

Radio-Frequency Sensor Fusion for Relative Navigation of Formation Flying Satellites

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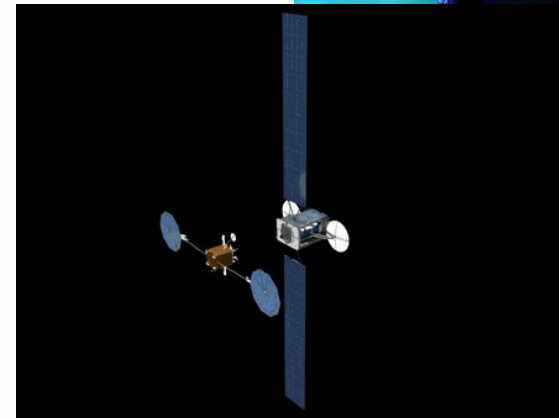
- **Formation flying (FF) and relative navigation in space**
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Artist's impression of future applications of formation flying satellites based on the PRISMA mission results (Source: SSC)

FF and relative navigation in space: motivation

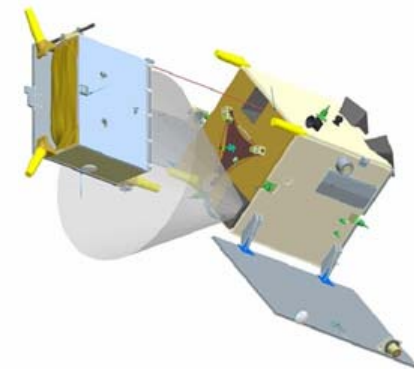
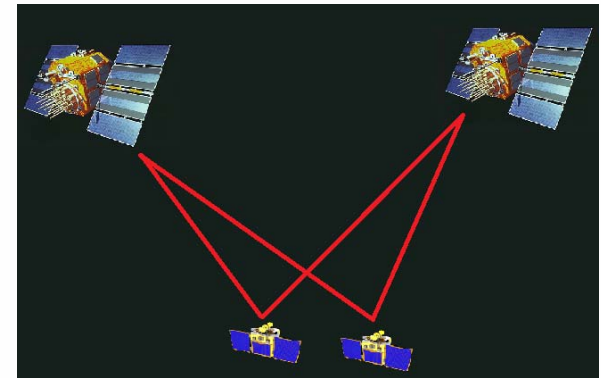
- **Spacecraft formation flying applications**
 - SAR interferometer and gravimeter
 - Multi spacecraft telescope
 - On-orbit servicing and rendezvous
- **Formation control -> relative navigation**
- **Autonomous systems require information with high levels of**
 - Robustness
 - Reliability
 - Availability



Artist's impression of the DARWIN constellation. (Source: ESA).
Artist's impression of a typical on-orbit servicing mission. (Source: ATK)

FF and relative navigation in space: techniques

- **Differential GPS**
 - Based on spaceborne GPS sensor
 - Various degrees of accuracy
- **Radio-frequency (RF)**
 - Formation flying radio-frequency (FFRF) sensor
 - Self contained relative navigation system
 - Coarse positioning and formation acquisition
- **Vision-based**
 - Proximity and rendezvous operations
- **Laser metrology**



Artist's impression of the VBS in PRISMA (Source: SSC)

The PRISMA mission

- **Demonstration of techniques for FF and rendezvous**
 - Novel relative navigation sensors
- **Launched on June 15th, 2010**
 - Sun-synchronous orbit
 - Altitude of 750 km
- **Joint effort**
 - Swedish National Space Board (SNSB)
 - Swedish Space Corporation (SSC) / OHB-Sweden
 - German Aerospace Center (DLR)
 - National Center for Space Studies (CNES)
 - Technical University of Denmark (DTU)
- **Space segment consists of 2 spacecraft**
 - Mango (chaser)
 - Tango (target)



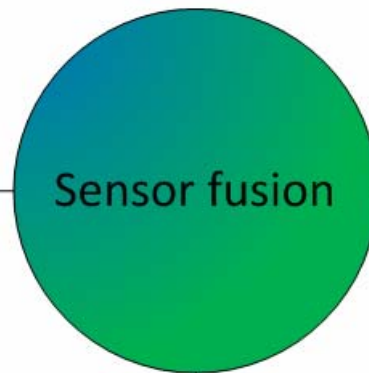
Artist's impression of the PRISMA satellites in orbit. (Source: DLR)

Sensor fusion: introduction

(D)GPS
measurements



FFRF
measurements

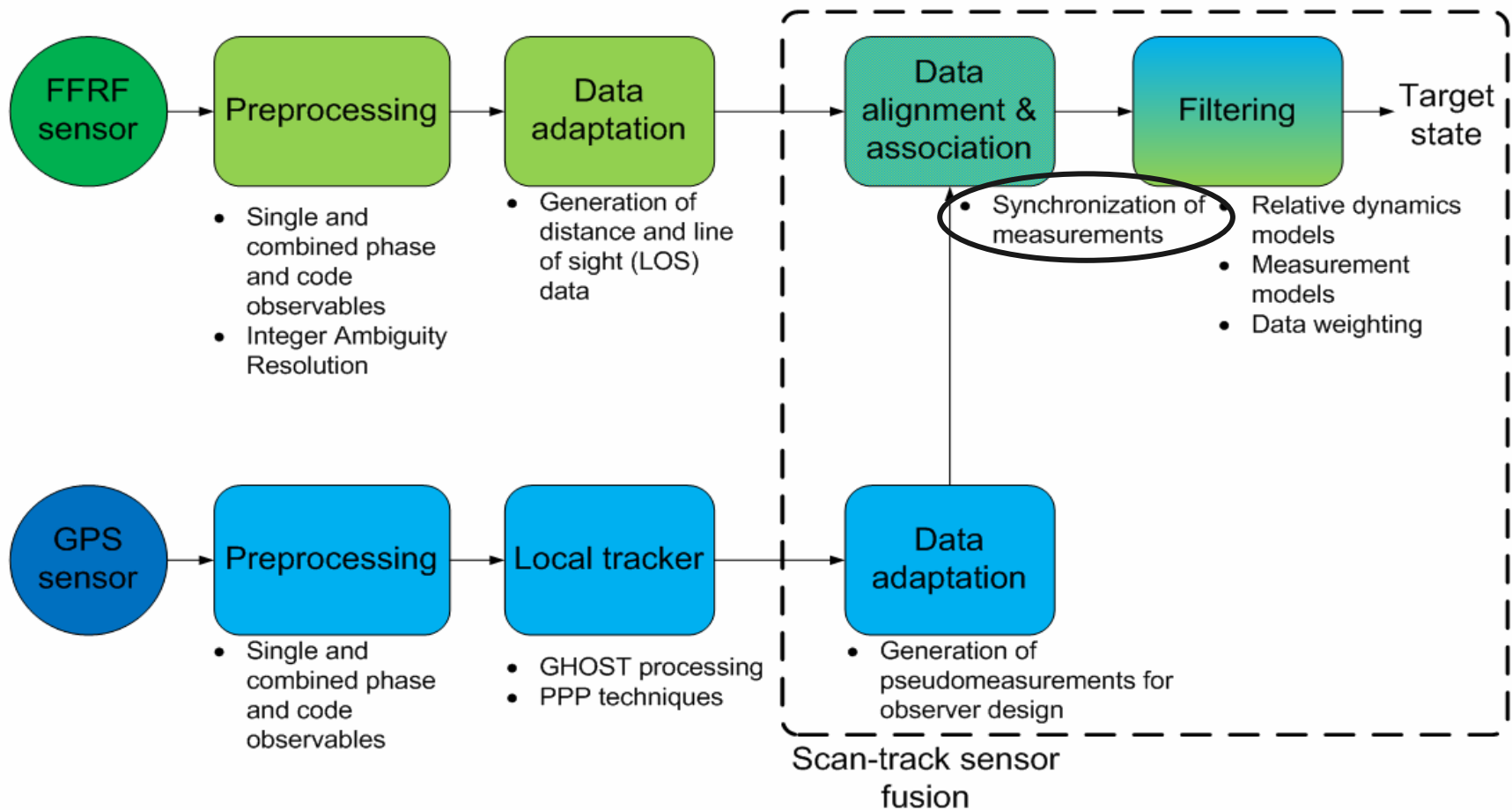


Relative navigation
solution

- Absolute position of Mango and Tango
- Earth-Fixed Earth-Centered reference frame

- Relative distance (d)
- Line of sight (LOS)
- RF reference frame

Sensor fusion: architecture



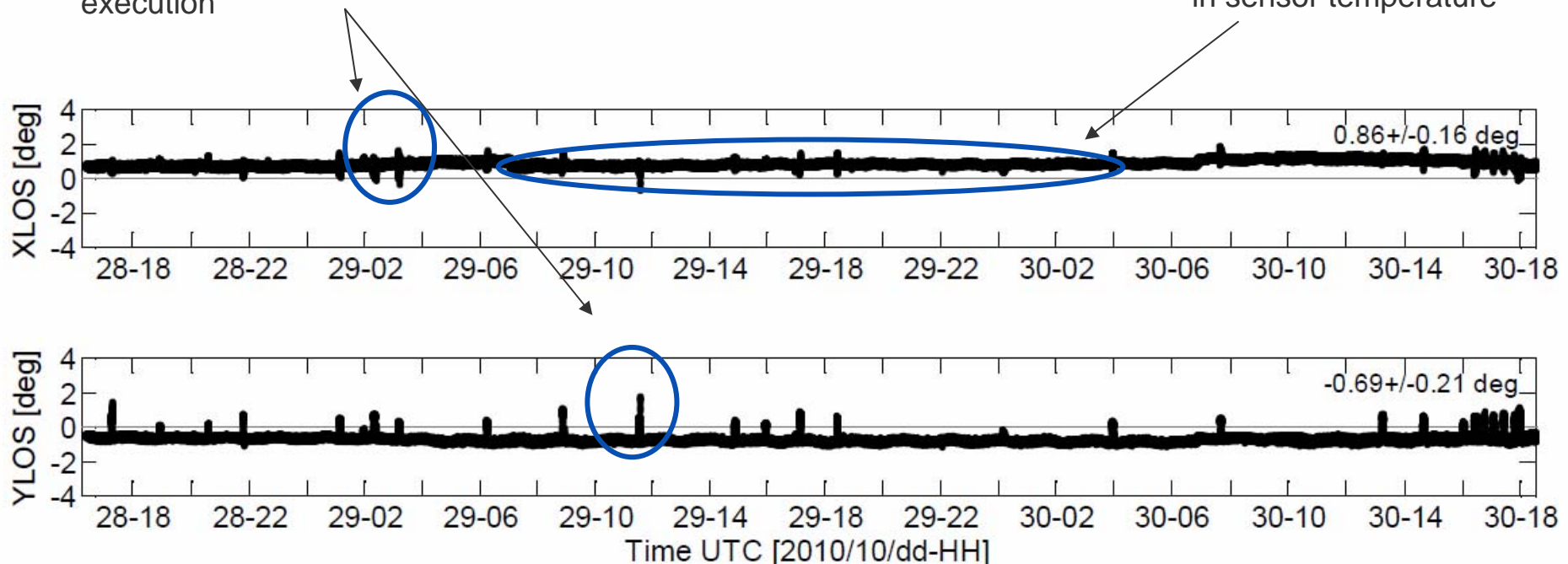
Sensor fusion: measurements

Assessment of FFRF LOS measurements (DLR's POD as reference)

Oct 28th (16:00) – Oct 30th (18:30), 2010

Large angular excursion
(measurement error) caused by
multipath during maneuver
execution

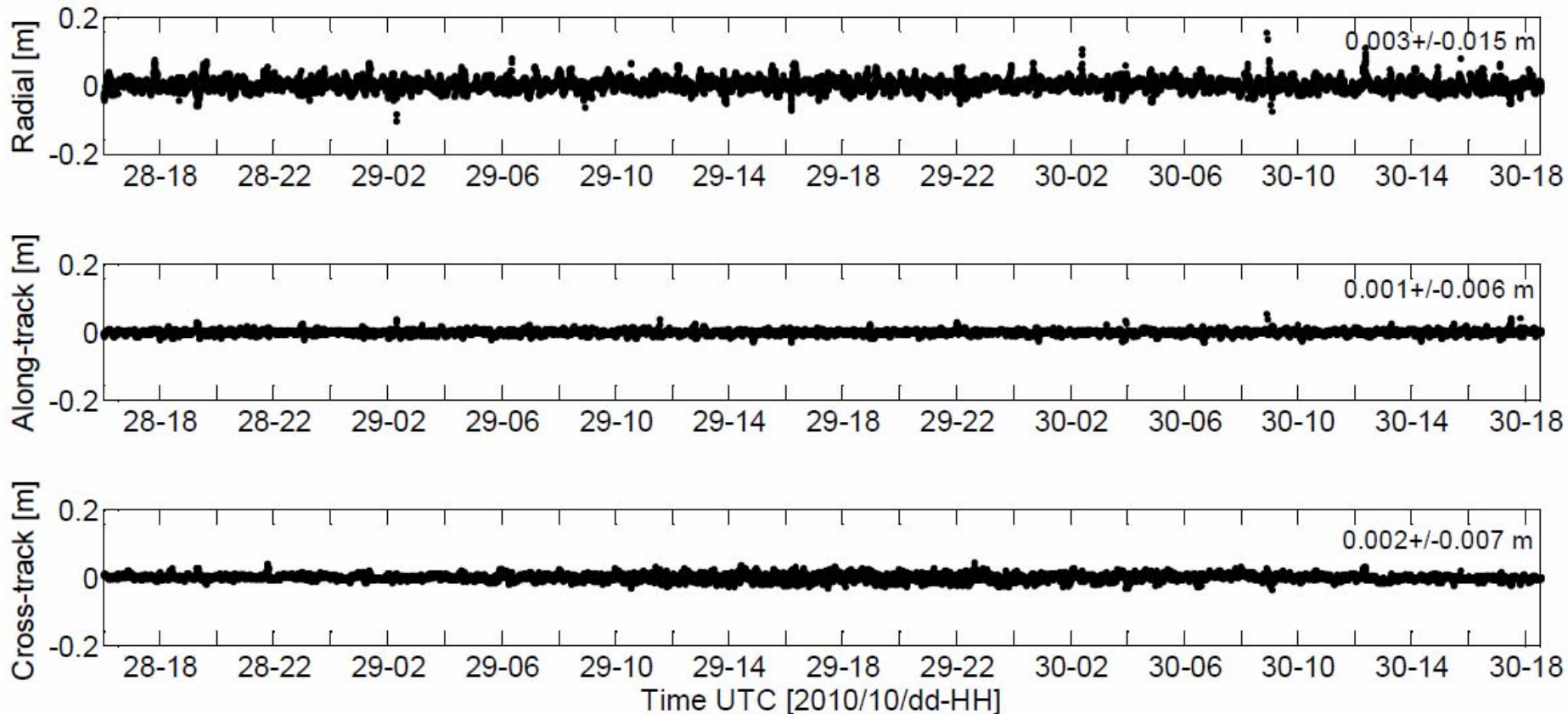
Non-constant bias
attributed to variations
in sensor temperature



Sensor fusion: measurements

Assessment of (D)GPS measurements (DLR's POD as reference)

Oct 28th (16:00) – Oct 30th (18:30), 2010



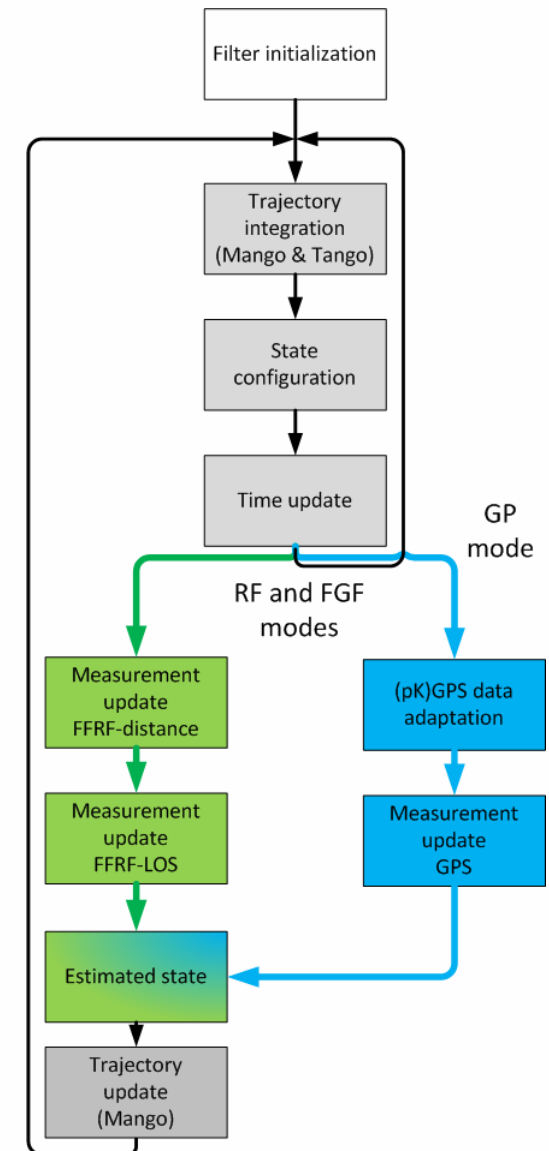
Sensor fusion: relative navigation filter

➤ Extended Kalman Filter (6+3 states)

- Relative state vector ($\Delta \mathbf{x}$)
- FFRF float biases (b_{xl}, b_{yl}, b_d)

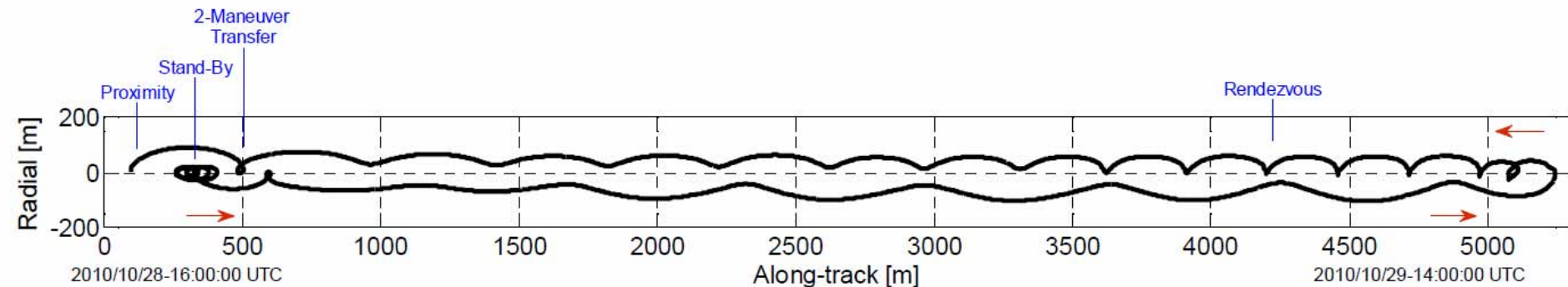
➤ Measurements

- Distance and LOS from FFRF sensor
- Precise kinematic from GPS sensor



Results and discussion

- **Accuracy of relative navigation solution**
 - Premise for analysis of filter properties
 - Should be similar regardless of the sensor(s) being used
- **Using both sensors at same orbit phases**
 - Increased robustness
 - Increased reliability
- **Handover between sensors at different orbit phases**
 - Increased availability
- **In-plane relative navigation solution (Oct 28th (16:30) – Oct 30th (18:30), 2010)**



Results and discussion

Initial assessment of accuracy

Oct 28th (16:00) – Oct 29th (01:00), 2010

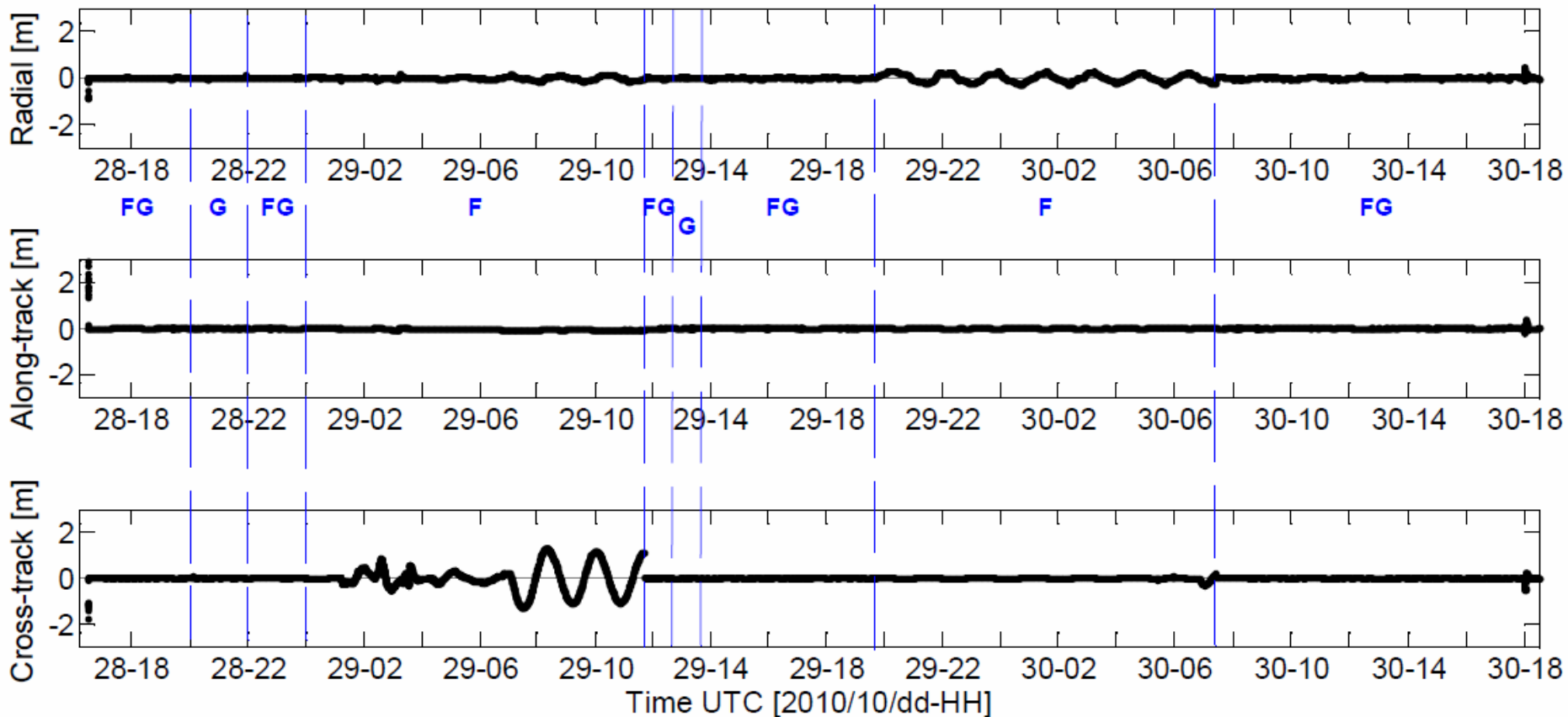
Formation in free drift and stand-by (approx. avg. ISD of 300 m)

Sensor	Error in position (cm)			Error in velocity (mm/s)		
	Radial	Along-track	Cross-track	Radial	Along-track	Cross-track
FFRF	0.1±2.7	-0.3±2.3	1.4±12.6	-0.010±0.10	0.001±0.04	0.063±0.15
GPS	0.2±1.6	0.1±0.6	0.3±0.8	0.010±0.22	0.002±0.07	0.006±0.21
FFRF+GPS	0.3±1.5	0.1±1.0	0.3±0.6	-0.001±0.09	-0.001±0.04	-0.001±0.07

Results and discussion

Handover tests

Oct 28th (16:30) – Oct 30th (18:30), 2010



Conclusions and future work

- **Sensor fusion allows the generation of relative navigation solution with increased:**
 - Robustness (tolerance to bad data points)
 - Flexibility (single design for different mission scenarios)
 - Reliability and availability (tolerance to measurement gaps or data outages)
- **FFRF/GPS sensor fusion provides concepts for precise relative navigation in HEO**
- **Simple design of the relative navigation filter**
 - Feasibility of the approach
 - Limitations in dynamical modelling and maneuver handling
- **Integral design using measurements from GPS/FFRF/VBS sensors**
- **Generation of precise kinematic GPS measurements using PPP techniques could enable sensor fusion for real-time relative navigation**