In-Flight Performance Validation of the TanDEM-X Autonomous Formation Flying System

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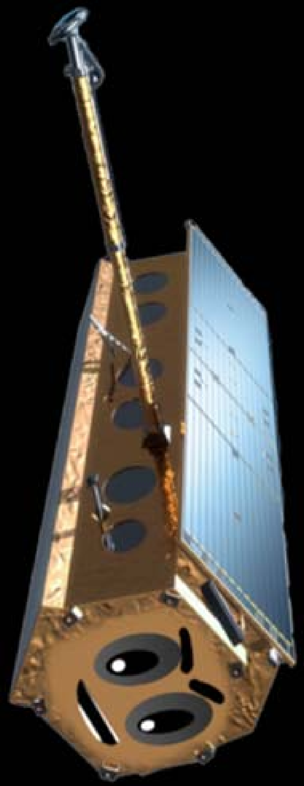
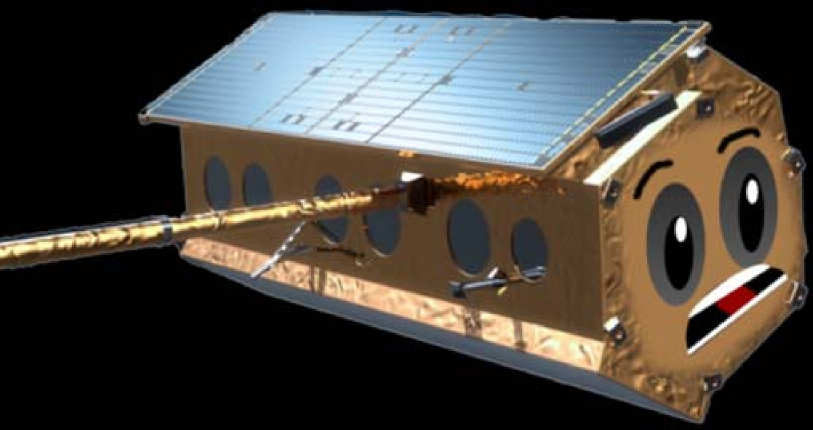
Enforcing Autonomous Formation Flying

- **TanDEM-X: unique opportunity to gain experience in designing formation flying autonomous GNC systems**
  - system performance & reliability
  - operational aspects
- **Add-on: onboard formation keeping system (TAFF)**
  - in-plane relative control of the formation using cold gas thrusters
  - demonstrate superior formation control performance
- **Specific constraints**
  - limited usage of onboard resources
  - deterministic maneuver planning (for mission operation activities)
  - no cold gas maneuver allowed during SAR acquisition

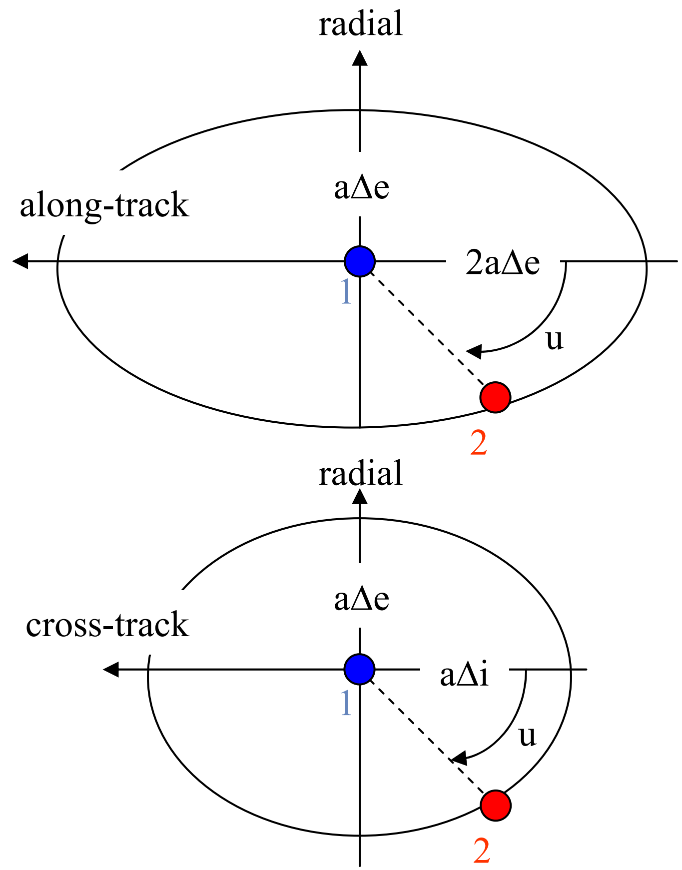
Challenges of Onboard Autonomy



- Never disturb the primary scientific mission objectives
- Convince people that autonomous formation keeping does not endanger the formation
- Demonstrate that onboard autonomy brings some added value



Formation Description

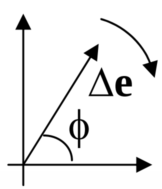


- natural elliptic relative motion
- latitude-dependent separation
- parameterization through a set of relative orbital elements : Δa, $\Delta \boldsymbol{e}$, $\Delta \boldsymbol{i}$, Δu describing the shape of the ellipse

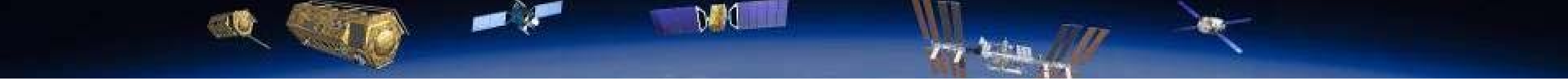
$$\Delta a = a_2 - a_1 \qquad \Delta \mathbf{e} = e_2 \begin{pmatrix} \cos\omega_2 \\ \sin\omega_2 \end{pmatrix} - e_1 \begin{pmatrix} \cos\omega_1 \\ \sin\omega_1 \end{pmatrix}$$

$$\Delta u = u_2 - u_1 \qquad \Delta \boldsymbol{i} = \begin{pmatrix} i_2 - i_1 \\ (\Omega_2 - \Omega_1)\sin i_1 \end{pmatrix}$$

- passive safety through proper phasing of $\Delta \boldsymbol{e}$ and $\Delta \boldsymbol{i}$
- secular drift of the phase of $\Delta \boldsymbol{e}$ due to J_2
  $\Rightarrow$ the formation needs to be actively controlled

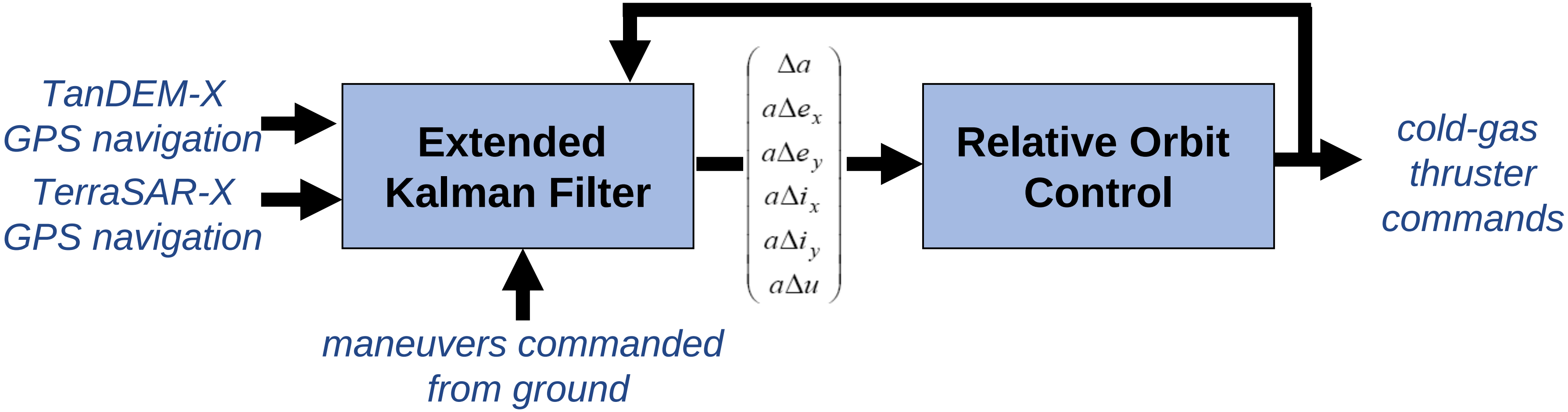


if $\Delta \boldsymbol{e} \,//\, \Delta \boldsymbol{i}$:
radial separation max when cross-track separation = 0



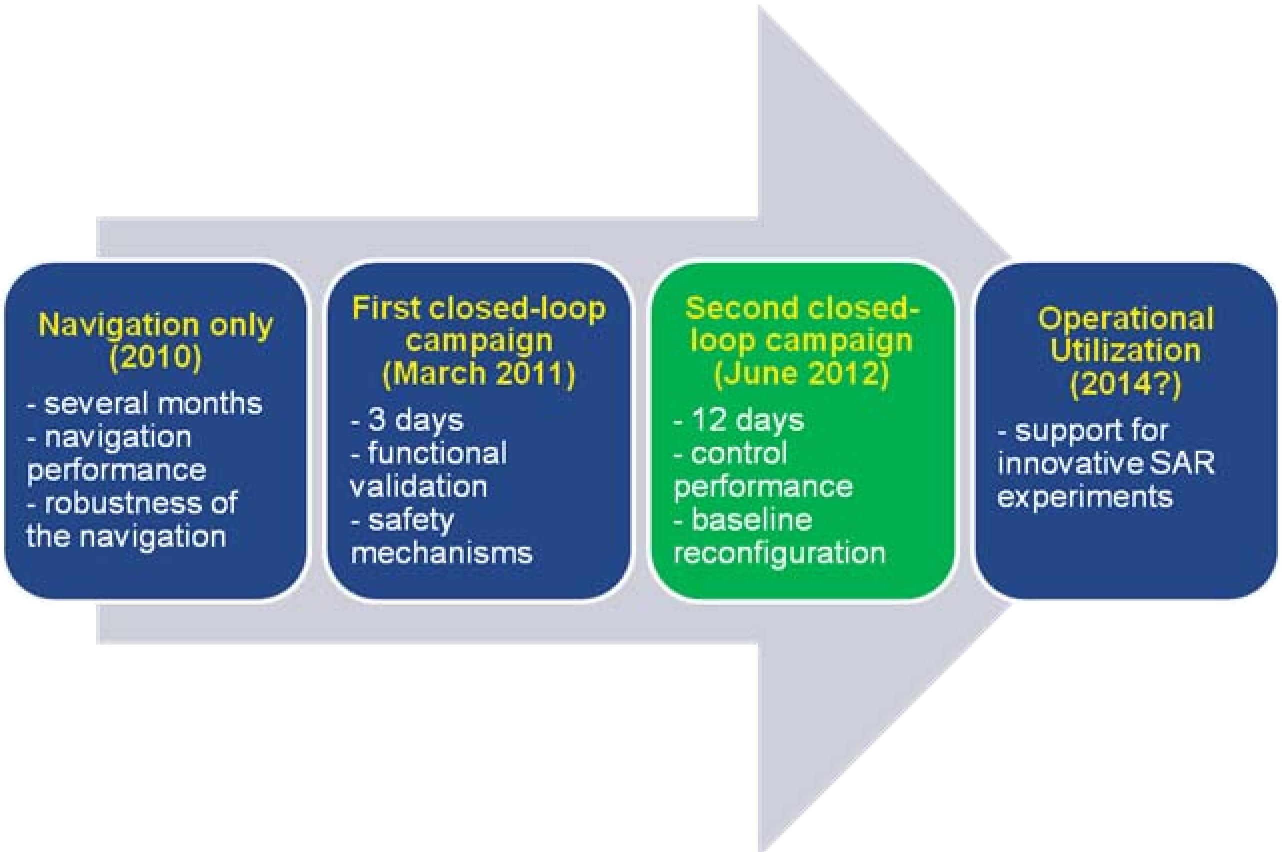
TanDEM-X Autonomous Formation Flying (TAFF)

- **Standalone real-time GNC system onboard TanDEM-X**



- **Streamlined and resource-sparing design**
  - usage of GPS navigation solutions output by the MosaicGNSS receivers
  - analytical relative motion model taking only J_2 into account: no need for numerical integration
  - analytical solution of the relative control problem

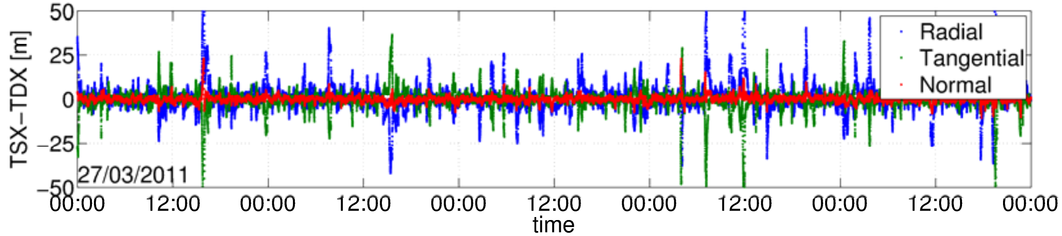
Validation Activities



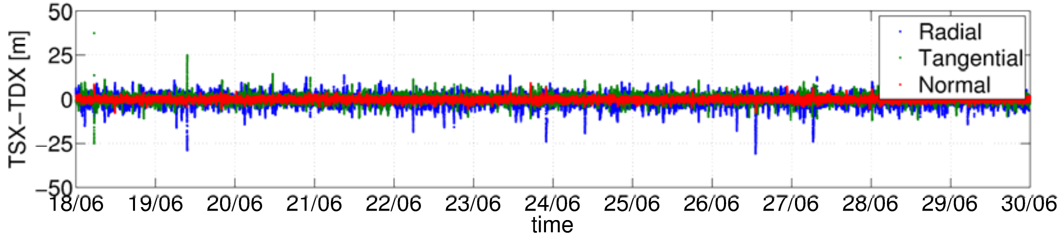
Relative Navigation Performance

- Robust relative GPS navigation input to TAFF (no hardware anomaly, no big outlier)

Closed-loop campaign 2011



Closed-loop campaign 2012

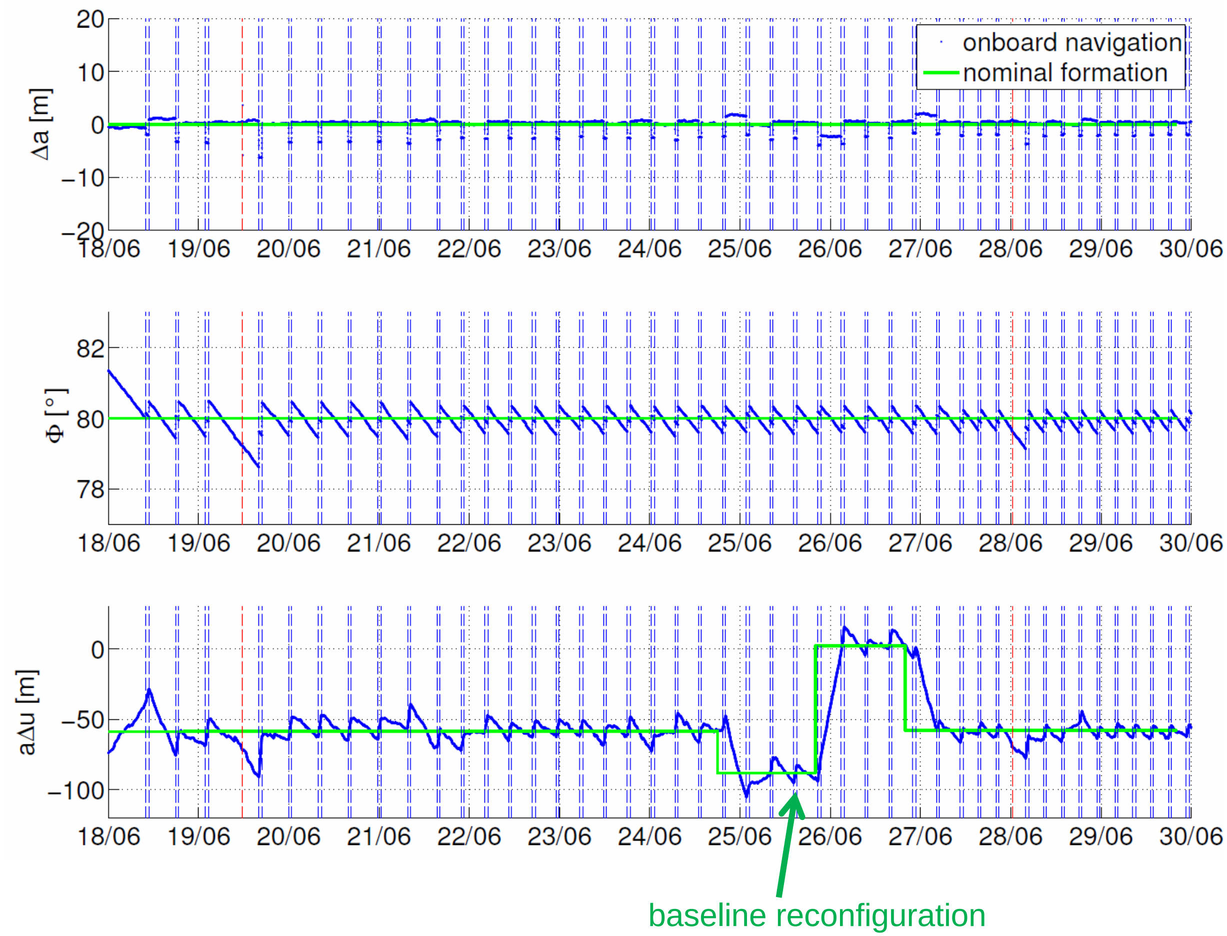


- Filtered navigation solution: great improvement of the radial component

Source	Radial [m]	Tangential [m]	Normal [m]
Differential GPS navigation	**-0.95±3.22**	+0.14±2.03	-0.30±1.13
Onboard relative navigation	**-0.01±0.43**	+0.48±1.39	-0.05±0.30

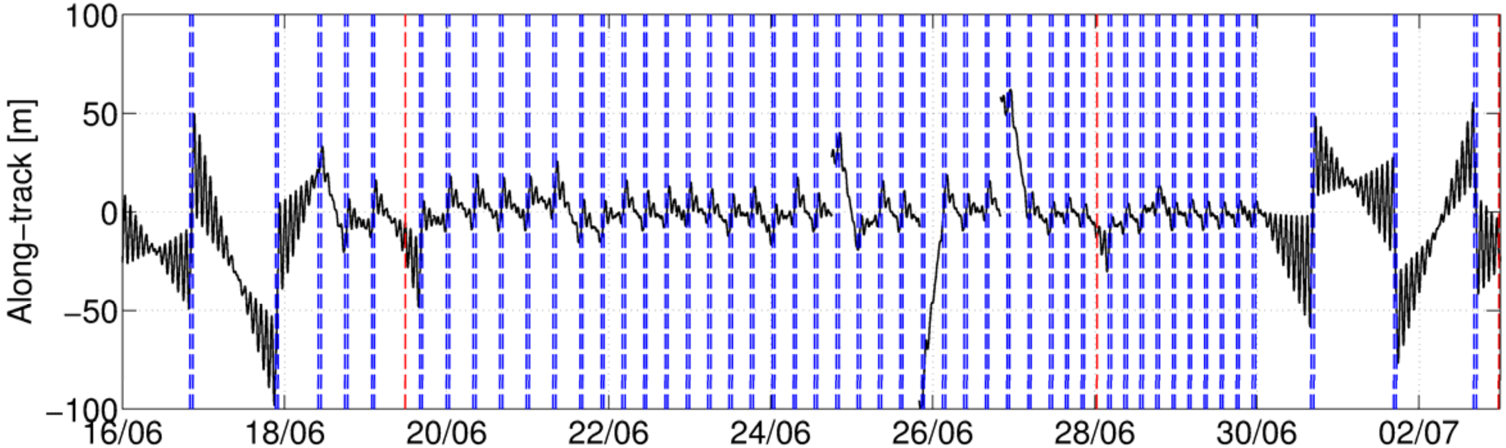
In-Plane Relative Control

- Formation successfully controlled during 12 days
- No anomaly detected during the campaign
- Several control periods investigated
- Baseline reconfiguration exercised



Relative Control Performance

- Great improvement of control performance due to smaller control periods



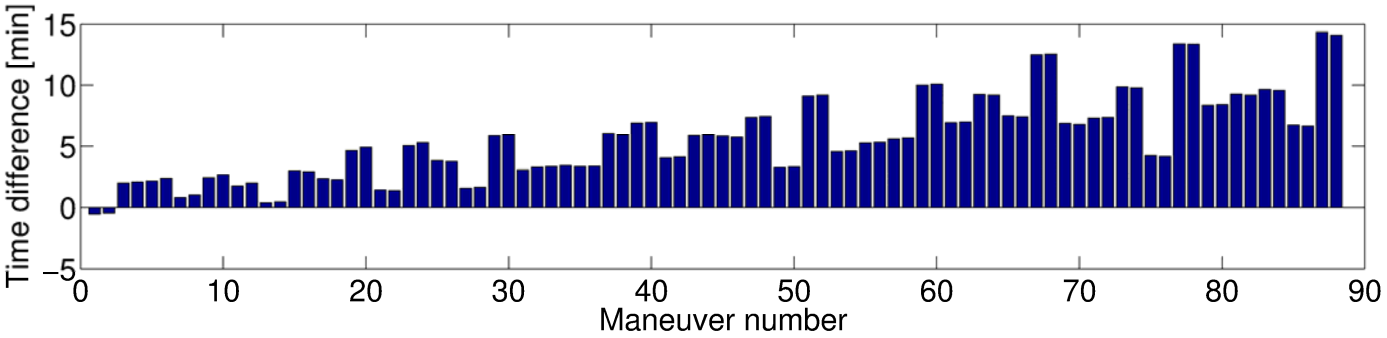
- Relative control performance of 10 m can be achieved

	radial [m] (rms/max)	along-track [m] (rms/max)
on-board control every 5 orbits	2.0/5.4	8.0/25
on-board control every 3 orbits	1.3/4.7	3.5/13.4

System Predictability

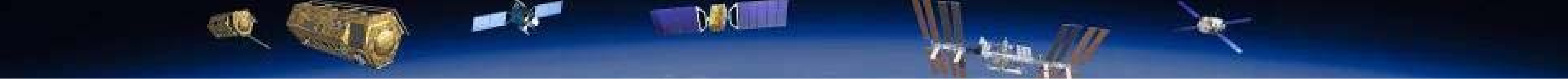
- **Deterministic maneuver planning**
  - relative orbit control done with a pair of along-track maneuvers
  - constant control period (typically 3 to 5 orbits)
  - state machine implemented for the autonomous execution of maneuvers

  ⇒ possible to predict the execution time of the maneuvers during the next two weeks with good precision (15 minutes)

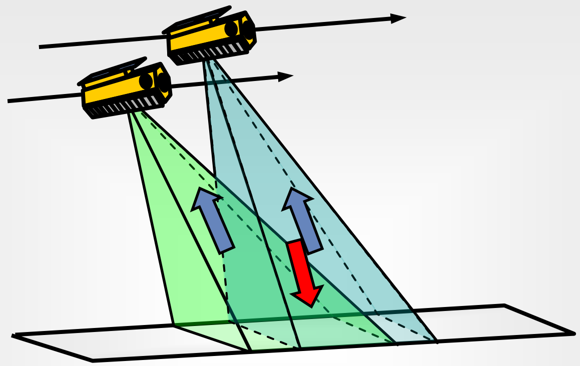
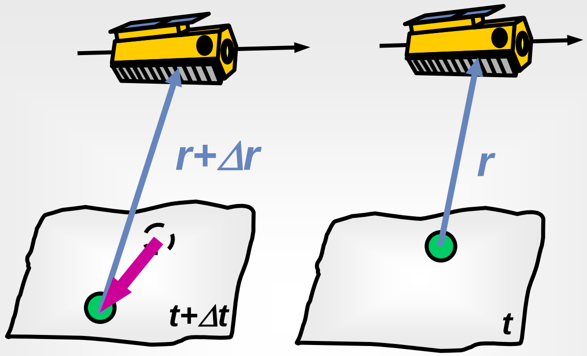


Do we need TAFF?

- TAFF has never been used operationally during the first three years of the mission
- The greatest advantage of TAFF lies only in the control performance, not in the reduction of operational effort (the formation keeping is also fully automatized on-ground)
- No need currently for better control performance
- This situation might change soon with secondary mission objectives where enhanced control performance is **required**

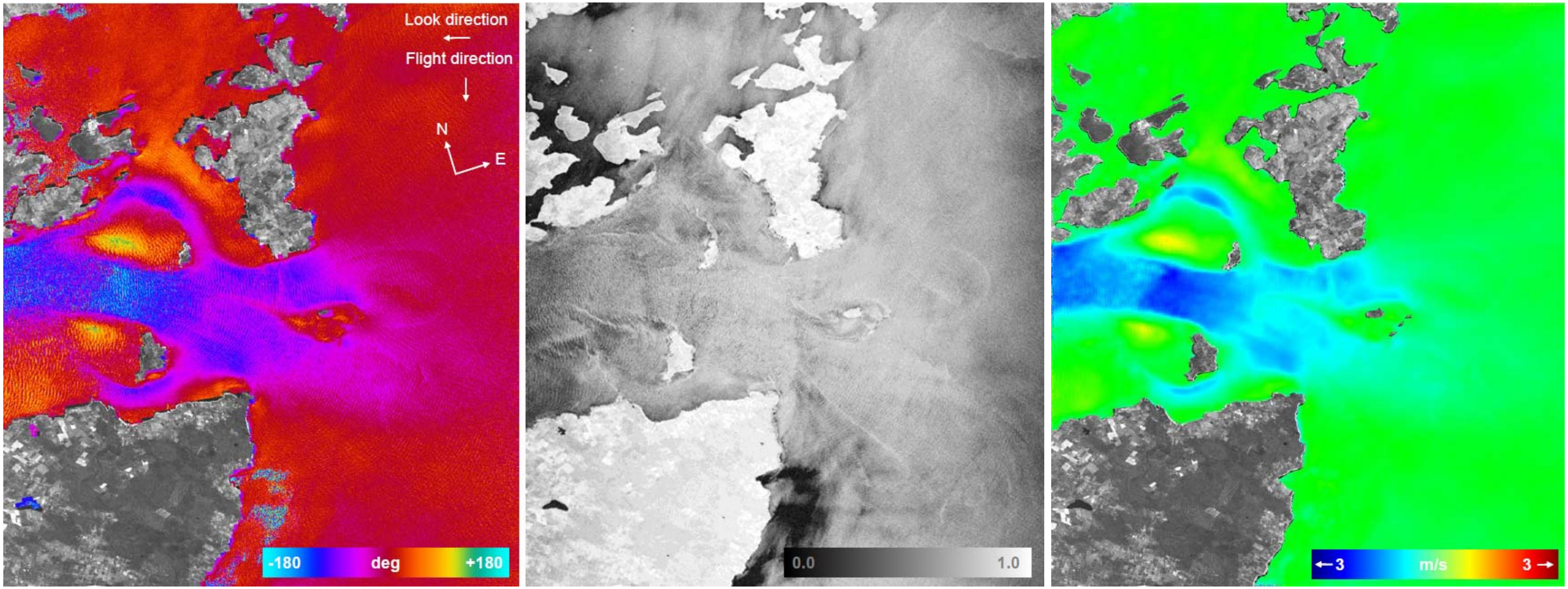


TanDEM-X Primary vs. Secondary Mission Objectives

Cross-Track Interferometry	Along-Track Interferometry (ATI)
 → **Digital Elevation Models (DEM)** → High Resolution SAR Images	 → **Large Scale Velocity Fields** (ocean currents, ice drift, …) → Moving Object Detection
DEM acquisition: →Cross-track baselines of 200 – 600 m → along-track variation of up to ± 1000 m →Required formation control accuracy: 20 m Radial / Normal, 200 m Tangential	**Oceanographic ATI:** →As small as possible cross-track baseline →Optimal along-track separation: 40 – 60 m (Tolerable: 10 – 40 m and 60 – 90 m) →Requires 10 m along-track control accuracy !

Promising First ATI Results:

The Tidal Current between Scotland and the Orkney Islands



Interferometric phase velocity

Coherence

Ground-range

10 km

source: Kahle et al, Formation Flying for Along-Track Interferometric Oceanography – First In-flight Demonstration with TanDEM-X, ISSFD 2012.

Conclusion

- TanDEM-X is the first scientific formation flying mission controlled autonomously
- TAFF is shown to be reliable and suited for operations
- Improved formation control accuracy will help supporting advanced SAR applications, like Along-track Interferometry