GALILEO on board the International Space Station and highly accurate GNSS/ACES time and frequency transfer based on phase clocks

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ACES Mission on board ISS

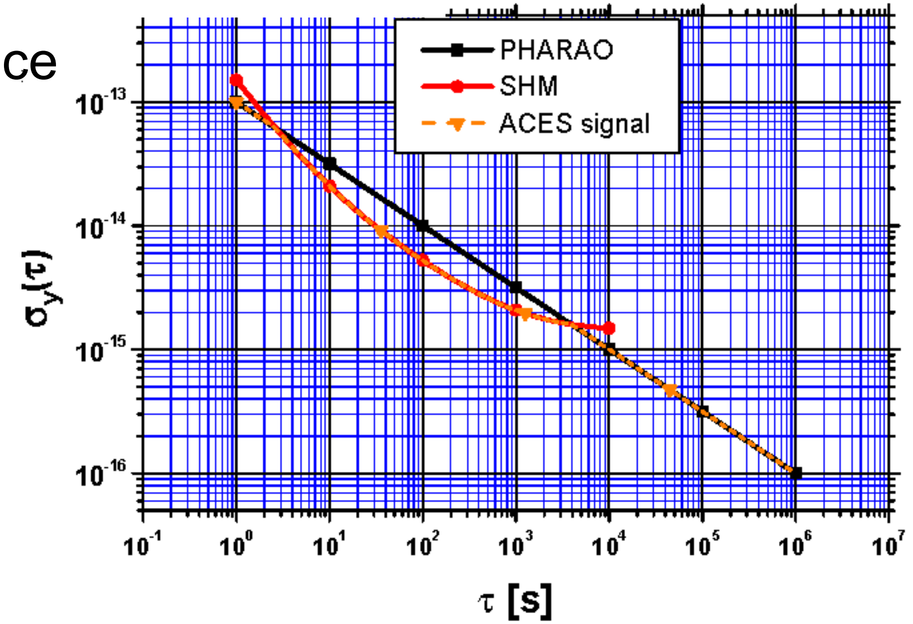
ACES= **A**tomic **C**lock **E**nsemble in **S**pace

Launch date: 2010

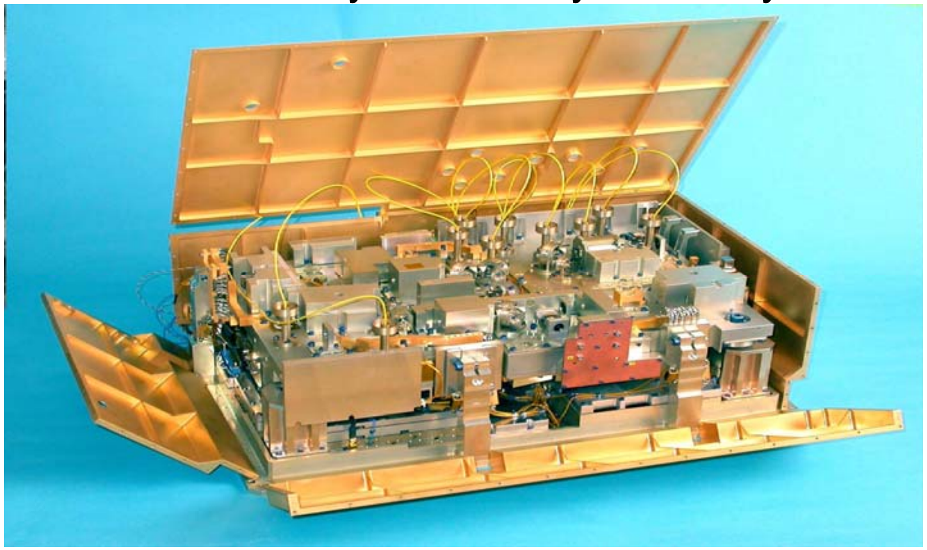
Mission duration: 18 months

Scientific objectives:

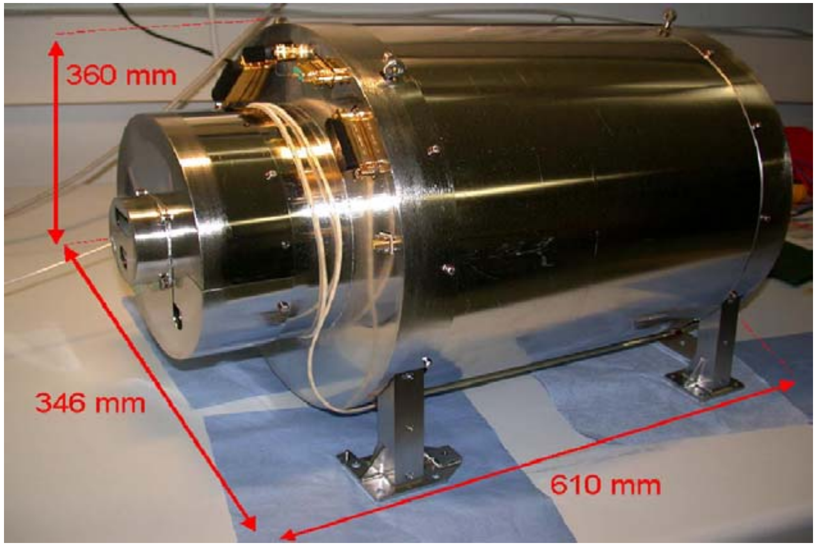
- Tests of general relativity (red-shift)
- Tests of fundamental physics (variations in α)
- Time and frequency transfer



PHARAO - Cold atom clock (cesium fountain)
long term performance, τ>45 min,
stability & accuracy 10^{-16} /day



Space H-maser
short tem performance, τ<45 min



(Cacciapouti,Dimarcq, Salomon, 2005)

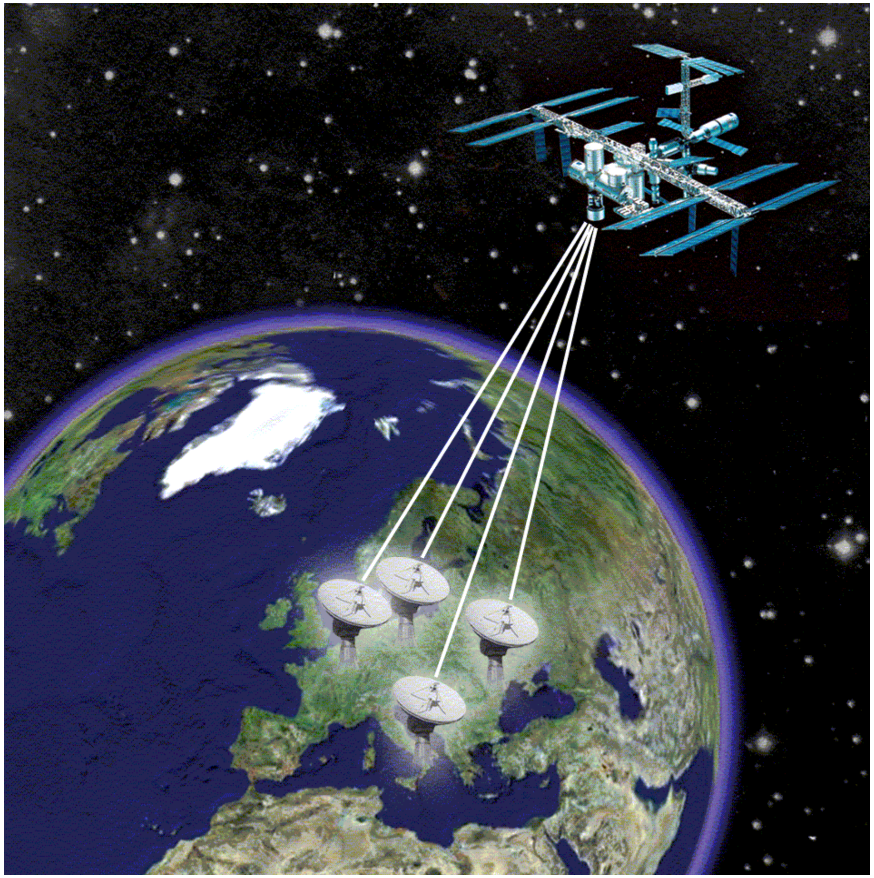
ACES Micro-Wave Link

Common View

Ground to ground clock comparison

Governed by short-term stability

< 0.3 ps over one ISS pass (300 s)



(Aguilar et al. 2005 ACES Workshop)

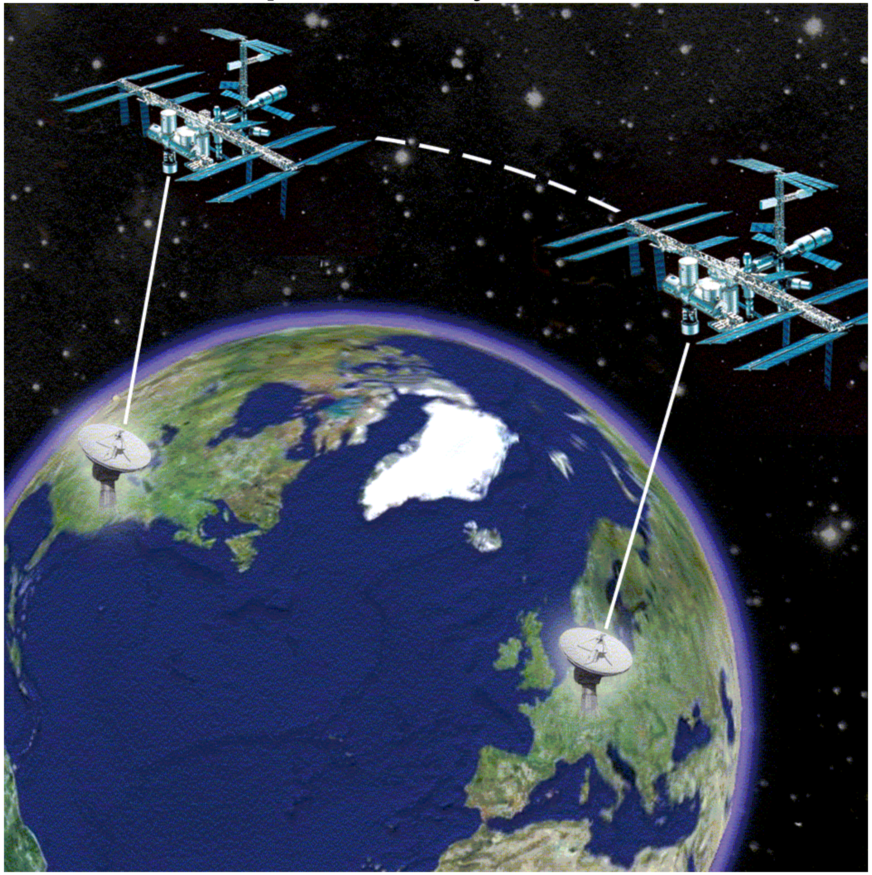
Non-Common View

Ground-to-space-to-ground clock comparison

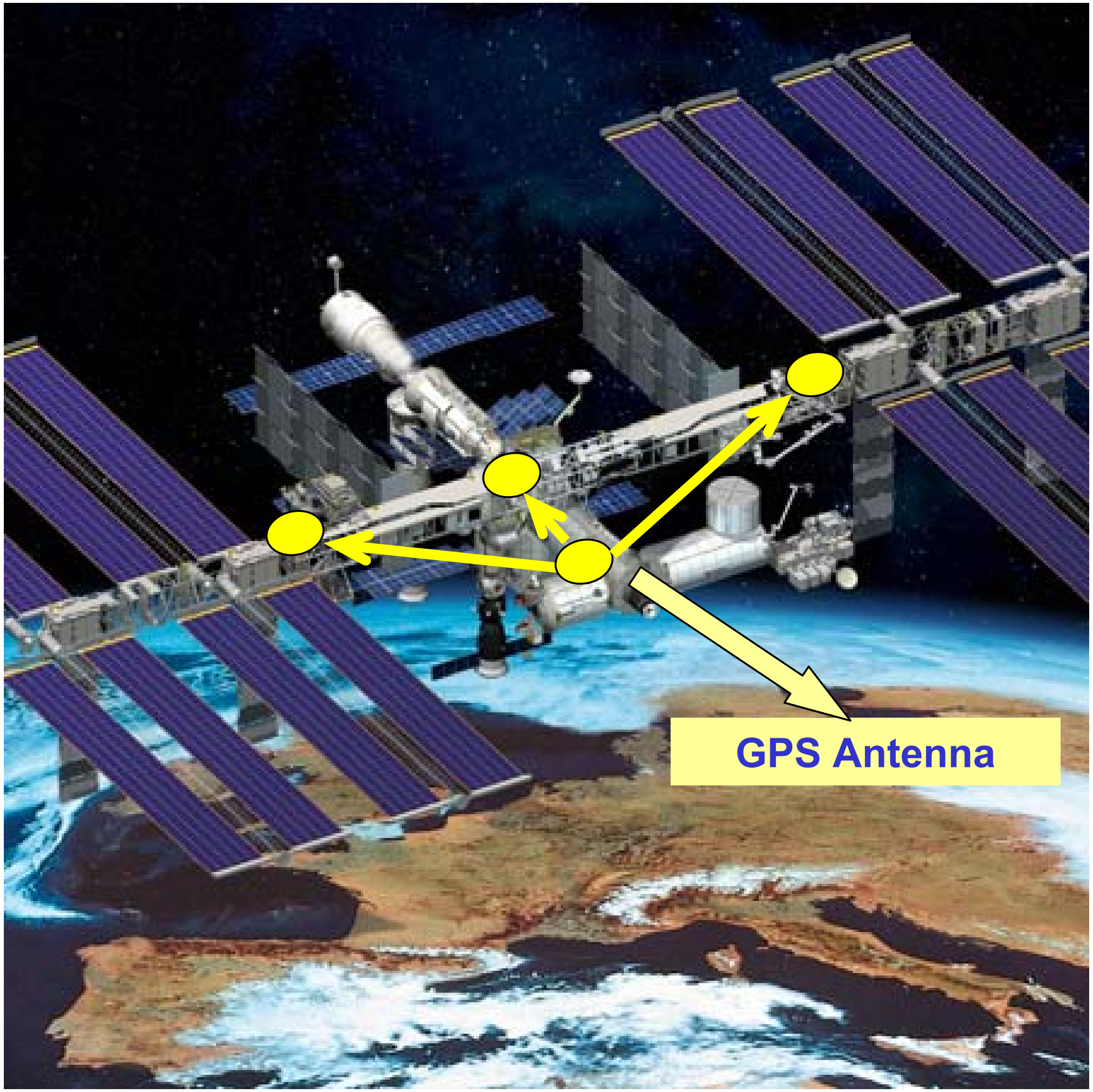
Governed by long term stability

< 2 ps for 1000 s time interval

< 20 ps for 1 day time interval



ISS Reference System



One or four GPS/GALILEO Antennas:

- Attitude
- ISS deformation
- Space Shuttle docking

Centre of Mass monitoring (”geocentre”)

ISS dynamics monitoring fully geometrically

Atmosphere density retrieval using ISS as a sensor

Galileo on Board the Space Station

Proposal submitted to the ESA Announcement of Opportunity: Life and Physical Sciences and Applied Research Projects 2004

We proposed to ESA to place a geodetic dual-frequency GPS/Galileo receiver on board the Space Station including a set of one/four GPS/GALILEO antennas in order to:

1. establish a highly accurate **reference system for the ISS** and its local environment
   - to monitor ISS centre of mass

2. Space Station **kinematic and reduced-dynamic POD** with an accuracy of 1-3 cm
   - to monitor ISS dynamics fully geometrically

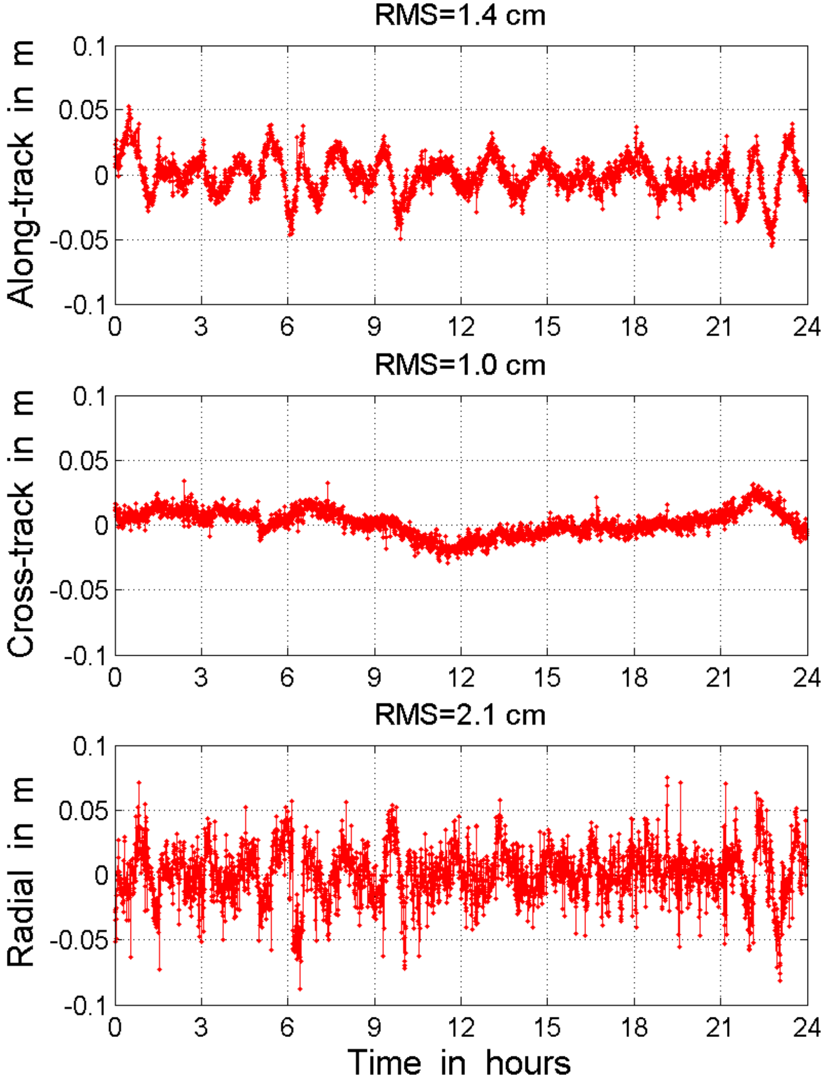
3. compute the relative positions between the **three/four GPS antennas** with the mm-accuracy
   - high-precision attitude information
   - relative positioning of the "Canadian arm" or the Space Shuttle docking
   - monitor deformation of the ISS platform

4. use the ISS solar panels as a sensor to retrieve **atmosphere density** and derive **TEC**
   - ISS orbits close to equator (i=51.6°)

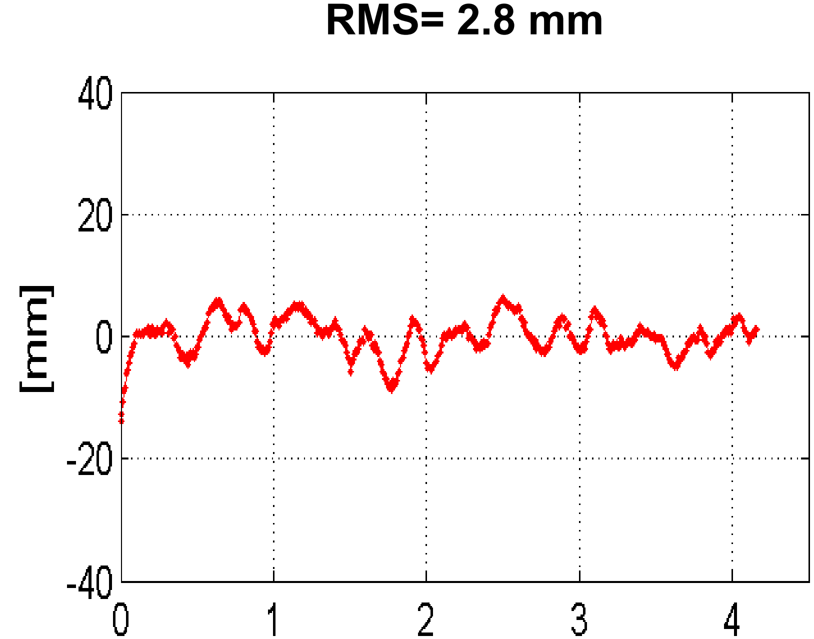
5. Galileo/GPS precise **time/frequency transfer**
   - Galileo/GPS receiver driven by the external frequency from the ACES clock ensemble

Motivation – 3 Different POD Strategies

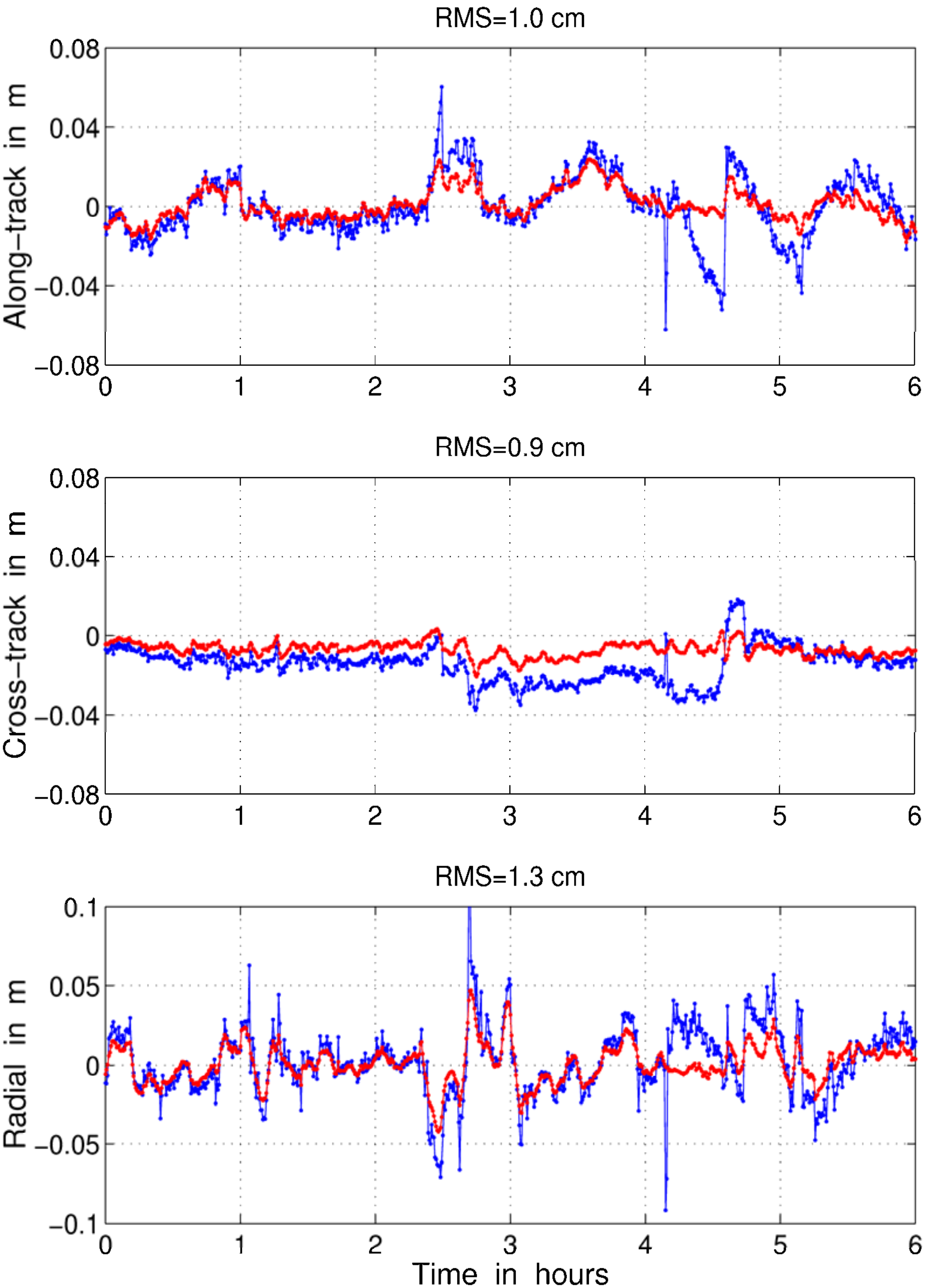
Kinematic POD GRACE-A



GRACE GPS Baseline with FIXED ambiguities



(Status 2003-2004)



Reduced-Kinematic POD

CHAMP day 200/2002

Kinematic POD with dynamic information in order to reduce influence of weak geometry and phase breaks (jumps).

Methods:

- Absolute constraints to the a priori orbit
- **Relative constraints (applied to kinematic position differences over time w.r.t. corresponding differences stemming from the dynamic orbit)**
- Gauss-Markov process

Normal system solution:

- Full normal matrix inversion

(86400 kinematic coordinates for one-day arc)

- *L - U* factorization

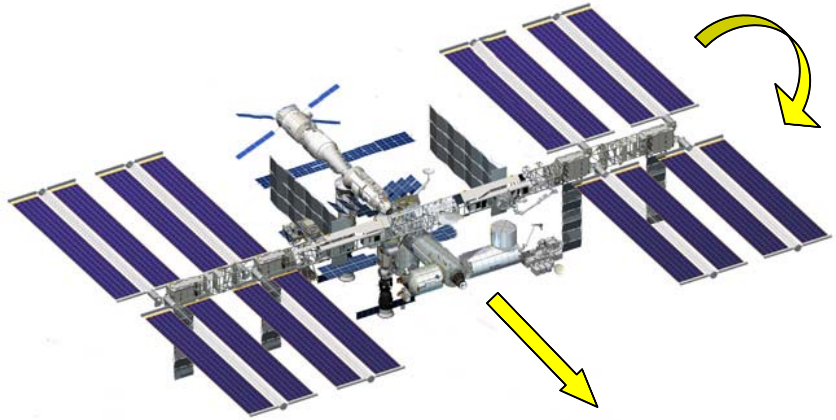
(block tridiagonal system), block forward elimination and back substitution.

Characteristics:

Smoothing effect

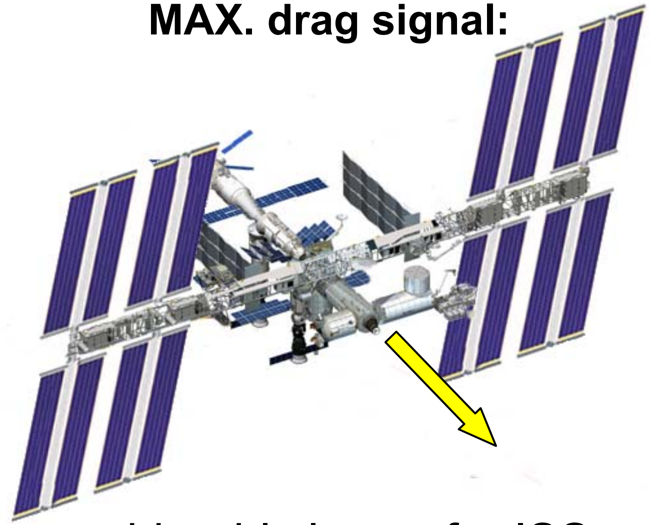
Retrieving the air density using Space Station as a sensor

MIN. drag signal:



360°/90 min

MAX. drag signal:



atmospheric density

$$a = \frac{1}{2} C_d \rho v_r^{\ 2} \frac{A}{m}$$

cross section area

mass of the satellite

atmospheric drag

LEO velocity
relative to the atmosphere

Form factor considerably larger for ISS compared to CHAMP and GRACE

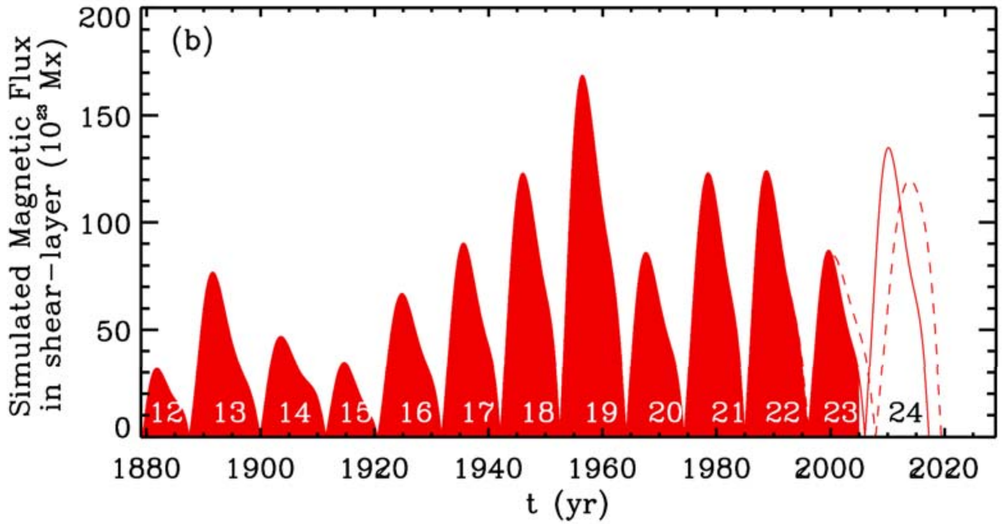
Drag signal considerably larger than gravity field errors.

Around 2010-2012 solar maximum to be expected (**max. drag signal**).

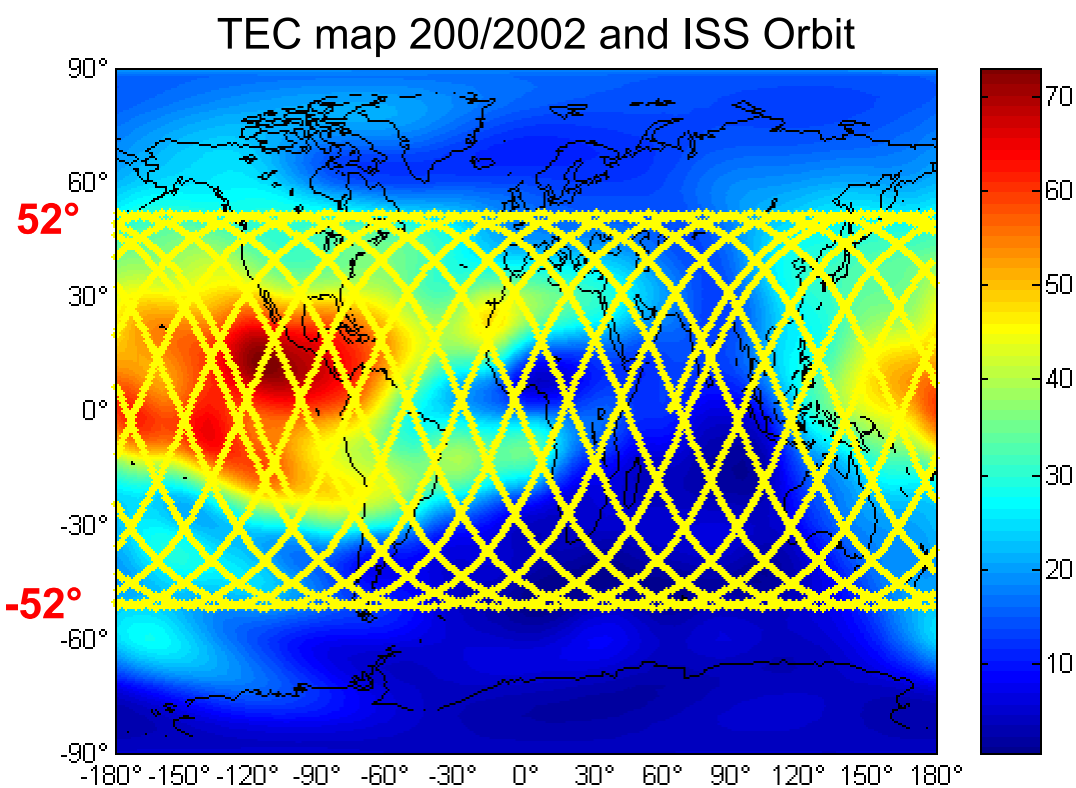
Multipath: almost clean antenna horizon (since several ISS modules cancelled)

No near field multipath (top of Columbus)

Solar Maximum in 2010-2012



The next solar max. will be 30-50% stronger than the last one
(GRL paper, Dikpati et al. 2006)



ISS orbits close to equator

Inclination = **51.6°**

Phase Clocks

→ **PHASE CLOCKS:** GPS satellite/station clocks estimated using **only phase data**

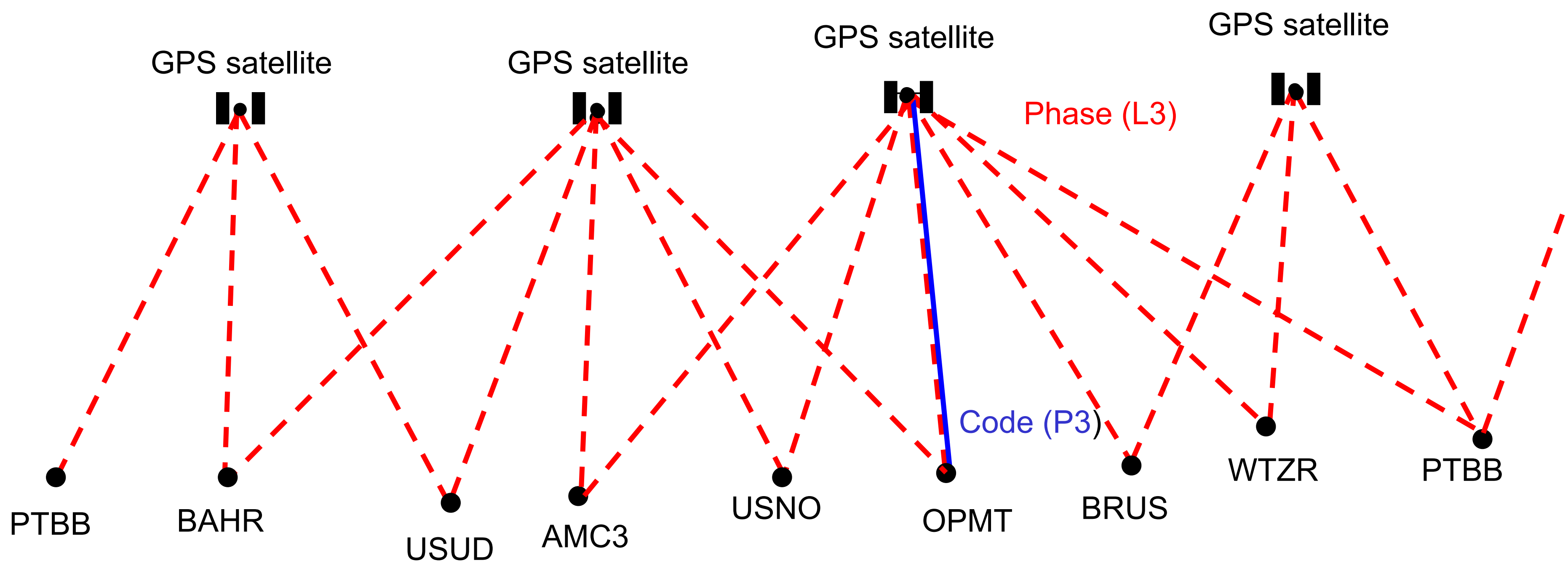
→ **Estimated Parameters :** GPS/station clock parameters every 30 sec + ambiguities

→ one clock bias over all clock labs (PPP is done using phase data only)

→ code measurements only for approximate clock synchronization

→ **code noise+multipath+DCBs+ICB are avoide**

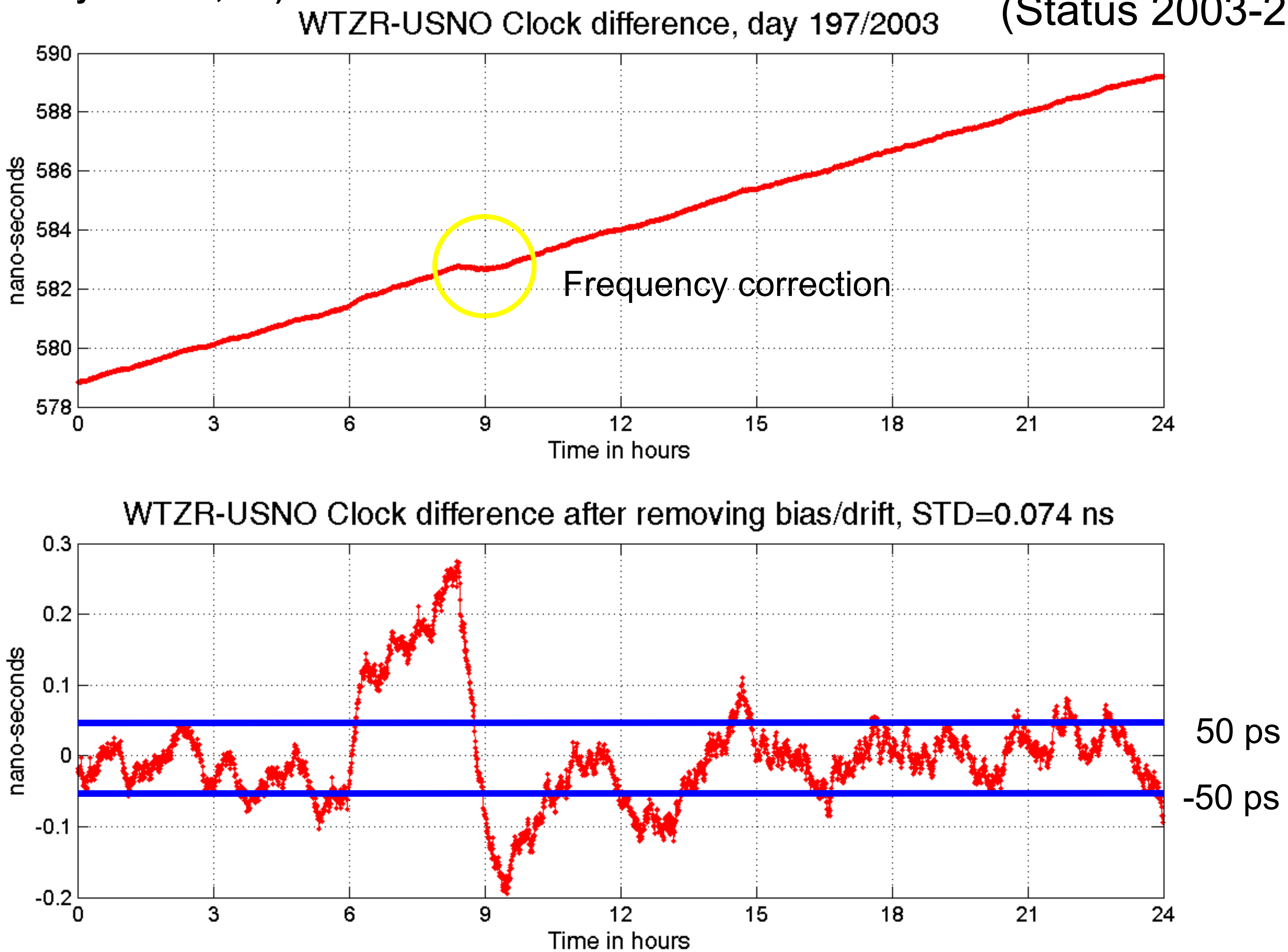
→ combined GALILEO/GPS solutions: inter-GNSS clock bias absorbed by ambiguities



Clock comparison using Phase Clocks

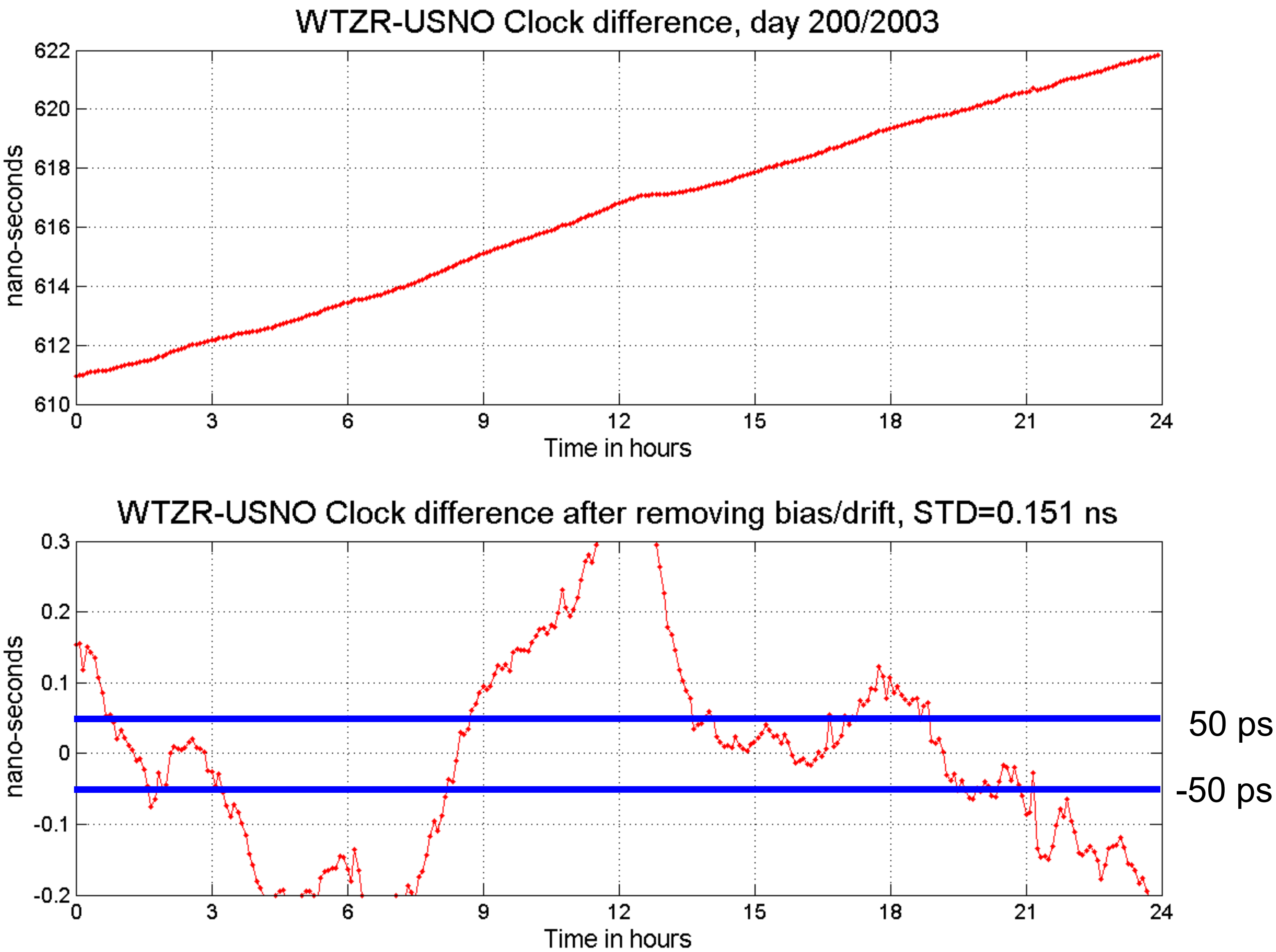
(Wettzell, Germany – USNO, US)

(Status 2003-2004)



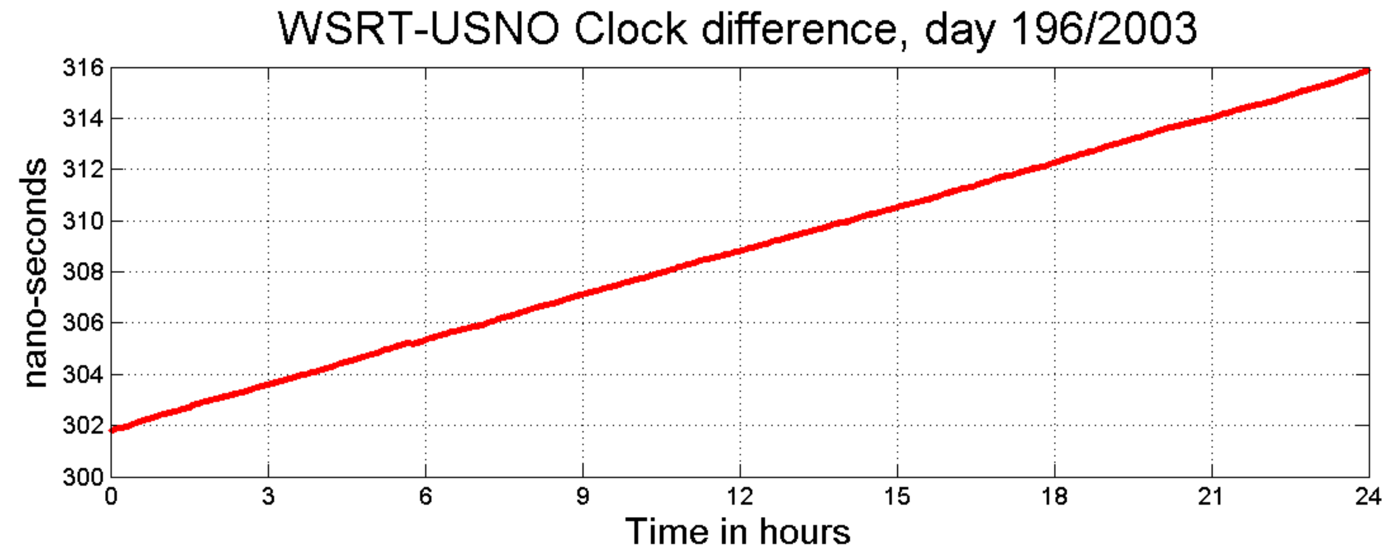
Only phase clocks estimated. Troposphere (TZD), station coord., EOPs, etc., fixed to IGS

CODE 5-min Clock

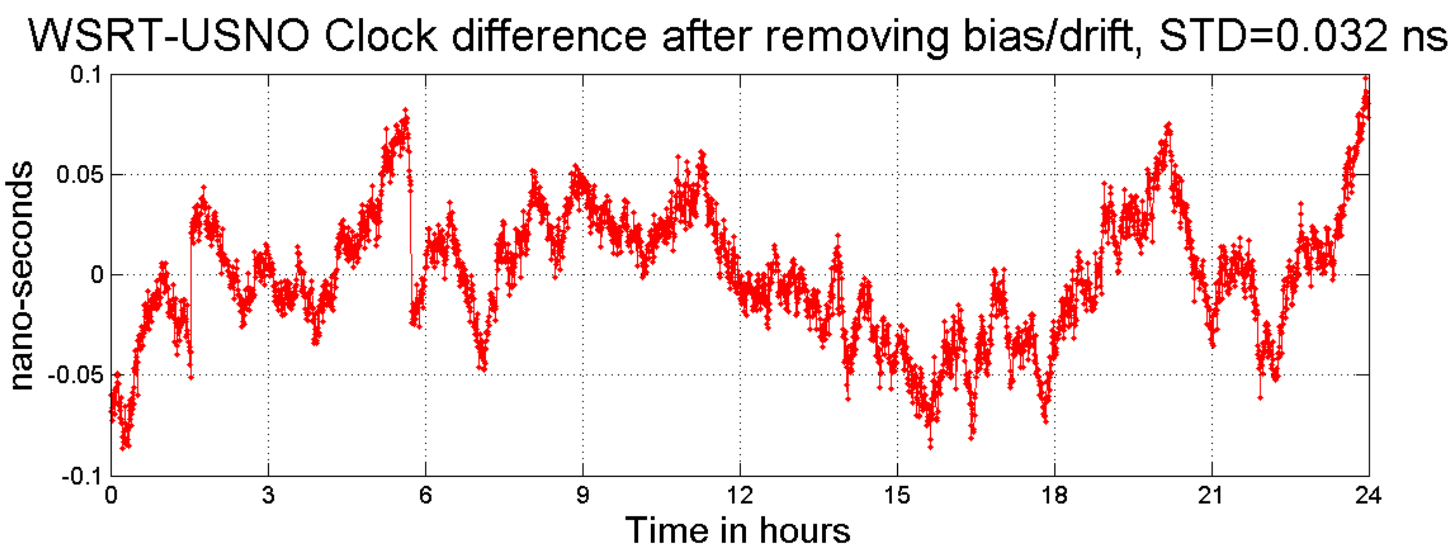


Clock comparison using Phase Clocks

(Westerbork, The Netherlands – USNO, US)



1cm ≈ 33 ps



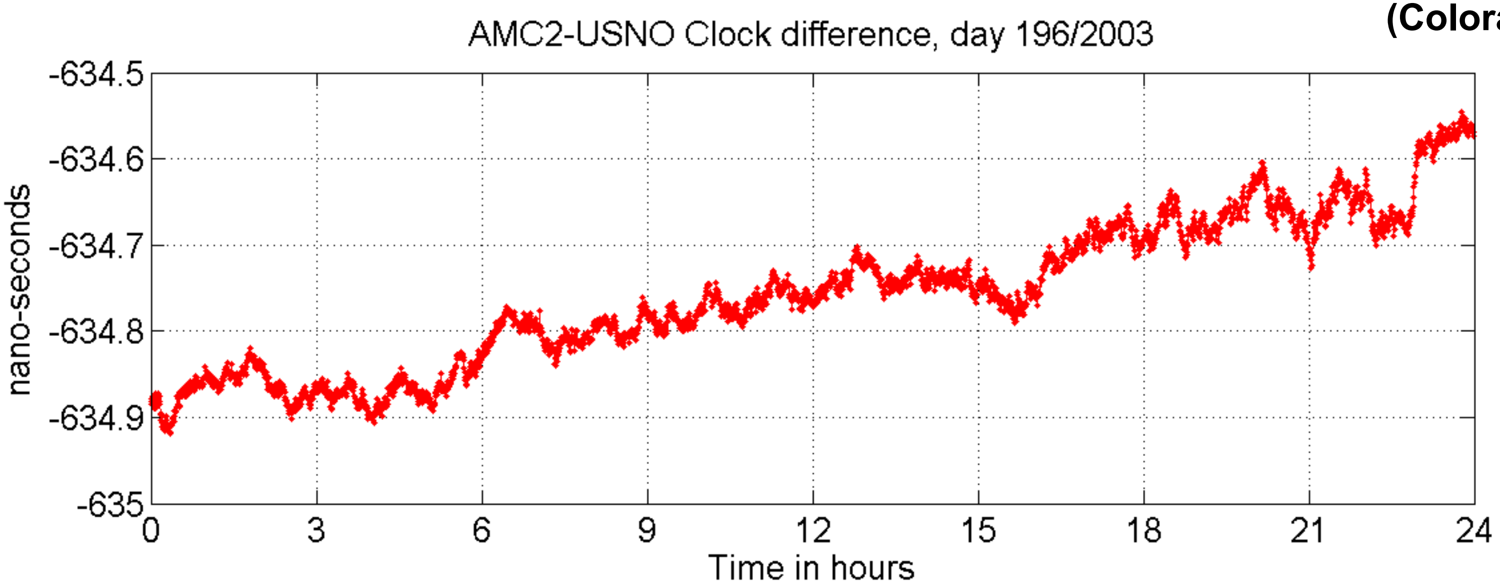
(3.7×10^{-16})

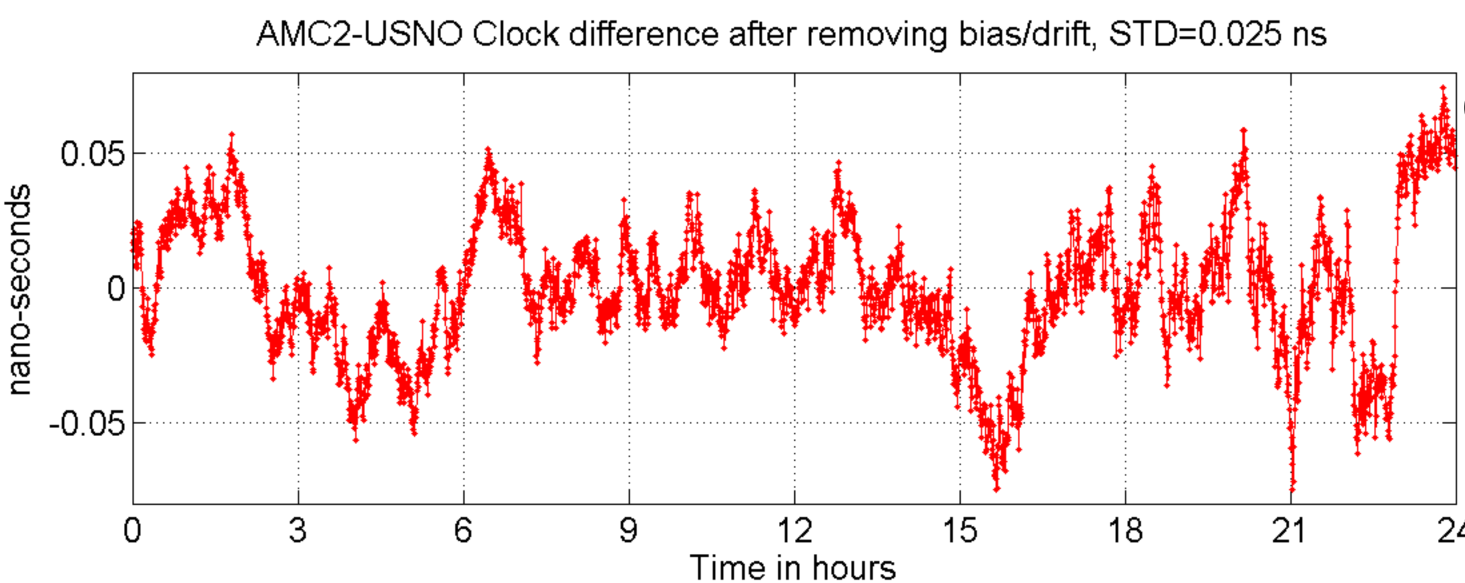
≈ 9 mm

Only phase clocks estimated. Troposphere (TZD), station coord., EOPs, etc., fixed to IGS

Phase Clocks

(Colorado Springs – USNO)





(2.9×10^{-16} per day)

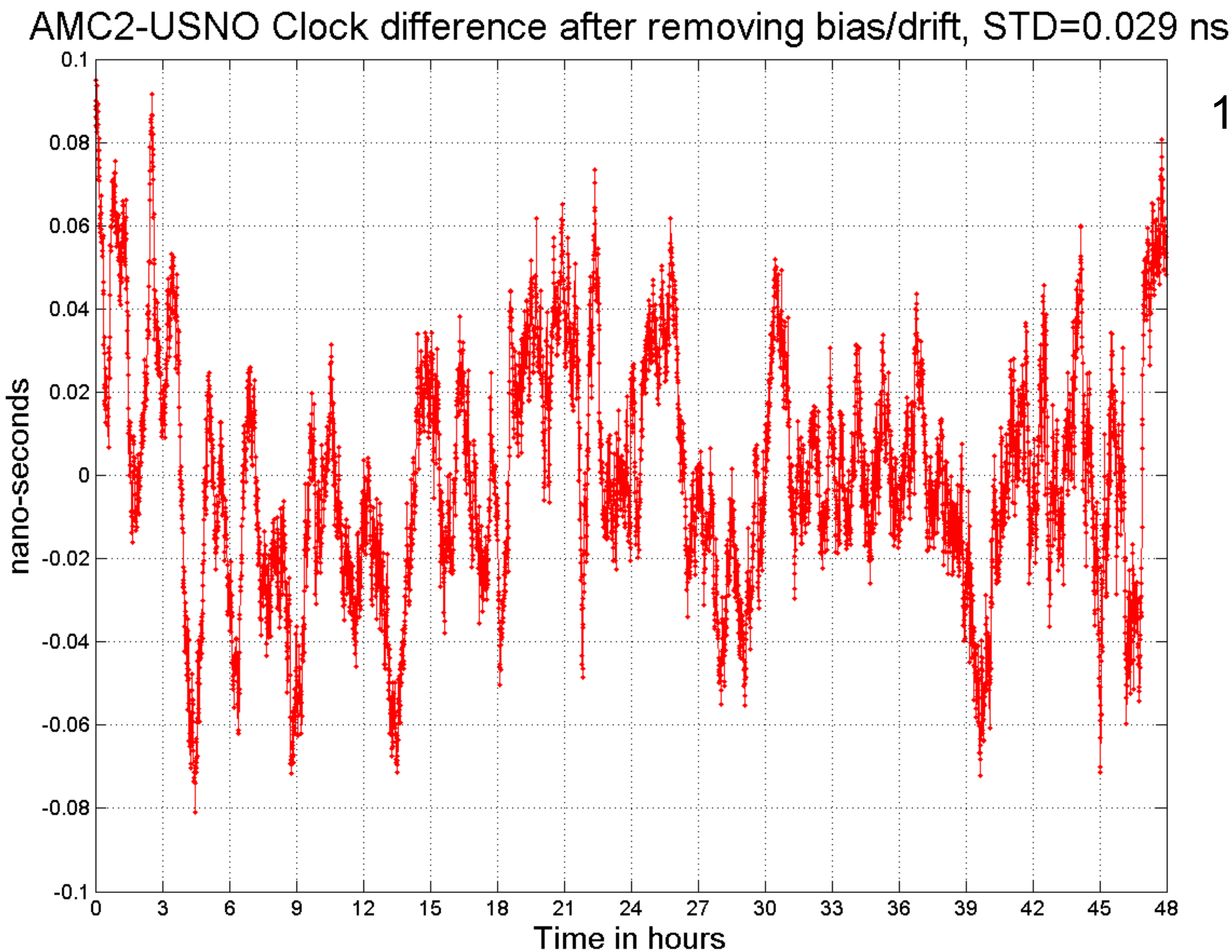
≈ 7 mm

Stability of GPS receiver and H-maser

Only phase clocks estimated. Troposphere (TZD), station coord., EOPs, etc., fixed to IGS

Phase Clocks over several days

(Colorado Springs, US – USNO, US)



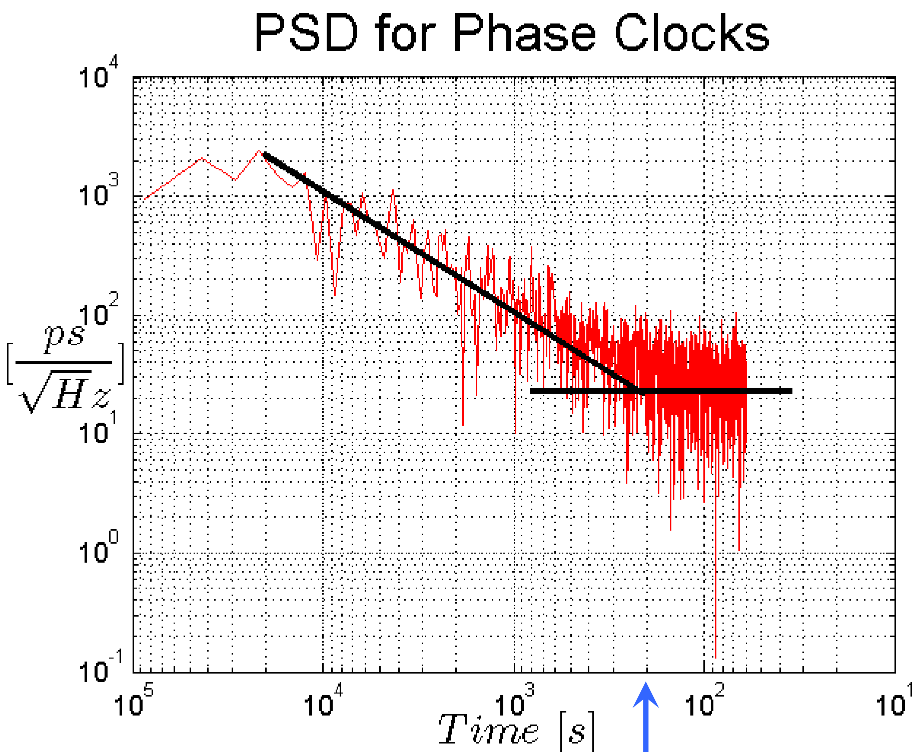
1cm ≈ 33 ps

relative precision

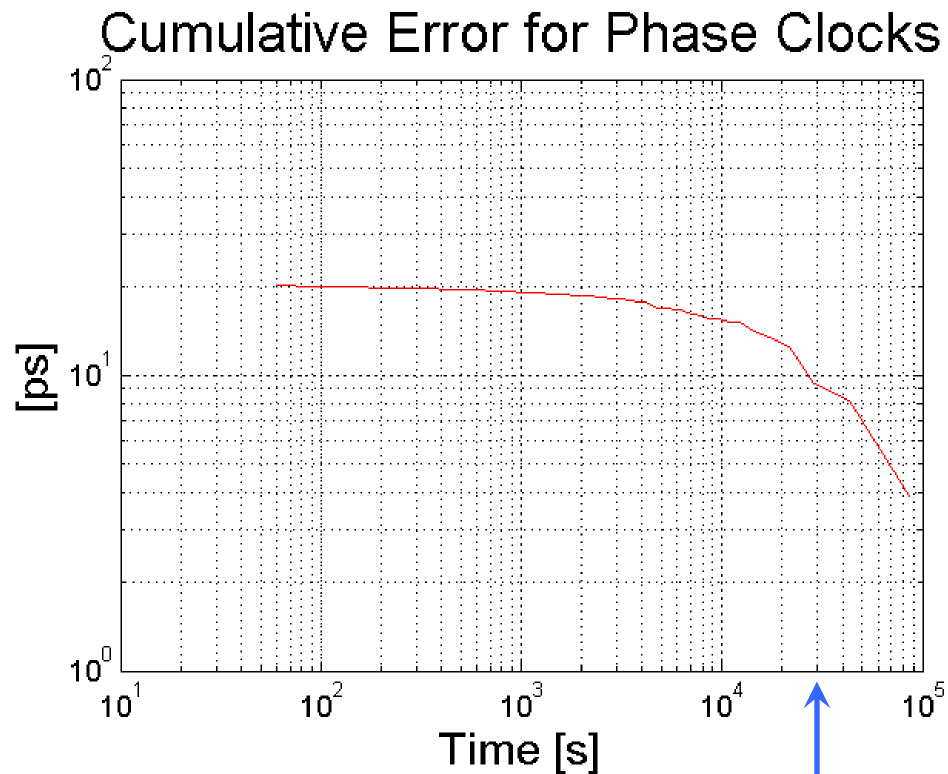
(3.3×10^{-16})

Only phase clocks estimated. Troposphere (TZD), station coord., EOPs, etc., fixed to IGS

Phase Clock – Power Spectral Density

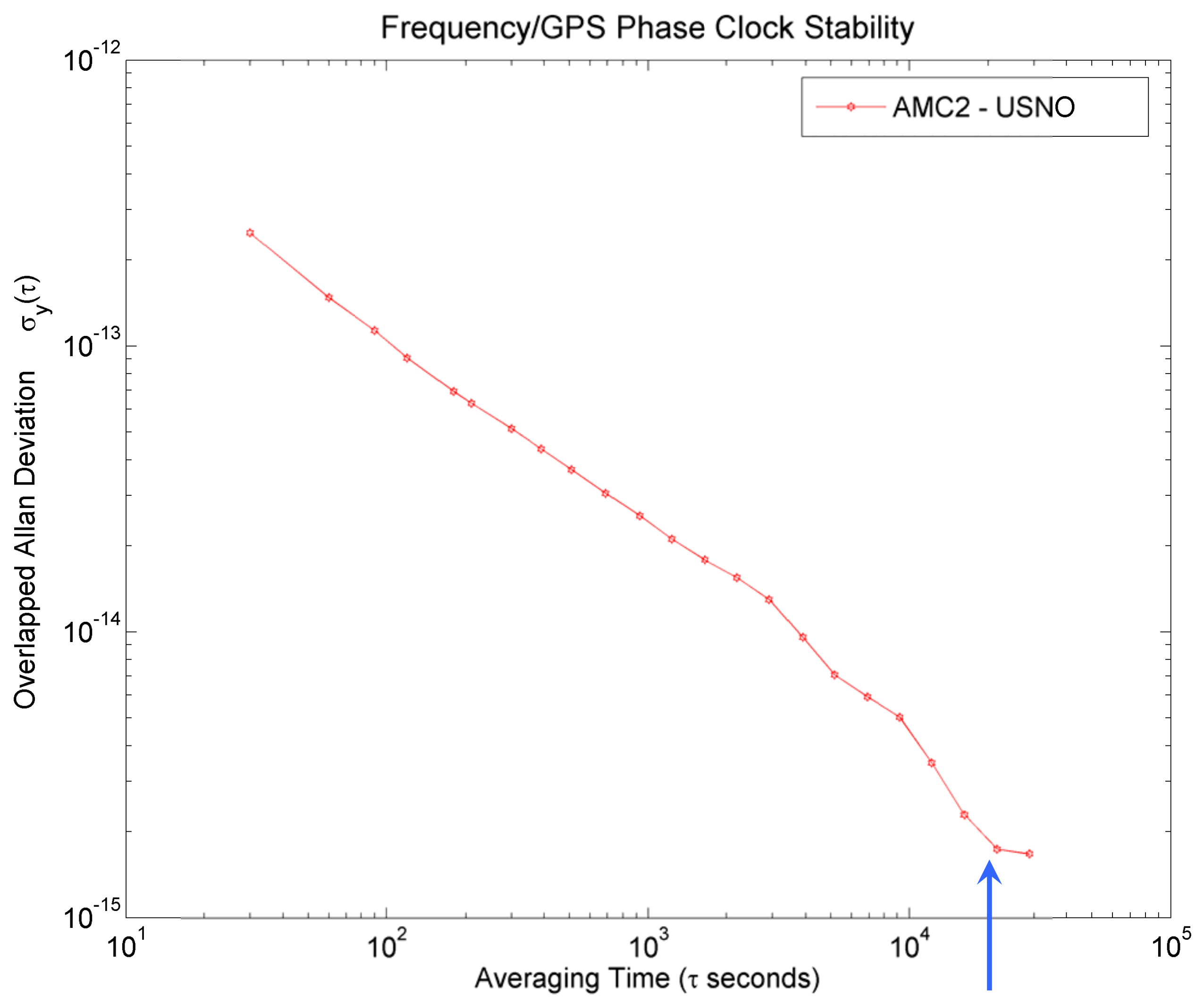


≈ 200 s



≈ 8 h

Phase Clocks - Allan Deviation



Allan deviation computed using the program CANVAS

5 hours ≈ 10^{-15}

Simulation of the GPS, GALILEO and MWL measurements for the SPACE STATION

Space Station: i=51.6°, altitude=400 km

GPS constellation + **GALILEO** constellation = 58 satellites

ground clock labs

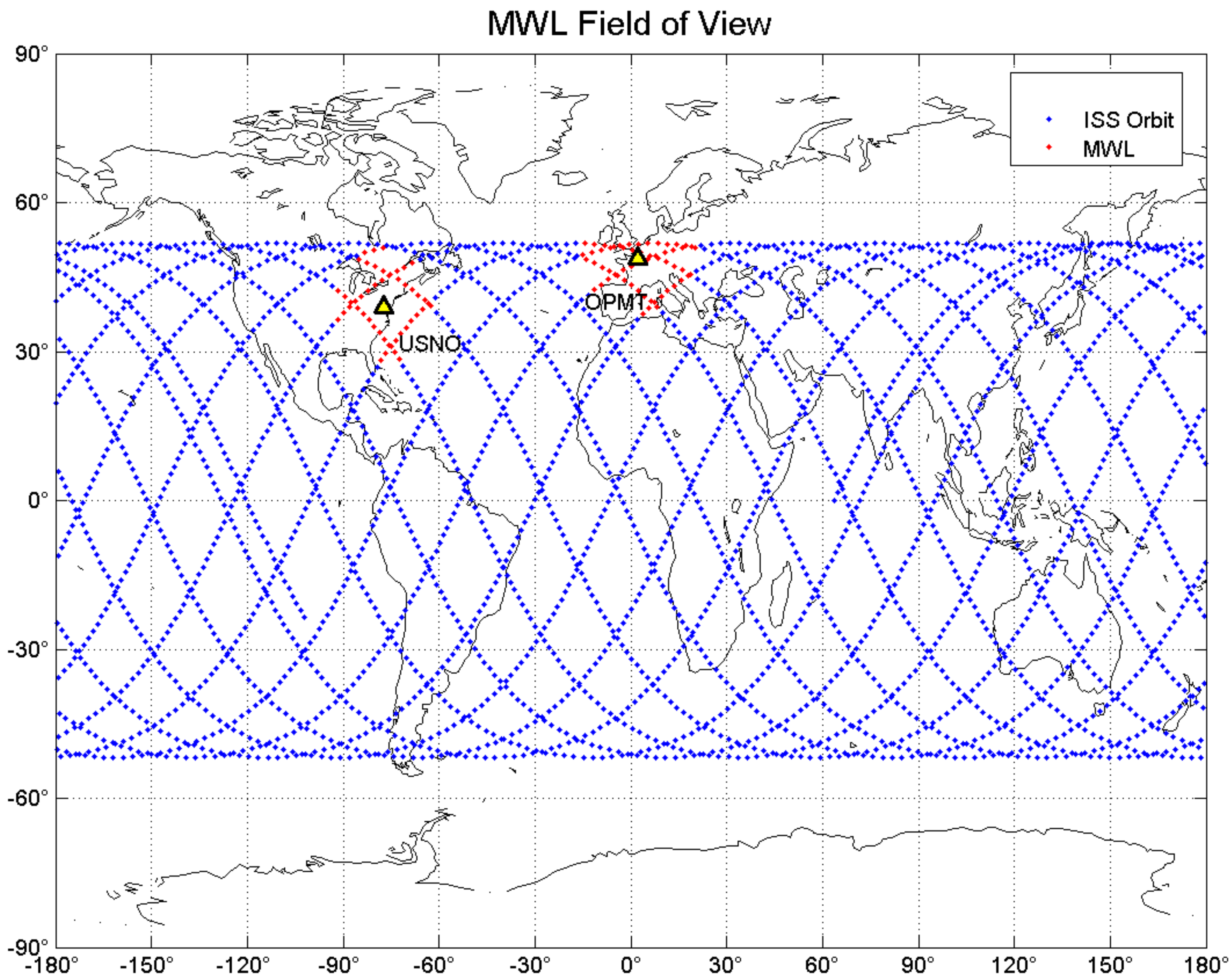
GPS observables:

L1, L2   σ(L1)=σ(L2)= 3 mm

GALILEO observables:
L1, E5a   σ(L1)=σ(E5a)= 3 mm

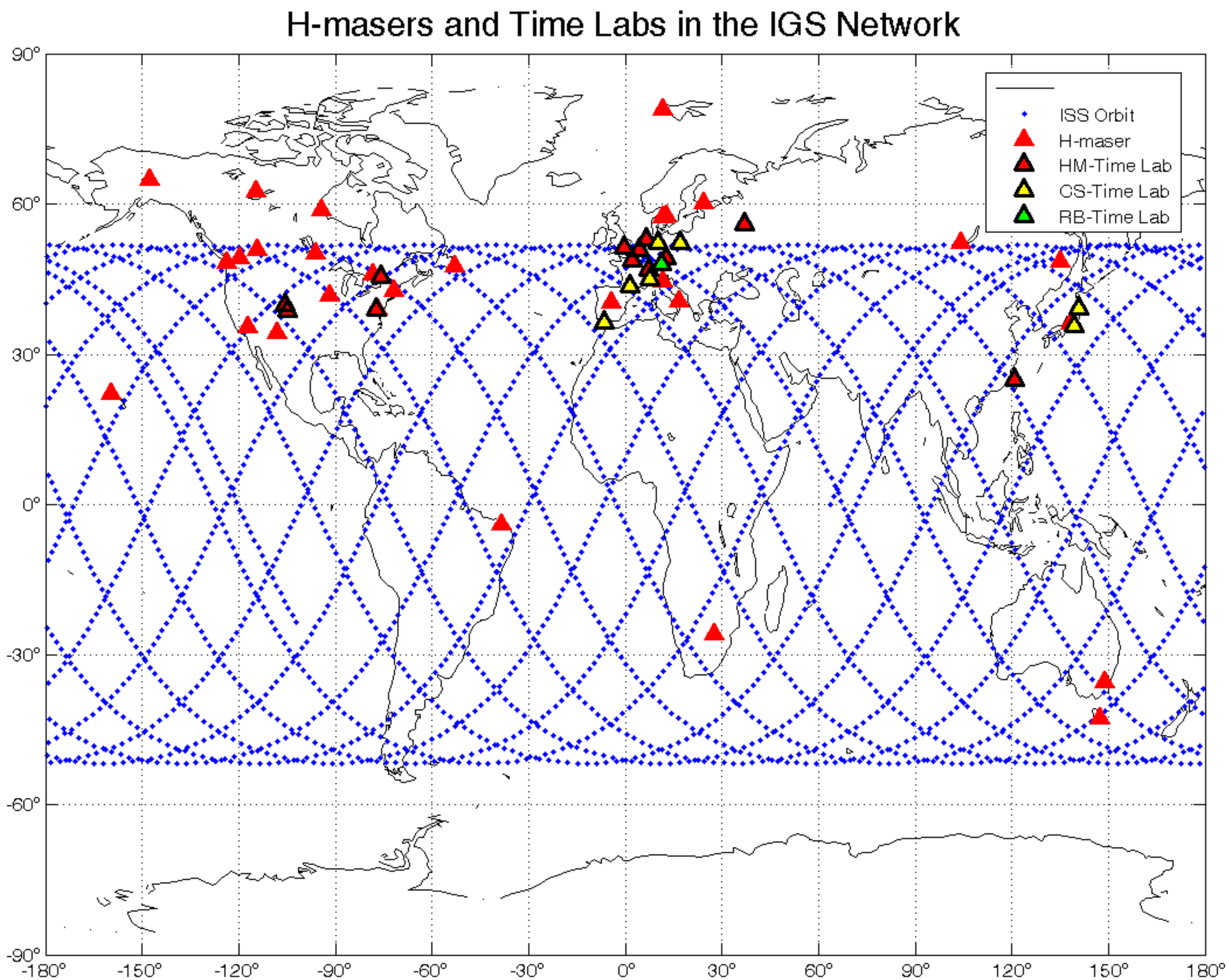
ACES MWL observables: (simulated as biased range)
Ku (13.475Ghz), Ku (14.70333Ghz), σ(Ku)= 0.3 mm

ACES MWL

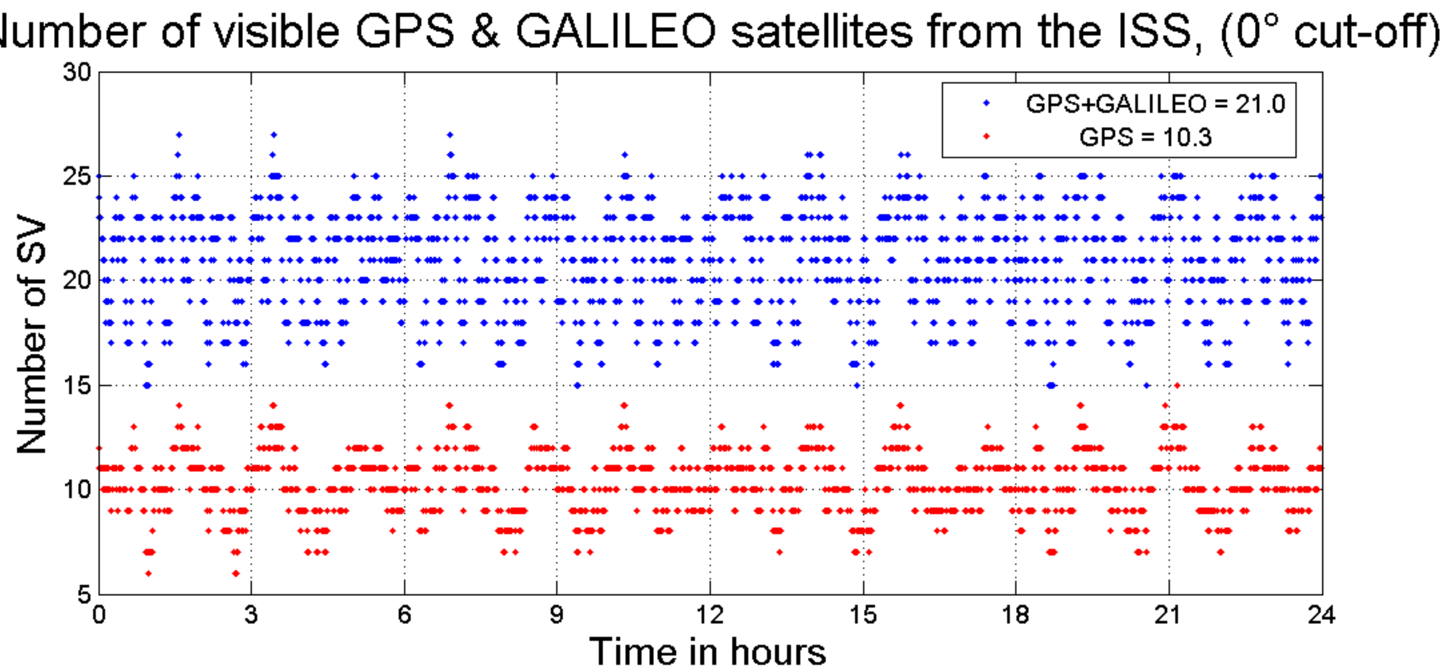


MWL Field of View
ISS Orbit
MWL
OPMT
USNO
90°
60°
30°
0°
-30°
-60°
-90°
-180°
-150°
-120°
-90°
-60°
-30°
0°
30°
60°
90°
120°
150°
180°

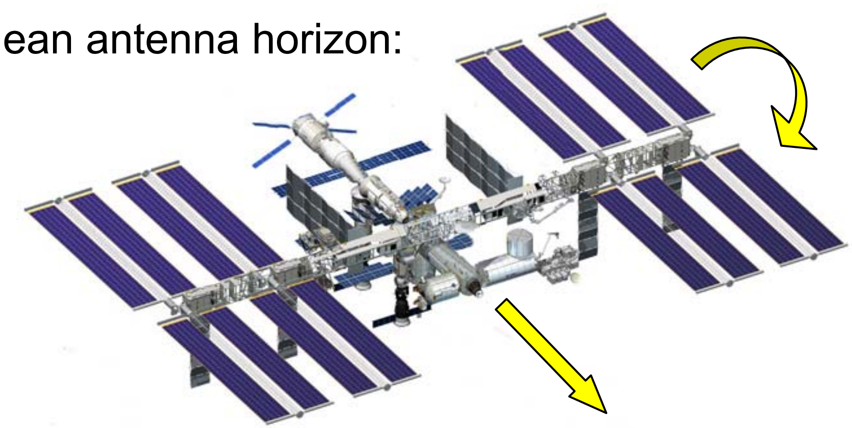
ACES and IGS clocks

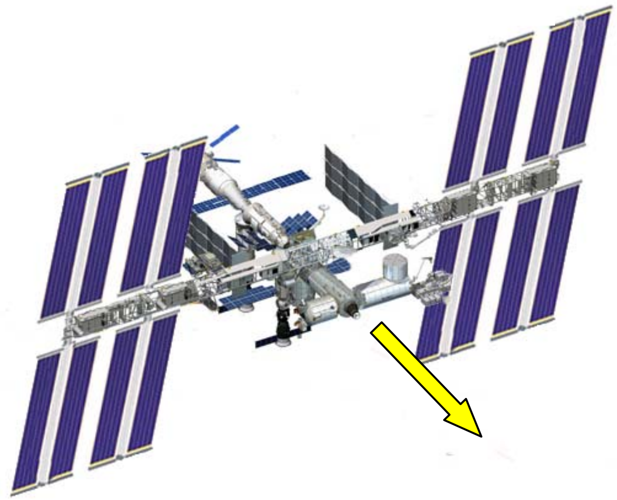


GPS and GALILEO on board Space Station



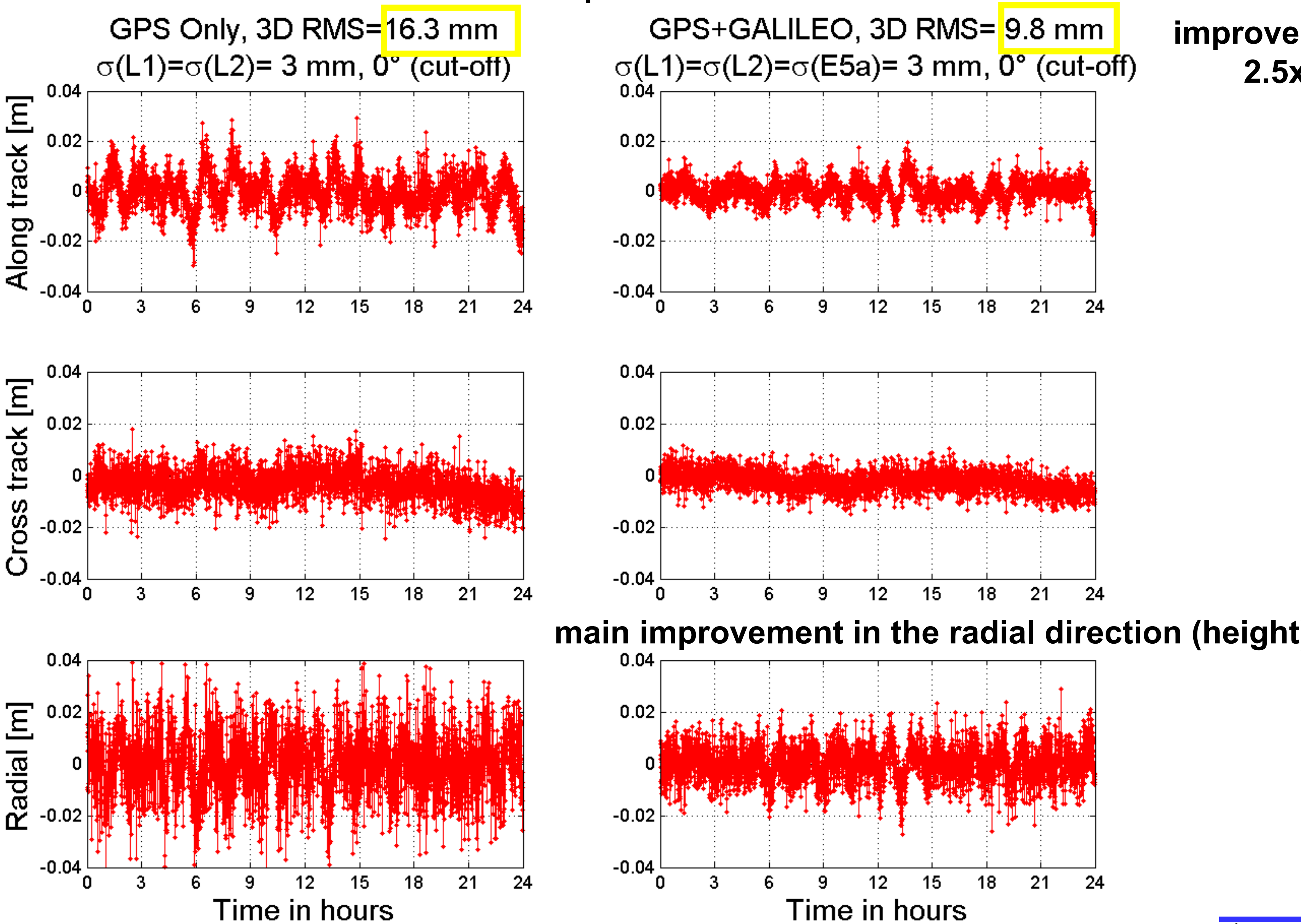
Clean antenna horizon:





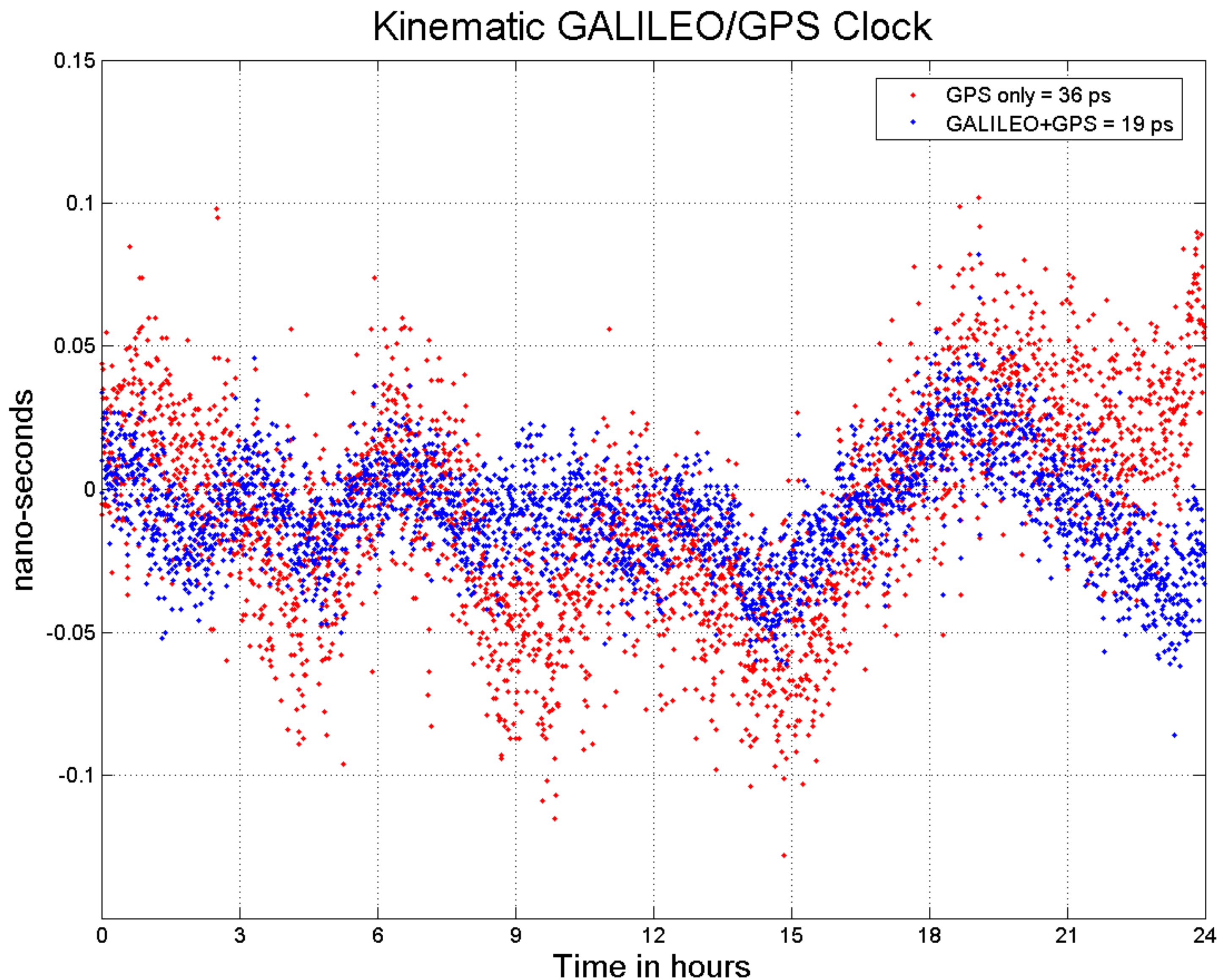
rotation of solar panels: 360° per orbit (ca. 90 min)

GALILEO+GPS: Kinematic POD for Space Station



improvement 2.5x

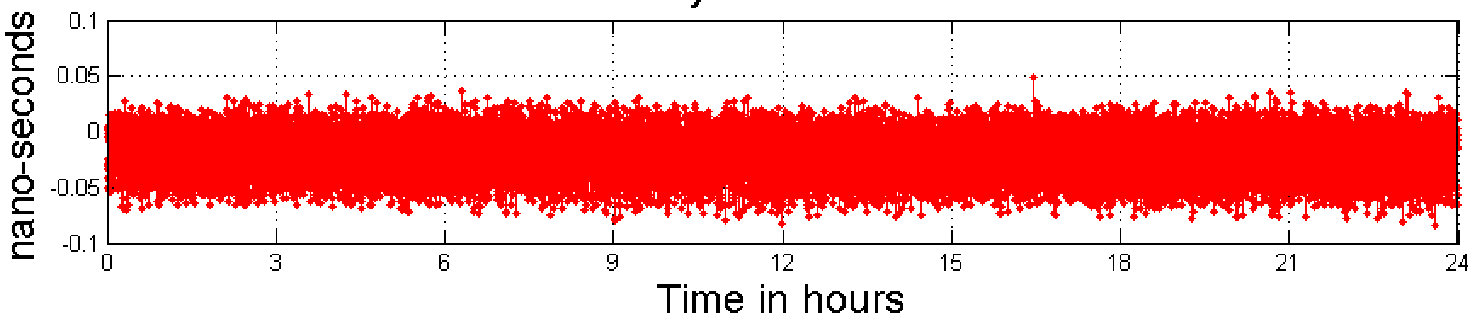
GALILEO+GPS: Kinematic POD for Space Station



receiver clock estimated in the kinematic POD

Combined GPS/GALILEO/MWL frequency transfer (MWL simulated as biased phase)

GPS Only: STD=0.026 ns



GPS observables:

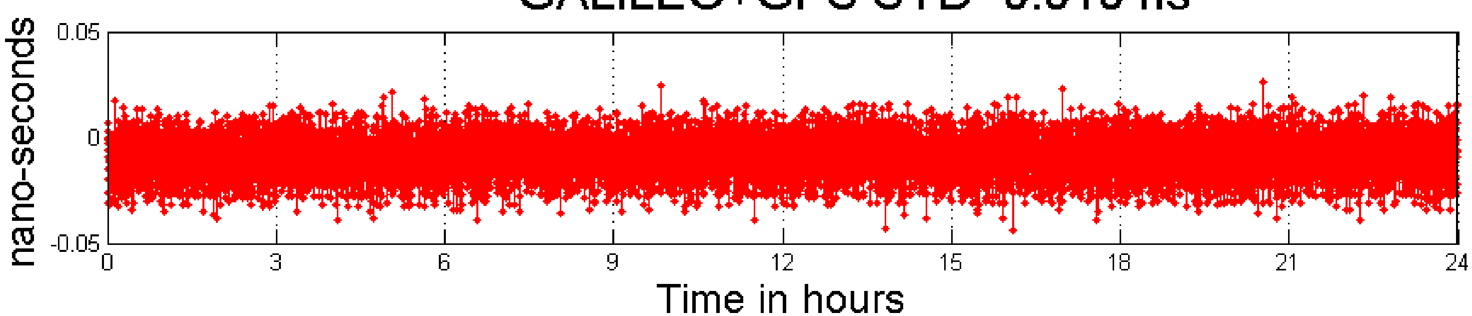
L1, L2   σ(L1)=σ(L2)= 3 mm → L3≈9 mm

GALILEO observables:

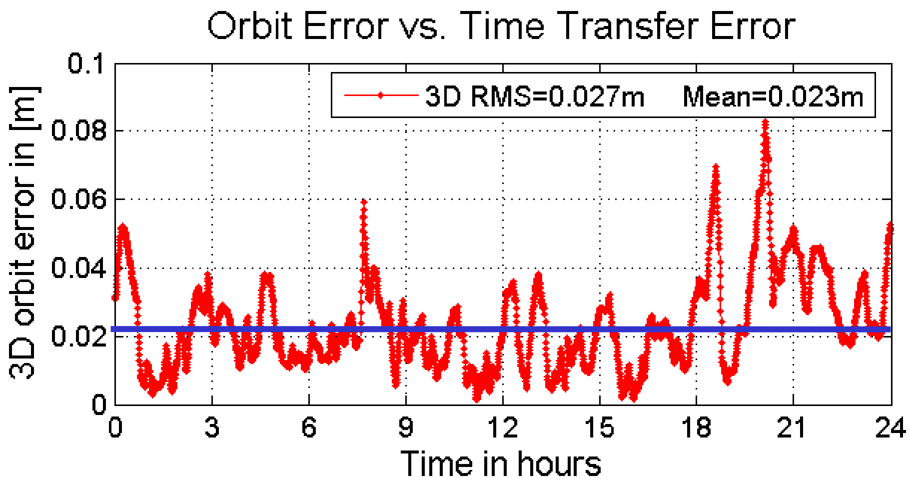
L1, E5a   σ(L1)=σ(E5a)= 3 mm → L3≈9 mm

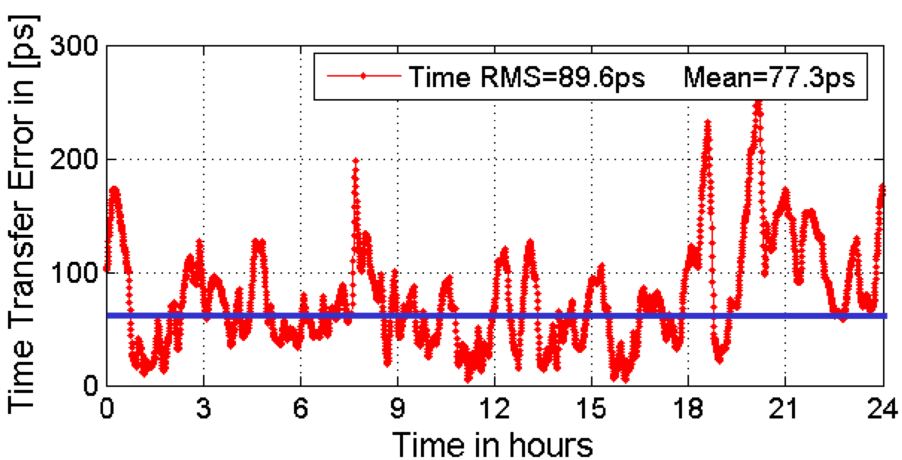
improvement 2.5x

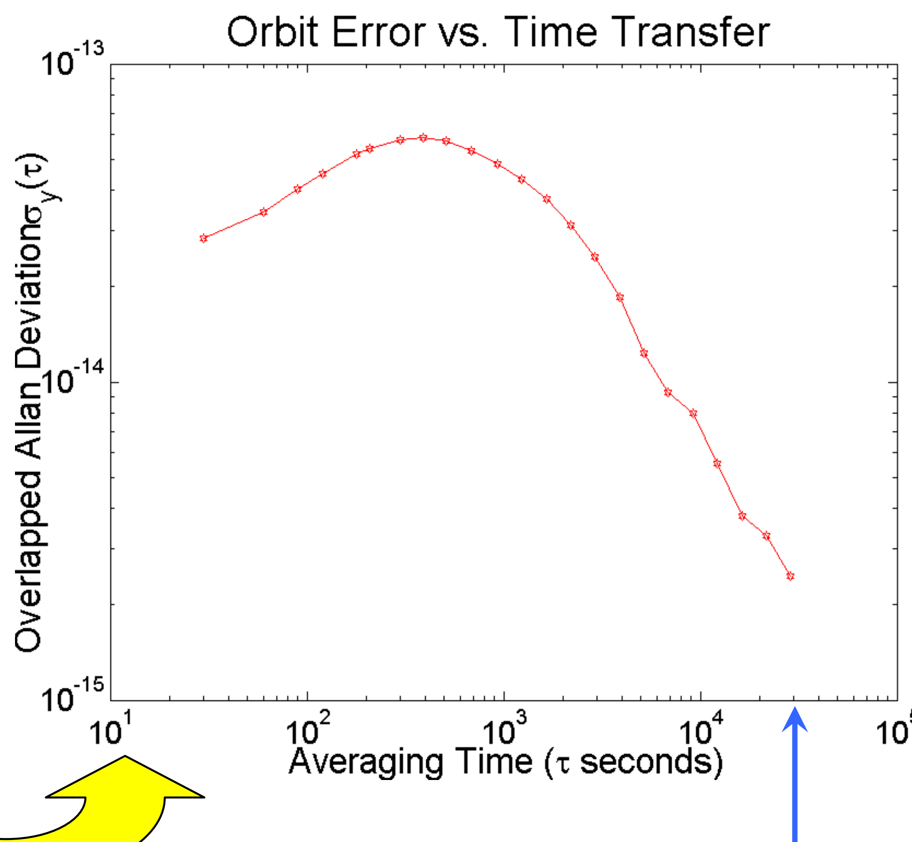
GALILEO+GPS STD=0.010 ns



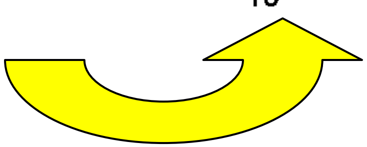
Orbit Accuracy and Time Transfer - GRACE







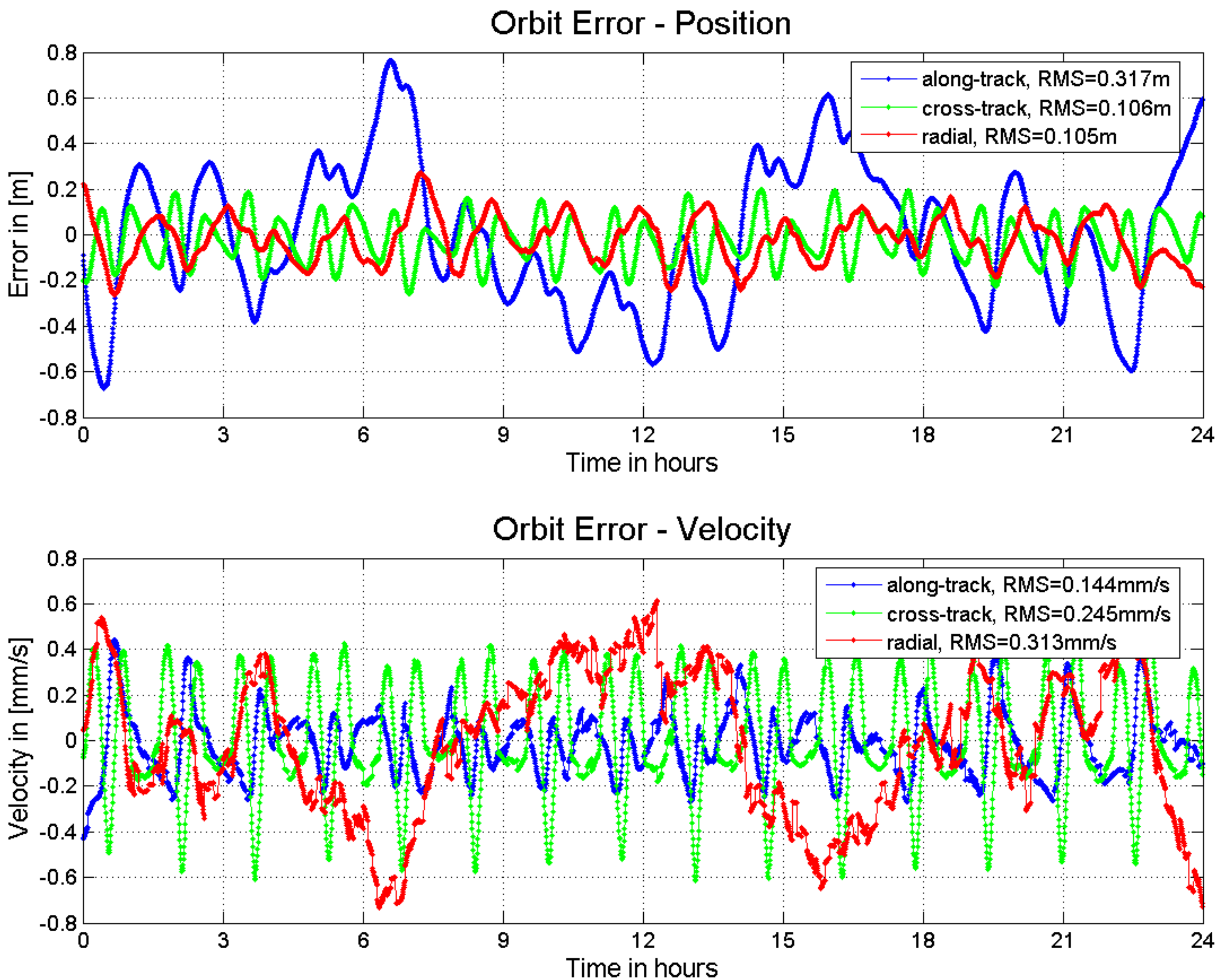
1cm ≈ 33 ps



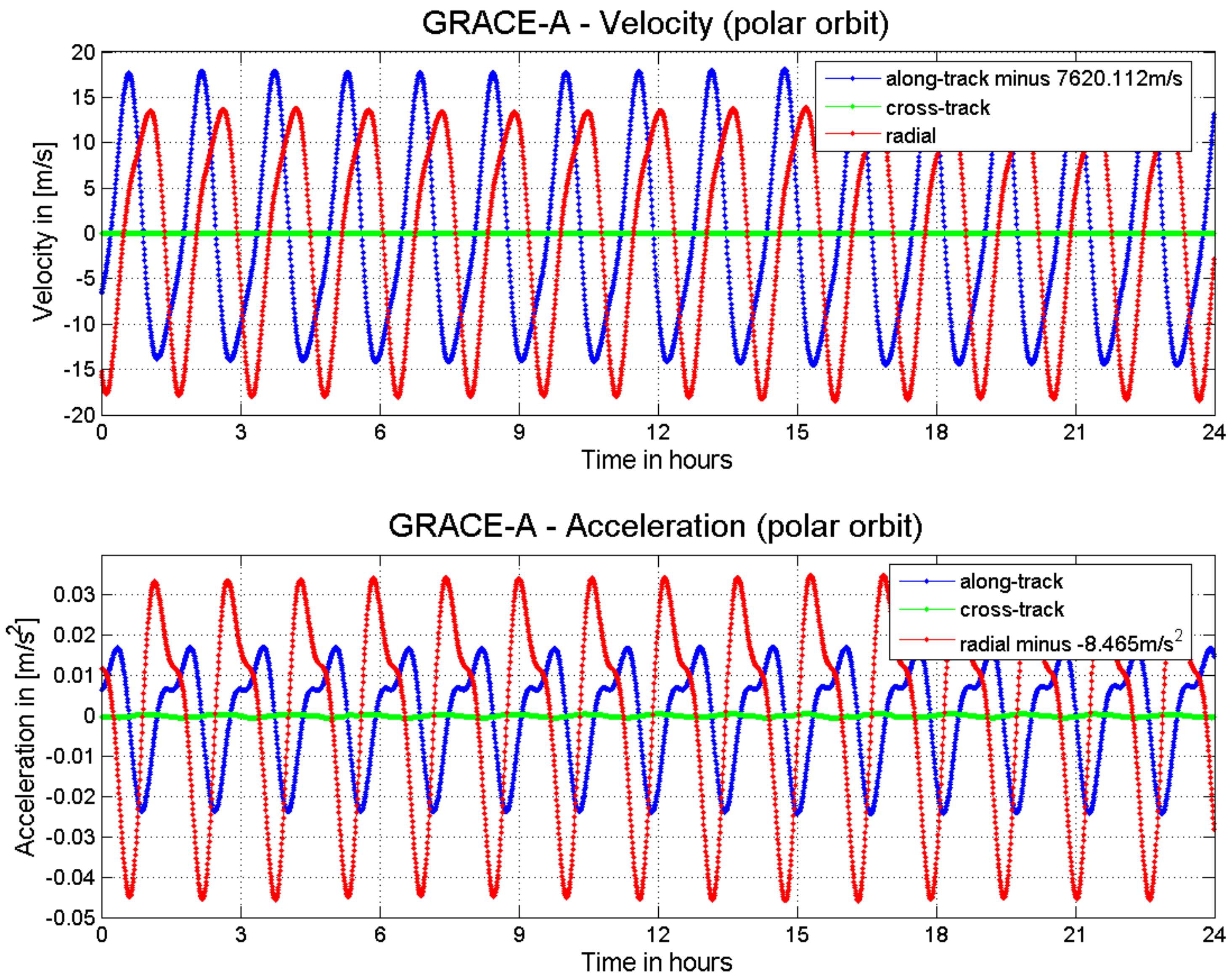
Allan deviation computed using the program CANVAS

8 hours ≈ 10^{-15}

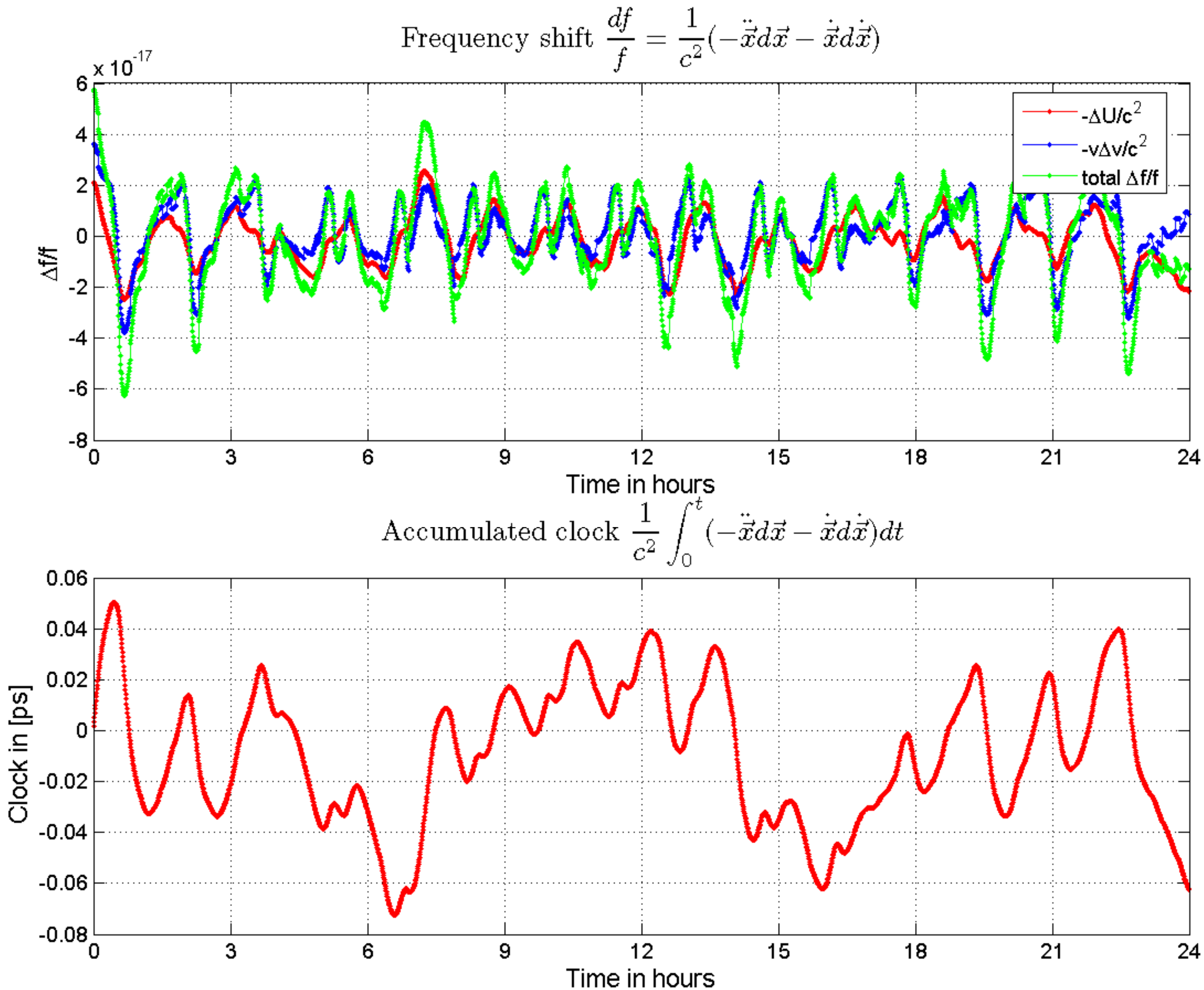
Orbit Error and Frequency Shift



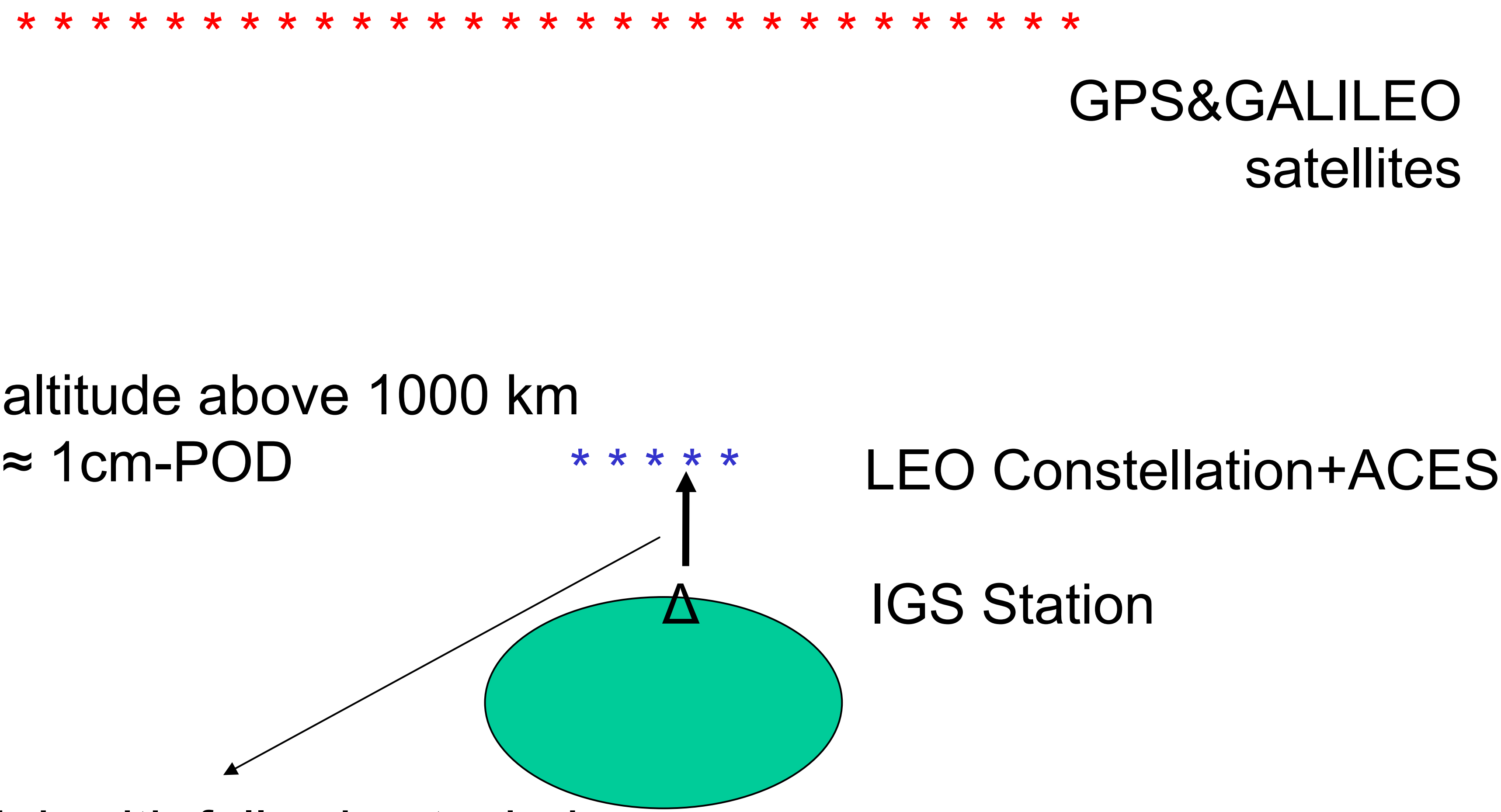
Orbit Error and Frequency Shift



Orbit Error and Frequency Shift



LEO Constellation + ACES
for Space Geodesy



Link with following techniques:
GPS+SLR+DORIS+MWL+VLBI

ESA Topical Team on ACES POD and Geodesy

Objectives:

- POD for ACES
- Time and frequency transfer
- Relativistic Geodesy (gravity from clocks)

Gravitational frequency shift $\Delta f/f = \Delta W/c^2$ $10^{-16} \approx 1$ m