Nove Geometrijske Metode Geodezije u Svemiru

Pioneering the Geometrical Approach of Space Geodesy and Paving the Way Towards Planetary Geodesy

Geometrijske metode satelitske geodezije i trasiranje puta prema planetarnoj geodeziji

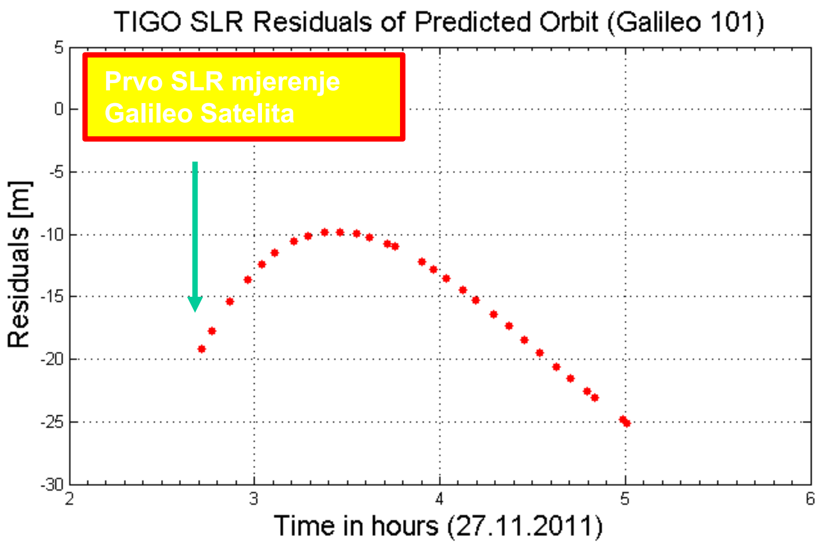
Dr.-Ing. Dražen Švehla

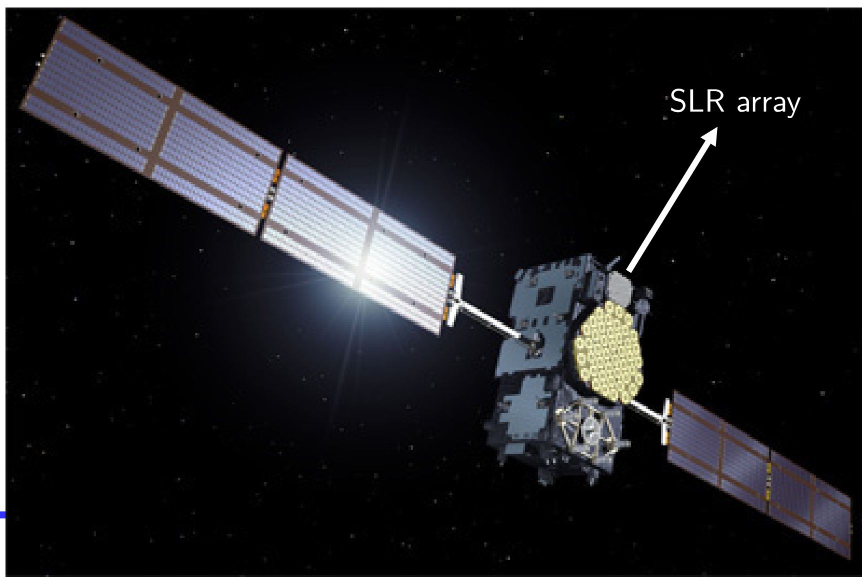
Sadržaj

- Highlights: 2000-2014
- GPS na satelitu u LEO orbiti: kinematička i dinamička metoda (CHAMP, GRACE, GOCE, Jason-2)
- Inter-kontinentalni transfer frekvencije i vremena pomoću metode faznih satova
- Metoda faznih satova i određivanje ambiguiteta (zero-differences)
- Određivanje terestričkog referentnog sustava kombiniranjem GPS, SLR i DORIS mjerenja sa satelita
- Prva SLR bazisna linija sub-milimetarske točnosti
- Kombinirano određivanje terestričkog i nebeskog referentnog koordinatnog sustava
- Galileo H-maser: prvo mapiranje perturbacija orbite GNSS satelita korištenjem sata satelita
- Galileo H-maser: određivanje J_2 koeficijenta gravitacijskog polja Zemlje
- Galileo H-maser: prvo geometrijsko mjerenje termalne inercije iluminiranog Galileo satelita
- Geometrijska metoda računanja sfernih harmonika, vremenskih promjena sile teže i orbita satelita

Prva SLR Mjerenja Galileo Satelita

ESA Press Release Dec/2011





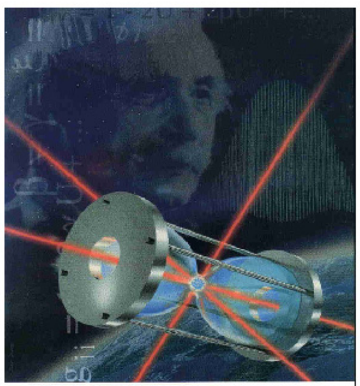
ESA Homepage
http://www.esa.int/SPECIALS/Galileo_IOV/SEM6HT7XZVG_1.html#subhead4

esa Topical Team on Geodesy
Applications of the ACES Mission

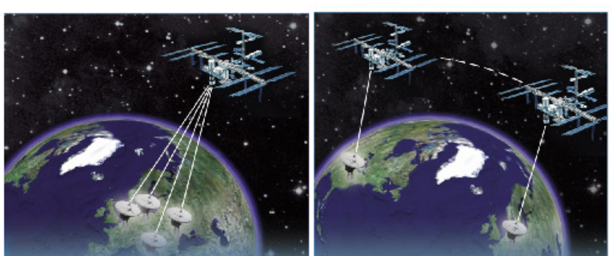
ACES and FUTURE GNSS–BASED EARTH OBSERVATION and NAVIGATION

26 – 27 May 2008

Institute of Astronomical and Physical Geodesy
Technische Universität München



(Credit CNES)



(Credit ASTRIUM)

esa Topical Team on Geodesy
Applications of the ACES Mission

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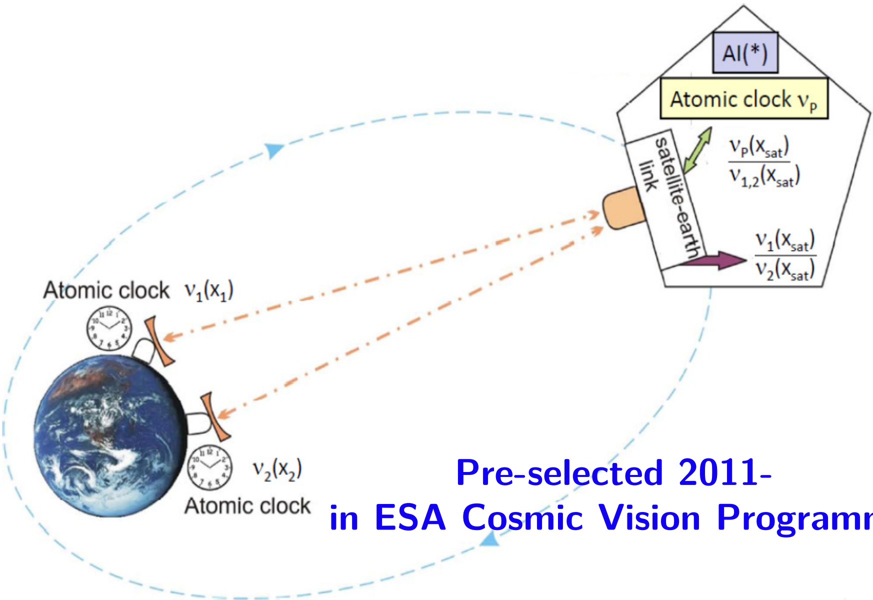
PROCEEDINGS



Koordinator Satelitske Misije - Geodetski Dio

Space-Time Explorer (STE-QUEST)
ESA Cosmic Vision (M-Class Mission)

Terestrički/Nebeski Koordinatni Sustav
Secondary Objective of the Mission

Pre-selected 2011-
in ESA Cosmic Vision Programme

Galileo@ISS
now GEROS
Selected 2012

Galileo@ISS or GEROS
GNSS Altimetry (coherent GNSS reflectometry)
TU München, GFZ, DLR, 25 co-authors

Standalone geodesy mission on ISS
Proposal (100 pages) submitted in 2008 ESA Topical Team on Geodesy

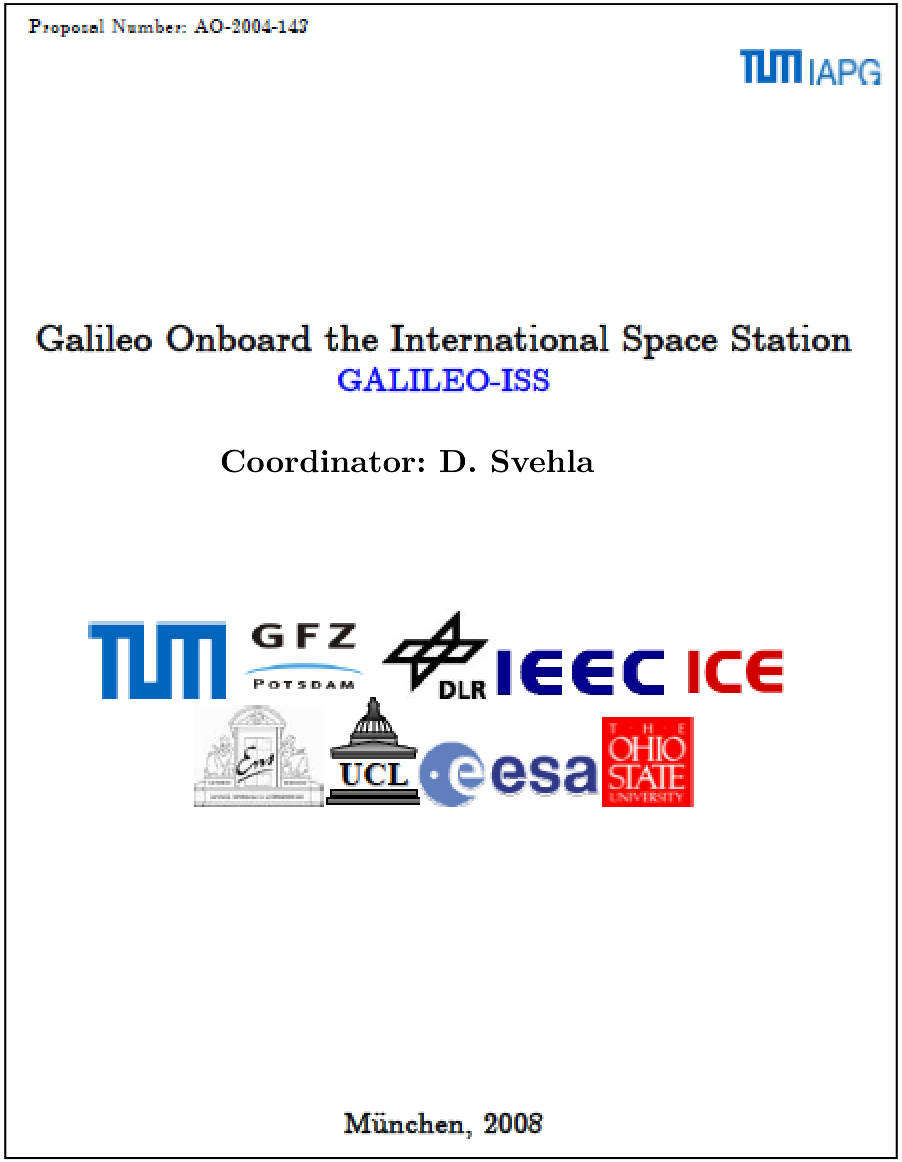
ACES
Geodesy Part Selected 2008

ACES – Geodesy Part
Time/Frequency Transfer, GNSS Radio-Occultation,
(TU München, GFZ, DLR)

OPS-SAT
Selected 2012

OPS-SAT (CubeSat)
SLR Demonstrator (Graz)

GNSS-Reflectometry (altimetrija) na Svemirskoj Postaji

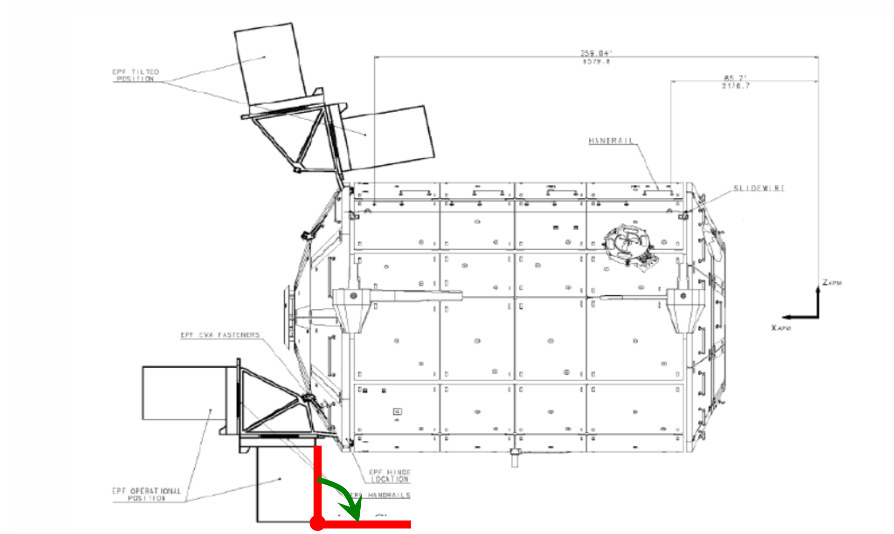

Proposal Number: AO-2004-143

Galileo Onboard the International Space Station

GALILEO-ISS

Coordinator: D. Svehla

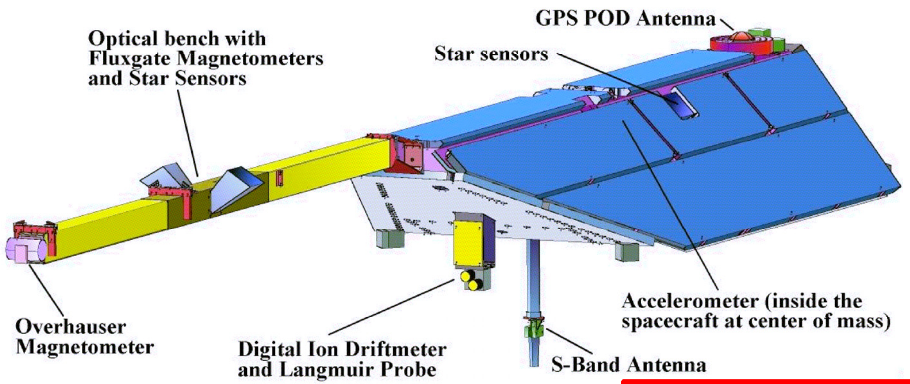
München, 2008



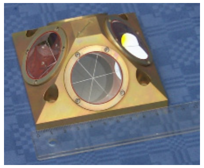
- ESA Phase A/B Studije 2013-

GPS na Satelitu u LEO Orbiti

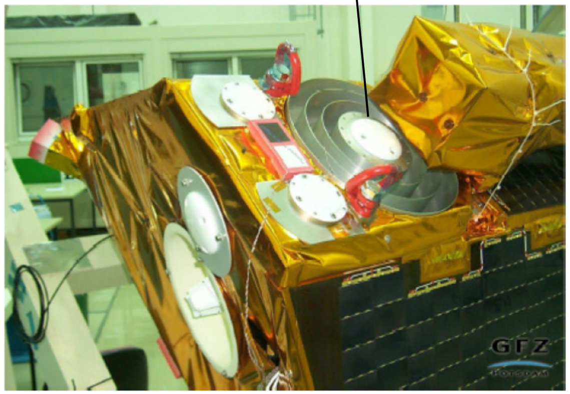
CHAMP satelit
visina 400 km



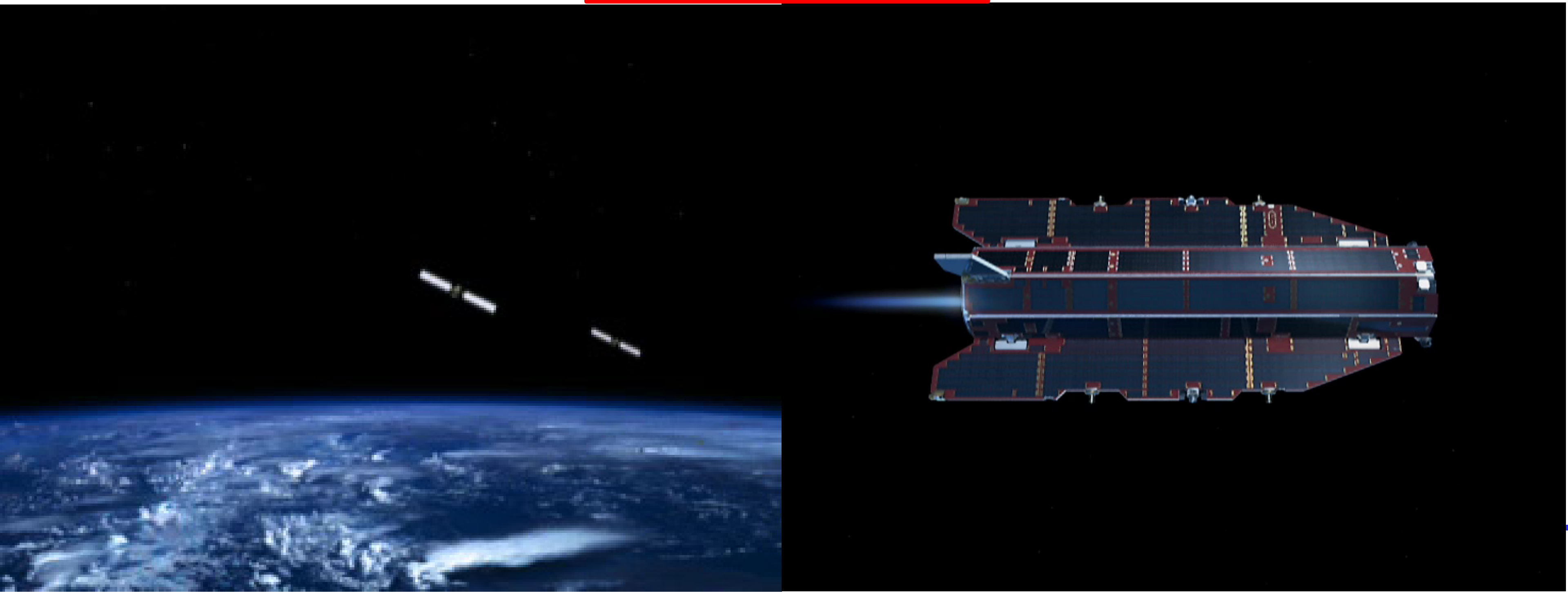
Laser retro-reflektor



Choke-ring
GPS antena

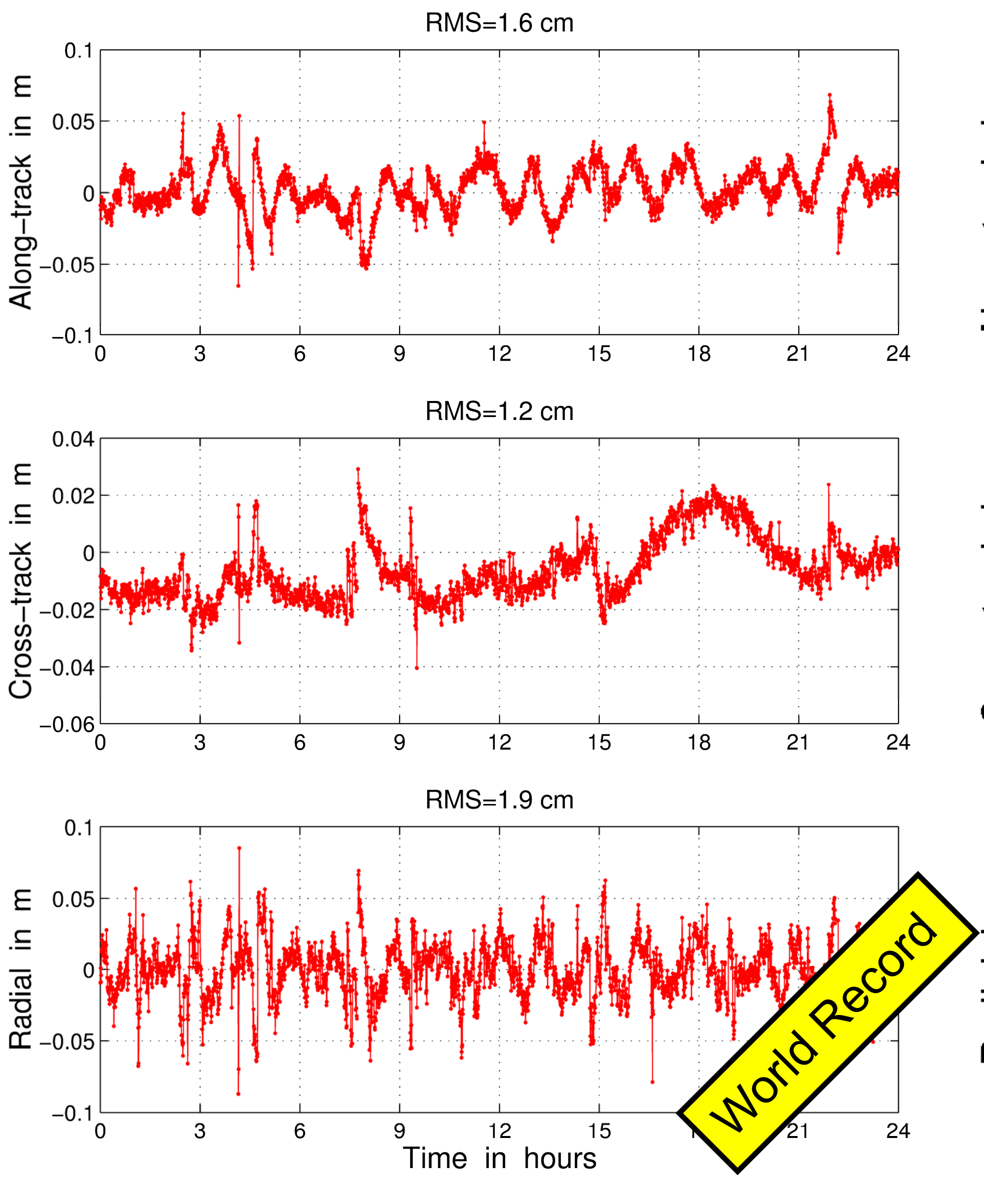


GOCE satelit
visina 220 km



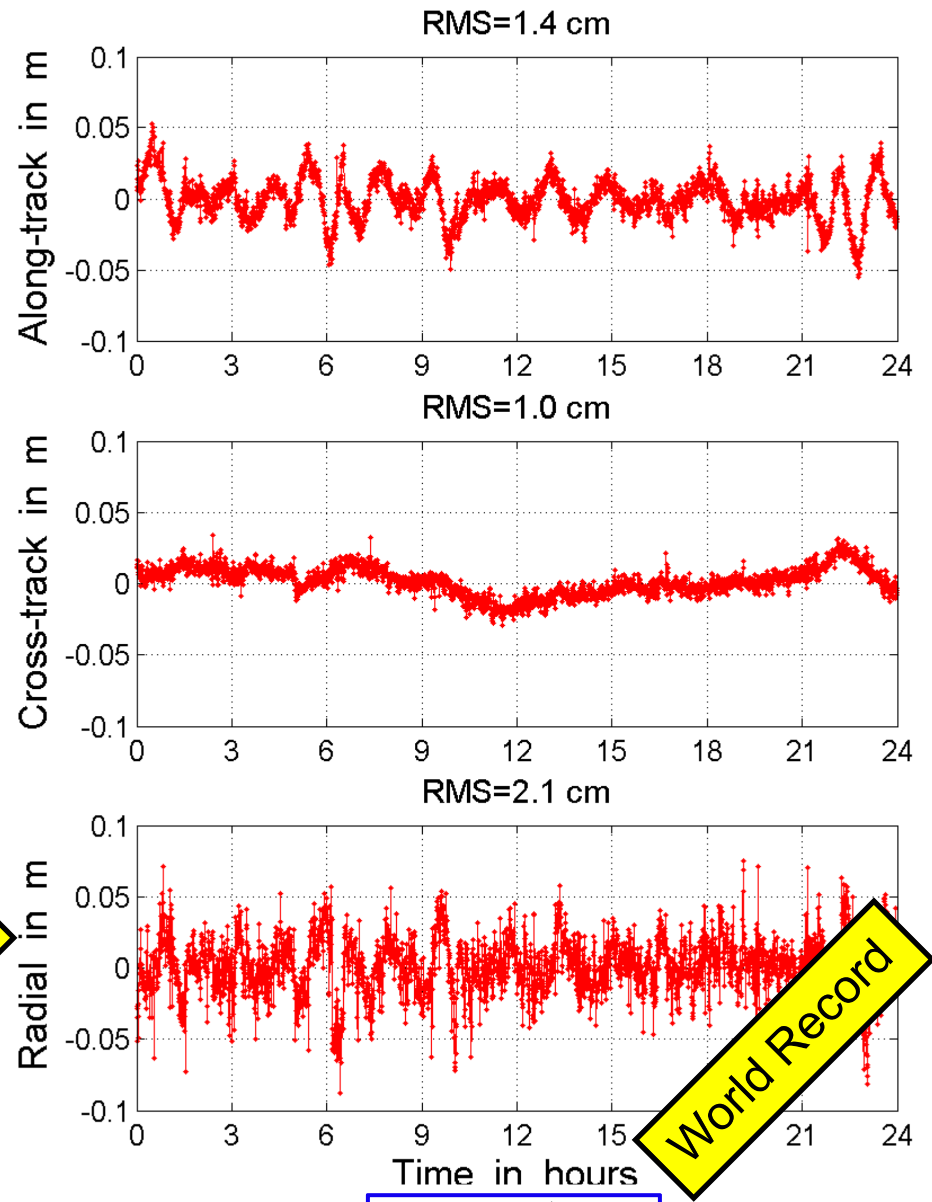
Prva Geometrijska Trajektorija Satelita

CHAMP



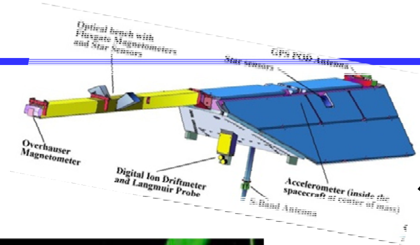
Day 200/2002

GRACE-A

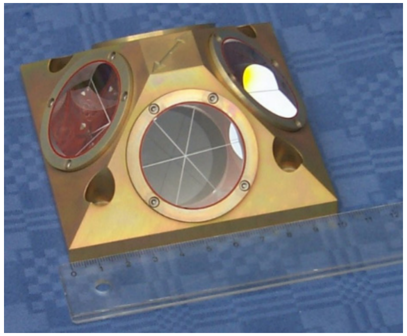


Day 200/2003

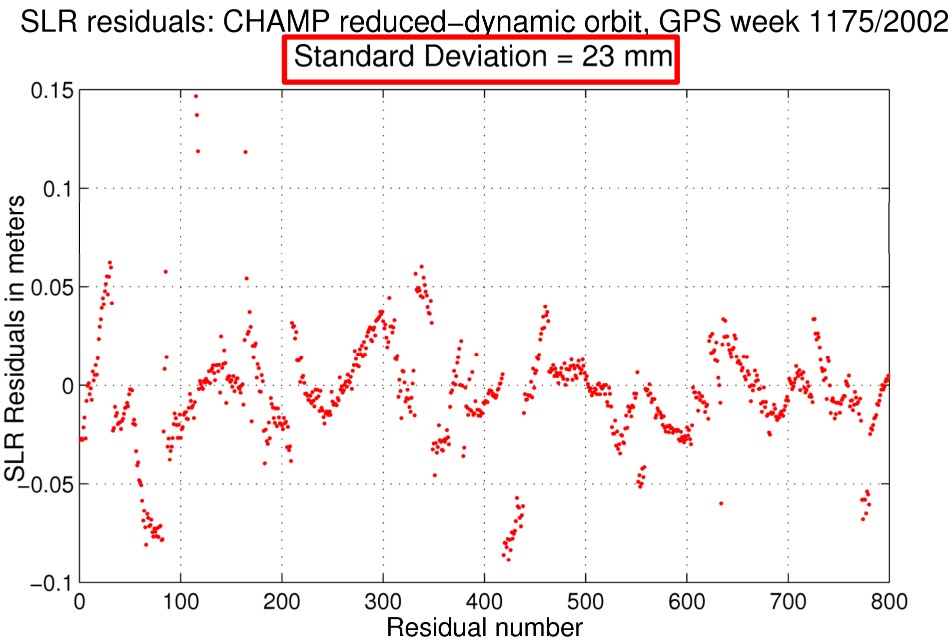
Satelitska Laserska Mjerenja (SLR)



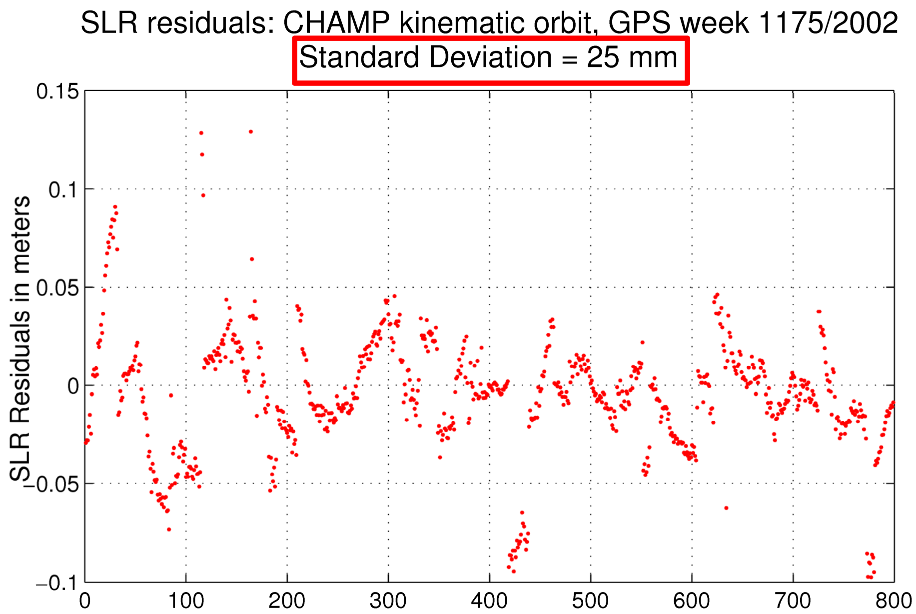
Laser retro-reflektor



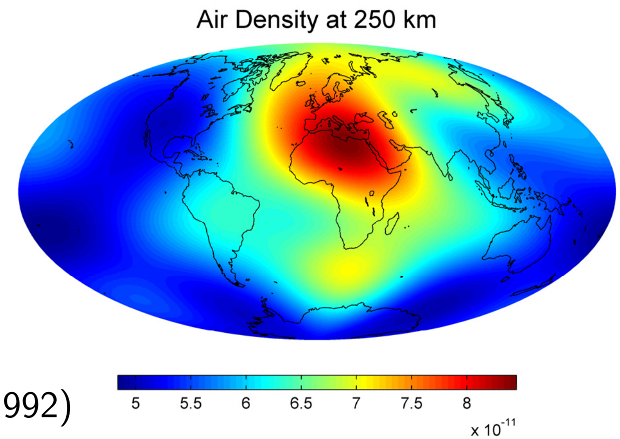
DINAMIČKA orbita



KINEMATIČKA orbita



Četiri Fundamentalne Metode Određivanja Orbita Satelita



1) Dinamička metoda (e.g. Topex-Poseidon, Tapley et al. 1992)
numerička integracija

2) Reducirana-dinamička metoda (Topex-Poseidon, Yunck et al. 1992)
numerička integracija

3) **Kinematička metoda** (CHAMP, **Švehla and Rothacher 2002**)
Geometričke orbite bazirane na Faznim Parametrima Satova

4) **Reducirana-kinematička metoda** (CHAMP, **Švehla and Rothacher 2003**)
Geometričke orbite sa dinamičkom infomacijom

Gravitacijsko Polje Zemlje Bazirano na Geometrijskoj Orbiti CHAMP Satelita

$$V = \frac{1}{2}\left(\frac{d\vec{r}}{dt}\right)^2 - \int_{\vec{r}} \vec{a}_{non-gravitational} d\vec{r} - \int_{\vec{r}} \vec{a}_{tides} d\vec{r} + C$$

Gravitacijski potencial ←

kinematička orbita (GPS trajektorija)

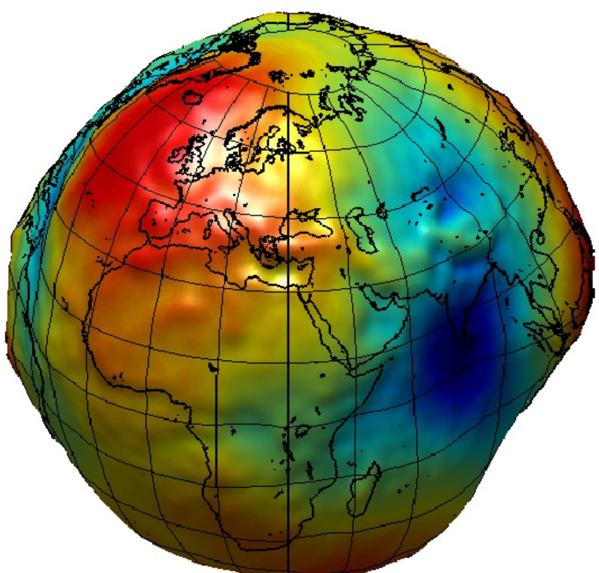
akcelerometer

plimni valovi

CHAMP/GRACE/GOCE kinematičke orbite korištene po čitavom svijetu!!!

EGM2008 Gravity Model

je baziran na GRACE kinematičkoj orbiti



Austria	(gravity)
Canada	(gravity)
China	(gravity/POD)
Denmark	(gravity)
Germany	(gravity/POD)
Japan	(POD)
Netherlands	(gravity/POD)
Switzerland	(POD)
Taiwan	(gravity/POD)
UK	(gravity)
US	(POD)

GOCE Gravitacijski Modeli - Kinematičke Orbite

Celestial Mechanics Approach	AIUB – University of Bern
Short-Arc Approach	TU Graz
Averaged Acceleration Approach	DEOS Delft, TU Delft, University of Louxemburg
Point-wise Acceleration Approach	University of Stuttgart/Austrian Academy of Sciences
Energy Balance Approach	TU Graz, TU München

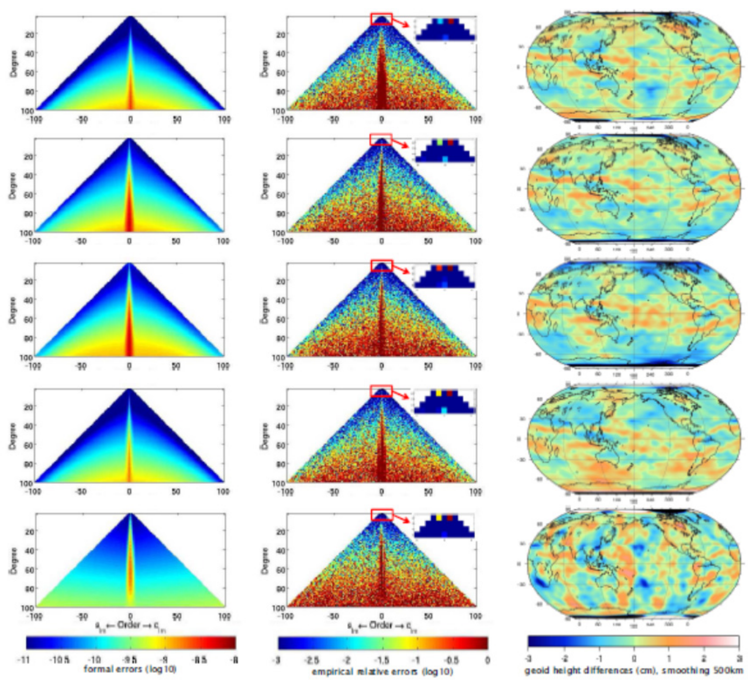
Celestial Mechanics Approach

Short-Arc Approach

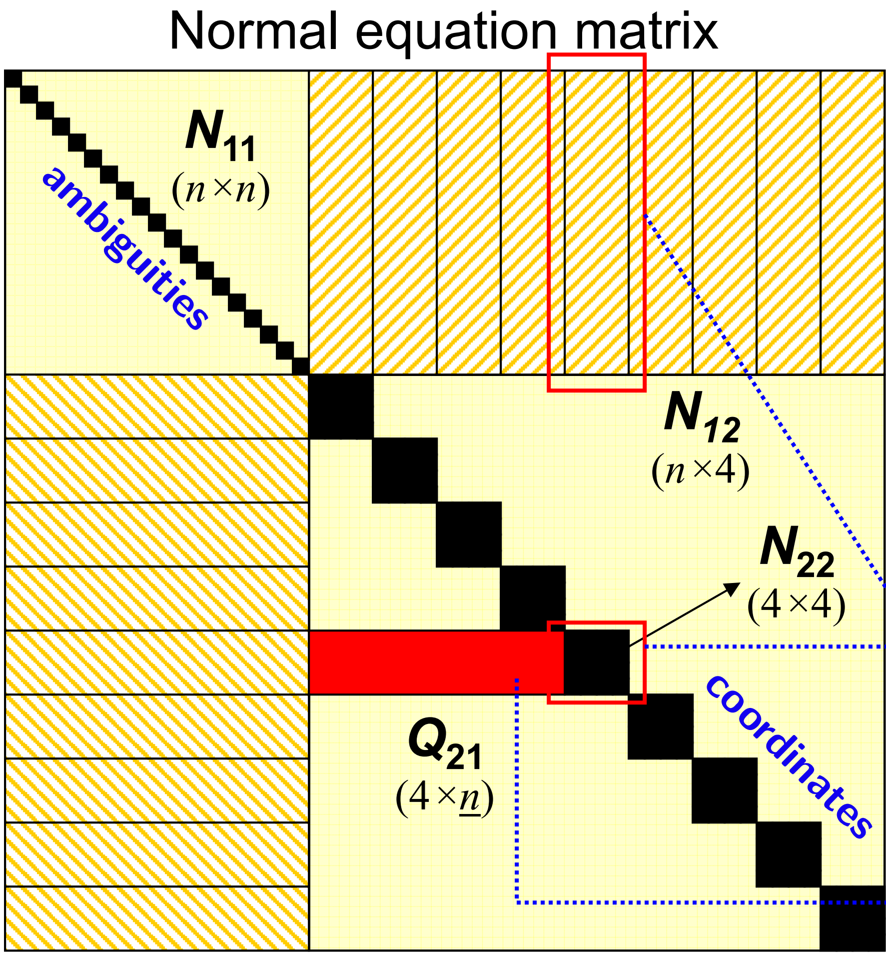
Averaged Acceleration Approach

Point-wise Acceleration Approach

Energy Balance Approach



(Baur et al, 2013)



$$\begin{bmatrix} N_{11} & N_{12} \\ N_{21} & N_{22} \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} b_1 \\ b_2 \end{bmatrix}$$

x_1 = ambiguities

x_2 = epoch-wise kinematic coordinates & clocks

$$\left(N_{11} - N_{12}N_{22}^{-1}N_{21}\right)x_1 = b_1 - N_{12}N_{22}^{-1}b_2$$

back substitution:

$$x_2 = N_{22}^{-1}\left(b_2 - N_{21}\right)x_1$$

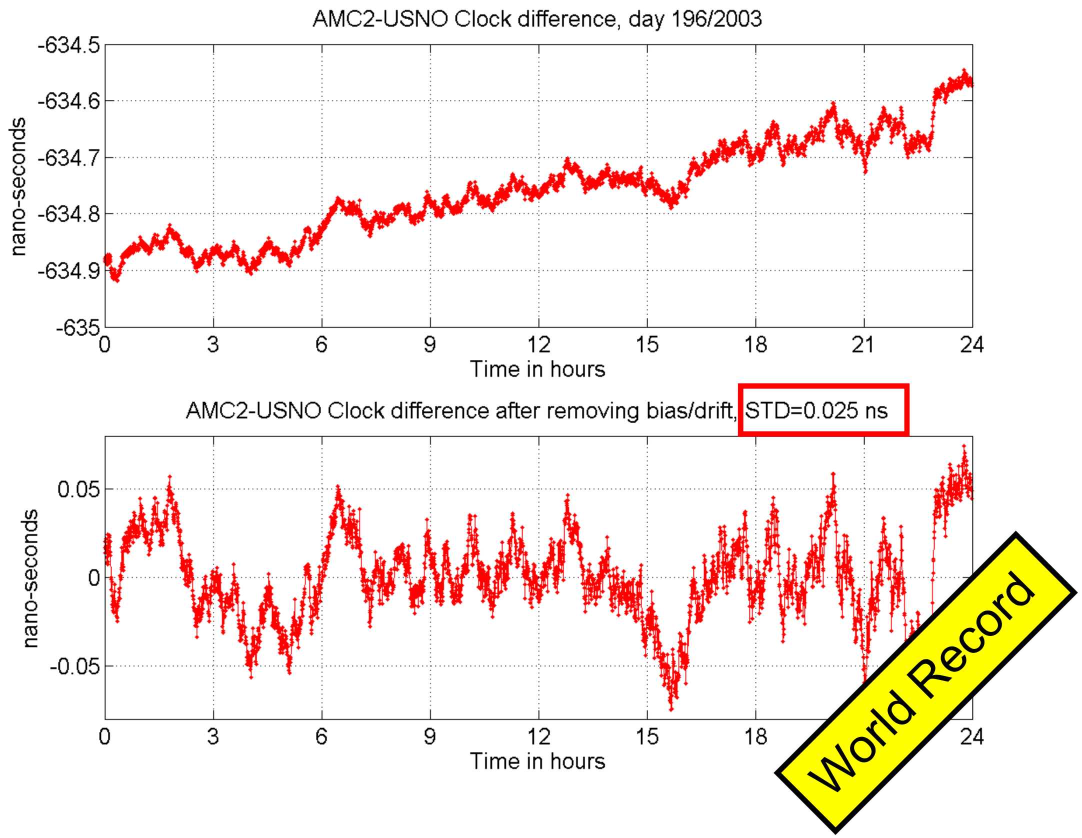
1) $\underset{(4\times4)}{Q_{22}} = \underset{(4\times4)}{N_{22}^{-1}} + N_{22}^{-1}N_{21}\underset{(n\times n)}{Q_{11}}N_{12}N_{22}^{-1}$

2) $\underset{(n\times4)}{Q_{12}} = -Q_{11}N_{12}N_{22}^{-1}$

3) $\underset{(4\times \underline{n})}{Q_{21}} = -\underset{(4\times4)}{N_{22}^{-1}}N_{12}N_{22}^{-1}$

Inter-Kontinentalna Usporedba Frekvencije Pomoću GPS-a
Fazni Parametri Satova Satelita

Colorado Springs (AMC2) – USNO (US Naval Observatory)



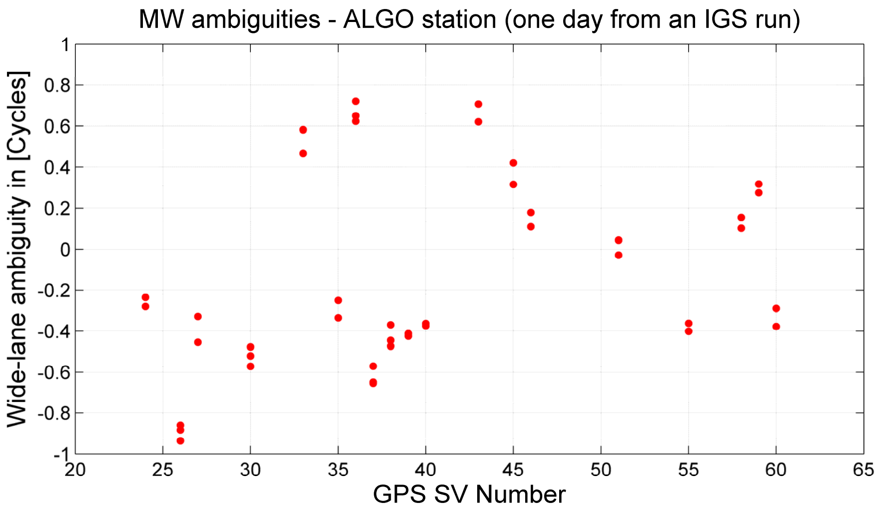
25 ps ≈ 7 mm

Stabilnost GPS prijamnika i H-maser-a

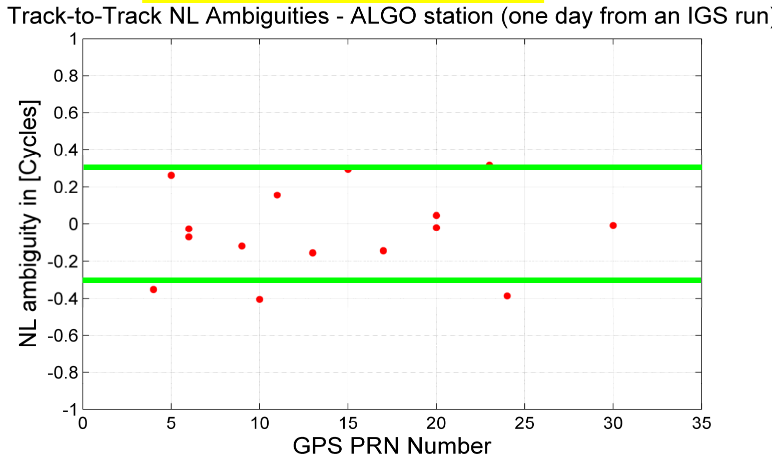
Određivanje Ambiguiteta Pomoću Faznih Parametara Satova

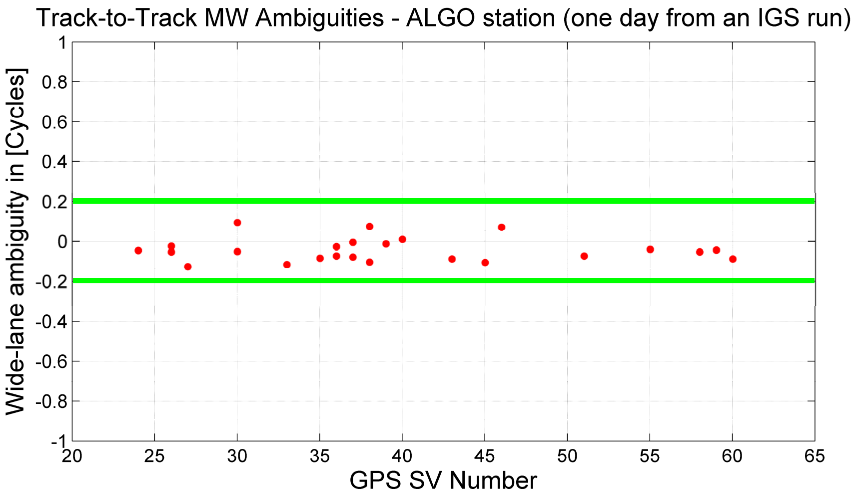
Track-to-Track Ambiguiteti

Wid-Lane Ambiguity

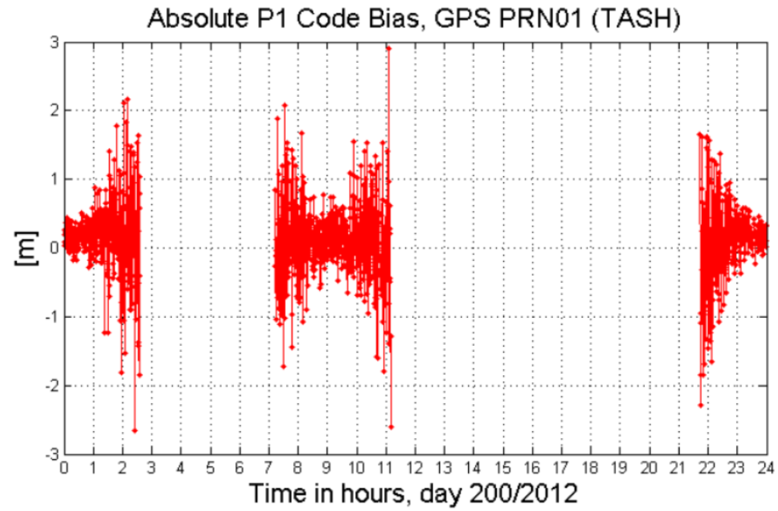


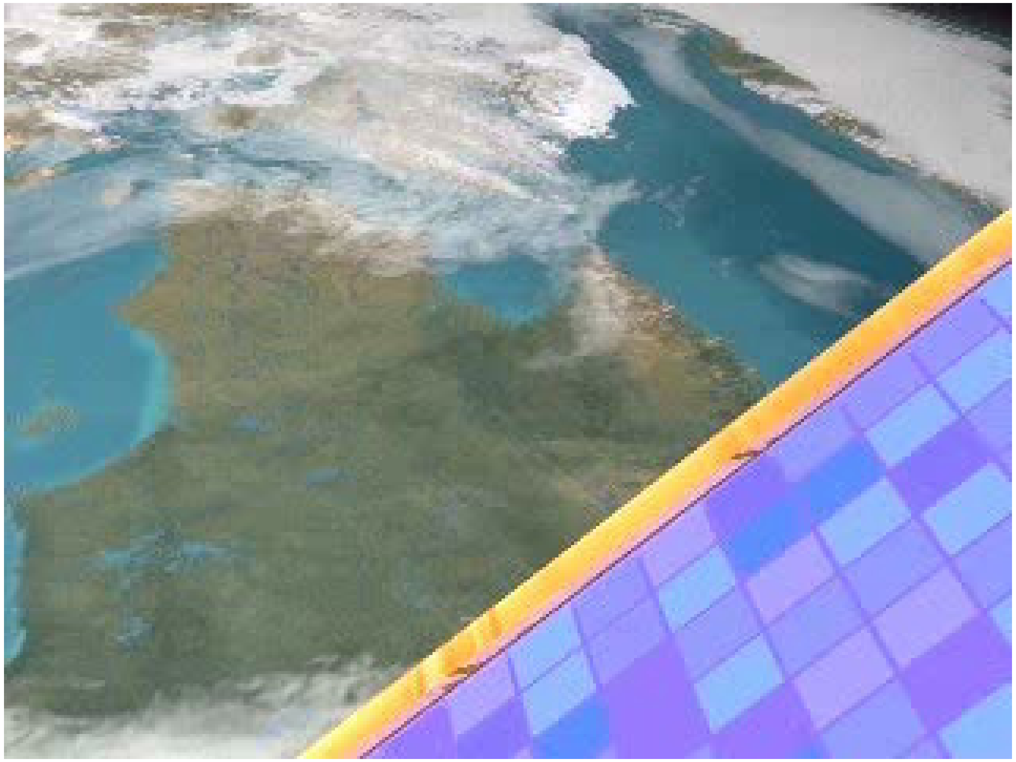
Narrow-Lane Ambiguity



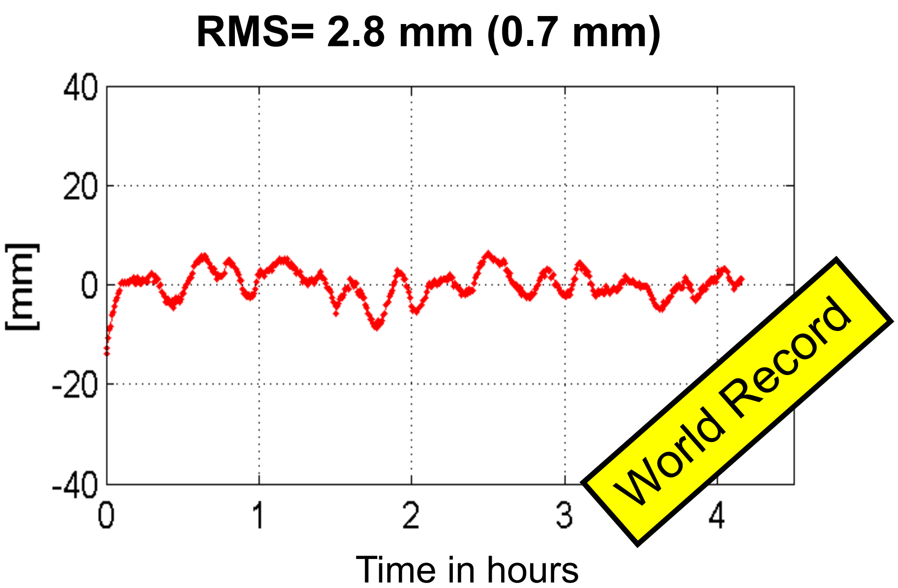


Absolutna Kalibracija Kodnih Mjerenja





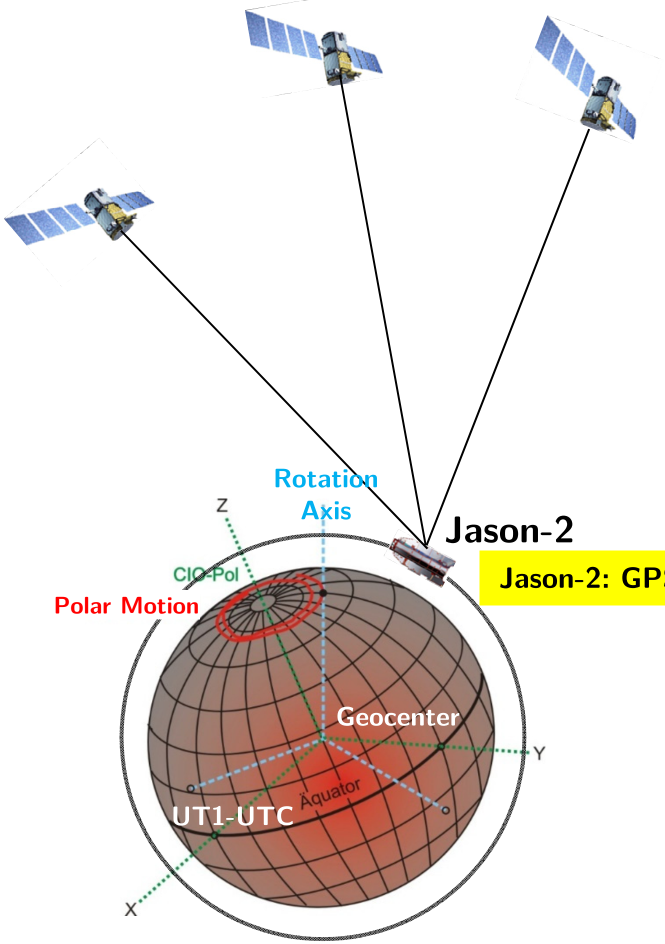
Usporedba sa Faznim Mjerenjima između satelita (K-Band)



(Status 2003-2004)

Terestrički Referentni Sustav Baziran na 30 GPS Satelita + Jason-2 (GPS, SLR, DORIS)

Konstelacija 30 GPS Satelita



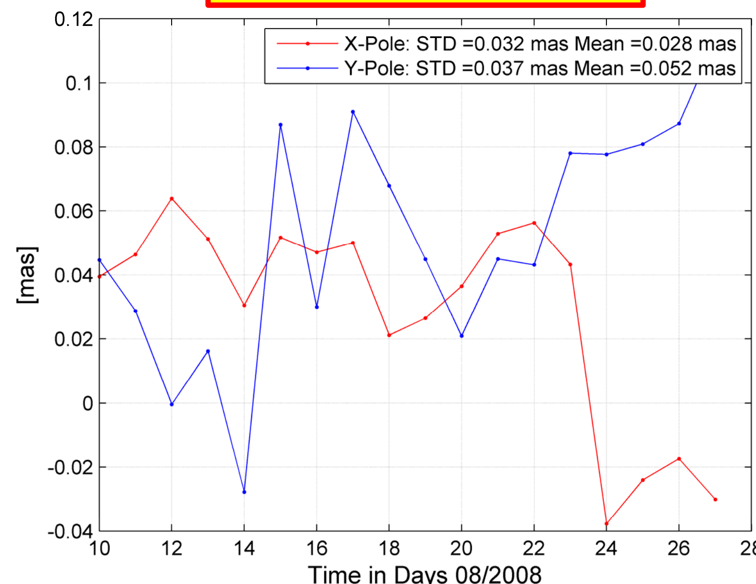
Jason-2: GPS+SLR+DORIS

Kordinate Geocentra

Weekly Geocenter Coordinates

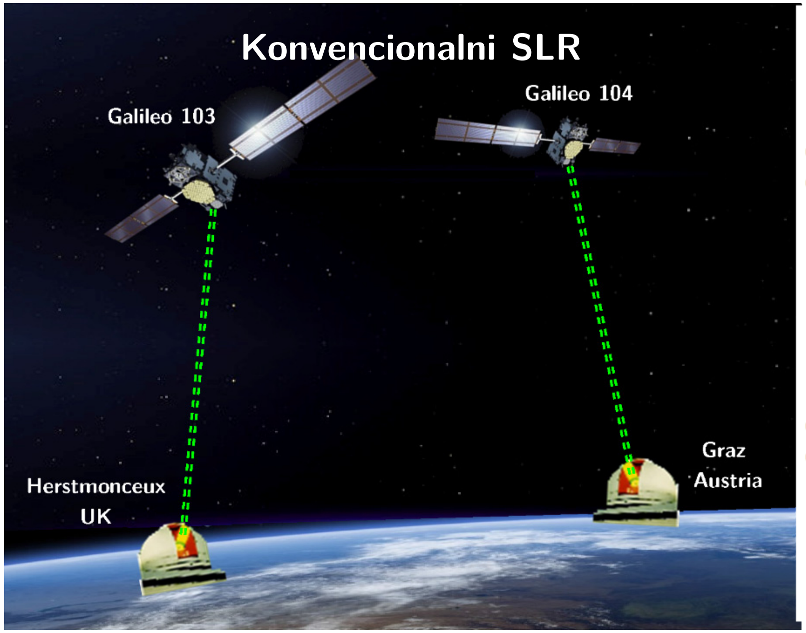
Week 1	Week 2	Week 3
dx = -0.83 mm	dx = -1.78 mm	dx = -1.72 mm
dy = -0.94 mm	dy = -1.67 mm	dy = -1.22 mm
dz = -5.90 mm	**dz = -5.75 mm**	**dz = -5.60 mm**
rx = 0.021 mas	rx = 0.067 mas	rx = 0.059 mas
ry = 0.052 mas	ry = 0.055 mas	ry = -0.011 mas
rz = -0.051 mas	rz = -0.077 mas	rz = -0.051 mas
scale = 0.13 ppb	scale = 0.14 ppb	scale = 0.16 ppb

Polar Motion

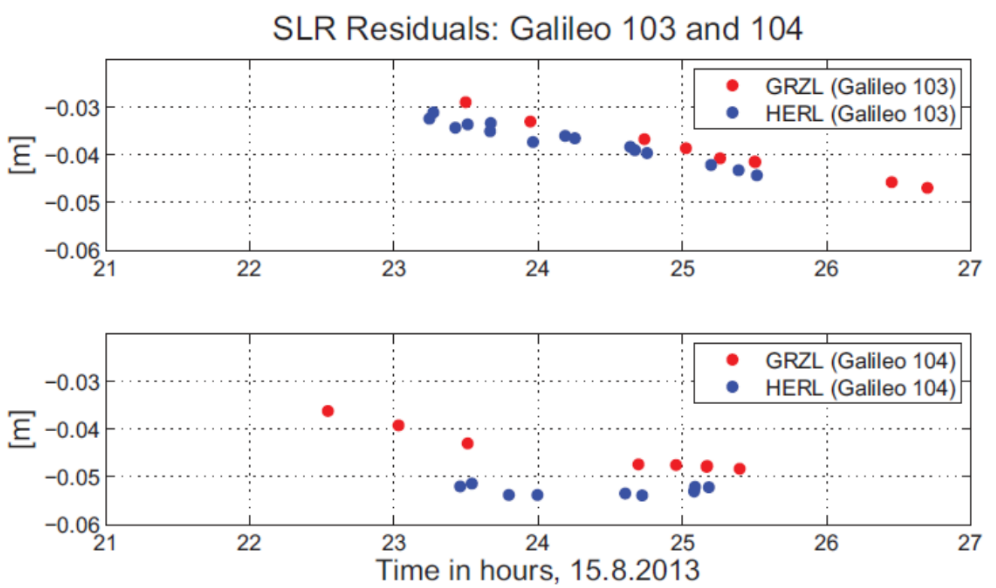


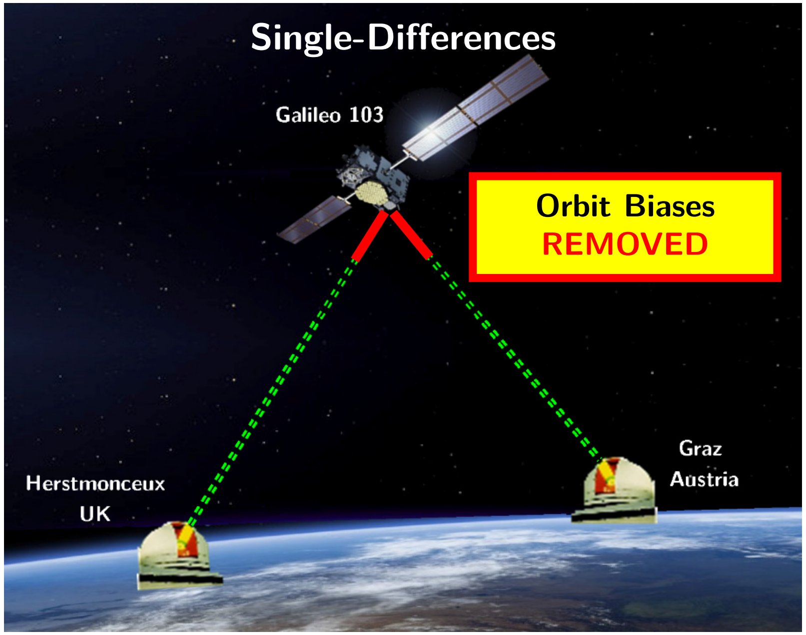
Global Geodetic Observing System (GGOS):
CILJ: 1 mm točnost, 0.1 mm/yr stabilnost

Prva SLR Bazisna Linija

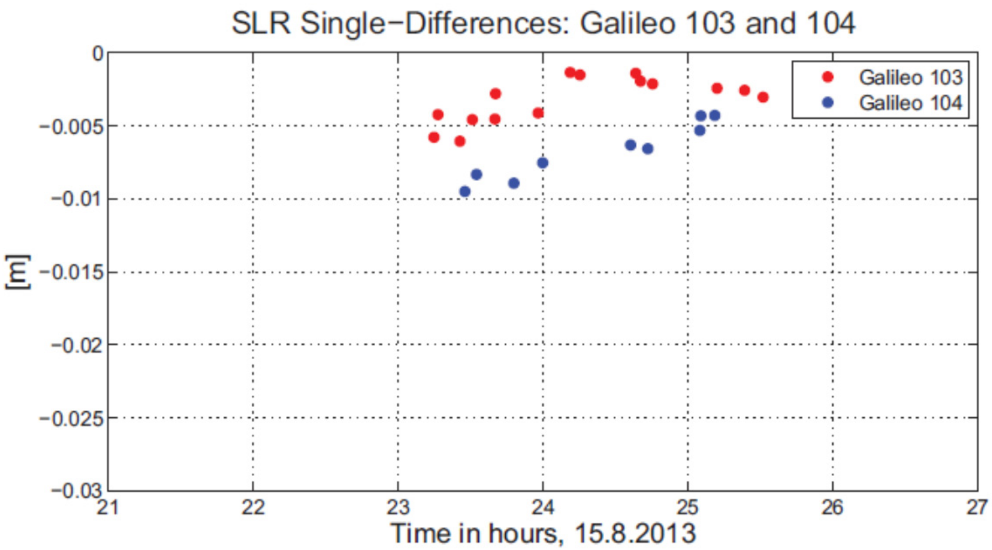


Konvencionalni SLR



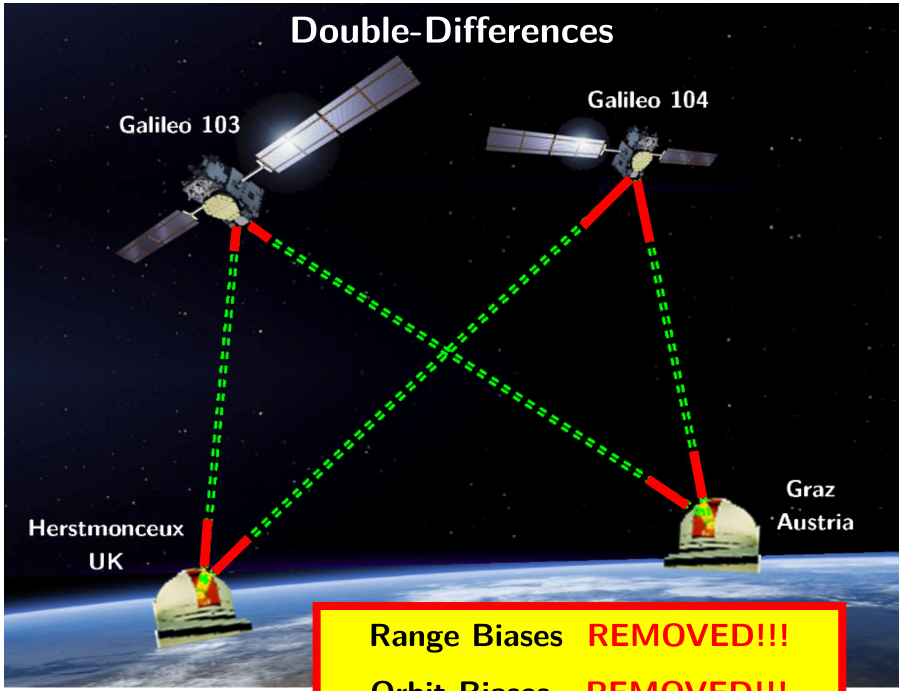


Single-Difference SLR



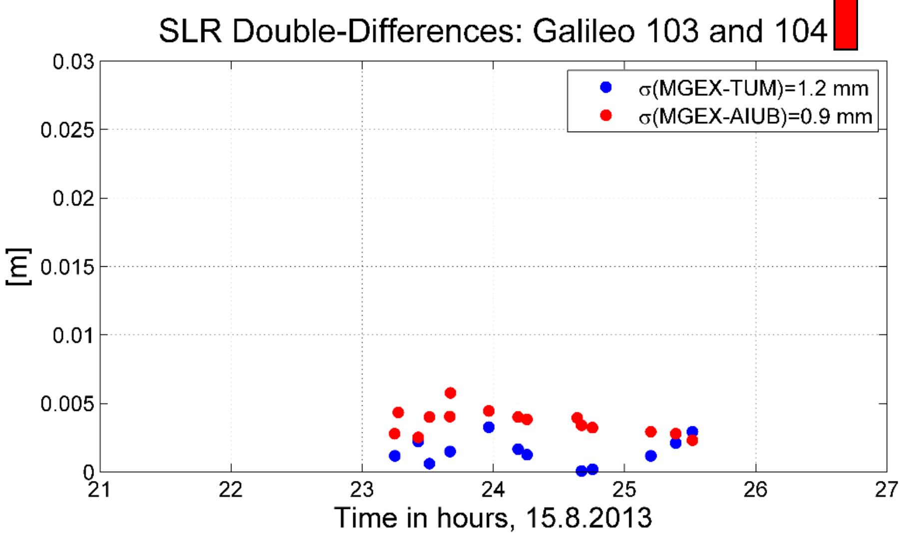
Prva SLR Bazisna Linija

RMS= 0.5 - 0.6 mm



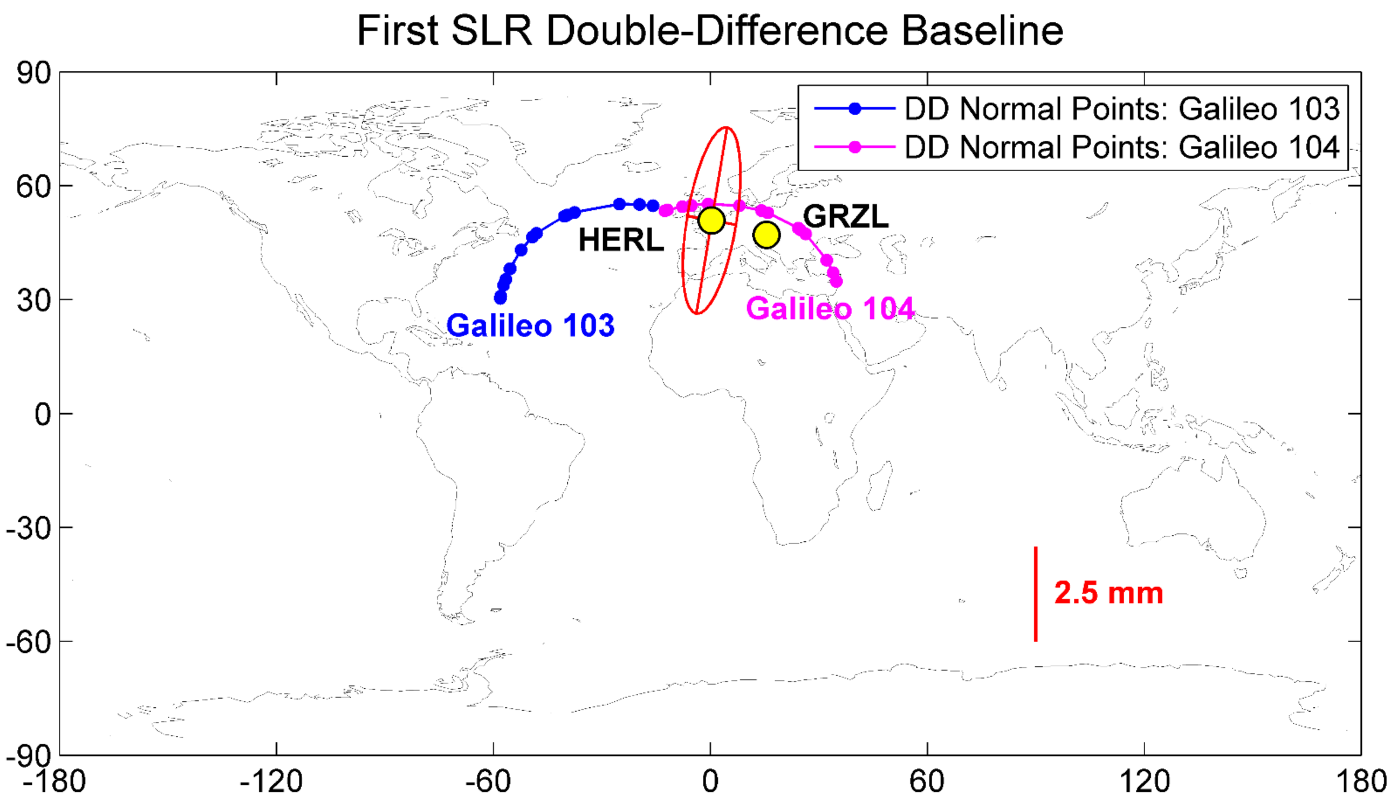
Range Biases REMOVED!!!

Orbit Biases REMOVED!!!

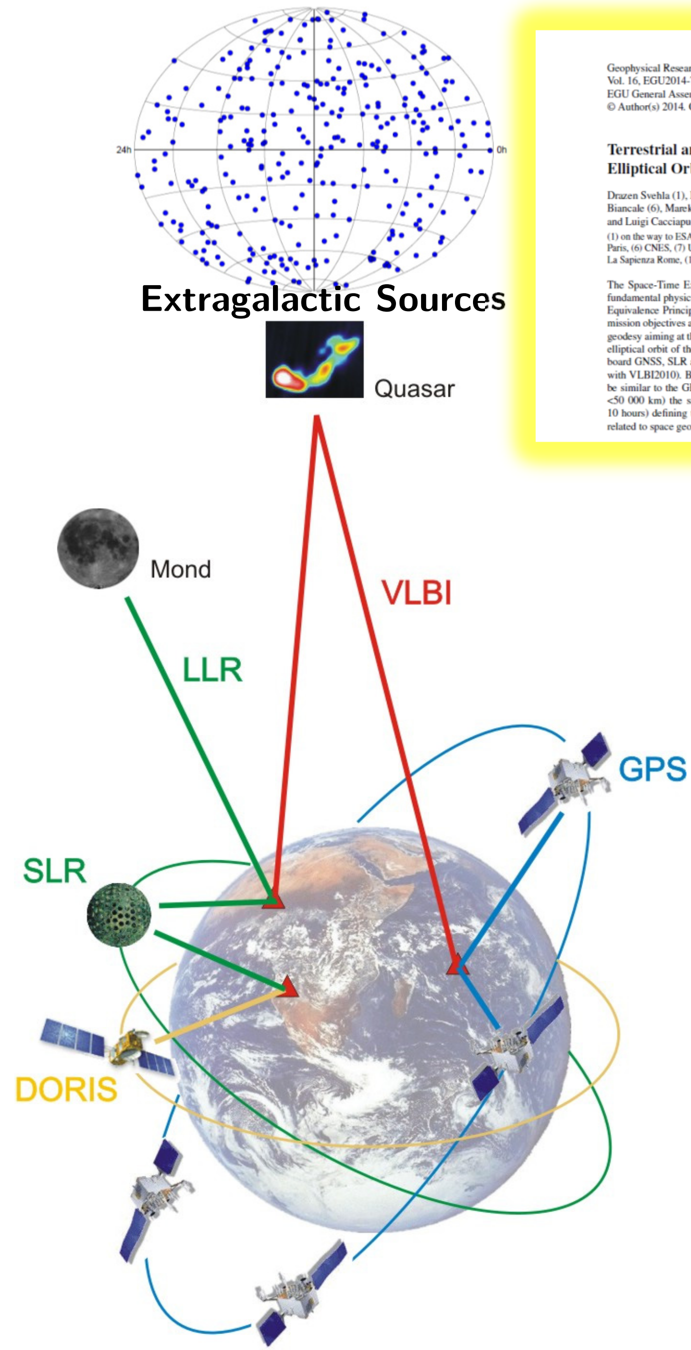


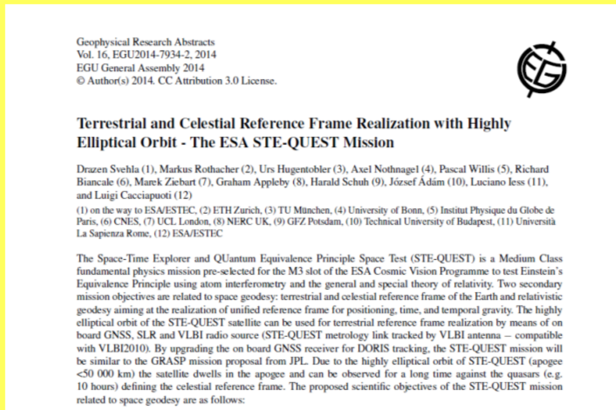
Prva SLR Bazisna Linija: Elipsa Pogrešaka

Estimated coordinates of HERL in (mm) using SLR double-differences from GRZL	
MGEX-TUM Orbits $\sigma_0 = \pm 1.2$ mm	MGEX-AIUB Orbits $\sigma_0 = \pm 0.7$ mm
N=1.2±2.5 E=2.1±0.8	N=4.2±7.2 E=8.1±2.4



Terrestrial and Celestial Reference Frame





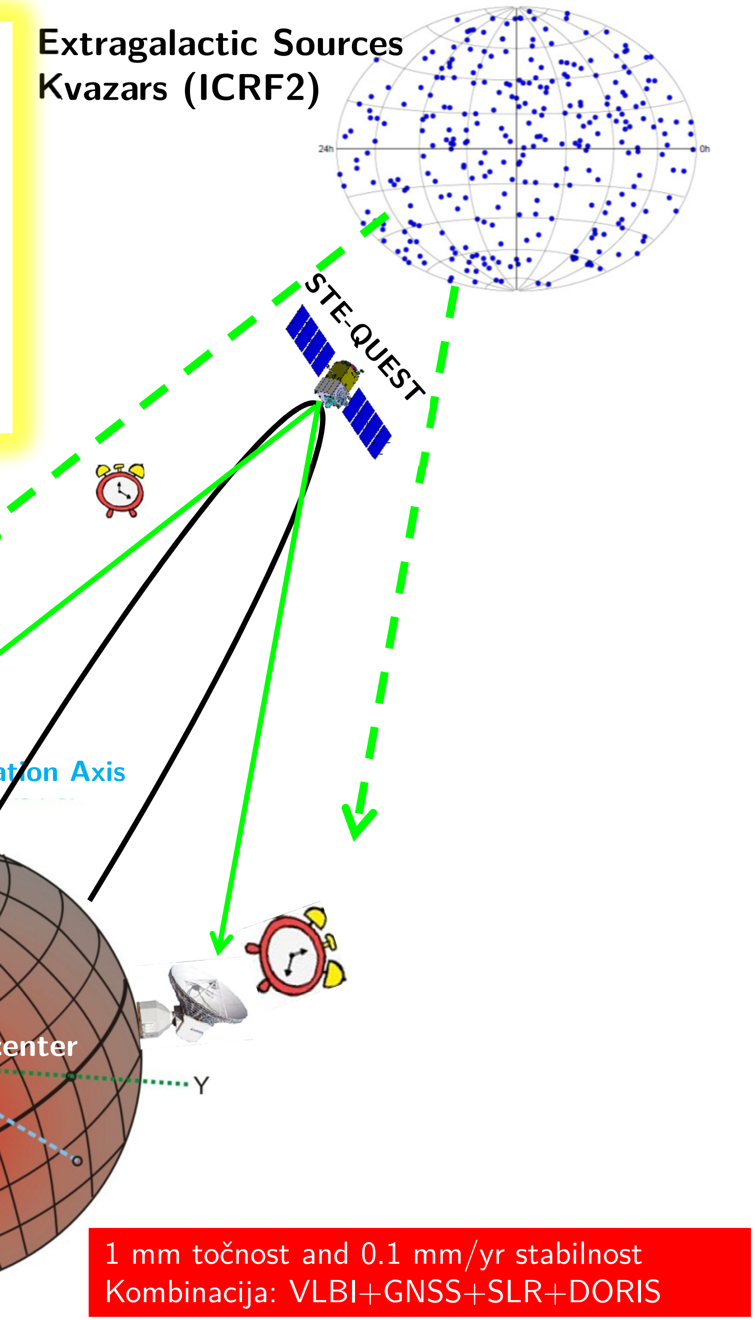
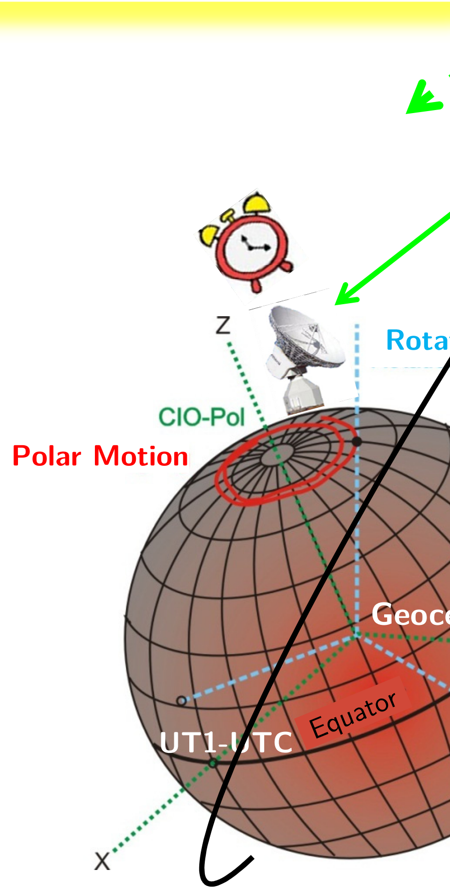
Geophysical Research Abstracts
Vol. 16, EGU2014-7934-2, 2014
EGU General Assembly 2014

Terrestrial and Celestial Reference Frame Realization with Highly Elliptical Orbit - The ESA STE-QUEST Mission

Drazen Svehla (1), Markus Rothacher (2), Urs Hugentobler (3), Axel Nothnagel (4), Pascal Willis (5), Richard Biancale (6), Marek Ziebart (7), Graham Appleby (8), Harald Schuh (9), József Ádám (10), Luciano Iess (11), and Luigi Cacciapuoti (12)

(1) on the way to ESA/ESTEC, (2) ETH Zurich, (3) TU München, (4) University of Bonn, (5) Institut Physique du Globe de Paris, (6) CNES, (7) UCL London, (8) NERC UK, (9) GFZ Potsdam, (10) Technical University of Budapest, (11) Università La Sapienza Rome, (12) ESA/ESTEC

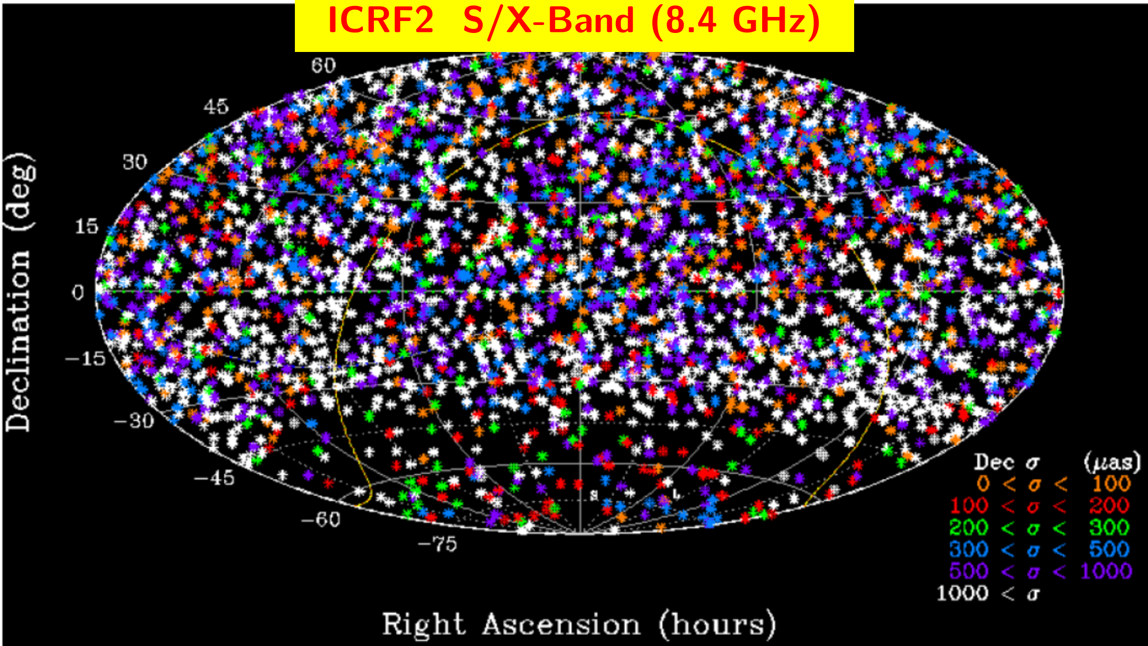
The Space-Time Explorer and QUantum Equivalence Principle Space Test (STE-QUEST) is a Medium Class fundamental physics mission pre-selected for the M3 slot of the ESA Cosmic Vision Programme to test Einstein's Equivalence Principle using atom interferometry and the general and special theory of relativity. Two secondary mission objectives are related to space geodesy: terrestrial and celestial reference frame of the Earth and relativistic geodesy aiming at the realization of unified reference frame for positioning, time, and temporal gravity. The highly elliptical orbit of the STE-QUEST satellite can be used for terrestrial reference frame realization by means of on board GNSS, SLR and VLBI radio source (STE-QUEST metrology link tracked by VLBI antenna – compatible with VLBI2010). By upgrading the on board GNSS receiver for DORIS tracking, the STE-QUEST mission will be similar to the GRASP mission proposal from JPL. Due to the highly elliptical orbit of STE-QUEST (apogee <50 000 km) the satellite dwells in the apogee and can be observed for a long time against the quasars (e.g. 10 hours) defining the celestial reference frame. The proposed scientific objectives of the STE-QUEST mission related to space geodesy are as follows:

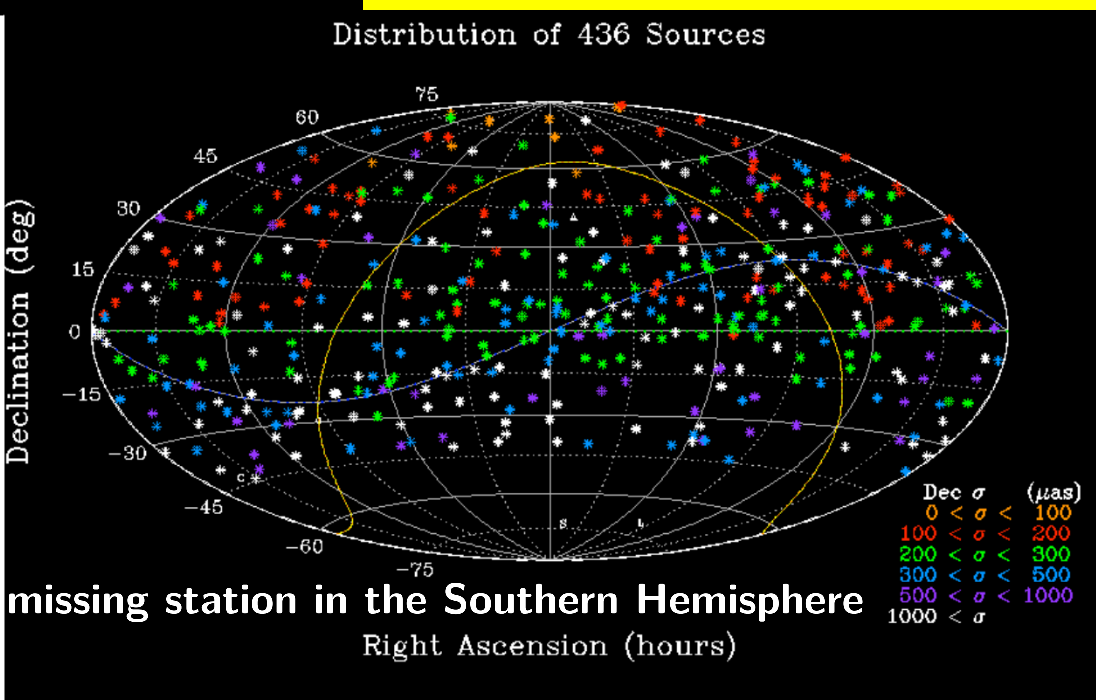
1 mm točnost and 0.1 mm/yr stabilnost
Kombinacija: VLBI+GNSS+SLR+DORIS

Nebeski Referentni Koordinatni Sustav

ICRF2 S/X-Band (8.4 GHz)



ICRF at X/Ka-Band (32 GHz)
469 Sources

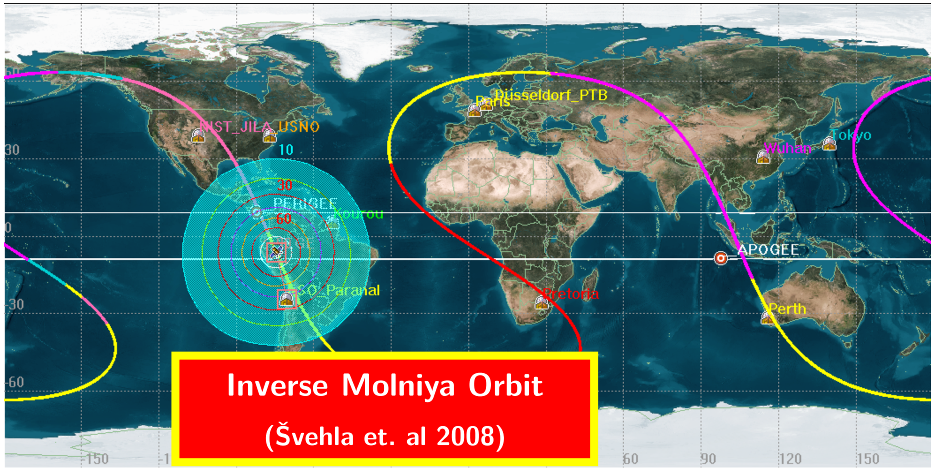


ICRF2 S/X-Band

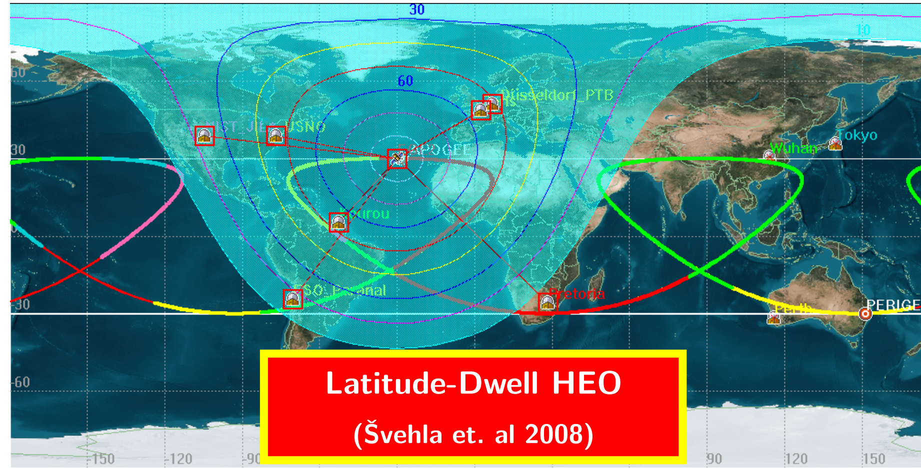
\# defining sources: 295
\# total sources: 3414 (3119 compact sources)
Noise floor: ~ 40 μas, 5-6× better than ICRF1
Axis stability: ~ 10 μas, 2× better than ICRF1
(IERS Conventions 2010)

(used sampling rate 112 Mbps at X/Ka-Band)

Orbit Design: Space-Time Explorer (STE-QUEST Misija)



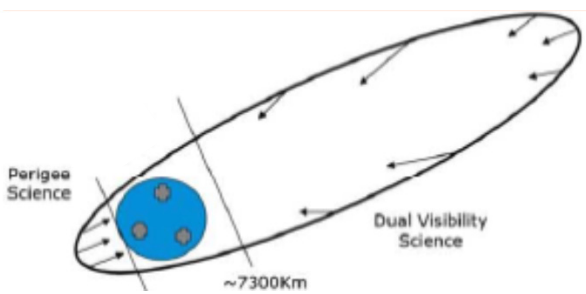
Inverse Molniya Orbit
(Švehla et. al 2008)

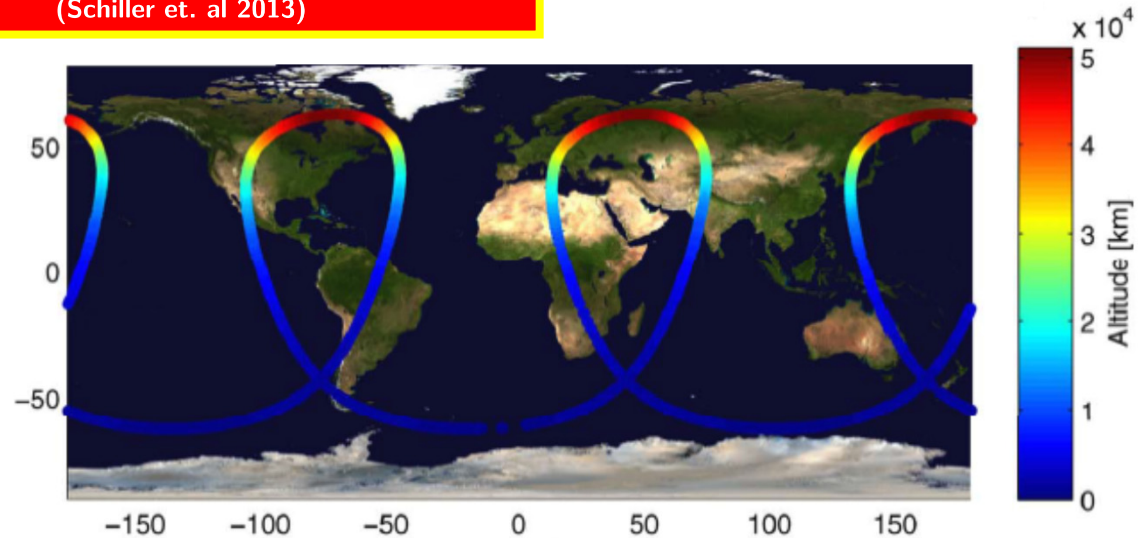


Latitude-Dwell HEO
(Švehla et. al 2008)

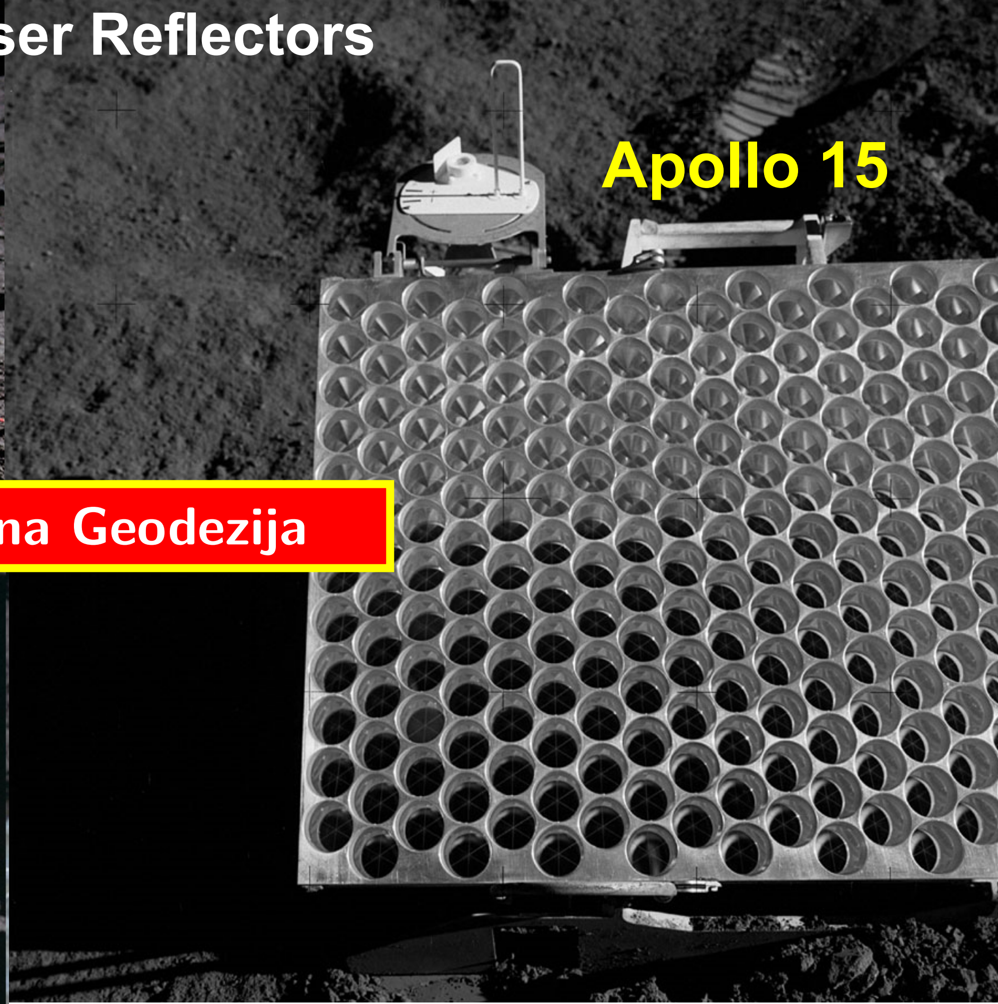
Finalbi Orbit Design (Latitude-Dwell HEO)
(Schiller et. al 2013)

Apogee: **30-50 000 km**
Perigee: **1500-2200 km**





Lunar Laser Reflectors



Planetarna Geodezija

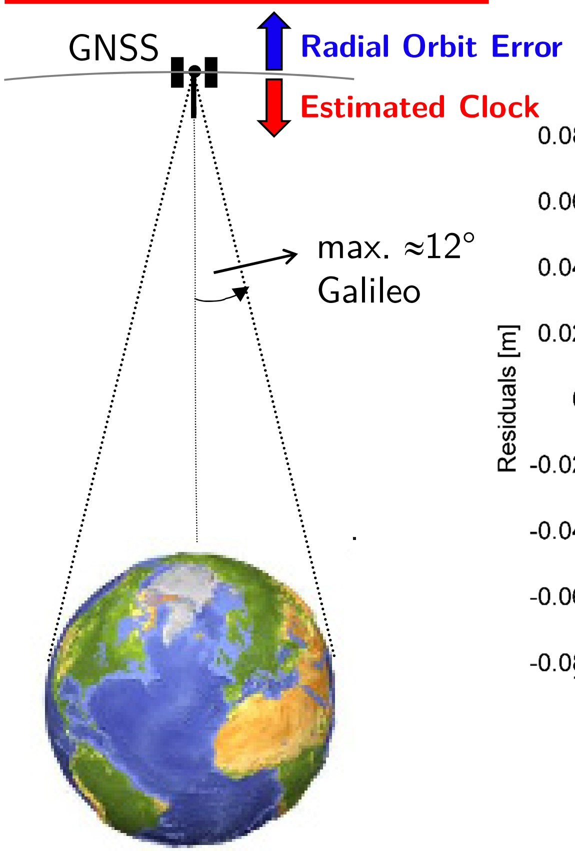
Open Reflector

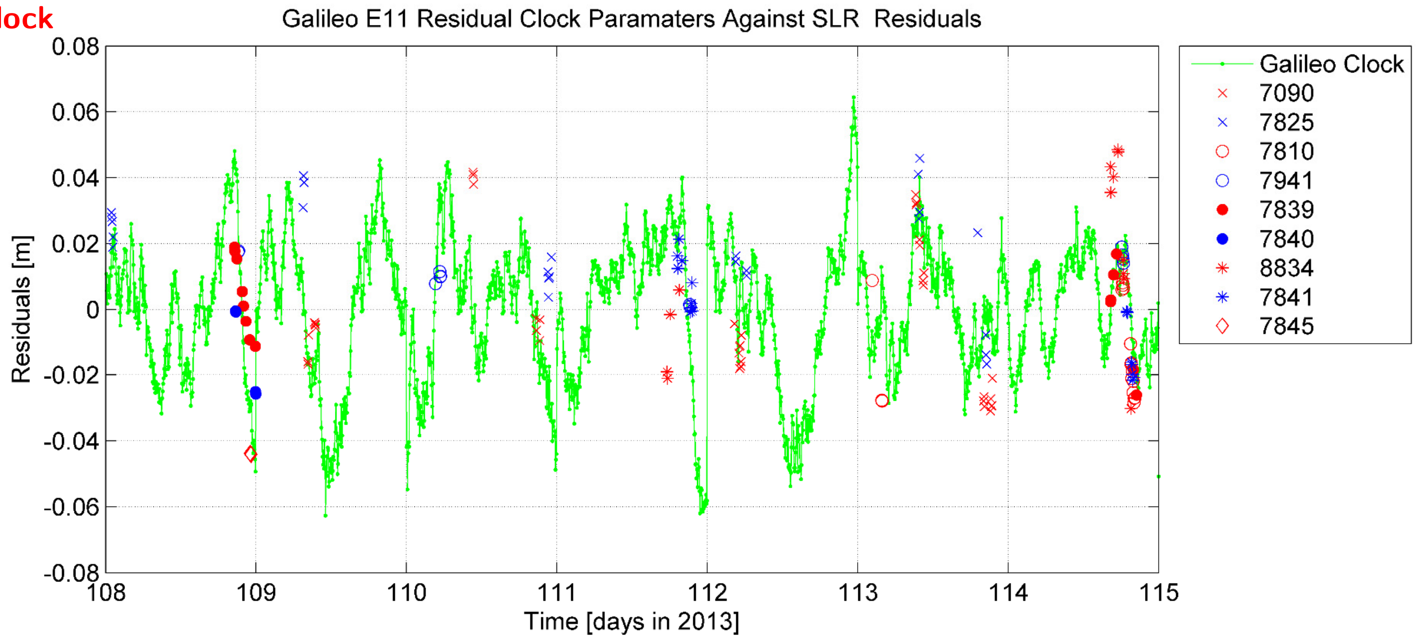
Galileo Rezidualni Parametri Satova Satelita Nakon J_2-Relativističke Korekcije

Ekvivalencija između Orbite i Sata:

Sat = − Radijalna Pogreška

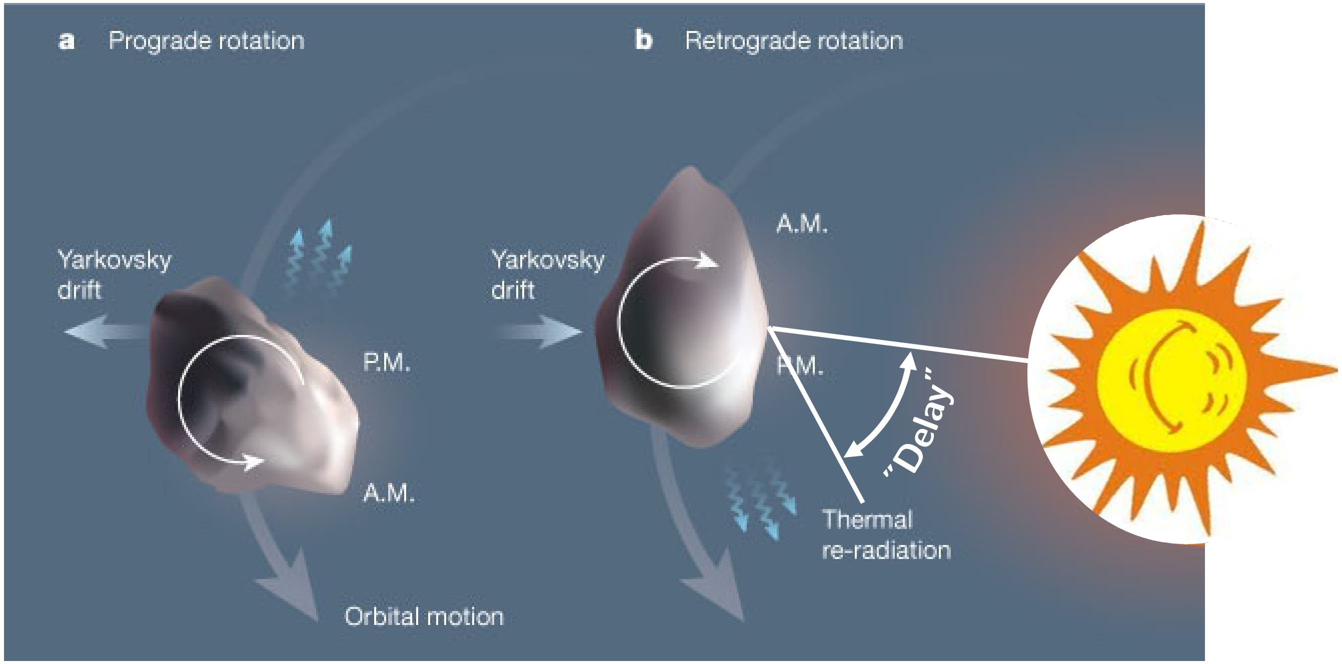
Galileo H-maser precizniji nego SLR!





Simulated Galileo H-Maser (mm)									
N	0.2 h	0.25 h	0.5 h	1.0 h	1.5 h	6 h	12 h	14 h	24 h
1	1.2	1.4	2.0	2.7	3.4	6.8	9.3	11.2	15.5
2	1.0	1.1	1.5	2.2	2.7	5.7	7.7	8.8	10.3
3	0.8	0.9	1.3	1.9	2.3	4.7	6.5	7.8	9.8
4	0.7	0.8	1.2	1.7	2.1	4.3	5.8	6.6	8.7
5	0.8	0.9	1.1	1.5	1.9	3.8	5.2	5.6	7.8

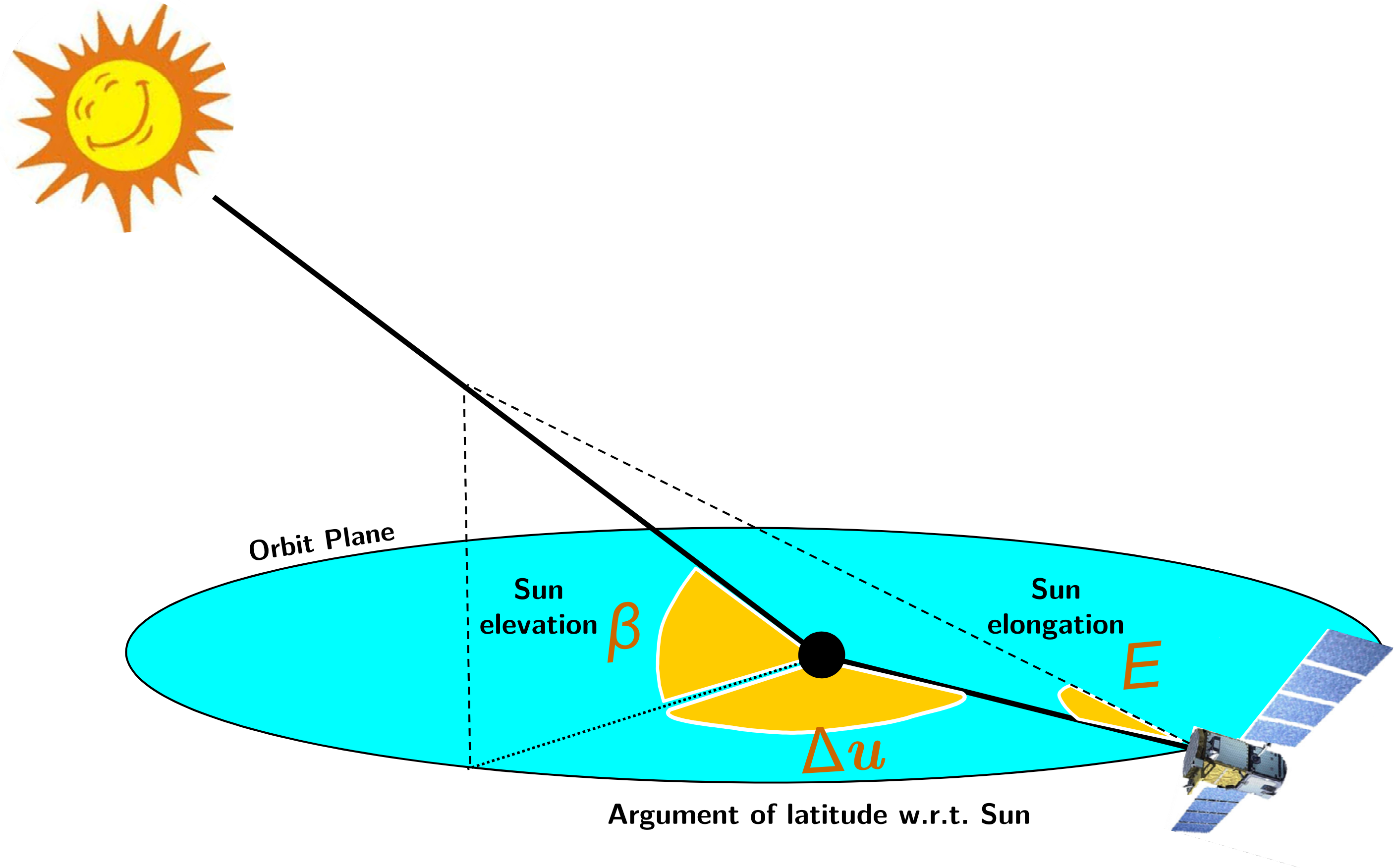
Termalna Inercija Iluminated Galileo Satelita - Yarkovsky Effect



Richard P. Binzel, ***Nature 425***, 131-132 (2003)
doi:10.1038/425131a

"An asteroid is warmed by sunlight and its "afternoon" side becoming hottest.
As a result, that face of the asteroid re-radiates most thermal radiation, creating a recoil force on the asteroid and causing it to drift a little.
The direction of the radiation depends on whether the asteroid is rotating in a prograde (anticlockwise) manner (a) or in a retrograde (clockwise) manner (b)."

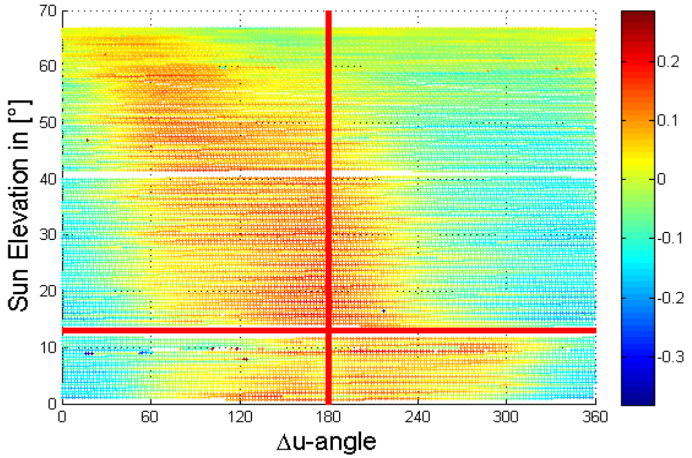
Sun-Fixed Referentni Koordinatni Sustav



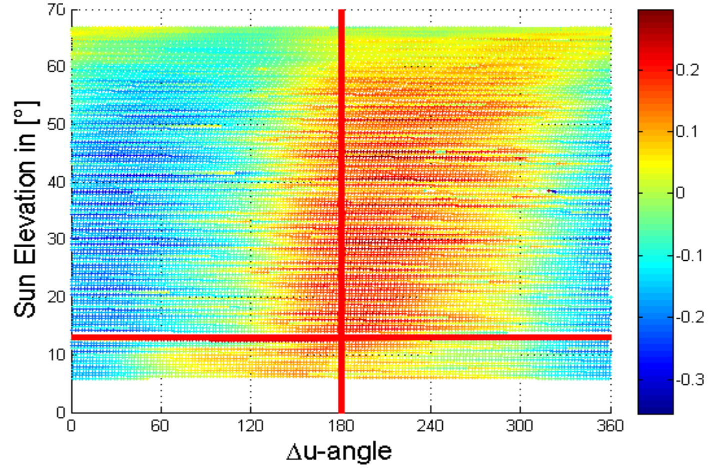
$$\cos E = -\cos\beta \cos\Delta u$$

Sun Elongation Angle

Rising Sun



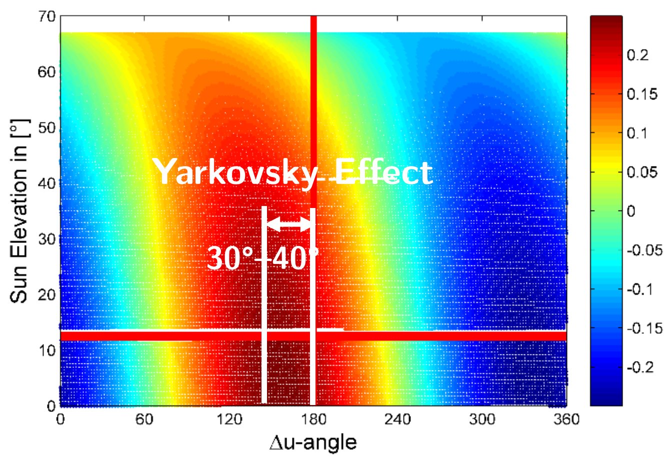
Setting Sun



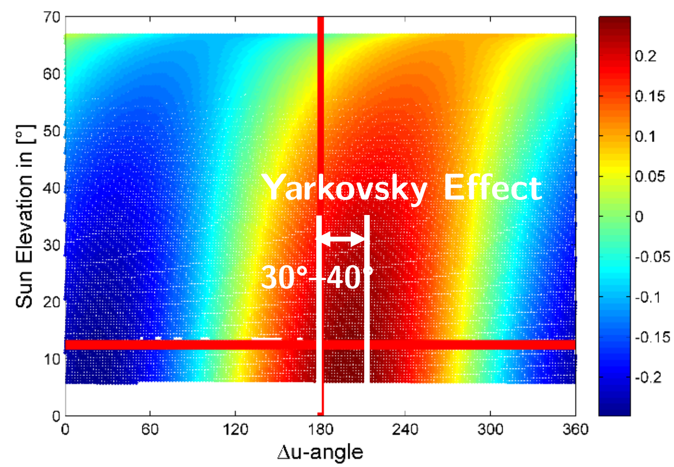
Rising Sun

Setting Sun

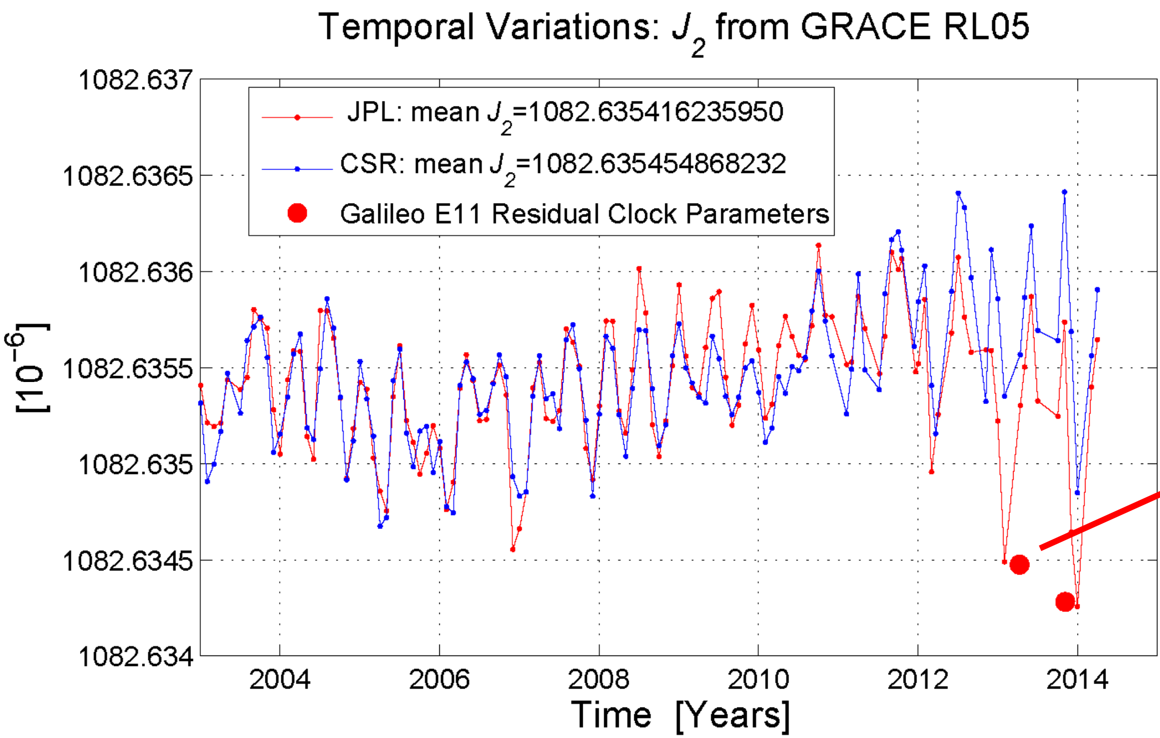
$$\Delta r = -\delta_{CLK} = 0.25 \cos\beta \cos u$$



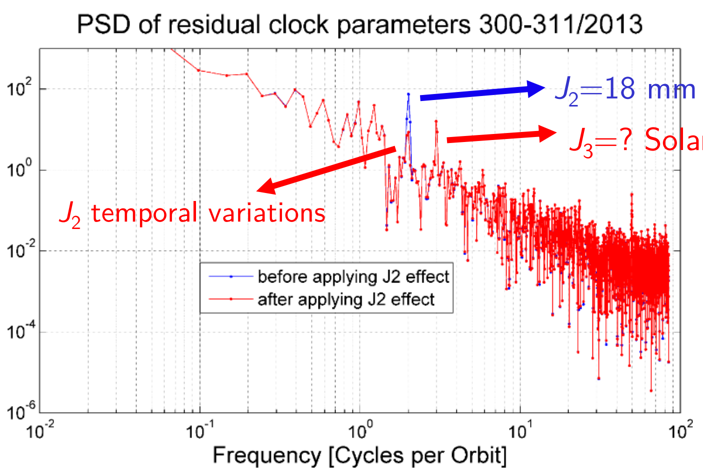
$$\Delta r = -\delta_{CLK} = 0.25 \cos\beta \cos(u - 220°)$$



Galileo H-maser: Određivanje J_2 Koeficijenta Gravitacijskog Polja Zemlje



J_2 prvi geometrijski rezultat baziran na circularnom modelu orbite



J_2=18 mm periodic relativistic effect

J_3=? Solar radiation pressure

$$\Delta t(J_2) = -\frac{3}{2}\frac{a_E^{\,2}}{a^2c^2}J_2\sqrt{\mathrm{GM}a}\cdot\sin^2 i\sin 2u$$

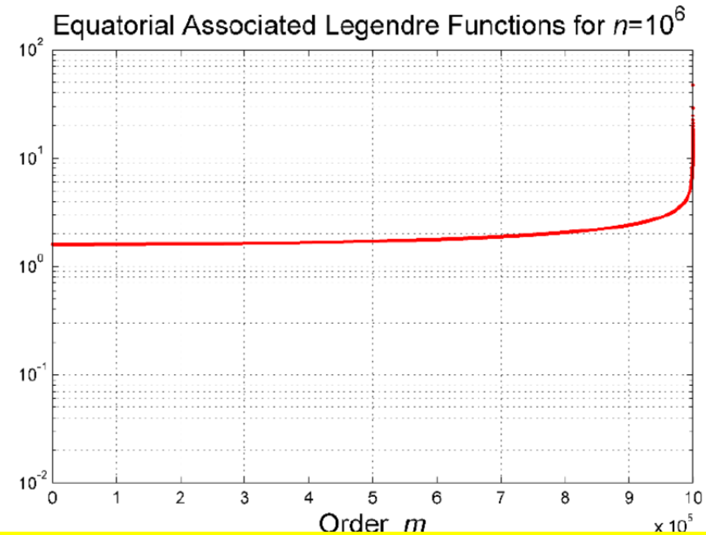
Geometrijska Metoda Računanja Sfernih Harmonika, Vremenskih Promjena Sile Teže i Orbita Satelita

Rotacija Sfernih Harmonika "Ortodroma u hyper-prostoru"

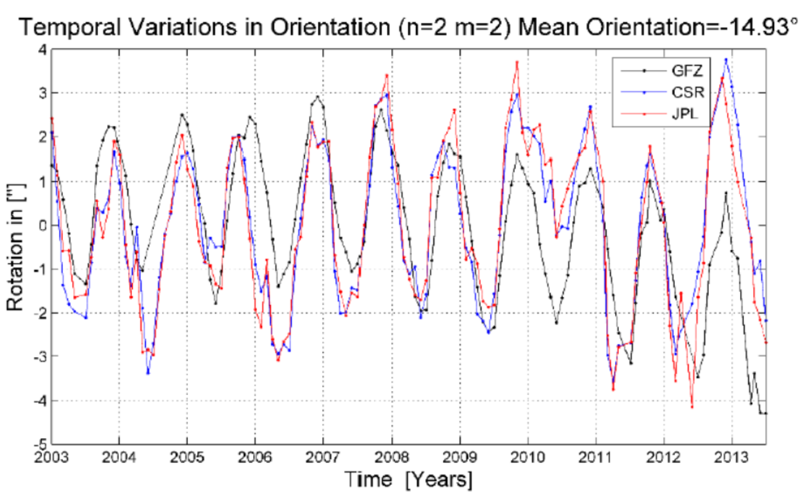
$$\begin{bmatrix} S_{n_{\max}m}(\alpha) \\ \cdots \\ S_{mm}(\alpha) \\ C_{mm}(\alpha) \\ \cdots \\ C_{n_{\max}m}(\alpha) \end{bmatrix} := \begin{bmatrix} S_{n_{\max}m} \\ \cdots \\ S_{mm} \\ C_{mm} \\ \cdots \\ C_{n_{\max}m} \end{bmatrix} \cos m\alpha + \begin{bmatrix} C_{n_{\max}m} \\ \cdots \\ C_{mm} \\ -S_{mm} \\ \cdots \\ -S_{n_{\max}m} \end{bmatrix} \sin m\alpha$$

$$\widehat{\Lambda}_m(\alpha) := \Lambda_m \cos m\alpha + \Lambda_m^* \sin m\alpha$$

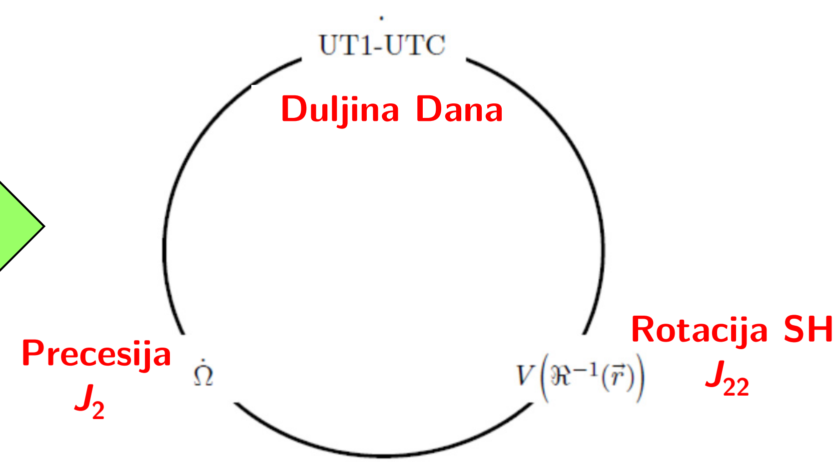
Računanje Sfernih Harmonika u Razvoju do Reda 10^6



Rotacija Tri-Aksijalnog Zemljinog Elipsoida



Ekvivalentnost između Precesije, Duljine Dana i Rotacije Sfernih Harmonika



PUNO HVALA Prof. Nikoli Solarić i Prof. Miljenku Solarić

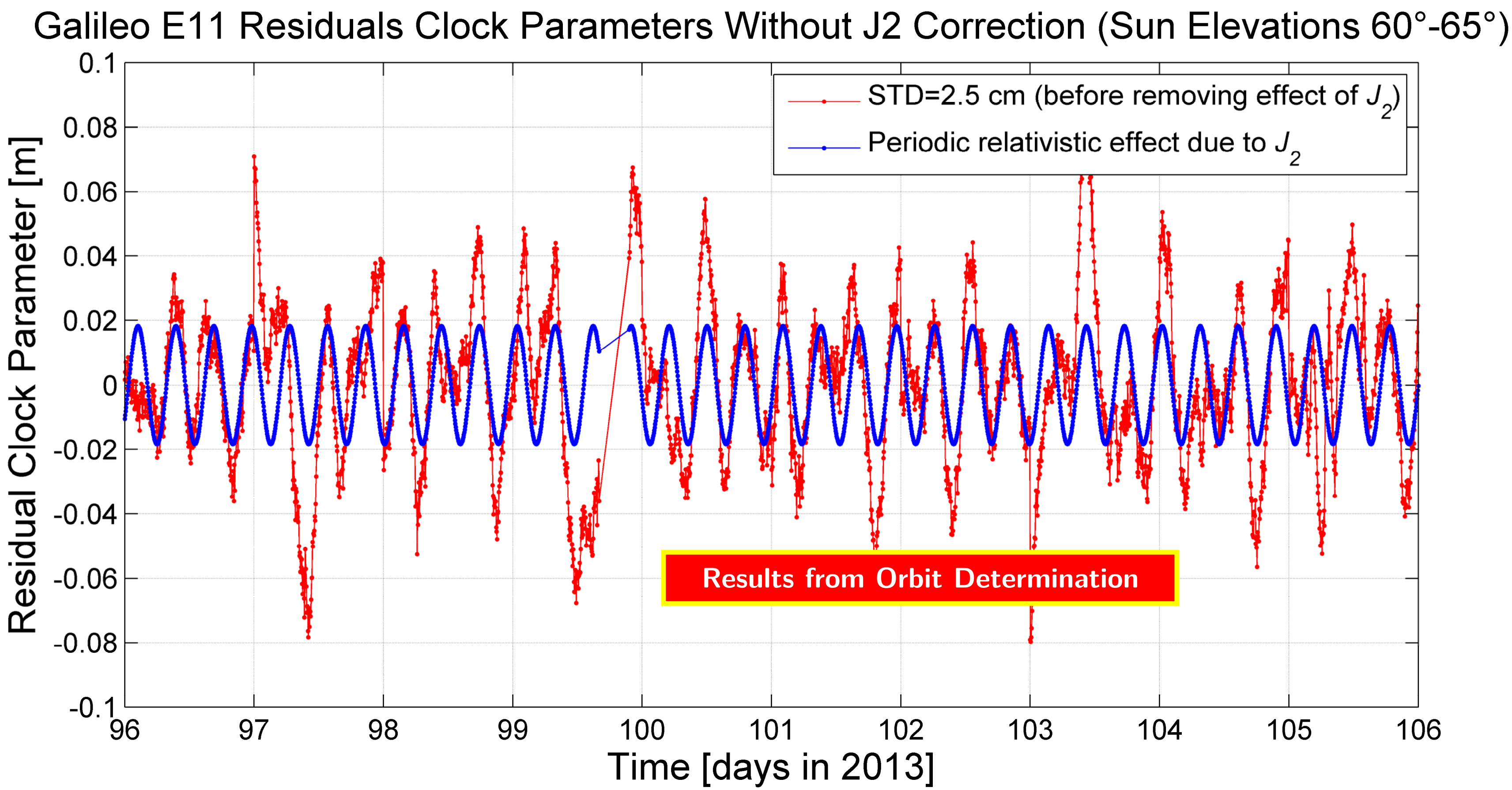
za sve svoje znanje koje su prenijeli generacijama nas studenata!

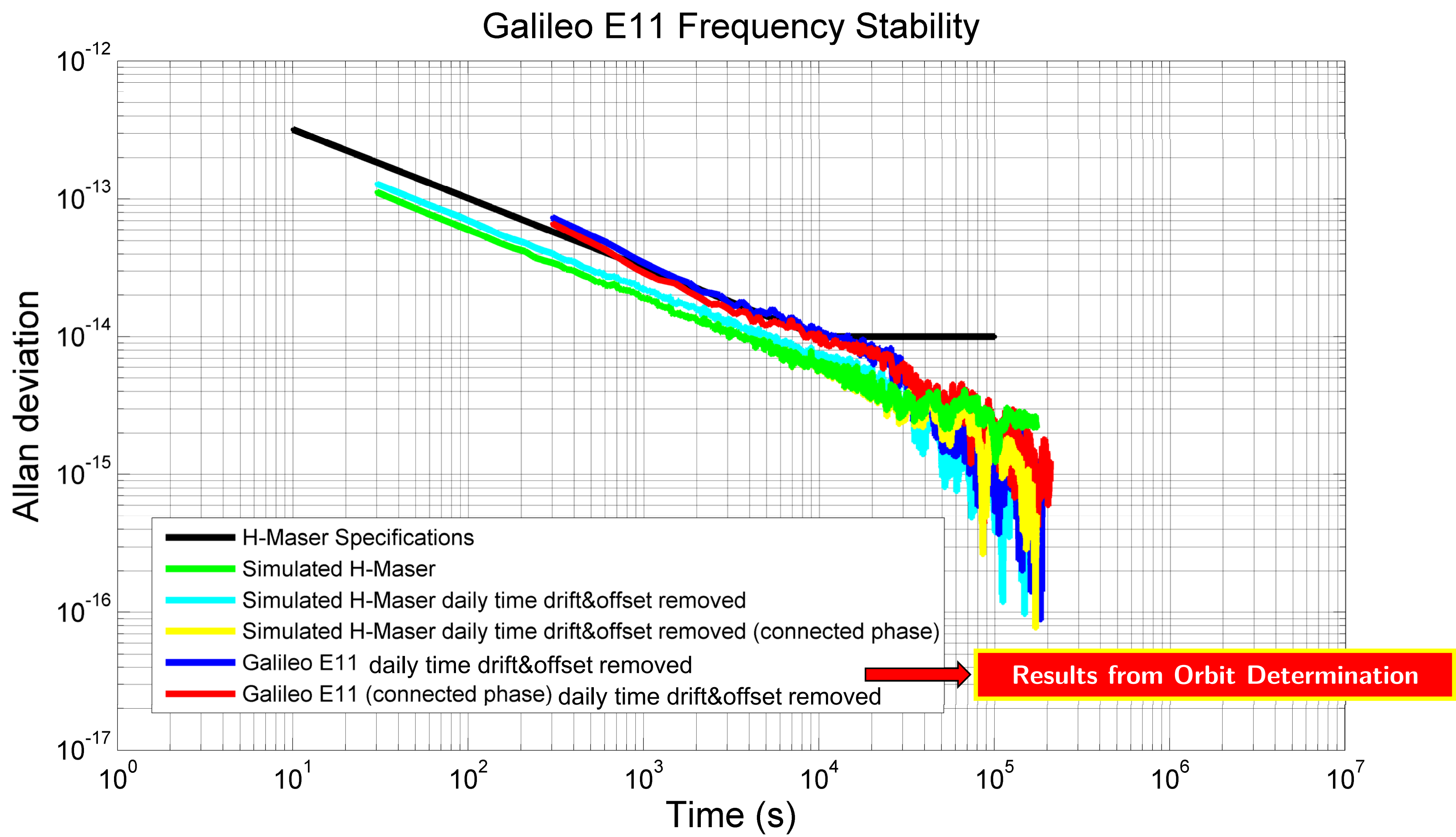
J_2 Periodic Relativistic Effect in the Estimated Galileo Clock Parameters (H-Maser)

$$\Delta t(J_2) = -\frac{3}{2}\frac{a_E^2}{a^2c^2}J_2\sqrt{\mathrm{GM}a}\cdot\sin^2 i\sin 2u$$

Galileo residual clock parameters (Clock Phase) estimated every 300 s over 10 days

daily time bias and time drift removed





Simulated Galileo H-Maser (mm)									
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5	0.8	0.9	1.1	1.5	1.9	3.8	5.2	5.6	7.8

N=1: daily time bias and drift removed

Galileo J_2 Radial Orbit Amplitude due to Temporal Gravity Variations