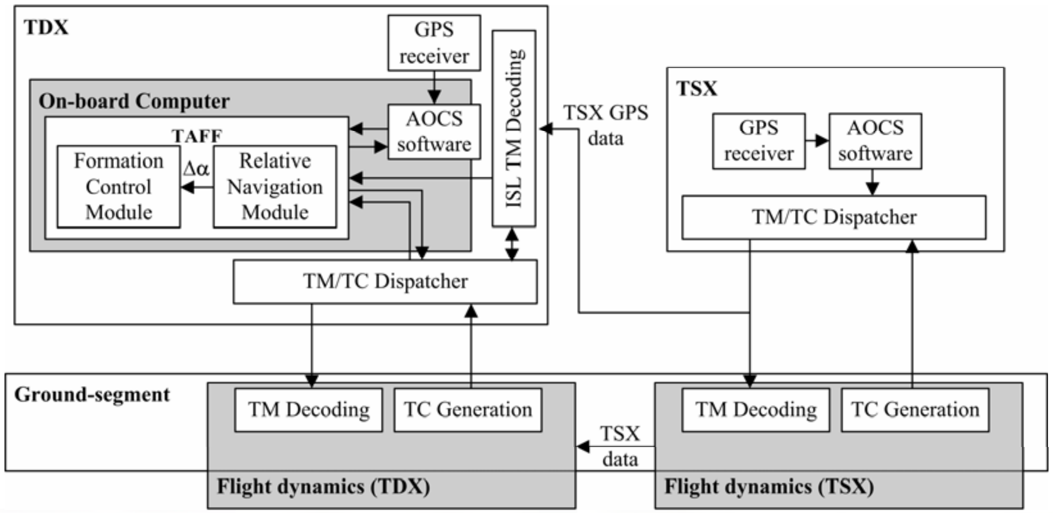
[1] Montenbruck O., Wermuth M., Kahle R.; *GPS Based Relative Navigation for the TanDEM-X Mission - First Flight Results*; ION-GNSS-2010 Conference, 21-24 Sep. 2010, Portland, Oregon (2010).

[2] Jäggi A., Montenbruck O., König R., Wermuth M., Moon Y., Bock H., Bodenmann D.; *Inter-agency comparison of TerraSAR-X and TanDEM-X baseline solutions*; Advances in Space Research 50(2):260-271 (2012). DOI 10.1016/j.asr.2012.03.027

[3] Wermuth M., Montenbruck O., Wendleder A.; *Relative Navigation for the TanDEM-X Mission and Evaluation with DEM Calibration Results*; 22nd International Symposium on Spaceflight Dynamics; 28 Feb – 4 Mar 2011, Sao Jose dos Campos, Brazil (2011).

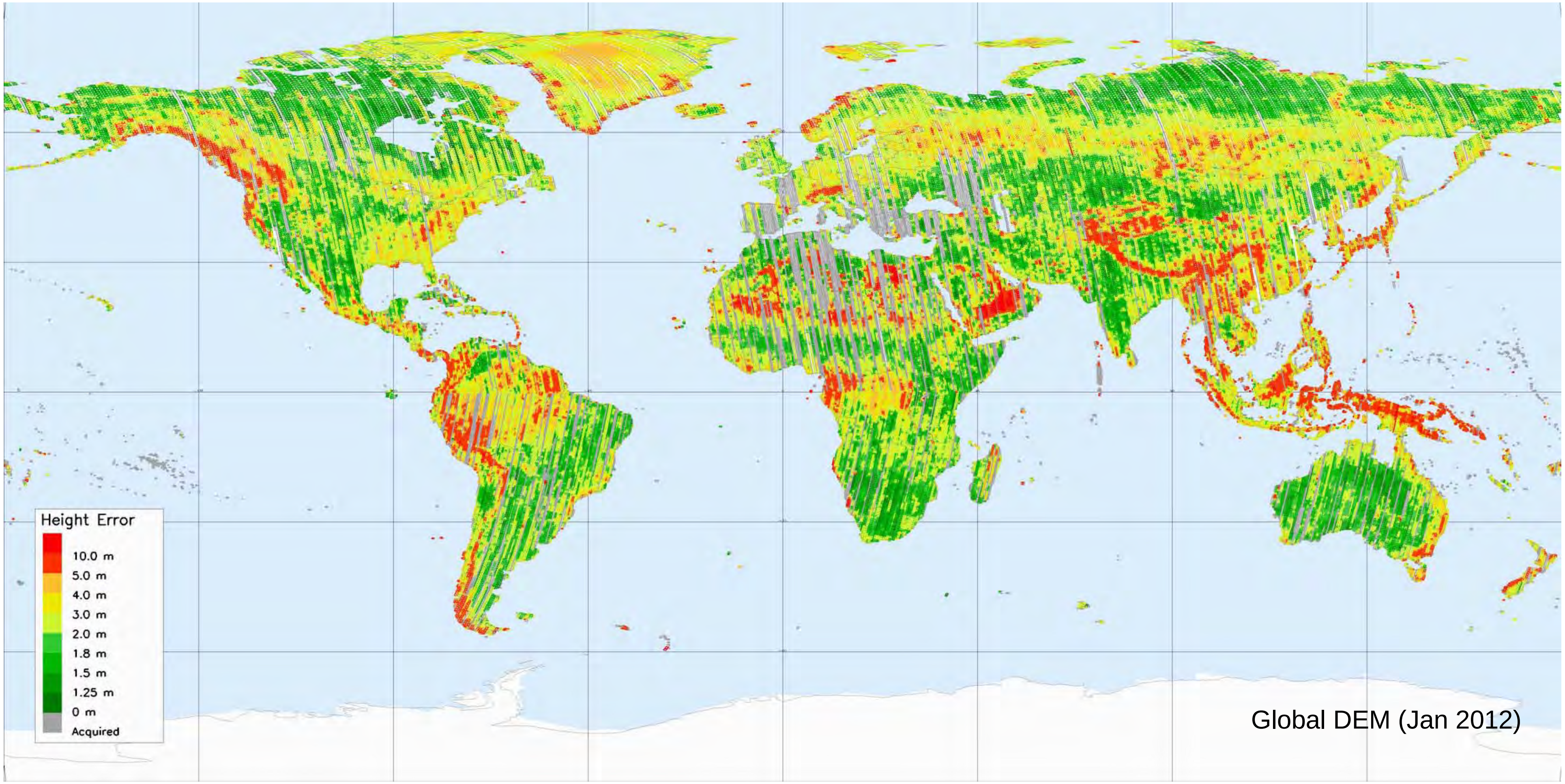
TanDEM-X Autonomous Formation Flying (TAFF)

- Design
  - Exerimental TDX onboard software supplement
  - Exchange of GPS navigation fix via inter-satellite link
- „Keep It Simple and Stupid (KISS)“
  - Analytical relative motion model
  - Estimation of relative orbital elements
  - Discrete control
- Control accuracy
  - 0.3 m radial (rms)
  - 7 m along-track (rms)

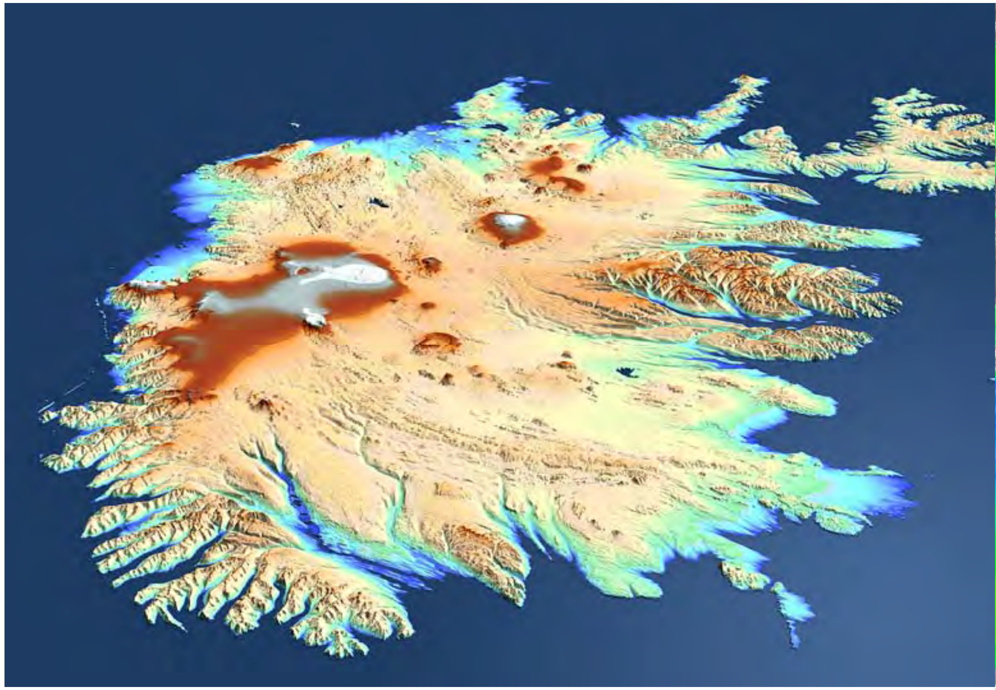


Ardaens J.S., Fischer D.; „TanDEM-X Autonomous Formation Flying System: Flight Results“; 18th IFAC World Congress, 28 Aug.-2 Sep 2011, Milano, Italy (2011).

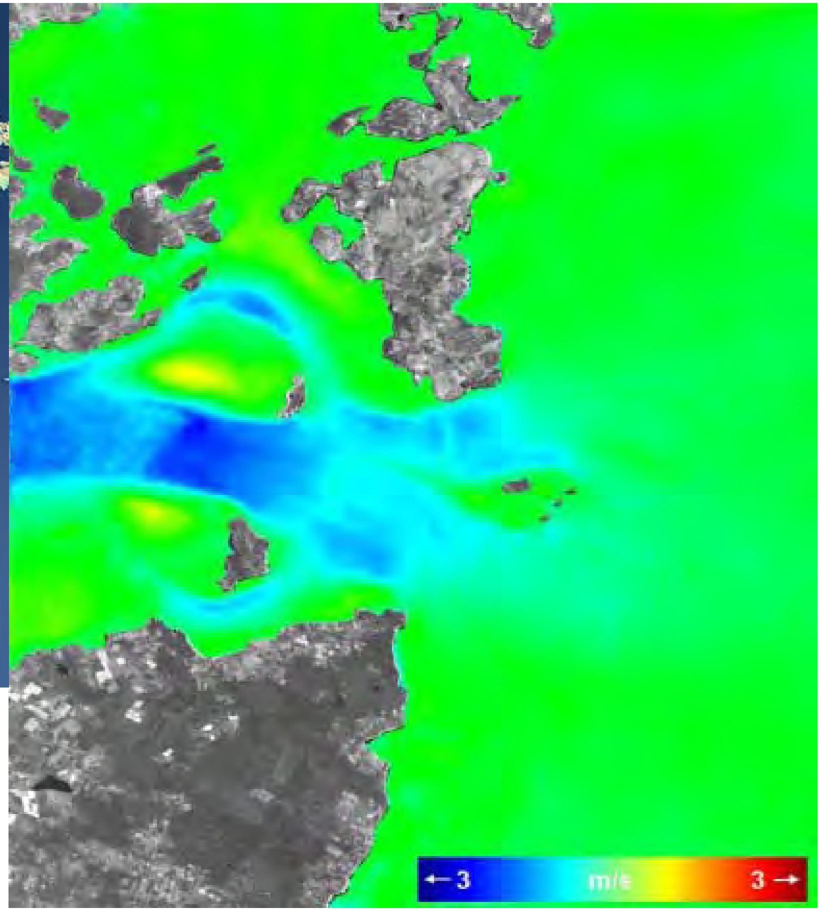
TanDEM-X Flight Results



TanDEM-X Flight Results

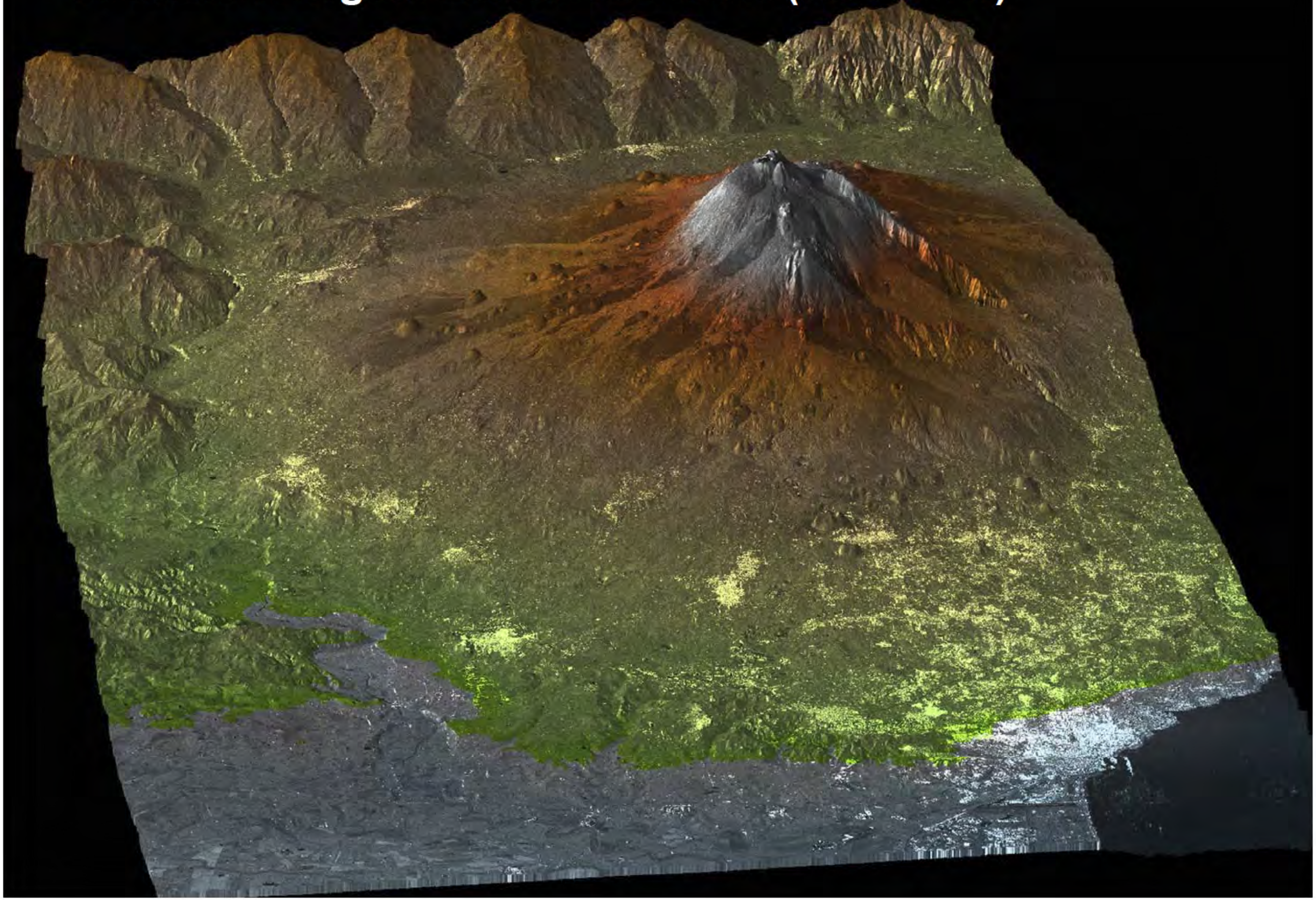


Digital elevation model of Iceland



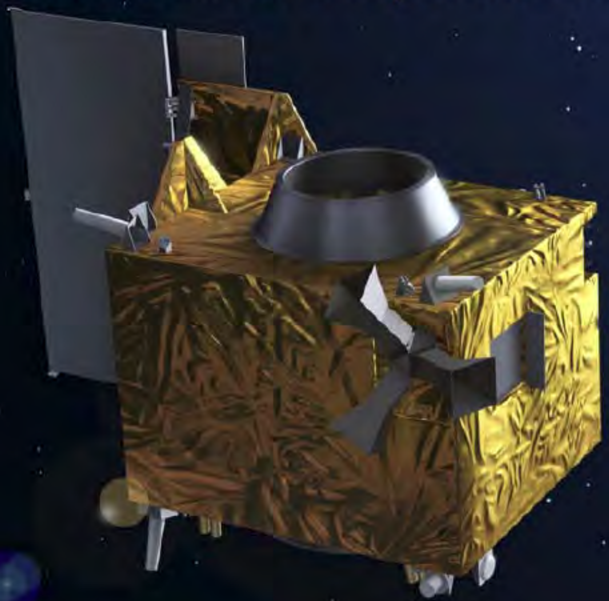
Ocean currents between
Scottland and Orkney Islands

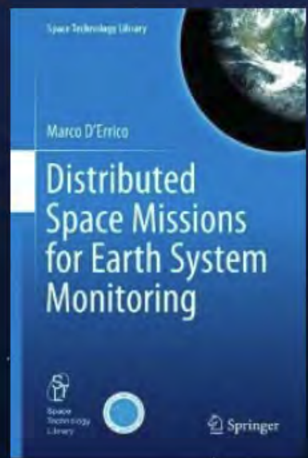
TanDEM-X Digital Elevation Model (Mt. Aetna)



Summary and Outlook

- Formation Flying in low Earth Orbit has become reality
- GPS offers high accuracy and autonomous navigation
- New and advanced navigation systems are required for high altitudes and non-cooperative missions





(Image:ESA)