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

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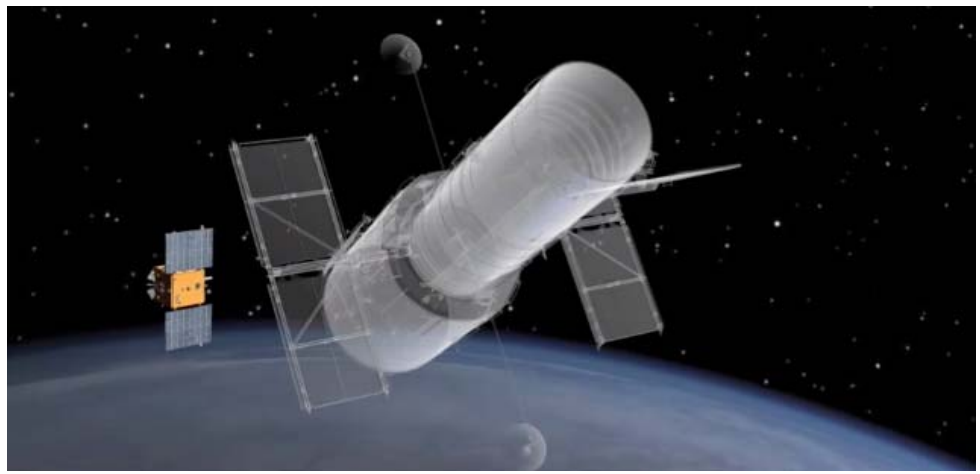
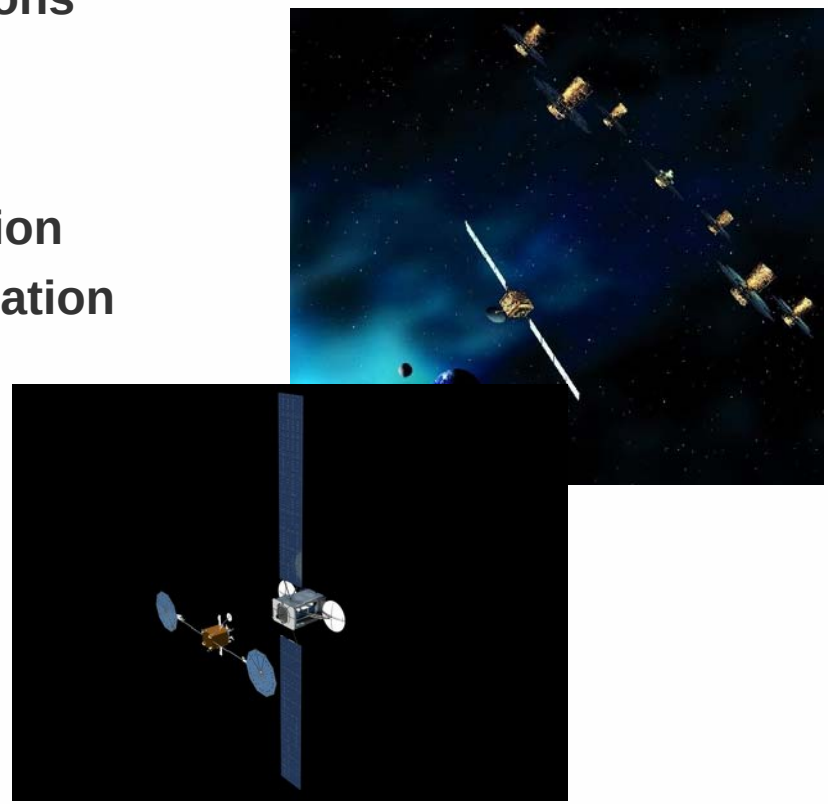


Artist's impression of future applications of formation flying satellites based on the PRISMA mission results (Source: SSC)

FF and relative navigation in space: motivation

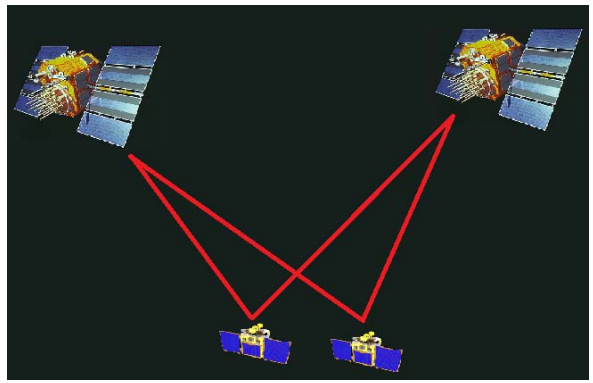
- **Spacecraft formation flying applications**
  - SAR interferometer and gravimeter
  - Multi spacecraft telescope
  - On-orbit servicing and rendezvous
- **Formation control -> relative navigation**
- **Autonomous systems require information with high levels of**
  - Robustness
  - Reliability
  -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

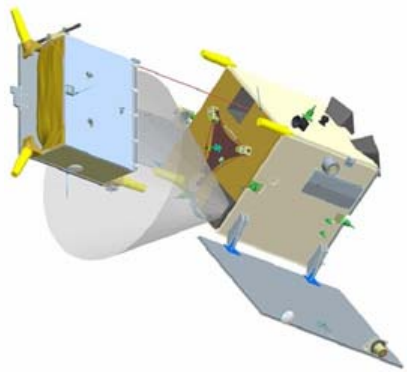


Artist's impression of the DARWIN constellation. (Source: ESA).
Artist's impression of a typical on-orbit servicing mission. (Source: ATK)

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

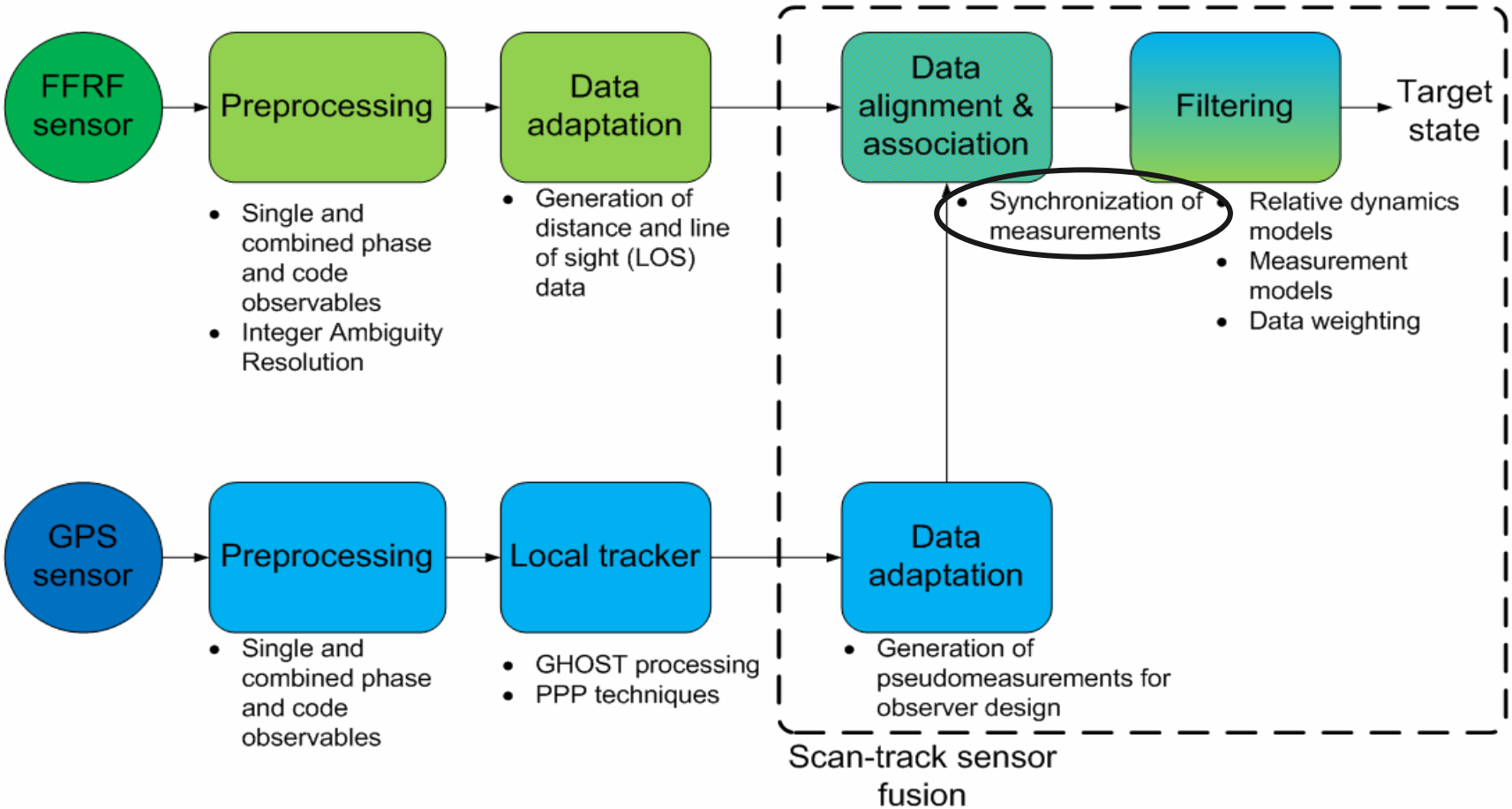
Sensor fusion

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

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

Relative navigation solution

Sensor fusion: architecture

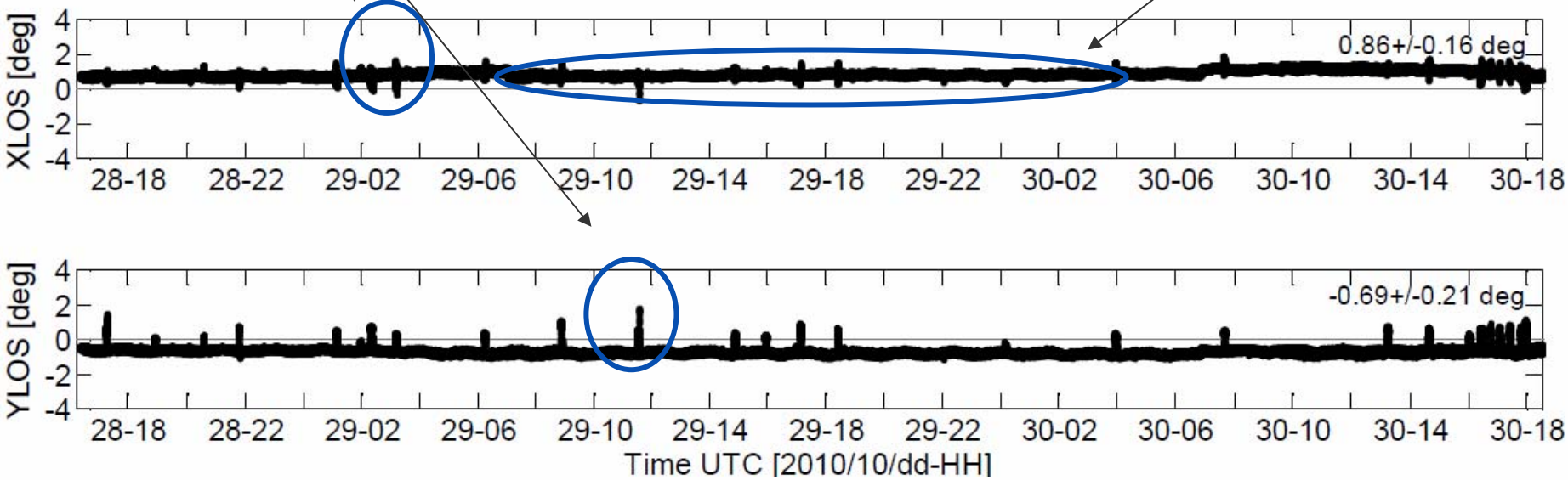


Sensor fusion: measurements

Assessment of FFRF LOS measurements (DLR‘s POD as reference) Oct 28th (16:00) – Oct 30th (18:30), 2010

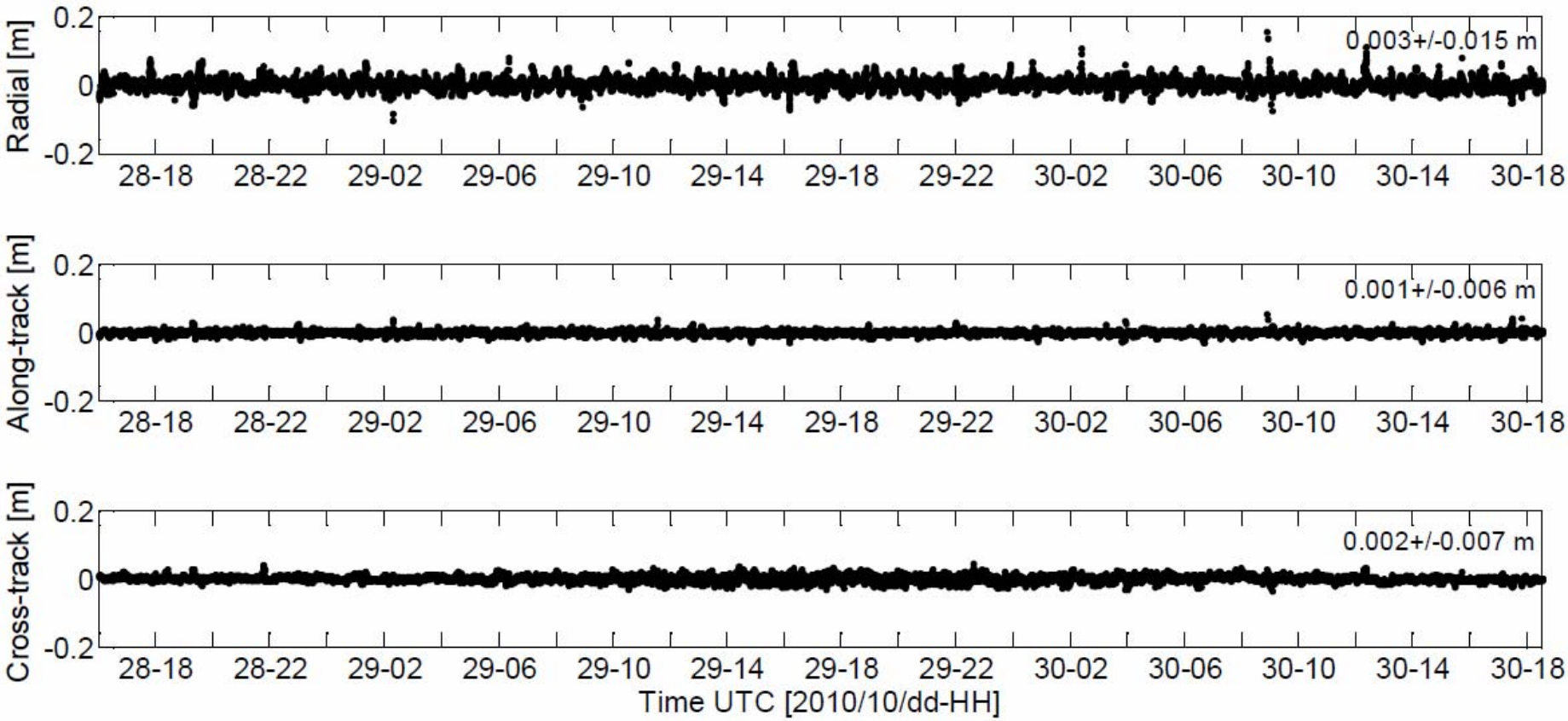
Large angular excursion (measurement error) caused by multipath during maneuver execution

Non-constant bias attributed to variations in sensor temperature



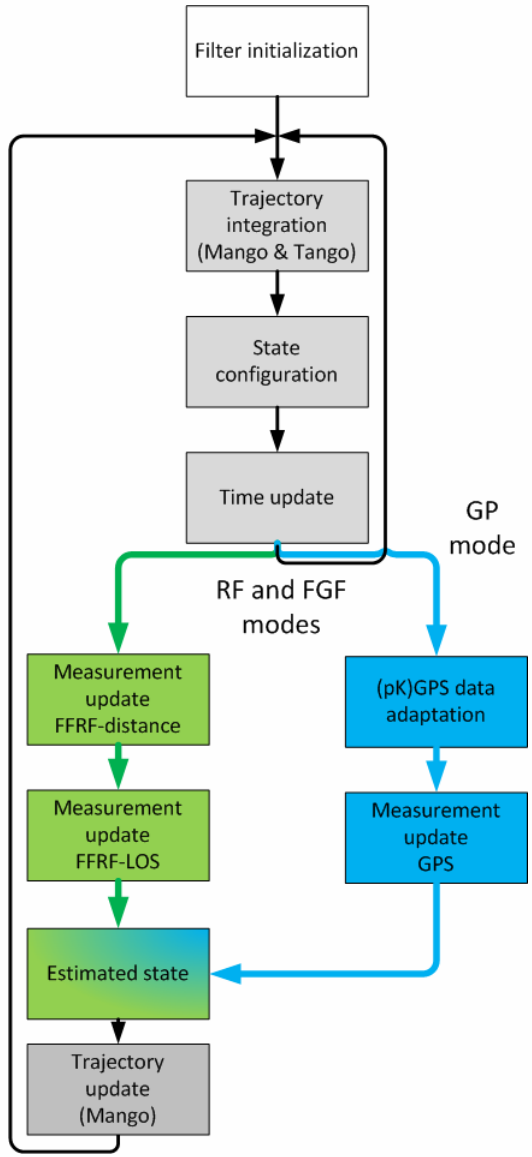
Sensor fusion: measurements

Assessment of (D)GPS measurements (DLR‘s POD as reference)
Oct 28th (16:00) – Oct 30th (18:30), 2010



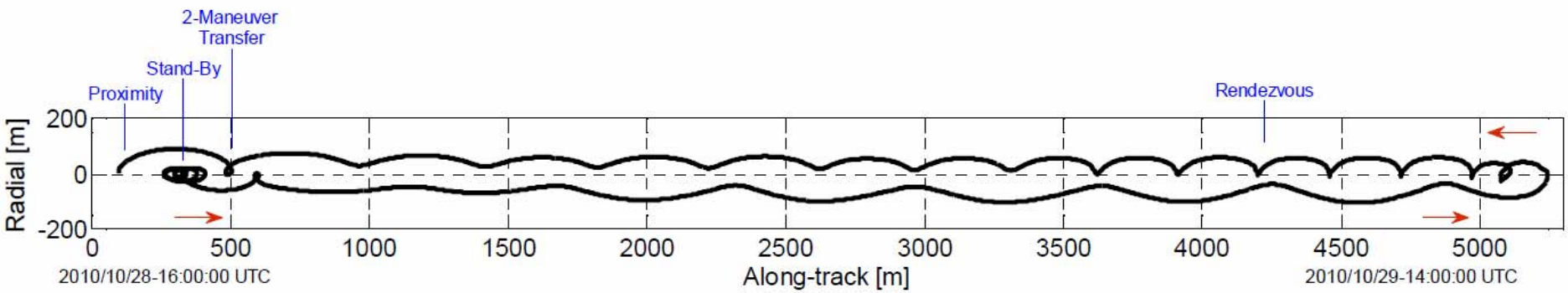
Sensor fusion: relative navigation filter

- **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

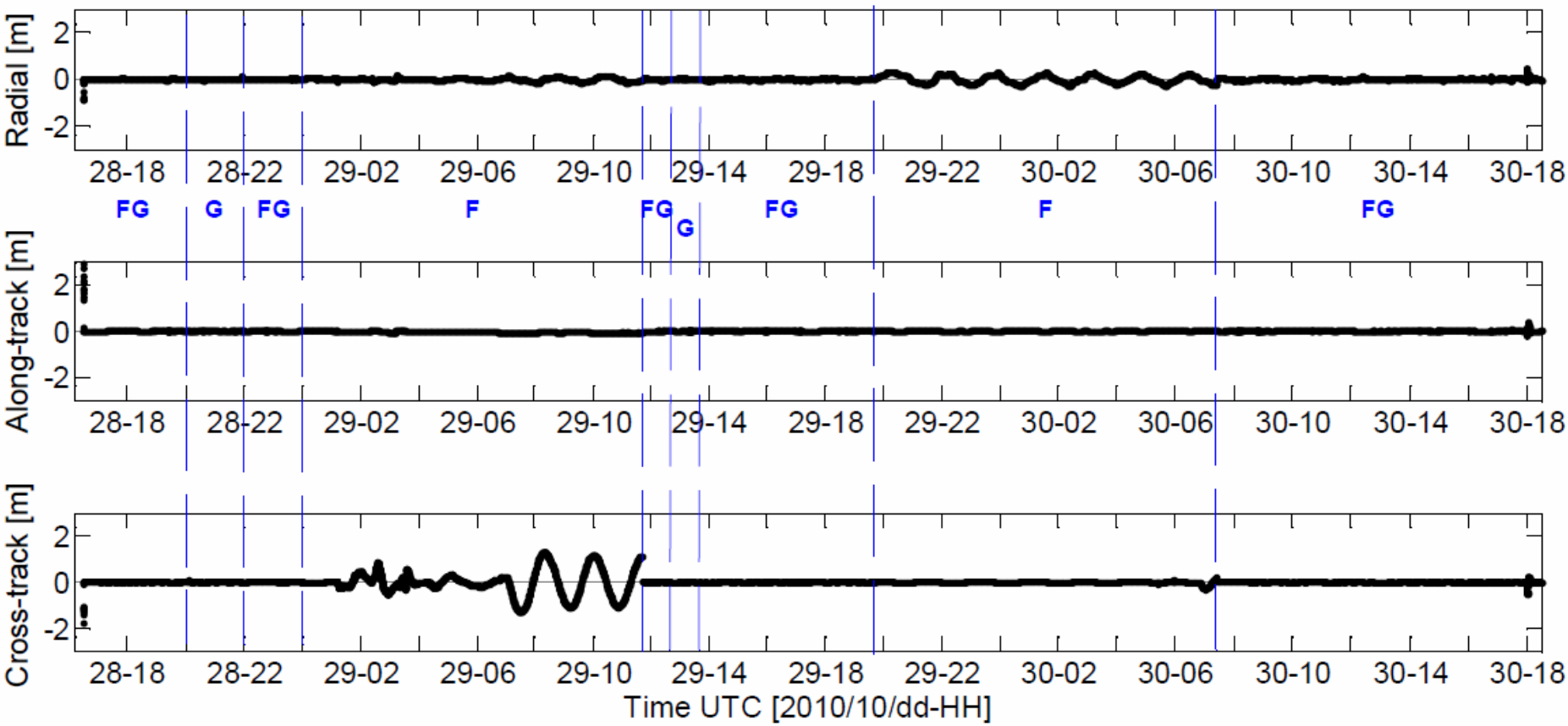
Initial assessment of accuracy
Oct 28th (16:00) – Oct 29th (01:00), 2010

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**