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Precision GNSS-Based Navigation for Miniaturized Distributed Space Systems

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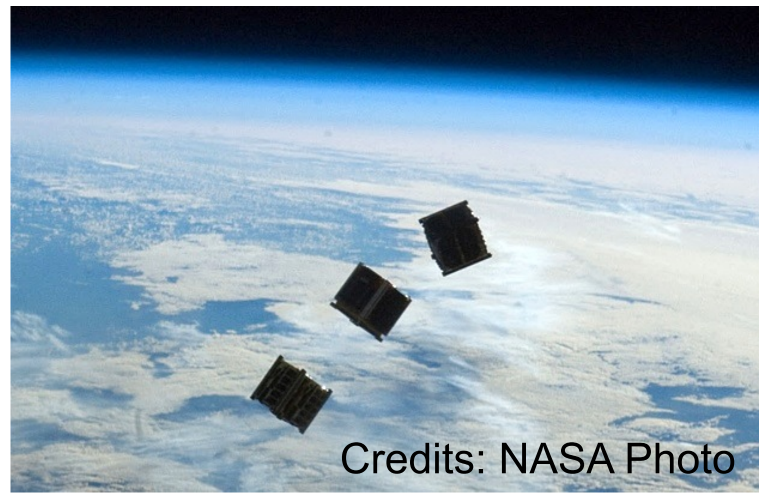
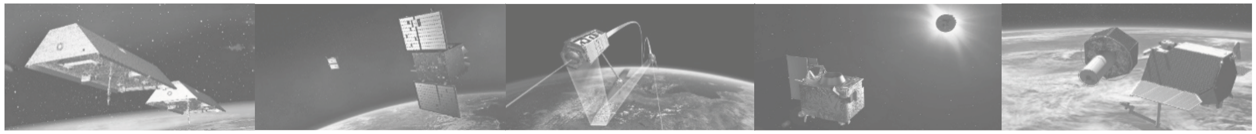
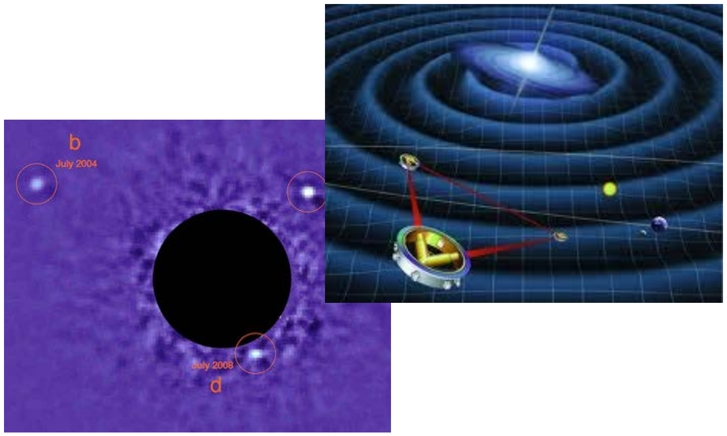


Credits: NASA Photo

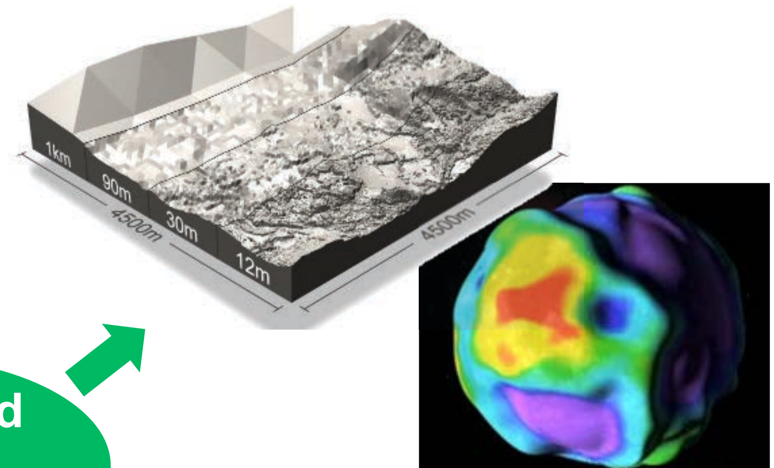


A Vision: Miniaturized Distributed Space Systems



Space Science

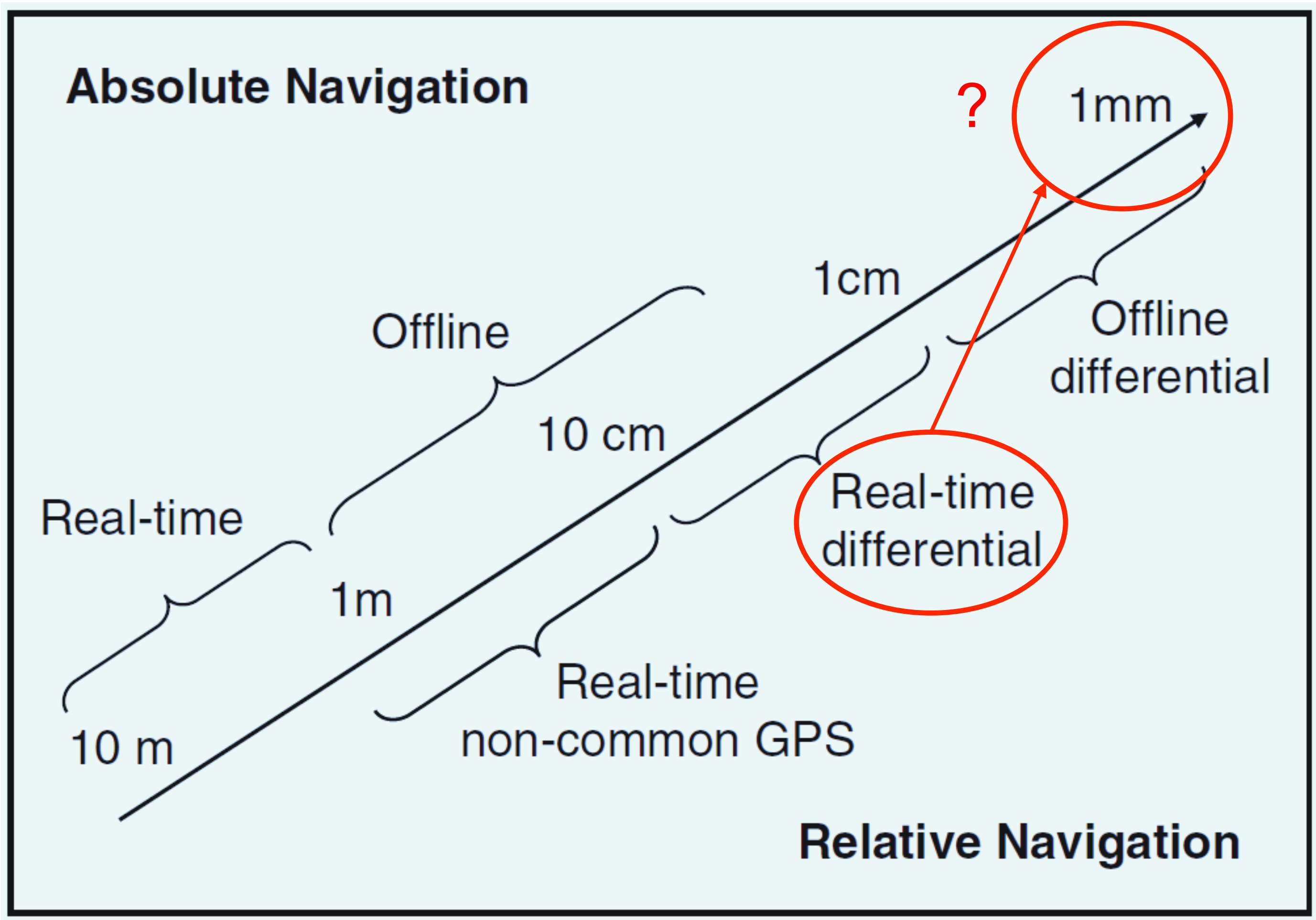
Distributed Space Systems

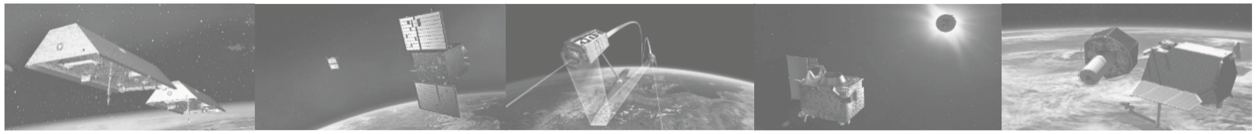


Planetary Science

Situational Awareness

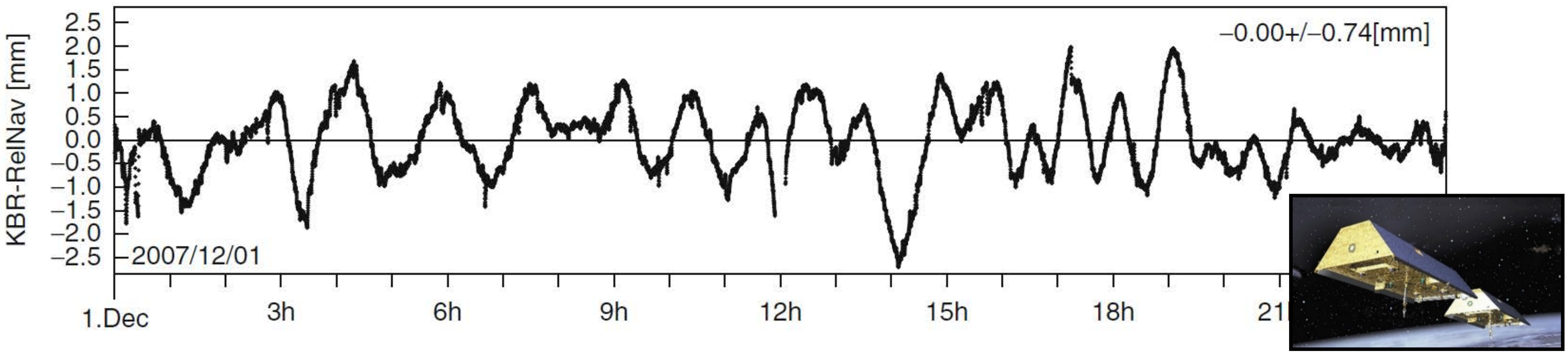
The Enabler: GNSS-Based Navigation (1)



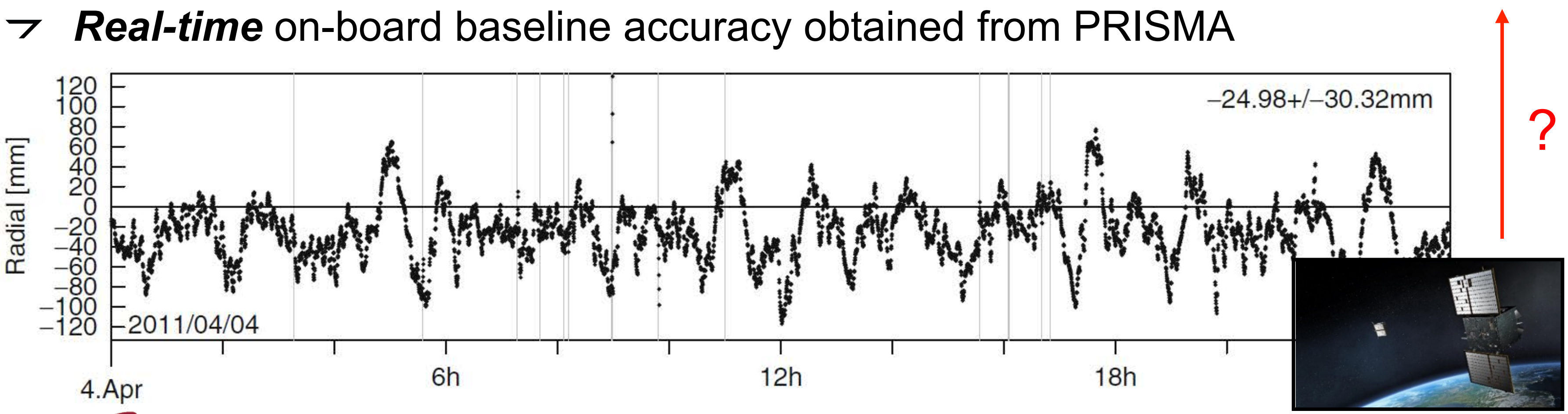


The Enabler: GNSS-Based Navigation (2)

- ***Offline*** on-ground baseline determination accuracy obtained from GRACE

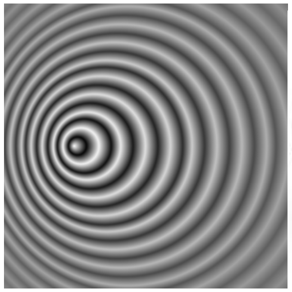


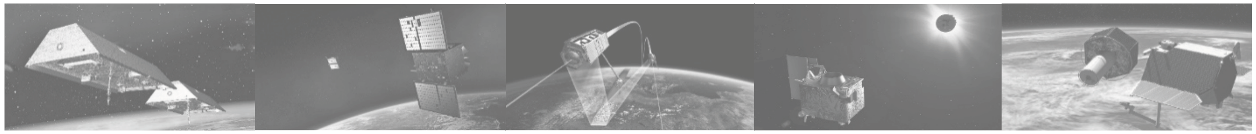
- ***Real-time*** on-board baseline accuracy obtained from PRISMA



Spaceborne GNSS: Technology Aspects (1)

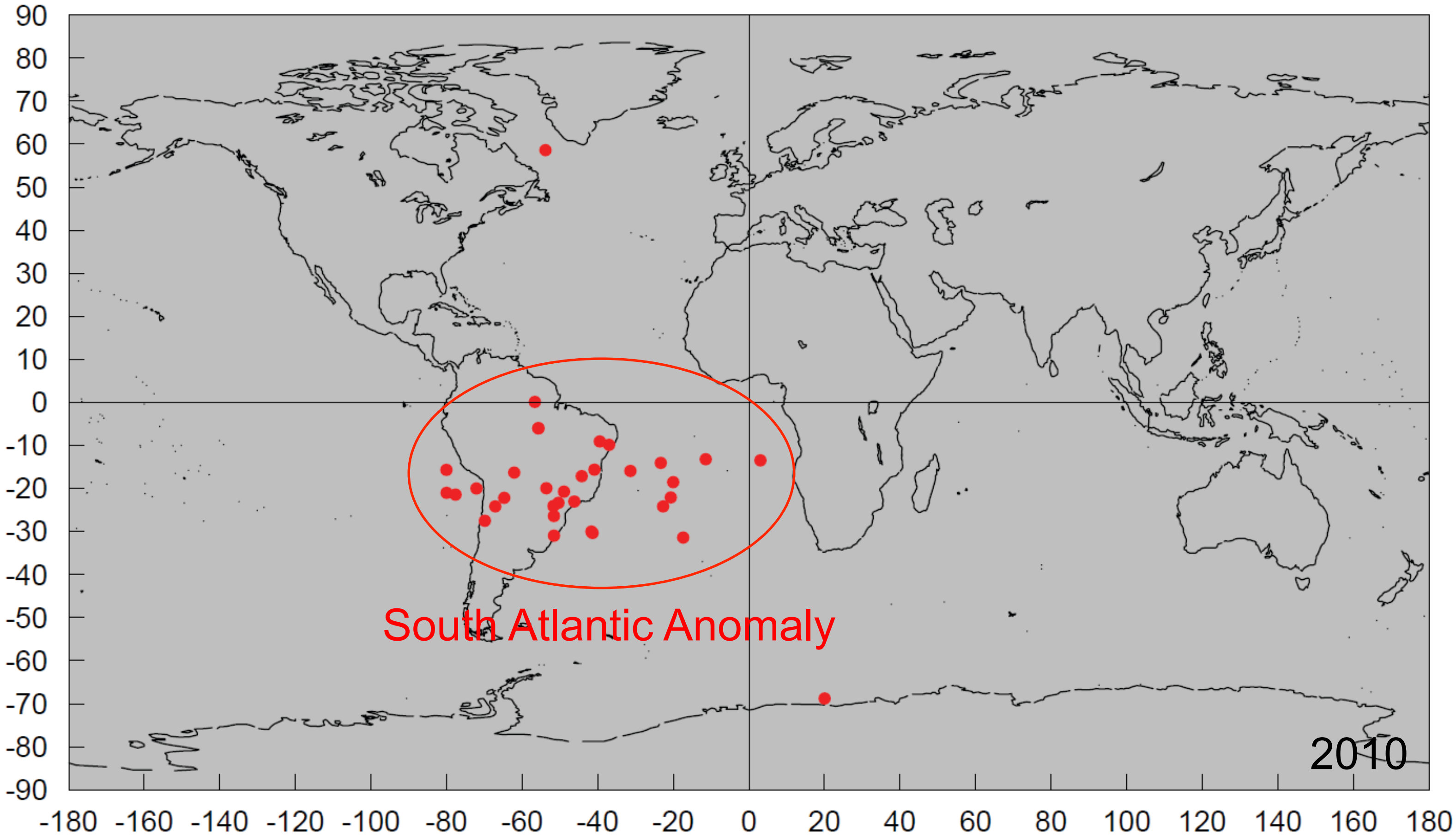
- Hostile environment
  - Thermal-vacuum, vibration, shock loads
  - Radiation long- and short-term effects
- Hard signal tracking
  - Constellation changes rapidly (Doppler shift)
  - Measurement noise and systematic errors
  - Time synchronization
  - Antenna system and multipath
- Regulatory issues
  - Threat of a possible abuse of GNSS
  - Free trade only permitted for locked receivers

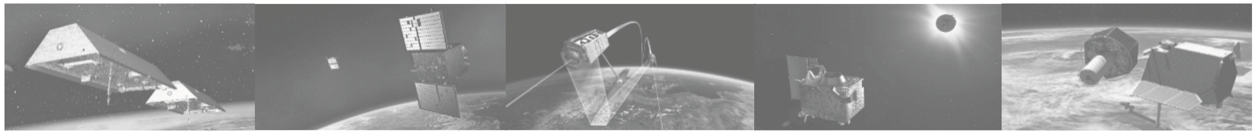




Spaceborne GNSS: Technology Aspects (2)

Single event latch-ups on-board PRISMA (Phoenix-S)

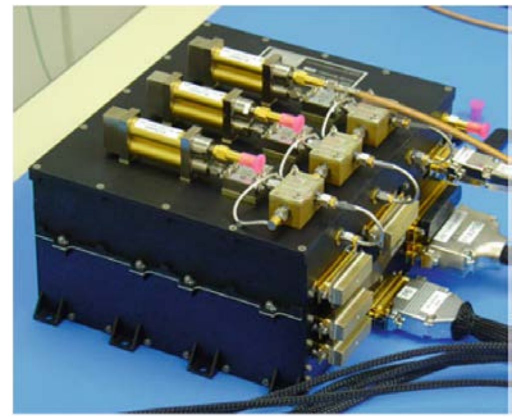




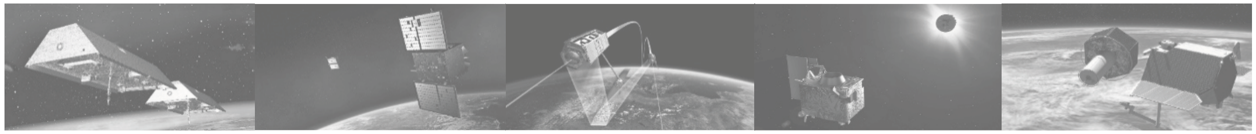
Spaceborne GNSS: Receivers and Frequencies (1)

- Annual review of "GPS World"
  - 500 different GNSS receiver models
  - 70 manufacturers world wide
- Spaceborne GNSS receivers
  - Niche market (small and specialized)
  - 500 LEO satellites expected btw. 2007-2016
- Costs
  - Spacegrade units priced from $100k to $1M
  - Commercial-off-the-shelf solutions available
- Single or multiple frequency? Choice driven by
  - Elimination of ionospheric path delays
  - Integer ambiguity resolution

JPL's Blackjack/TanDEM-X



DLR's Phoenix/PRISMA



Spaceborne GNSS: Receivers and Frequencies (2)

Multipe frequency GNSS receivers for space applications

Manufacturer (Country)	Receiver	Channels	Ant	Power weight
JPL (US)/BRE (US)	BlackJack/IGOR	16×3 C/A, P1/2	4	10 W, 3.2/ 4.6 kg
RUAG (A)	POD Receiver	8×3 C/A, P1/2	1	10 W, 2.8 kg
SAAB (S)	GRAS/GPSOS	12 C/A, P1/2	3	30 W, 30 kg
Thales Alenia Space (IT,FR)	Lagrange	16×3 C/A, P1/2	1	30 W, 5.2 kg
	TopStar 3000 G2	6×2 C/A, L2C	1	
BRE (US)	Pyxis POD	16–64 C/A, P1/2, L2C, L5	1–2	20 W, 2 kg
EADS Astrium (D)	LION	32; GPS, GAL	1	
Javad (US/RUS)	Triumph DG3TH	216; GPS, GAL, GLO	1	2.5 W*, 100 g*
NovAtel (CA)	OEM4-G2L	12×2 C/A, P2	1	1.5 W*, 50 g*
Septentrio (B)	PolaR×2	16×3 C/A, P1/2	1(3)	5 W*, 120 g*

Observation Types and Measurement Models (1)

- Basic observables

$$\rho = |\mathbf{r} - \mathbf{r}_{\text{GPS}}| + c\delta t - c\delta t_{\text{GPS}} + I$$ Pseudorange

$$\varphi = \lambda\Phi = |\mathbf{r} - \mathbf{r}_{\text{GPS}}| + c\delta t - c\delta t_{\text{GPS}} - I + \lambda A + \lambda\Psi$$ Carrier-phase

- Single-difference data types

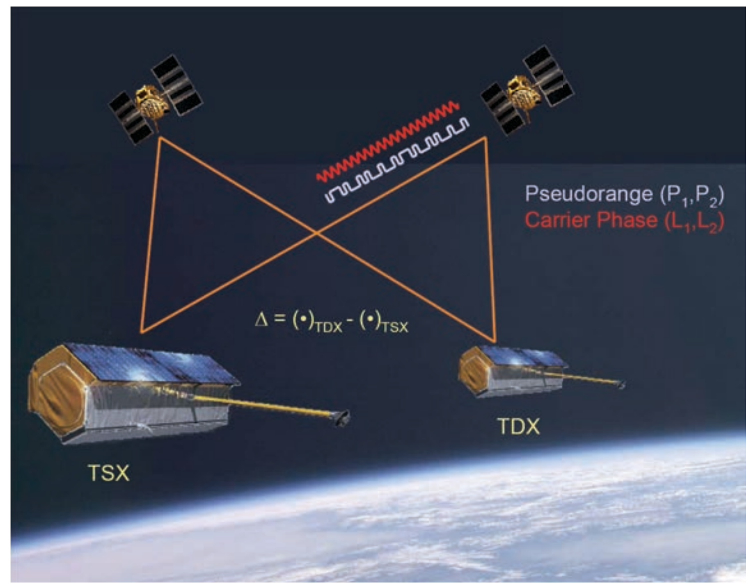
$$\begin{aligned} \Delta\rho_{AB} &= \rho_B - \rho_A \\ \Delta\varphi_{AB} &= \varphi_B - \varphi_A \end{aligned}$$

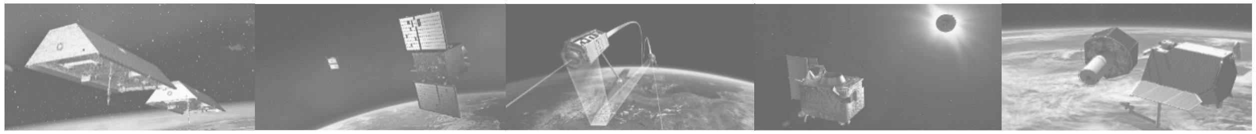
A, *B*: receivers

- Double-difference data types

$$\begin{aligned} \nabla\Delta\rho_{AB}^{ij} &= \Delta|\mathbf{r} - \mathbf{r}_{\text{GPS}}|_{AB}^{ij} \\ \nabla\Delta\varphi_{AB}^{ij} &= \Delta|\mathbf{r} - \mathbf{r}_{\text{GPS}}|_{AB}^{ij} + \lambda\nabla\Delta A_{AB}^{ij} \end{aligned}$$

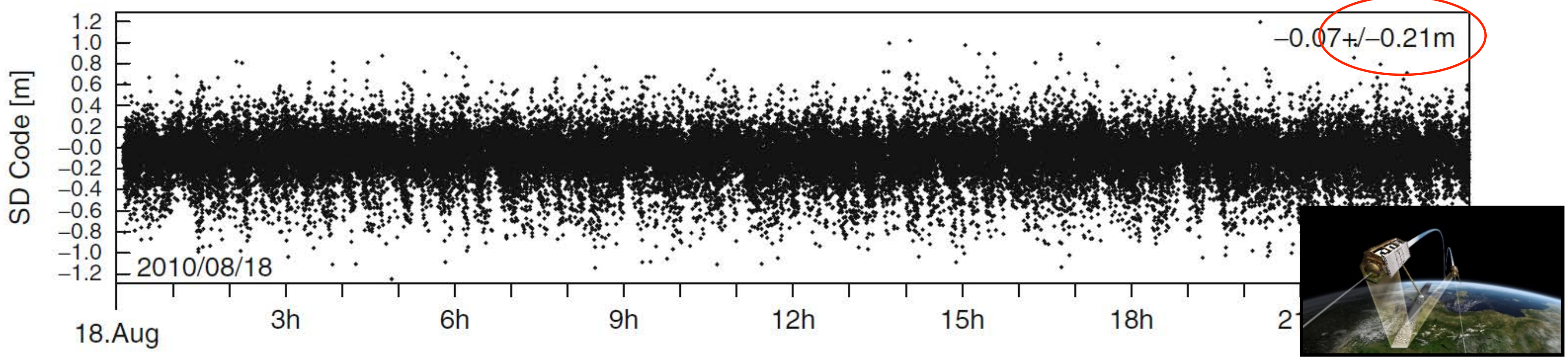
i, *j*: GNSS satellites



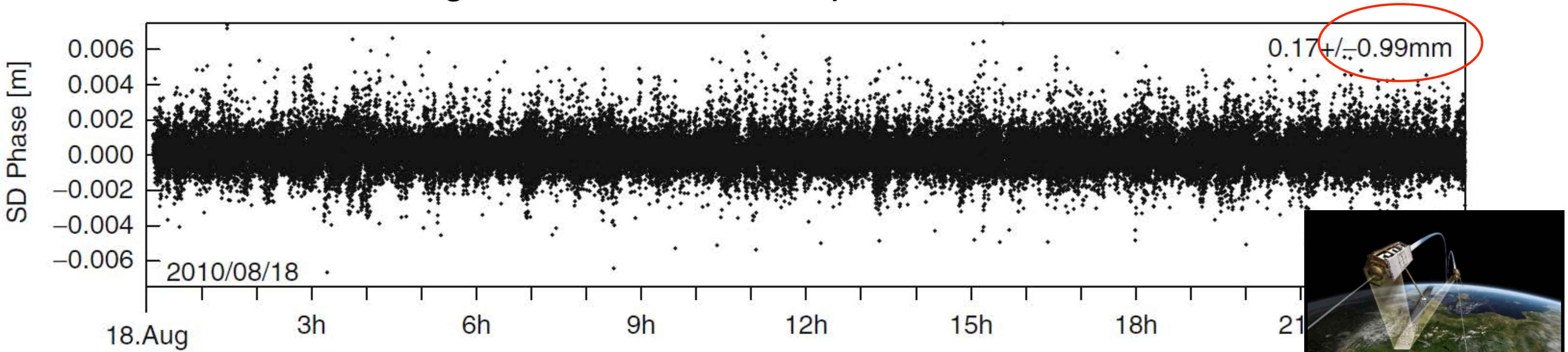


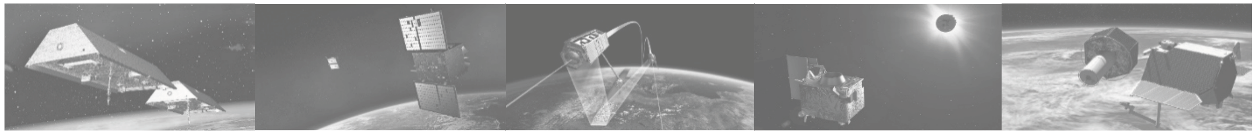
Observation Types and Measurement Models (2)

- Residual of L1 single-difference pseudorange measurements from TanDEM-X



- Residuals of L1 single-difference carrier-phase measurements from TanDEM-X





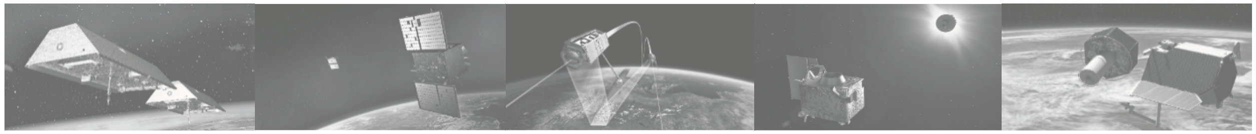
Integer Ambiguity Resolution (1)

- Integer ambiguity resolution translates carrier-phase measurements into pseudoranges with millimeter noise level (our ultimate goal)
- Conceptually, we can compare code and phase measurements and round to the nearest integer

$$\nabla\Delta A_{AB}^{ij} = \left[\frac{1}{\lambda}\left(\nabla\Delta\varphi_{AB}^{ij} - \nabla\Delta\rho_{AB}^{ij}\right)\right]_{\text{round}}$$

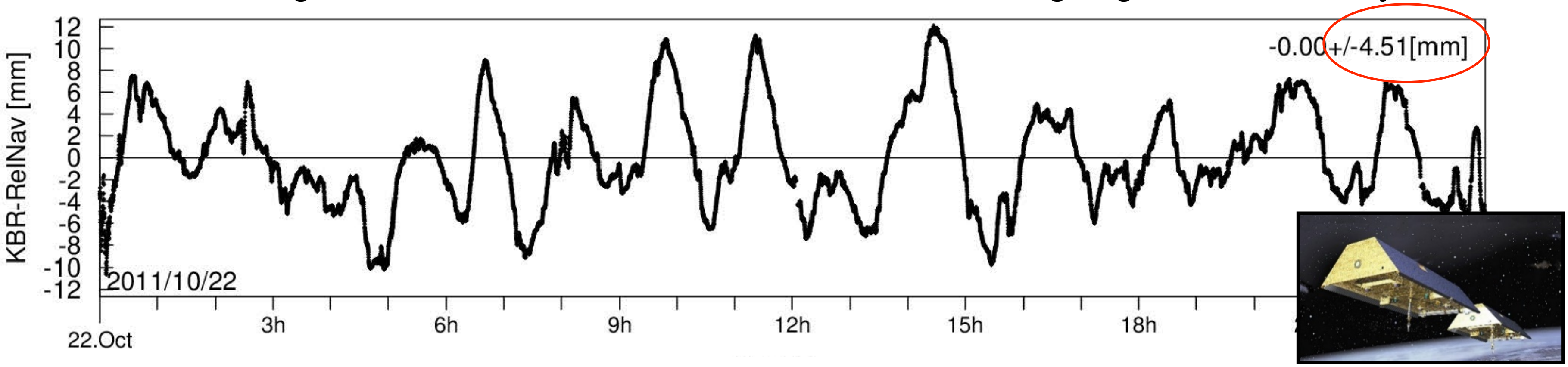
- In practice more advanced methods are required, especially for large baselines, high solar activity, and orbit/attitude maneuvers

Real-time: Wide- and narrow-lane combinations ⟷ Off-line: Linear mixed real/integer adjustment problem

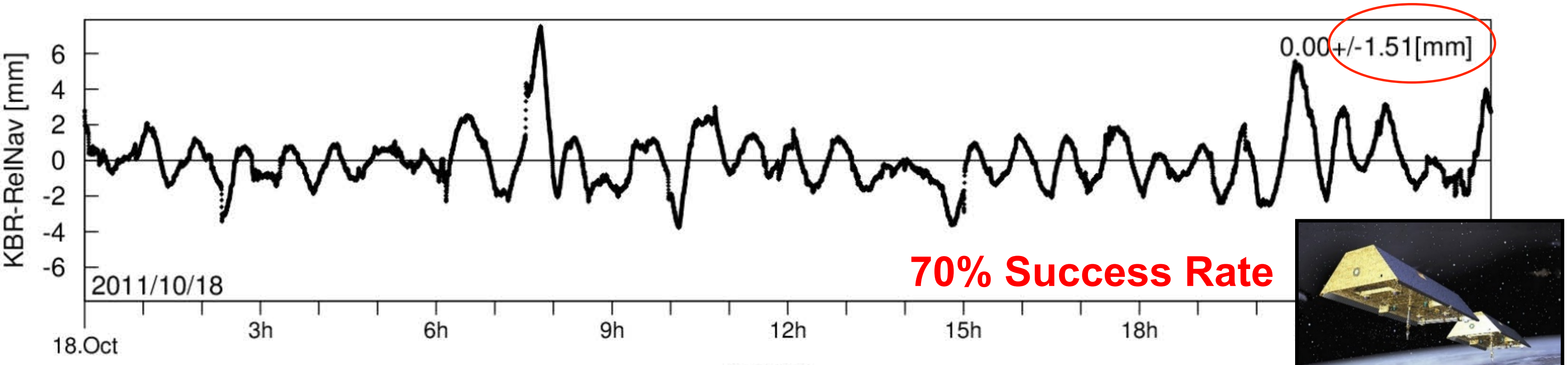


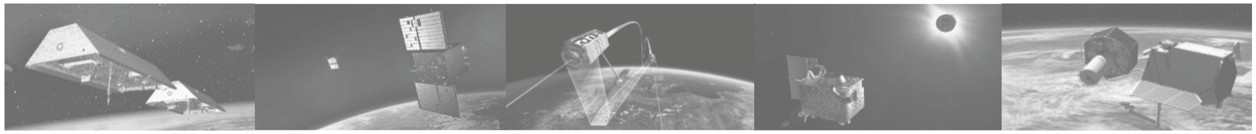
Integer Ambiguity Resolution (2)

- Offline on-ground “float solution” from GRACE during high solar activity



- “Fixed solution” from GRACE using “on-the-fly” LAMBDA method



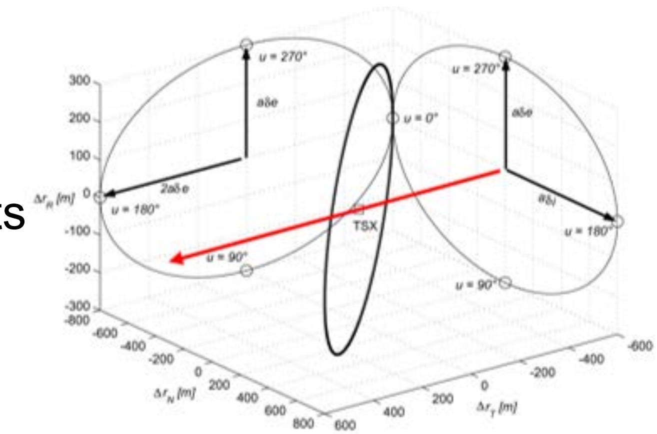


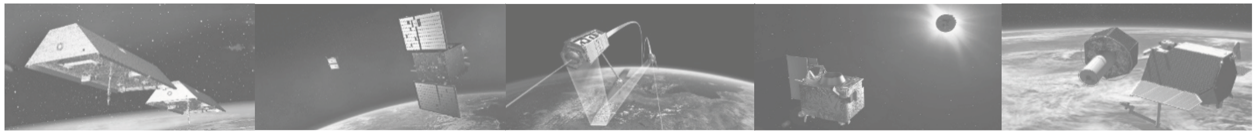
Reduced Dynamics Orbit Determination (1)

- Numerical models
  - Compliant with high measurement accuracy
  - Individual satellite's accelerations are modelled, numerically integrated, and subtracted

$$\begin{pmatrix} \Delta\mathbf{r}_{AB} \\ \Delta\mathbf{v}_{AB} \end{pmatrix} = \begin{pmatrix} \Delta\mathbf{r}_{AB} \\ \Delta\mathbf{v}_{AB} \end{pmatrix}_0 + \int_{t_0}^{t} \begin{pmatrix} \mathbf{v}_B \\ a_B(t',\mathbf{r}_B,\mathbf{v}_B) \end{pmatrix} dt' - \int_{t_0}^{t} \begin{pmatrix} \mathbf{v}_A \\ a_A(t',\mathbf{r}_A,\mathbf{v}_A) \end{pmatrix} dt'$$

- Analytical relative dynamics models
  - Solutions of linearized equations (HCW, TH)
  - Cartesian coordinates or relative orbit elements
  - Useful for formation design and control
  - Suitable for precision navigation?

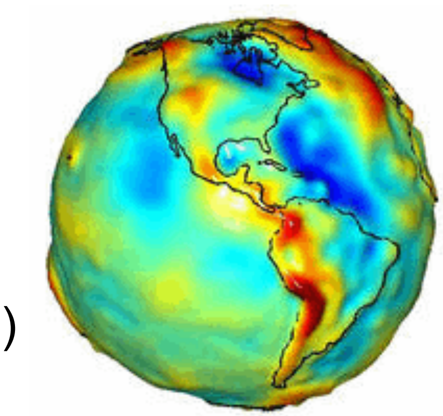


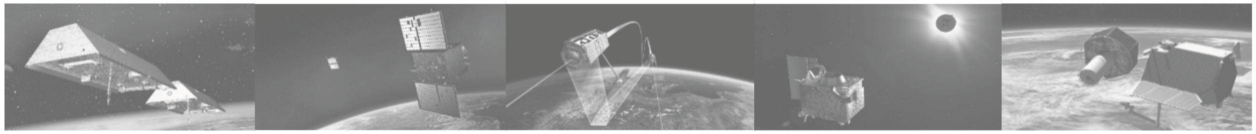


Reduced Dynamics Orbit Determination (2)

- Conservative forces
  - Gravity field models (GGM03S, EIGEN-05C)
  - Third-body perturbations (Sun, Moon)
- Non-conservative forces
  - Atmospheric drag (Harris-Priester, Jacchia)
  - Solar radiation pressure (Conical shadow)
  - Orbit control maneuvers (impulsive or quasi-continuous)
- Un-modelled forces
  - Force model is a trade-off btw. accuracy/complexity
  - ***Empirical accelerations*** compensate deficiencies
    - Exponentially correlated random variables (onboard)
    - Piece-wise constant acceleration at 6-15 min intervals (offline)

Offline: $n \sim 70\text{-}120$
Onboard: $n \sim 2\text{-}30$

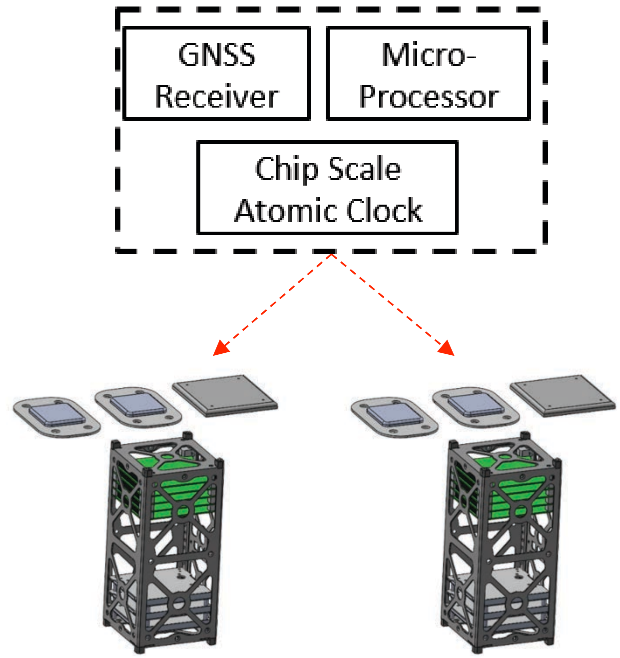




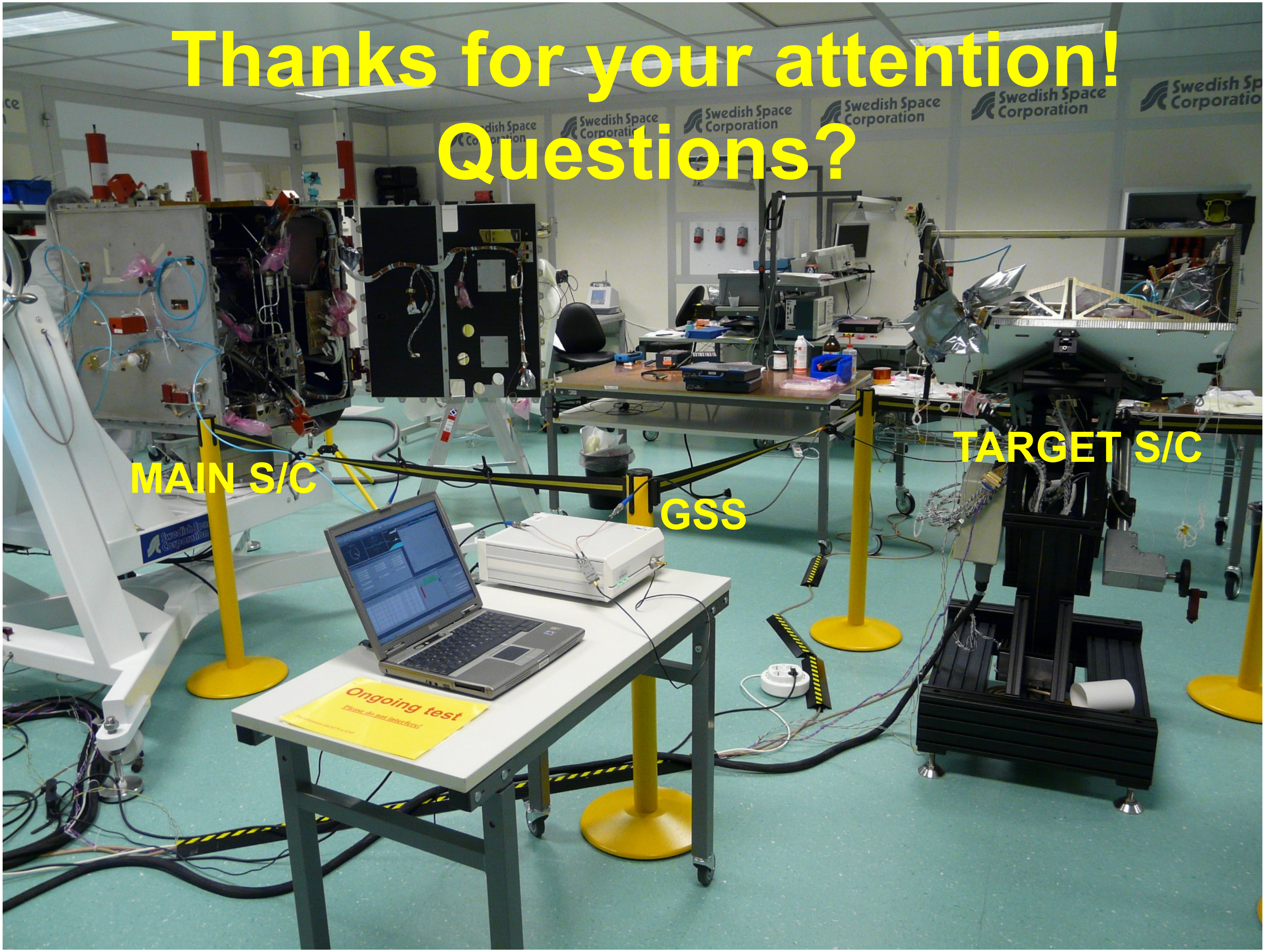
Beyond State-of-the-Art: DiGiTal (Nasa Ames)

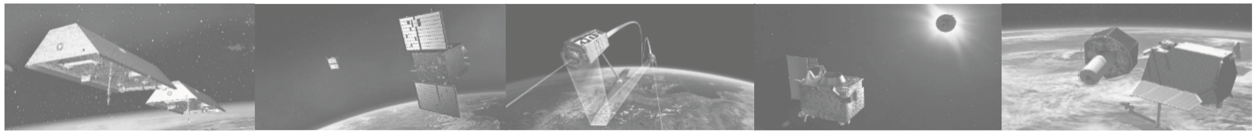
- Distributed GNSS Timing and Localization (DiGiTaL) Navigation System
  - Miniaturized system for nanosatellites
  - Targeting 0.5U volume unit
  - Plug-in ready unit (high compatibility)
  - Peer-to-peer, decentralized
  - Improved real-time accuracy (cm-level)
  - Qualification testing to TRL-6
  - Demonstration on BioSentinel nanosatellite

HW/SW Design

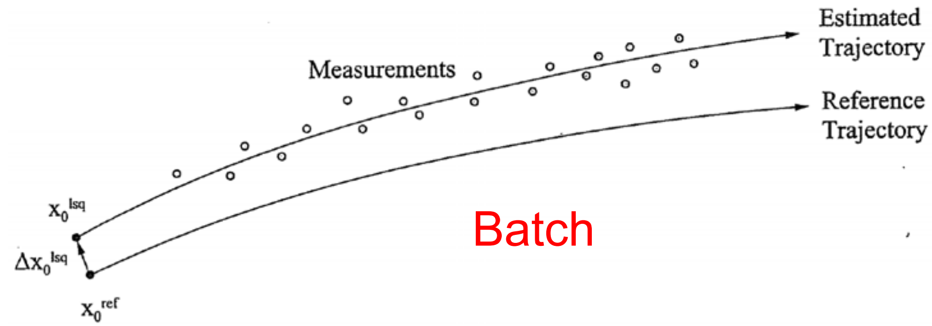


DiGiTaL Prototype

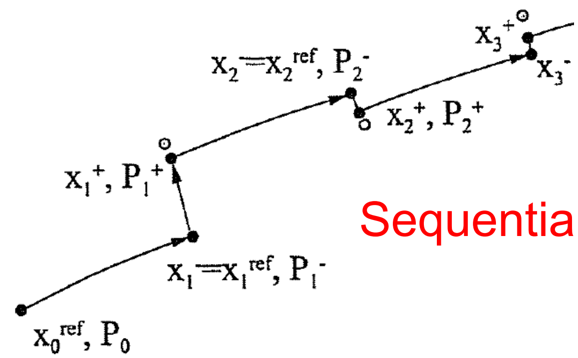

Thanks for your attention!
Questions?
Swedish Space Corporation
MAIN S/C
GSS
TARGET S/C
Ongoing test
Please do not interfere!



Estimation (Filter Concept)



- Batch estimation (e.g., least squares)
  - Thousands of unknowns for 24h data arc
  - Normal matrix can be partitioned to eliminate clocks
  - Float and fixed solution partially de-coupled
- Sequential estimation (e.g., extended Kalman filter)
  - Reduced number of unknowns
  - Float and fixed solution strongly coupled
  - Special care with “implementation” and “tuning”
  - Forward and backwards processing possible
- Alternative filter concepts (e.g., adaptive, unscented)
  - Higher robustness and improved convergence
  - Only in the case of strong non-linearities



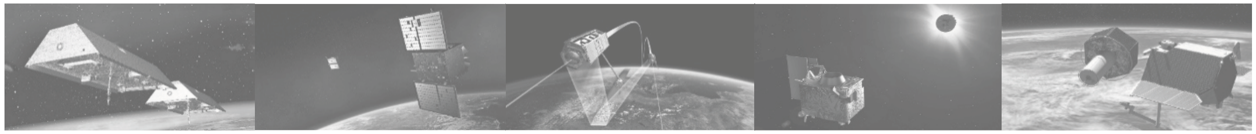
Estimation (State Parameters)

- Position and velocity
- Force model parameters
- Receiver clock offset
- Ambiguity parameter
- Ionospheric parameters

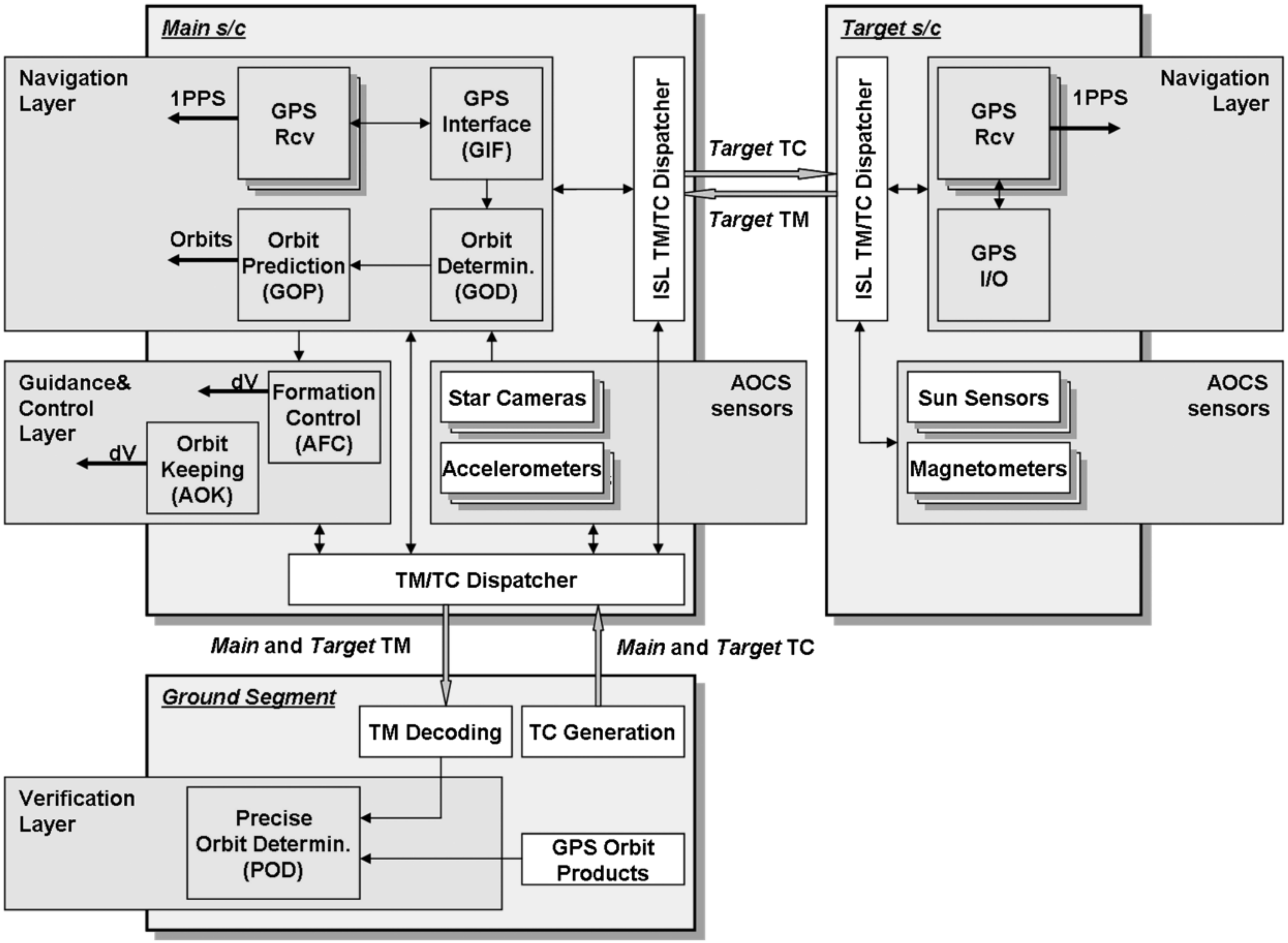
PRISMA (single-frequency, short-baseline)

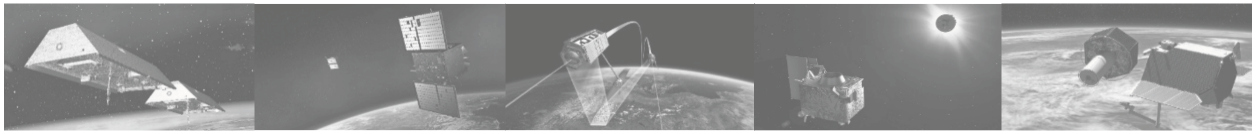
$$\left((\boldsymbol{x}; \boldsymbol{p}; c\delta t; \boldsymbol{N})^{\mathrm{M}}; (\boldsymbol{x}; \boldsymbol{p}; c\delta t; \boldsymbol{N})^{\mathrm{T}}; \delta \boldsymbol{v} \right)$$

- Absolute or relative formulation possible
- Variety of approaches in literature
  - Typically 12 tracking channels
  - 18 to 80 state parameters
  - Measurement update has the largest computational effort
  - Trade-off necessary on a case-by-case basis



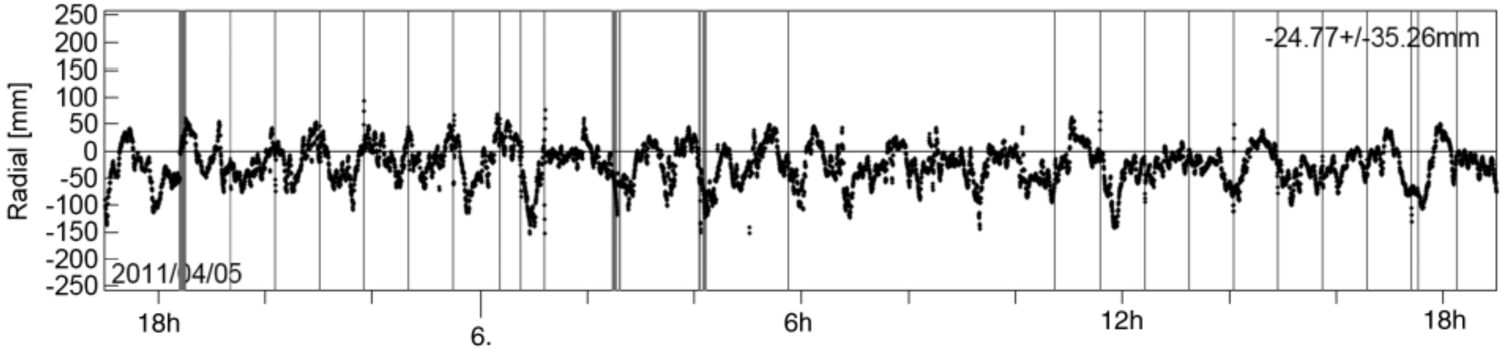
Mission Results: Real-Time Navigation (1)

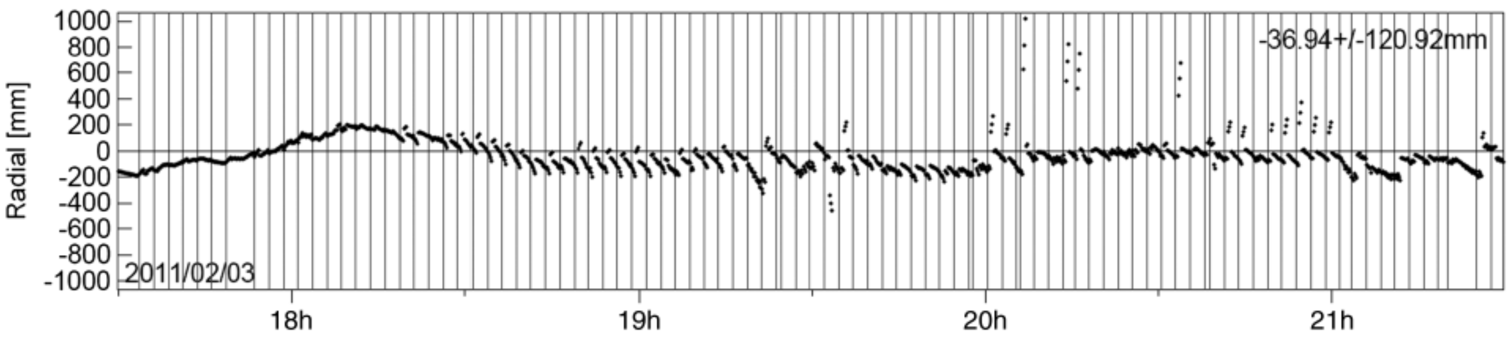


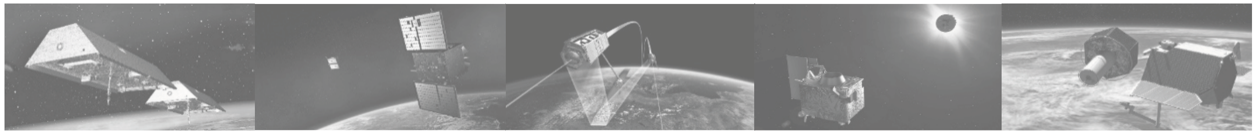


Mission Results: Real-Time Navigation (2)

Operational Scenario	Applied settings	Rel. position-3-D, cm	Rel. velocity-3-D, mm/s
Sparse control/short range (3 April)	Performance	4.74 ± 1.96	0.12 ± 0.13
Sparse control/far-range rendezvous (5/6 April)	Performance	5.30 ± 2.60	0.20 ± 0.36
Forced motion control (3 Feb.)	Frequent thrust	14.83 ± 8.01	1.59 ± 1.76
Large Mango attitude rotations (31 March)	Robust	6.84 ± 2.94	0.08 ± 0.04







Beyond State-of-the-Art: MIDAS (Stanford's CEAA)