Non-Gravitational Forces Acting on Geodetic Satellites

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ETH Zurich, 14.11.2012

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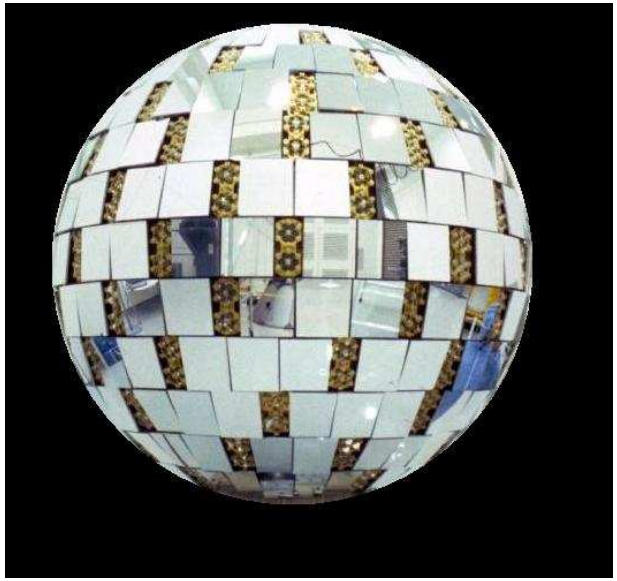
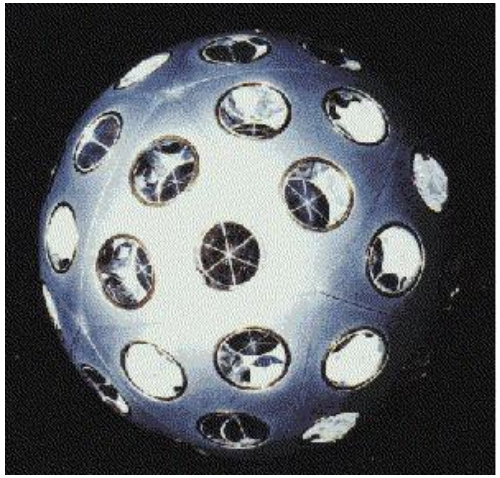
Geodetic satellites

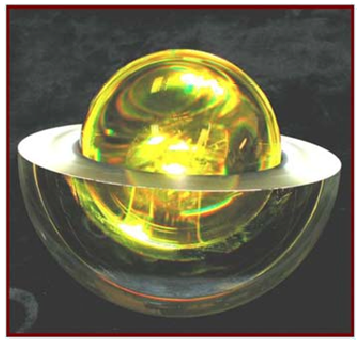
	AJISAI	Starlette	Stella	LAGEOS-1	LAGEOS-2
Diameter [m]	2.15	0.24	0.24	0.60	0.60
Mass [kg]	685	47	48	407	405
Area-to-mass [m^2/kg]	58.0e-4	9.6e-4	9.4e-4	6.9e-4	7.0e-4
Radiation coeff. C_R	1.03	1.134	1.131	1.13	1.13
Semi-major axis [m]	7'866'500	7'334'700	7'176'100	12'274'000	12'158'000
Orbit altitude [m]	1'500'000	800'000 – 110'000	830'000	5'860'000	5'620'000
Eccentricity	0.0016	0.0205	0.0010	0.0039	0.0137
Inclination [deg]	50.04	49.84	98.57	109.90	52.67
Draconitic year [days]	89	73	57	560	222



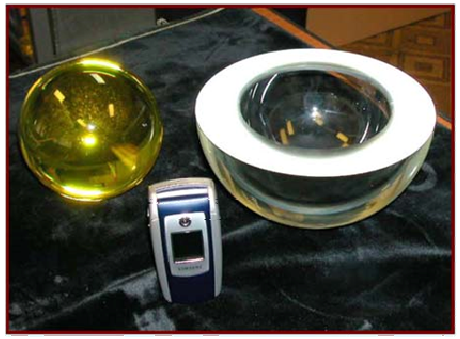


+ Etalon-1/2

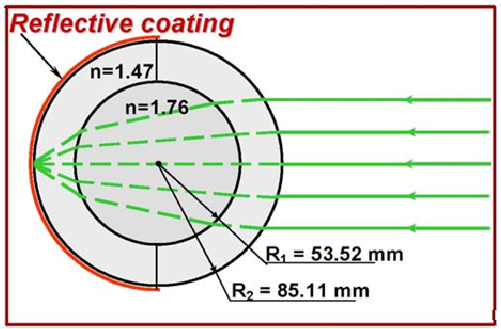
New geodetic satellites

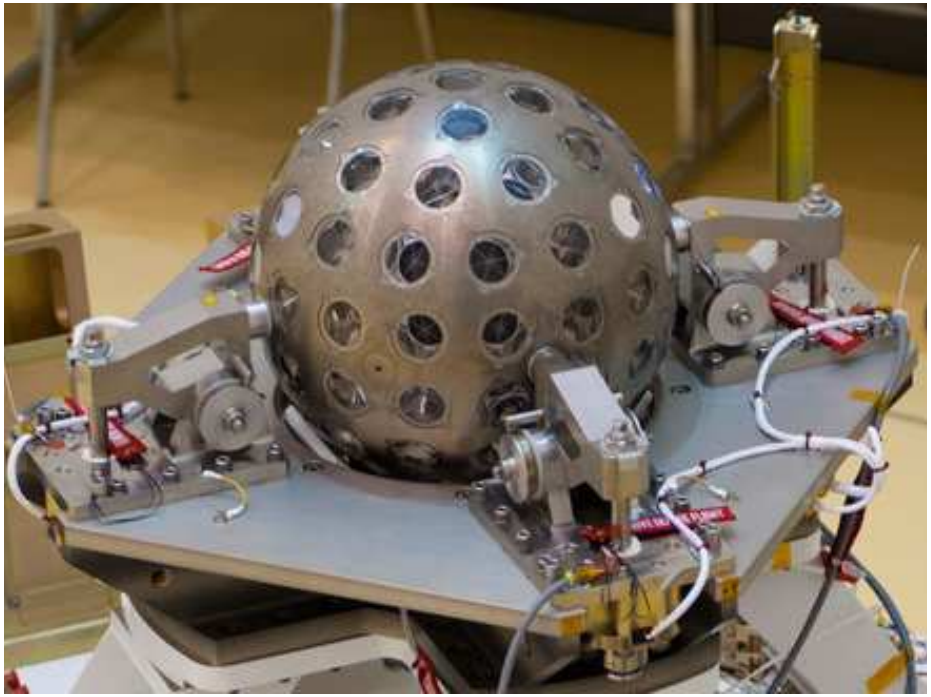


dissembled



Ready for testing





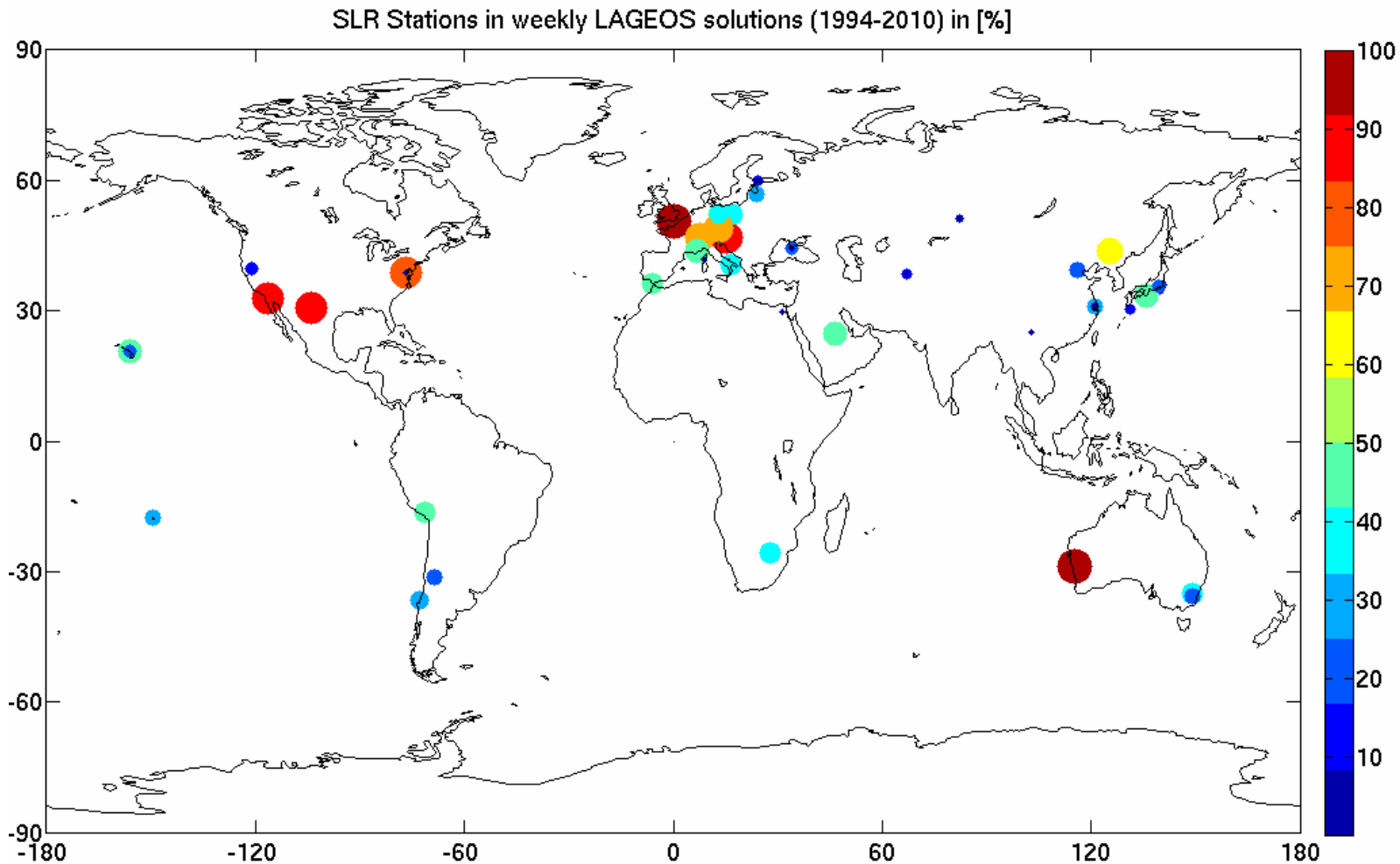
Blits – launched in September 2009

Blits-M to be lauched in 2013

LARES – launched in February 2012

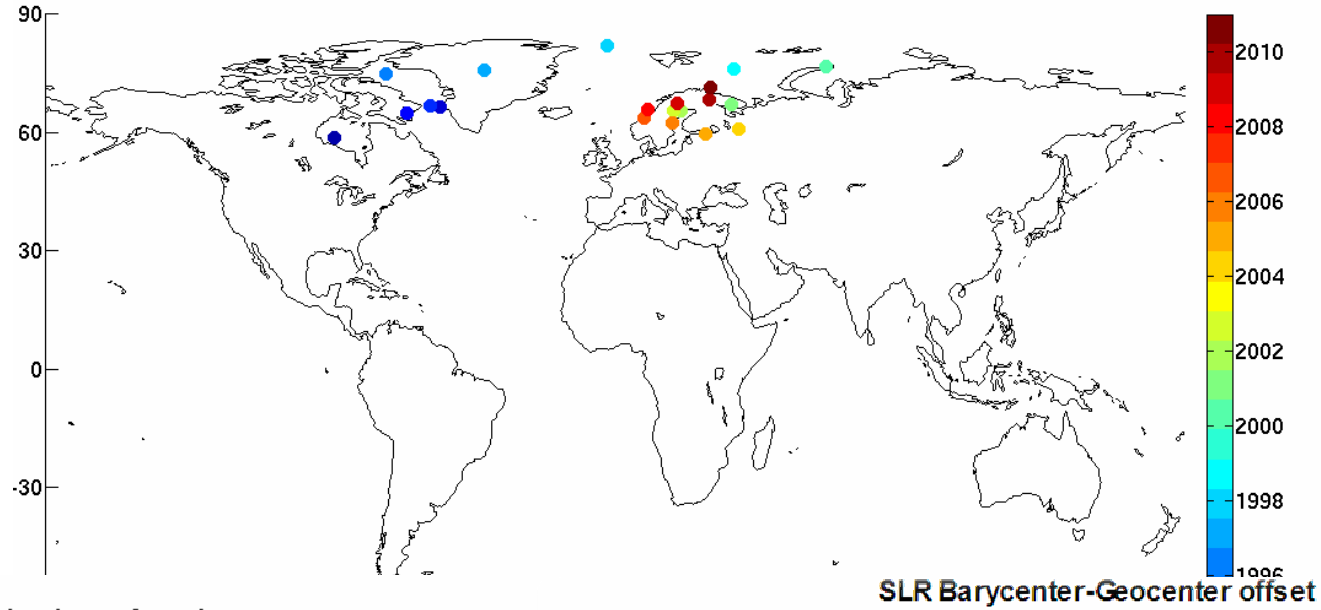
LARES-2 to be lauched in 2014 (?)

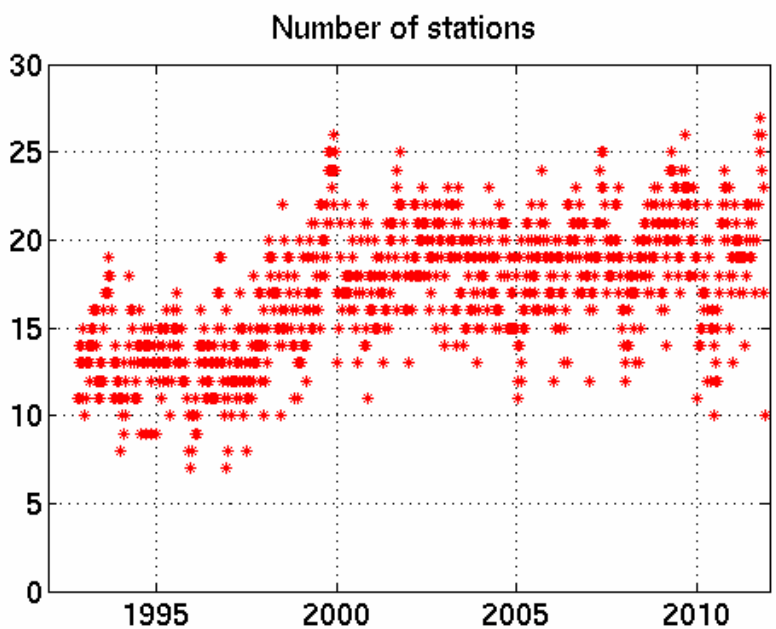
Network of SLR stations

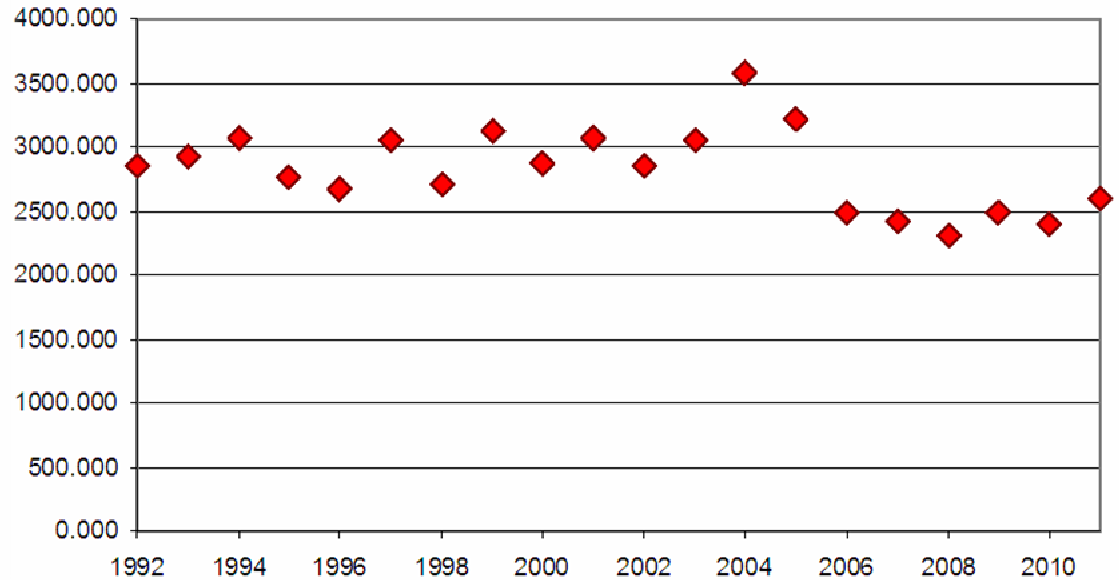


Regular observations: Yarragadee, Herstmonceux, Greenbelt, McDonald, Monument Peak, Graz, Zimmerwald, Wettzell, Changchung, Potsdam, Grasse, Matera, Mt. Stromlo, Haleakala, Arequipa, Riyadh, Hartebeesthoek, Borowiec, Simosato, San Fernando

Barycenter of SLR network







Semi-major axis of LAGEOS-1

Estimated parameters:

➢ Station coordinates	~18 stations per week
➢ Osculating orbital elements	1 set per week x 2 sat.
➢ Dynamic orbit parameters (WC/WS, S0, SC/SS)	1 set per week x 2 sat.
➢ Earth rotation parameters (X-Pole, Y-Pole, LOD)	1 set per day
➢Range biases (for the selected stations)	~2 x 2 satellites

Bernese Software, v.5.1

~110 parameters per week
~3000 obs. to LAGEOS-1/-2 per week

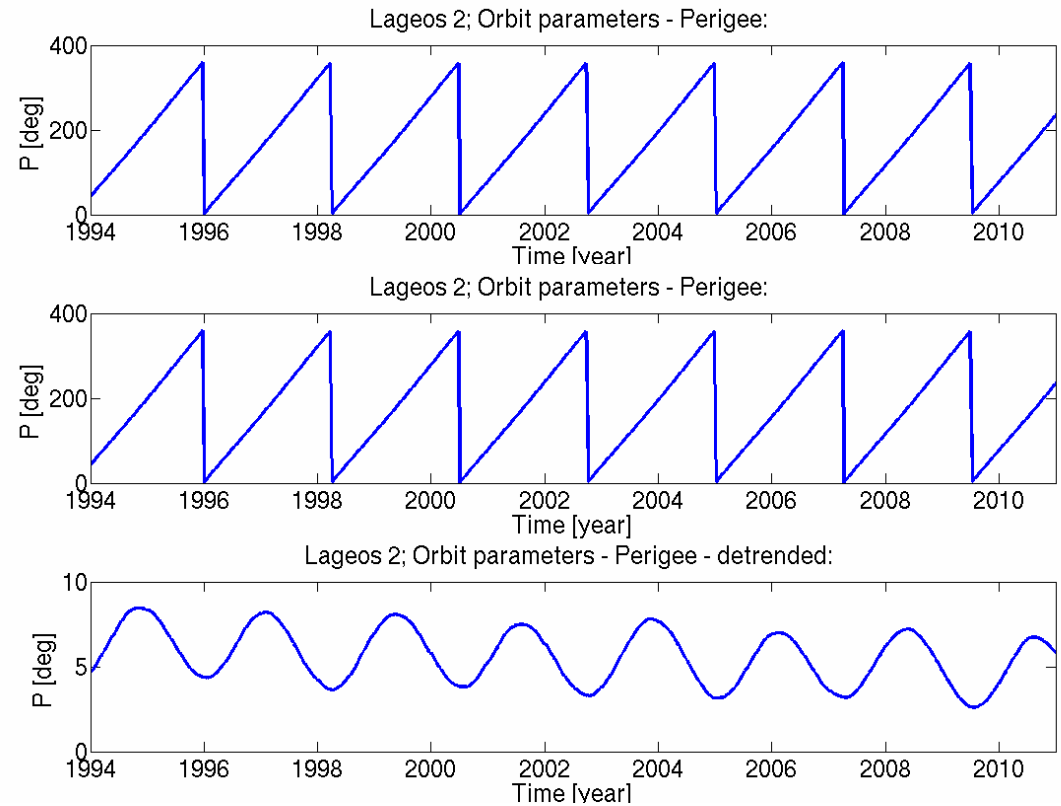
Gravitational forces – Arg. of Perigee of LAGEOS-2

$$\frac{d\omega}{dt} = \sqrt{\frac{p}{GM\,e^2}}\left(\cos v\, R' + (1+\frac{r}{p})\sin v\, S'\right) - \frac{d\Omega}{dt}\cos i$$

Only due to C_{20}:

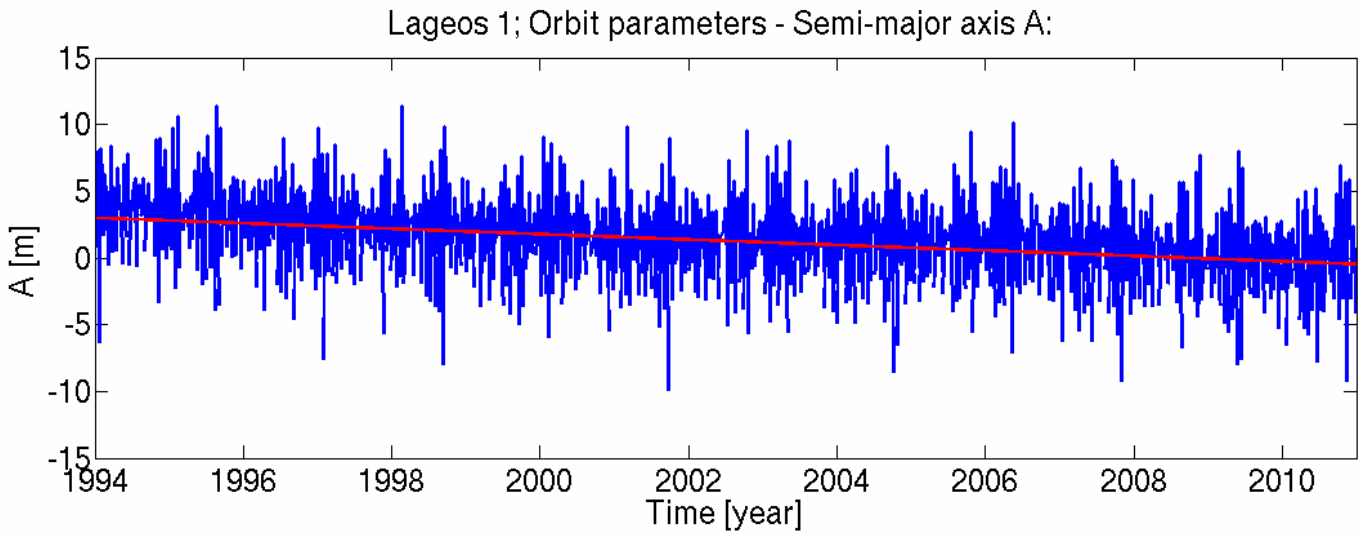
$$\frac{d\omega}{dt} = \frac{3}{4}\frac{\sqrt{GM}\,R_E^{\,2}}{a^{\frac{7}{2}}(1-e^2)^2}C_{20}(1-5\cos^2 i)$$

LAGEOS 1: 99.20 % of drift explained by C_{20}
LAGEOS 2: 99.71 % of drift explained by C_{20}
Rest can be explained by other zonal harmonics and relativistic effects



Gravitational forces dominate within forces acting on geodetic satellites

Semi-major axis of LAGEOS-1



The secular decay of semi-major axis cannot be explained by gravitational forces

$$\frac{da}{dt} = \sqrt{\frac{p}{GM}} \frac{2a}{1-e^2} \left(e \sin v \; R' + \frac{p}{r} S' \right)$$

LAGEOS 1:

$$\frac{da}{dt} = -0.203 \quad m/year$$

LAGEOS 2:

$$\frac{da}{dt} = -0.255 \quad m/year$$

Non-gravitational forces

1. Atmospheric drag
   - drag due to the electrically neutral atmosphere
   - drag due to charged particles
2. Radiation pressure
   - direct solar radiation pressure

   direct radiation

   umbra and penumbra radiations

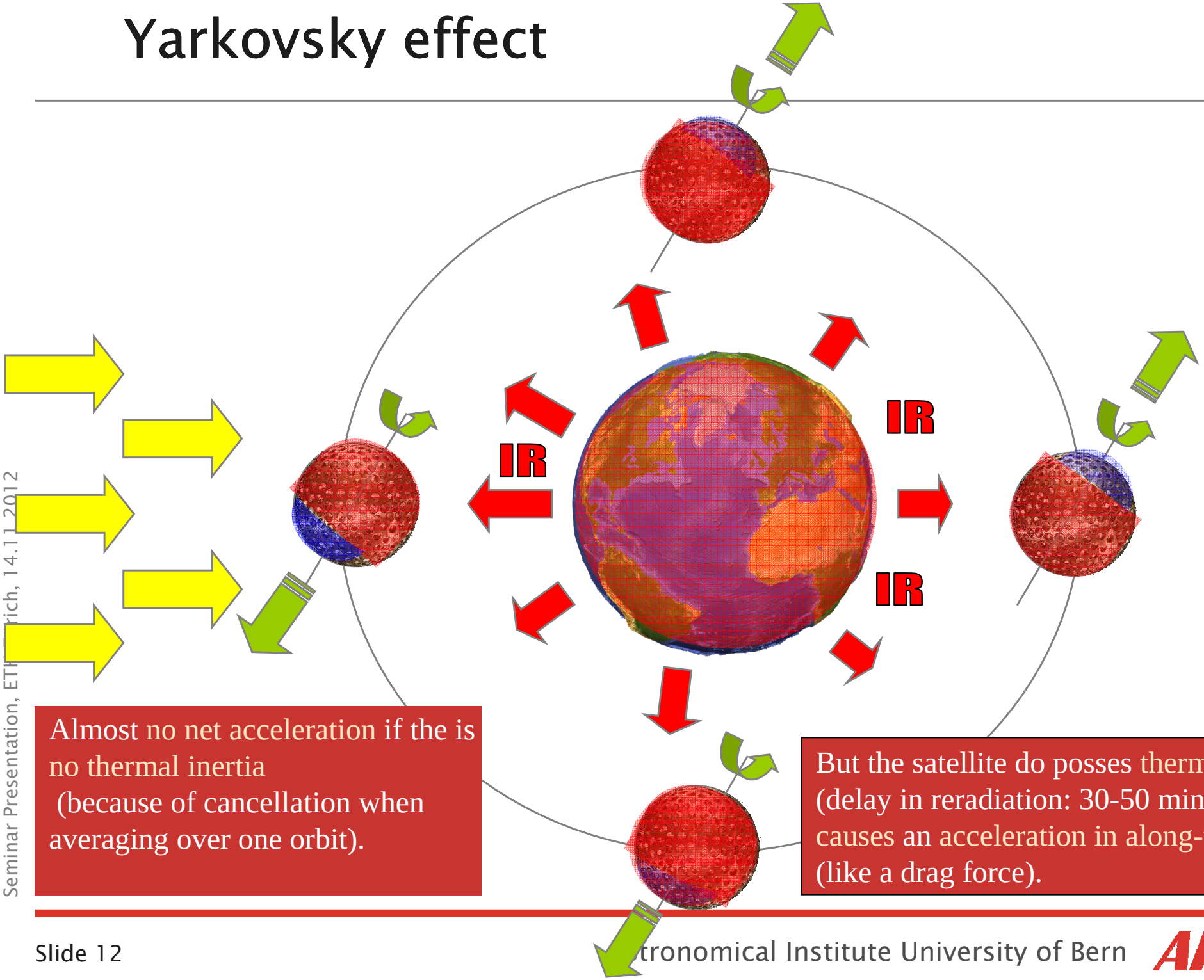
   Light aberration
   - Earth radiation pressure

   albedo infrared emissivity

   albedo reflectivity
3. Thermal satellite re-radiation forces
   - Yarkovsky effect
   - Yarkovsky-Schach effect
4. Forces due to the satellite asymmetricity
5. Effects induced by the Earth's magnetic field
6. Other non-gravitational forces

Thermal forces

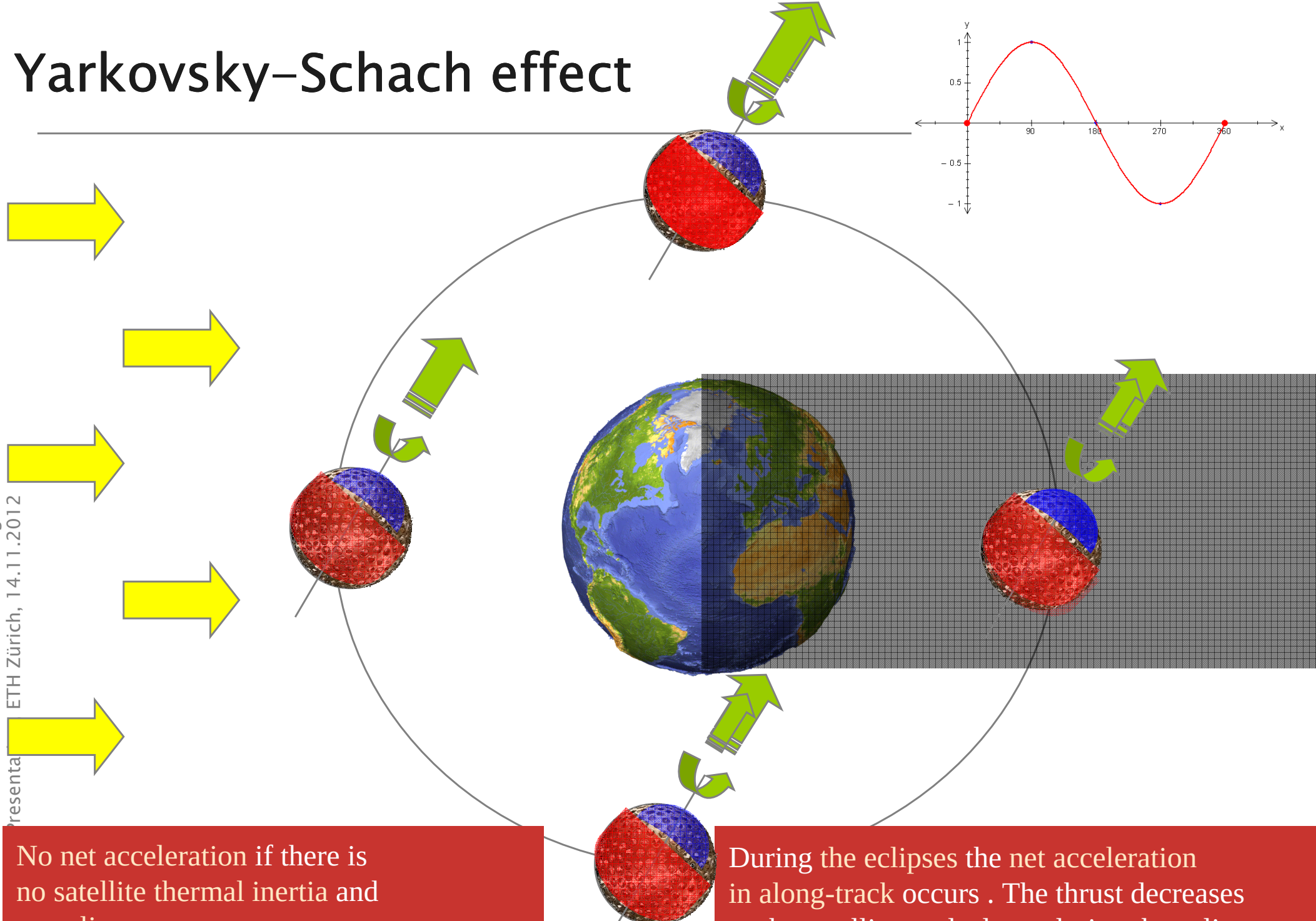
Yarkovsky effect



Almost no net acceleration if the is no thermal inertia
(because of cancellation when averaging over one orbit).

But the satellite do posses thermal inertia (delay in reradiation: 30-50 min.), which causes an acceleration in along-track (like a drag force).

Yarkovsky–Schach effect

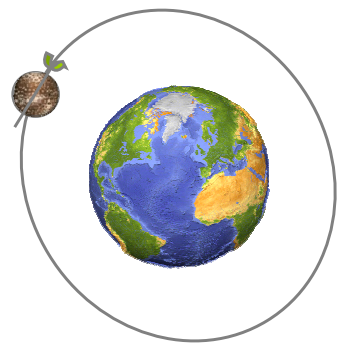


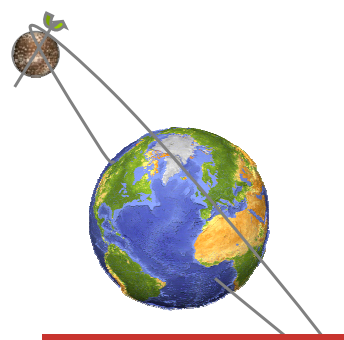
No net acceleration if there is
no satellite thermal inertia and
no eclipses.
Only once-per-rev components are affected.

During the eclipses the net acceleration
in along-track occurs . The thrust decreases
as the satellite cools down during the eclipse.
The along-track acceleration can be positive or negative.

Empirical orbital forces – along-track

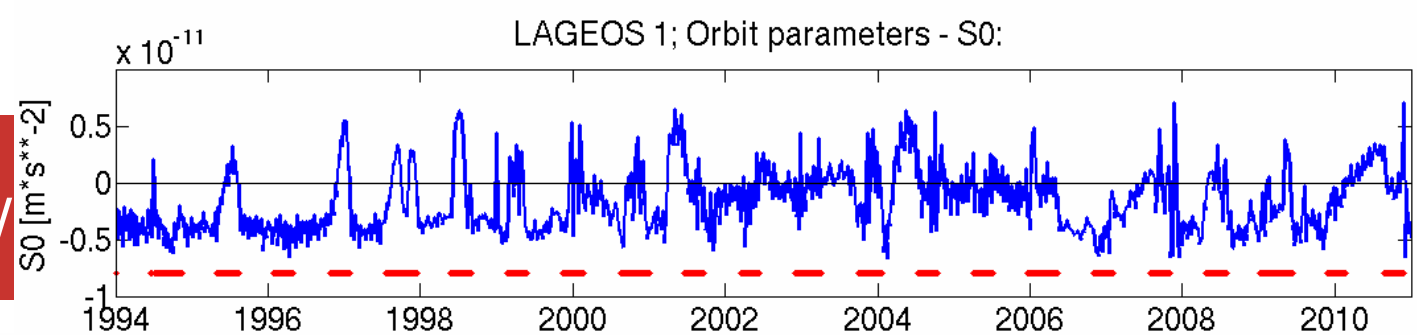
Red line – eclipsing day

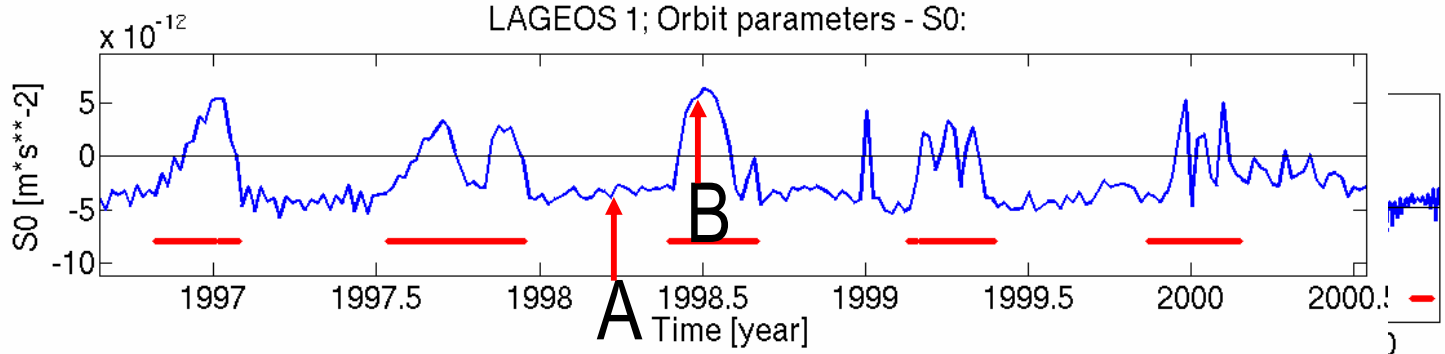


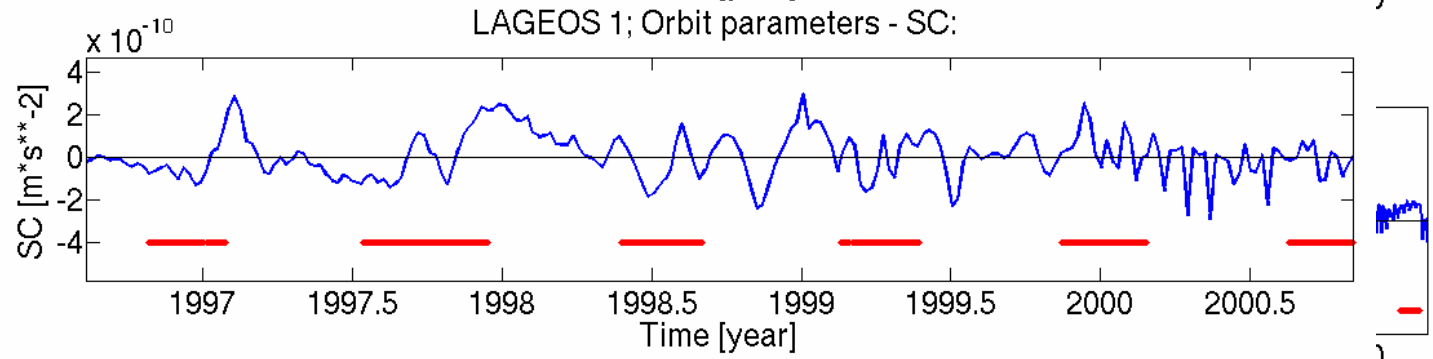


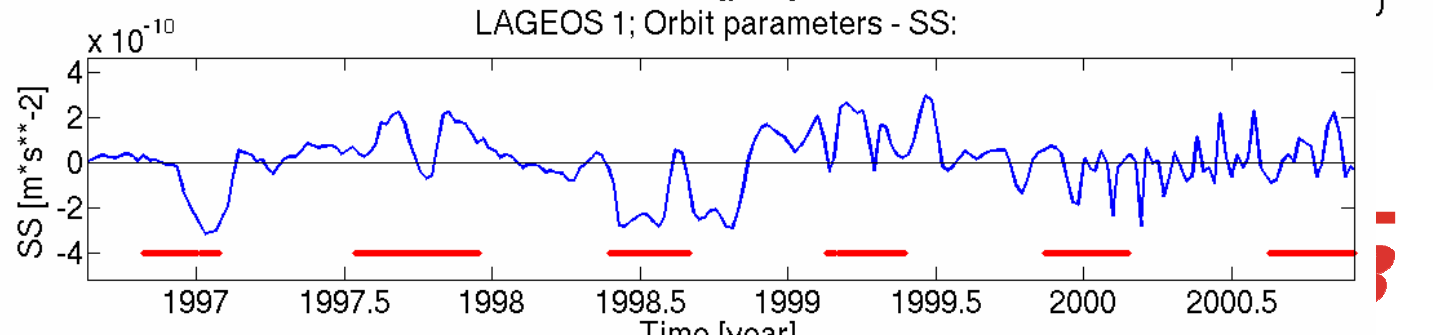
View from the Sun

$$\frac{da}{dt} \approx \sqrt{\frac{p}{GM}}$$

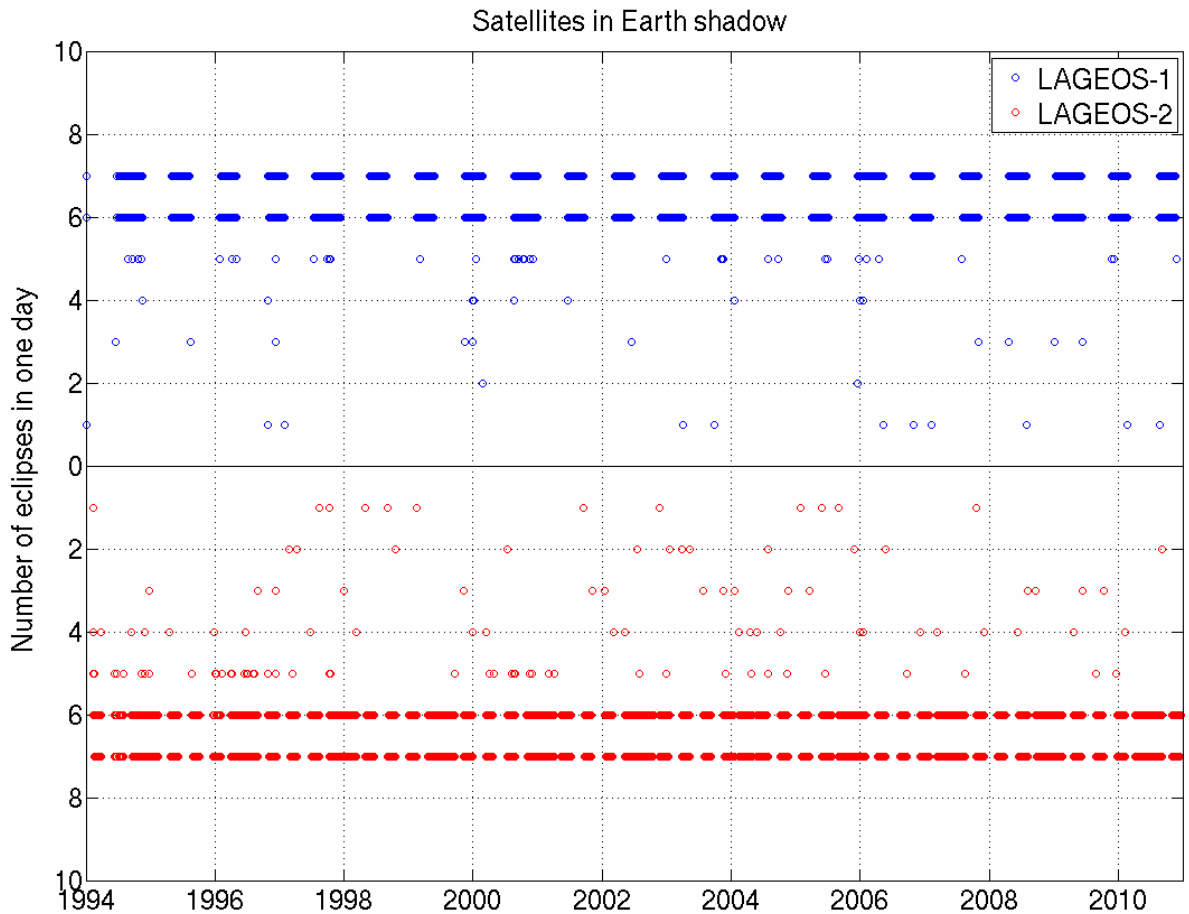






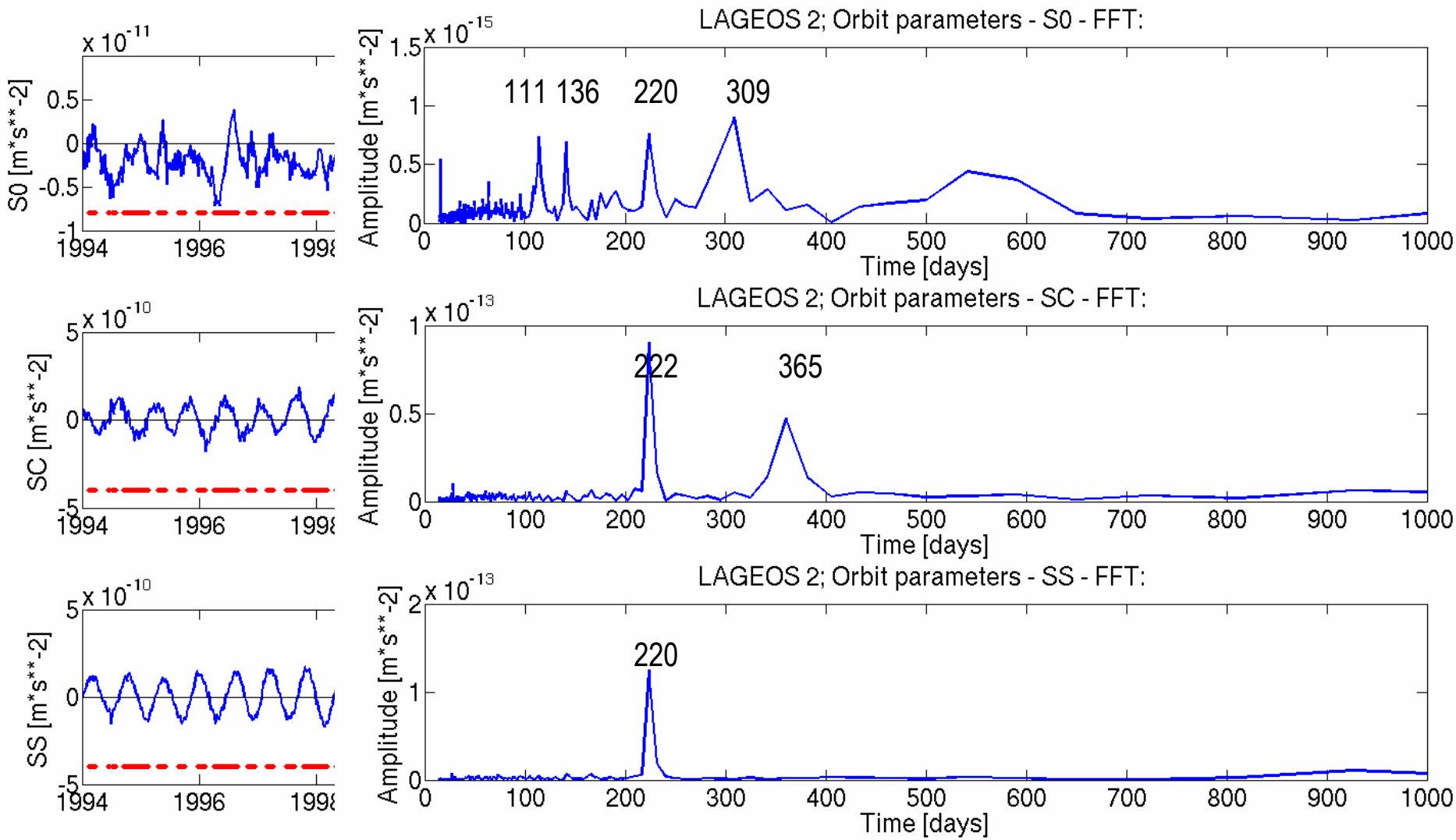


Empirical orbital forces – along-track



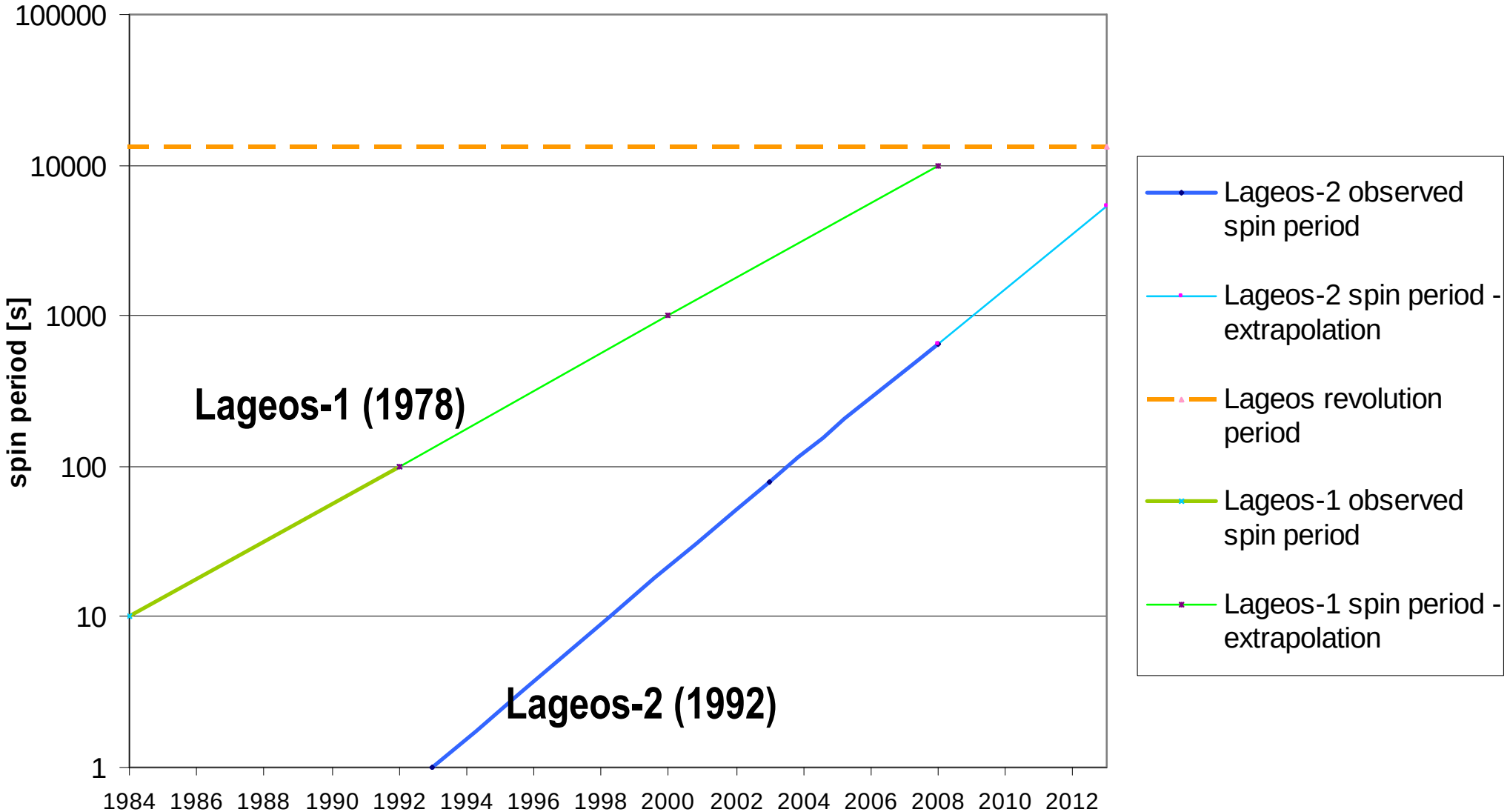
	LAGEOS 1			LAGEOS 2		
	During Eclipses	Outside the eclipses	Overall	During Eclipses	Outside the eclipses	Overall
Weeks	**39%**	**61%**	**100%**	**40%**	**60%**	**100%**
S0 [10e-12 ms^{-2}]	**-0.999**	**-2.251**	**-1.757**	**-1.366**	**-2.276**	**-1.913**

Empirical orbital forces – along-track



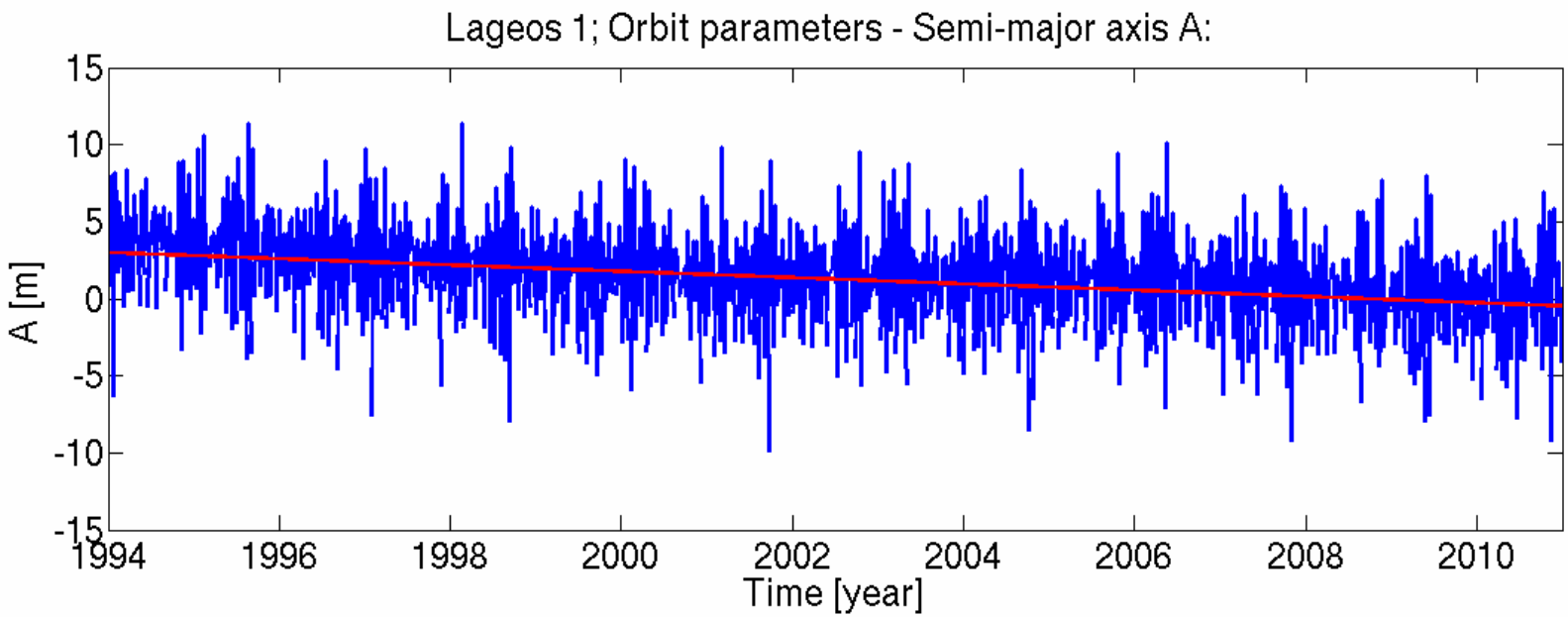
Period (days): 111 – eclipses, 222 – draconitic year, 365 – annual signal

Spin rate of LAGEOS-1/2



Values from Kucharski et.al., "**16 years of LAGEOS-2 Spin Data: From launch to present**", **Proceedings of the conference held 12-17 October, 2008 in Poznan, Poland. Published online at http://cddis.gsfc.nasa.gov/lw16, p.61"**

Semi-major axis of LAGEOS-1



The decay of Semi-major axis of LAGEOS-1:

’80: -0.40 m/y

’90: -0.34 m/y

‘00: -0.14 m/y

Air drag

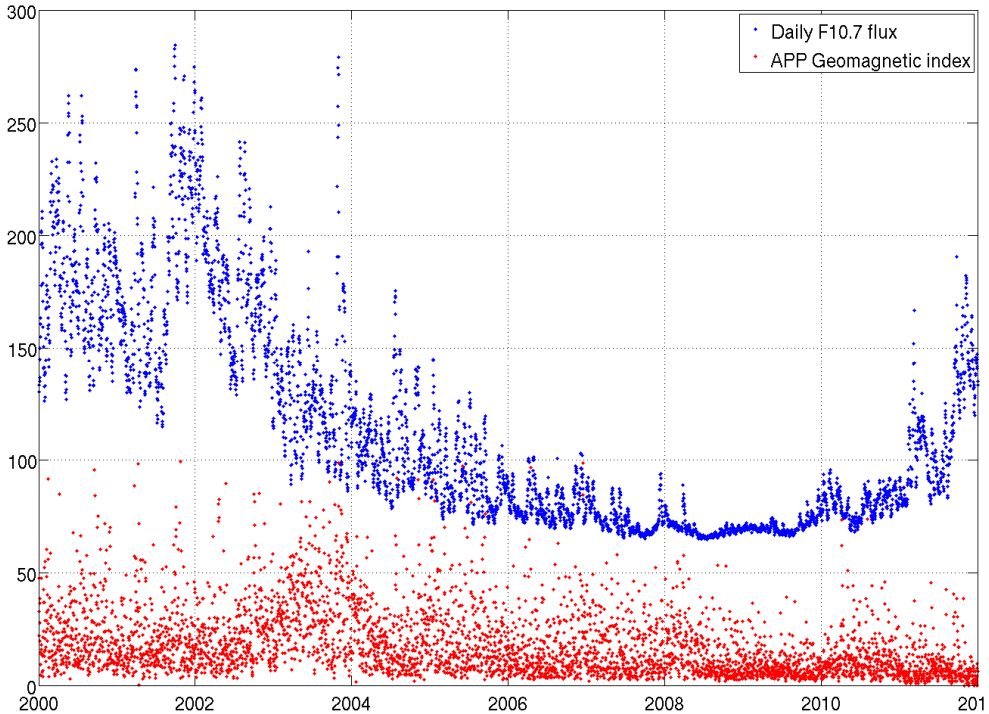
Air drag

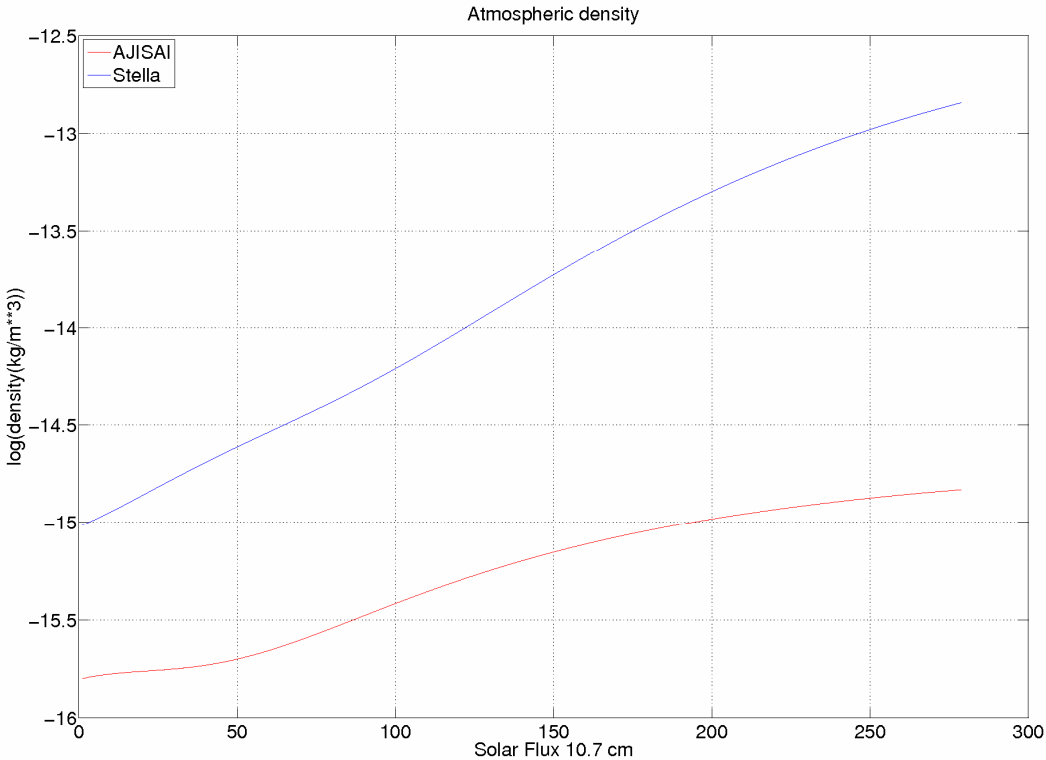
$$a_{drag} = -\frac{C_D}{2}\rho\frac{A}{m}v_{rel}^{\ 2}\frac{v_{rel}}{|v_{rel}|}$$

Air density (ρ) of the high atmosphere depends on:

- Altitude of a satellite
- Time of the day, day of the year
- Geographic latitude and longitude,
- Solar activity
- Geomagnetic activity

Air drag

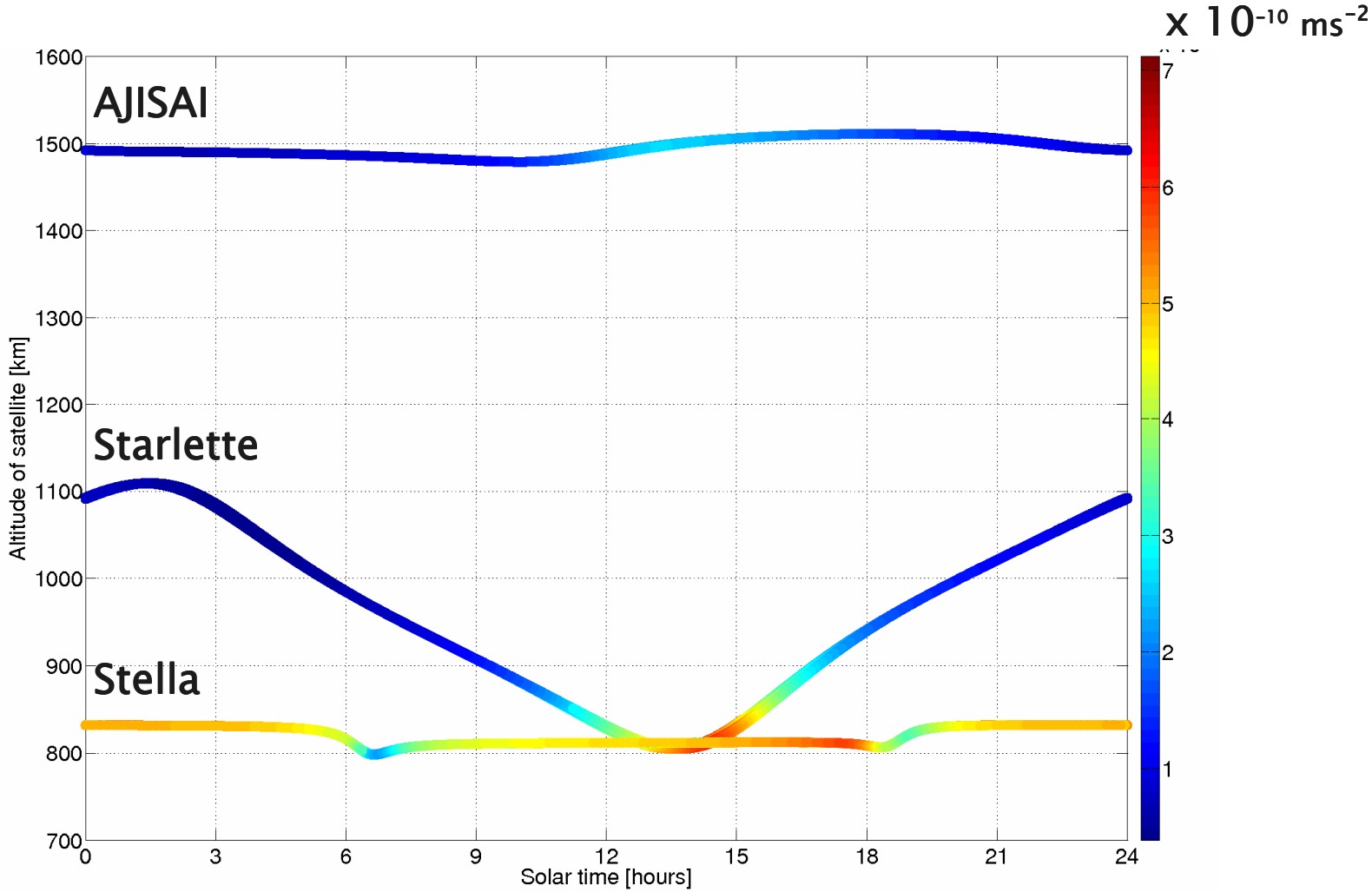




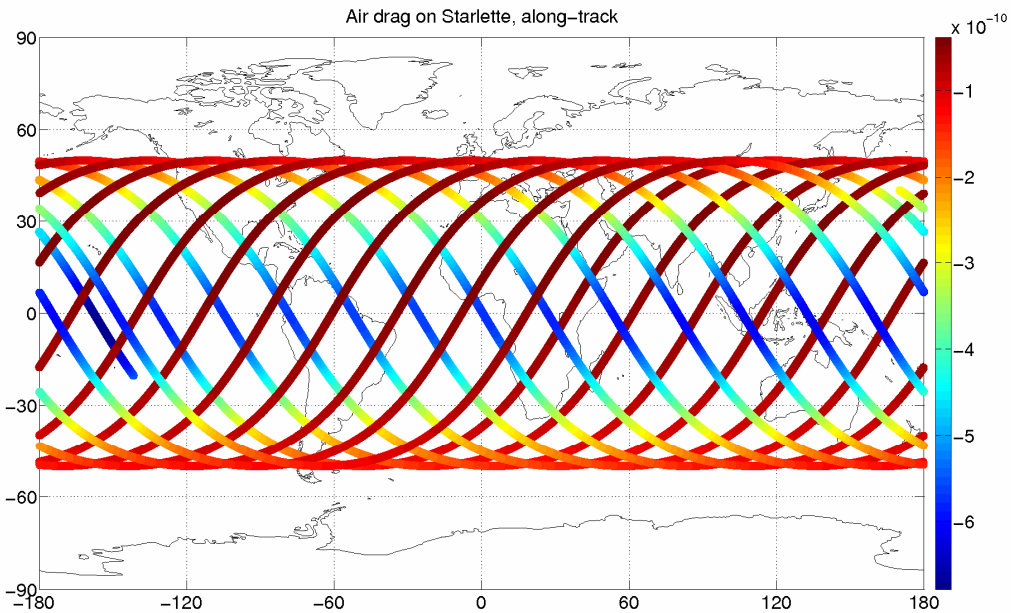
Time series of:
- daily F10.7cm solar flux index,
- APP Geomagnatic index

The relationship between atmospheric density at AJISAI's and Stella's altitudes and solar flux 10.7cm index

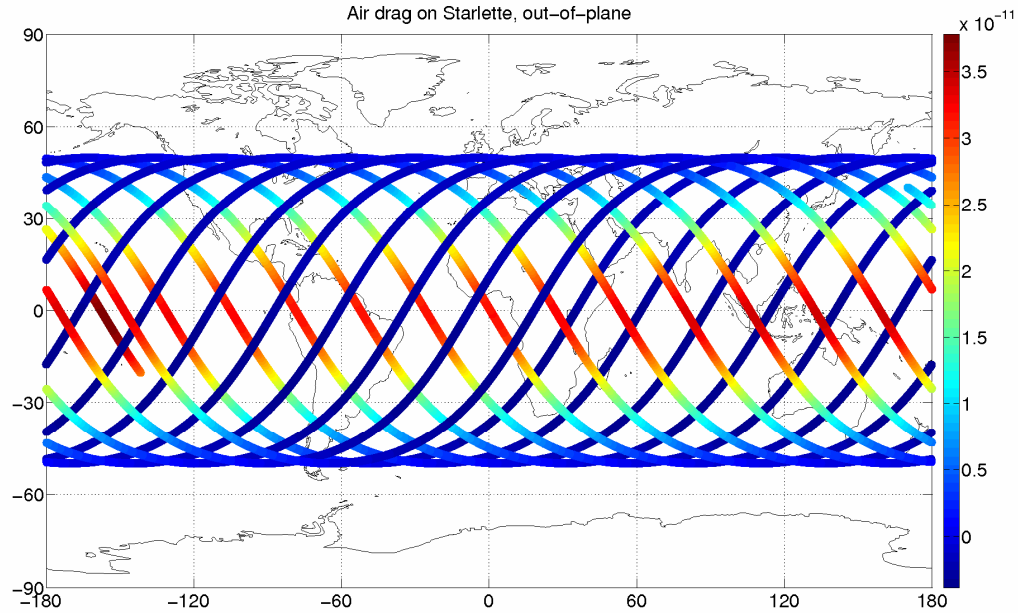
Total acceleration due to the air drag



Acceleration due to the air drag



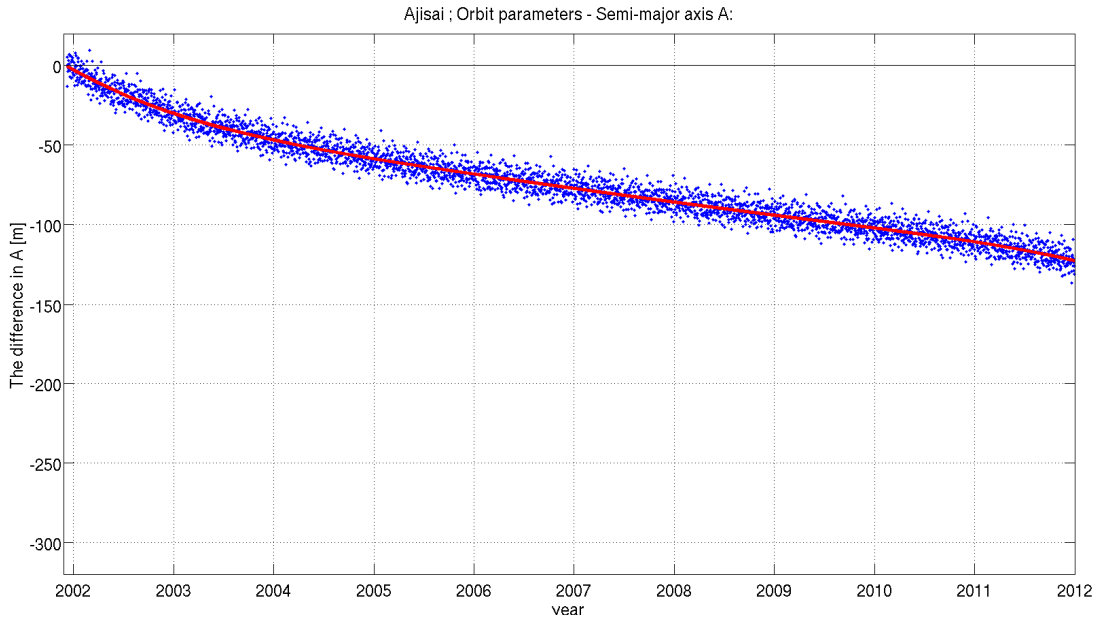
Starlette – along-track



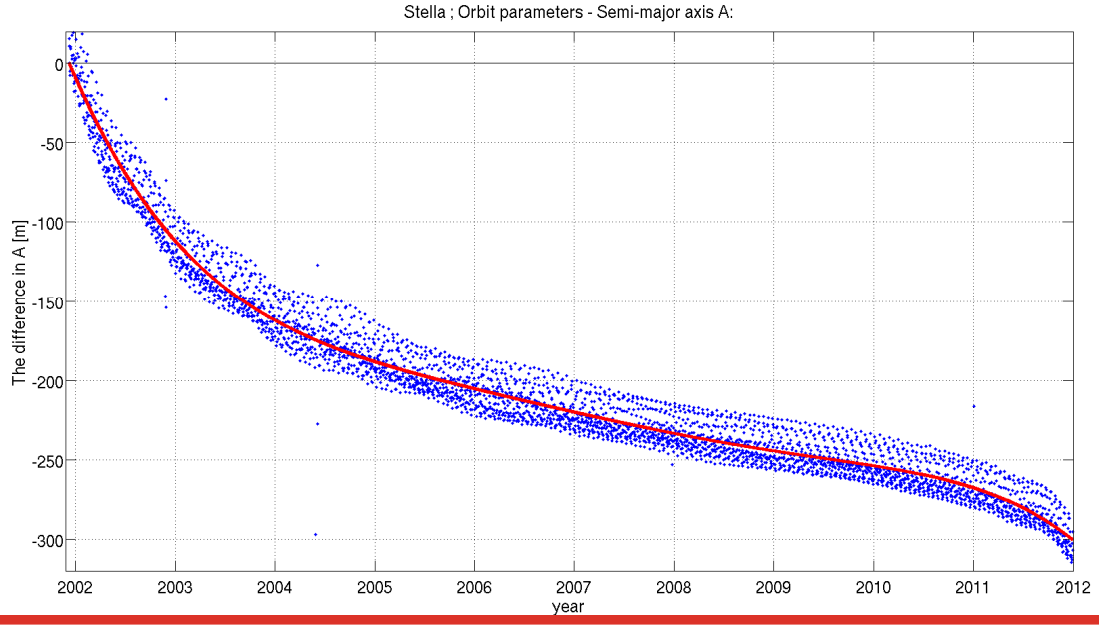
Starlette – out-of-plane

- Acceleration due to air drag in out-of-plane is 20x smaller than in along-track.
- Acceleration in along-track is always negative.
- Acceleration in radial direction is negligible.

Decay of the semi-major axes

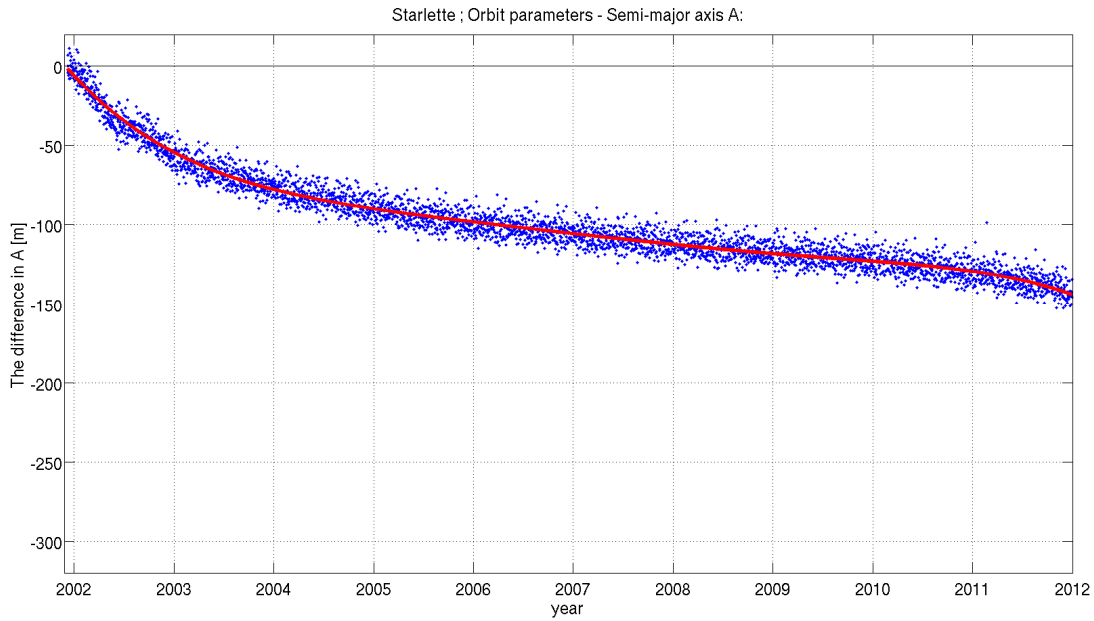


AJISAI: 12 m/year
(2002-2012)



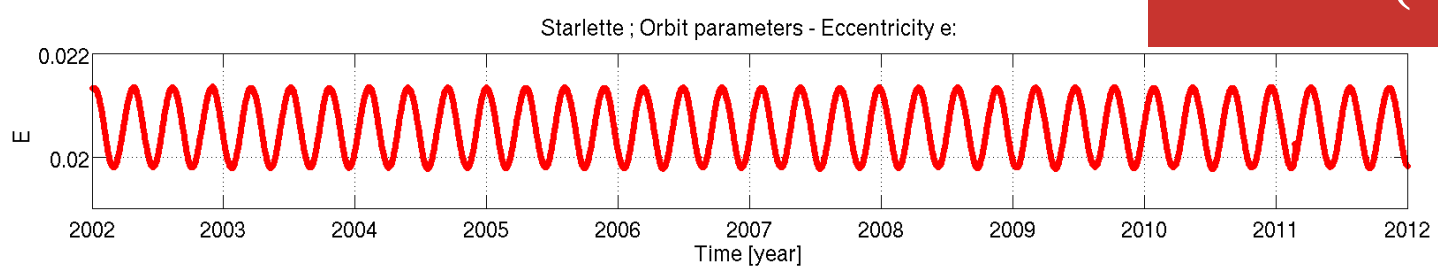
Stella: 30 m/year
(2002-2012)

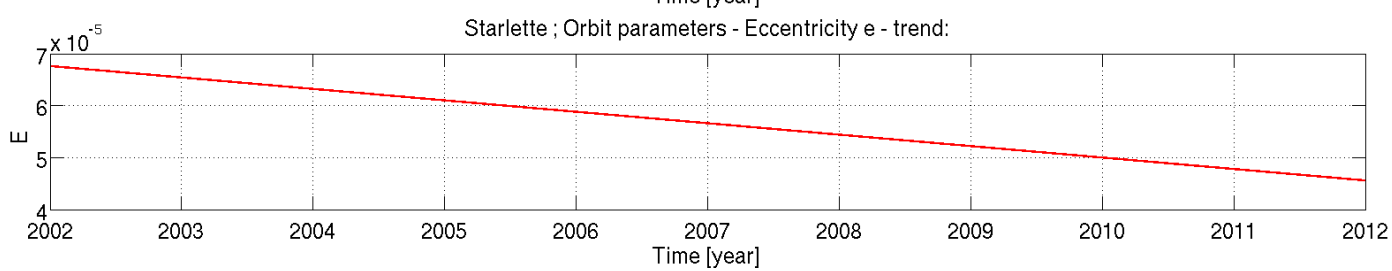
Decay of the semi-major axis and eccentricity



Starlette: 14 m/year
Semi-major axis
(2002-2012)

Starlette: $1.3 \cdot 10^{-6}$/year
orbital eccentricity
(2002-2012)



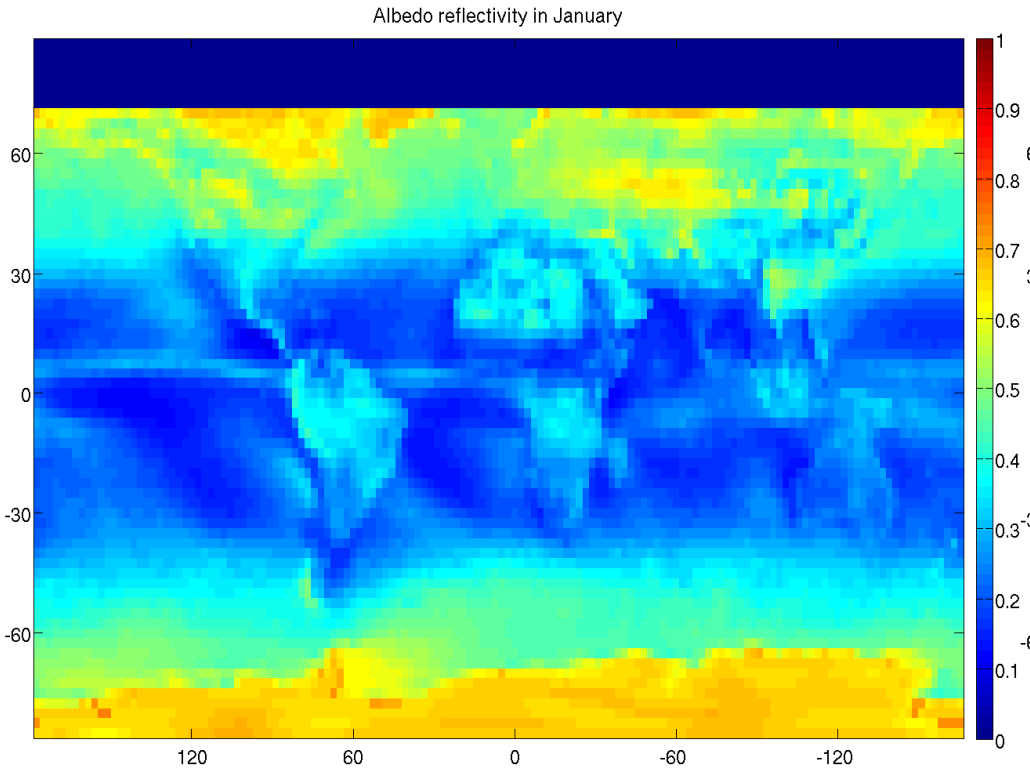


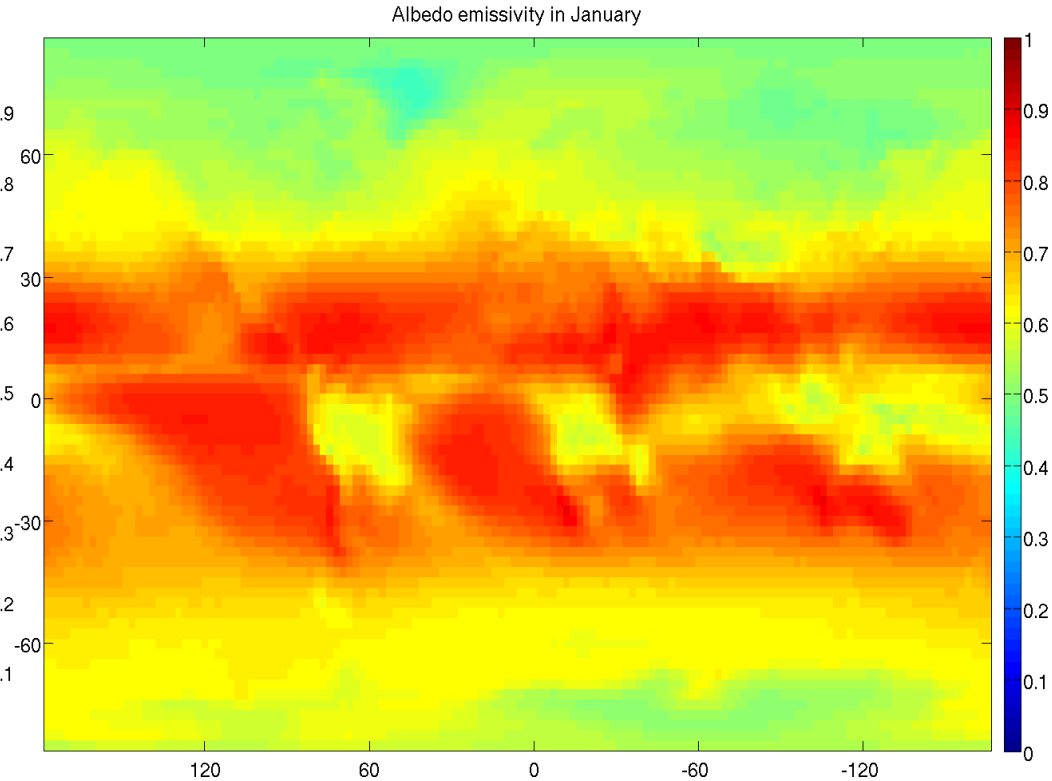
Secular drift

Albedo

Albedo

- albedo reflectivity (within visible spectrum)
- albedo emissivity (within infrared spectrum)





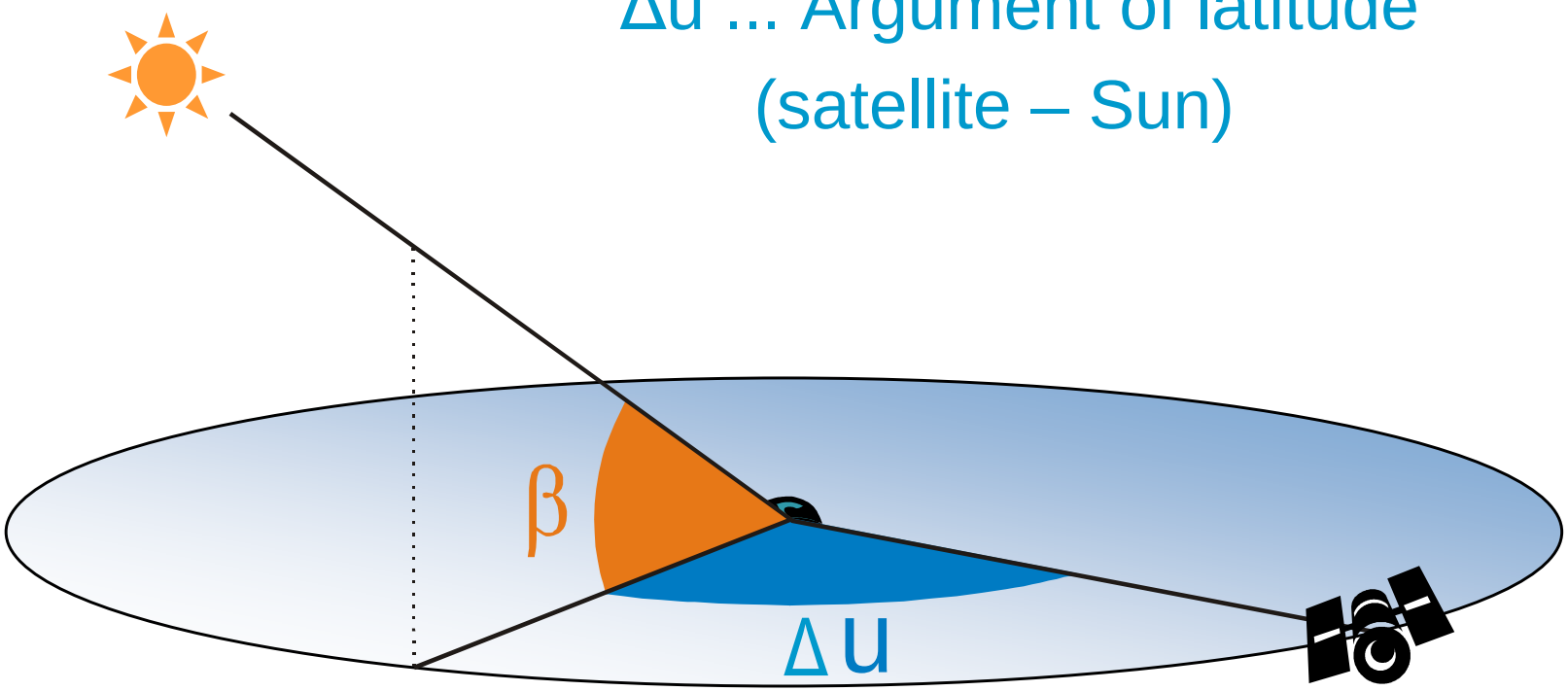
The Earth emissitivy renders about 60% of total albedo effect and introduces a rather constant force in the radial direction.

Source of data: monthly global maps from the CERES mission, grids 2.5x2.5 (Rodriguez-Solano et al., 2011)

Coordinate system β – Δu

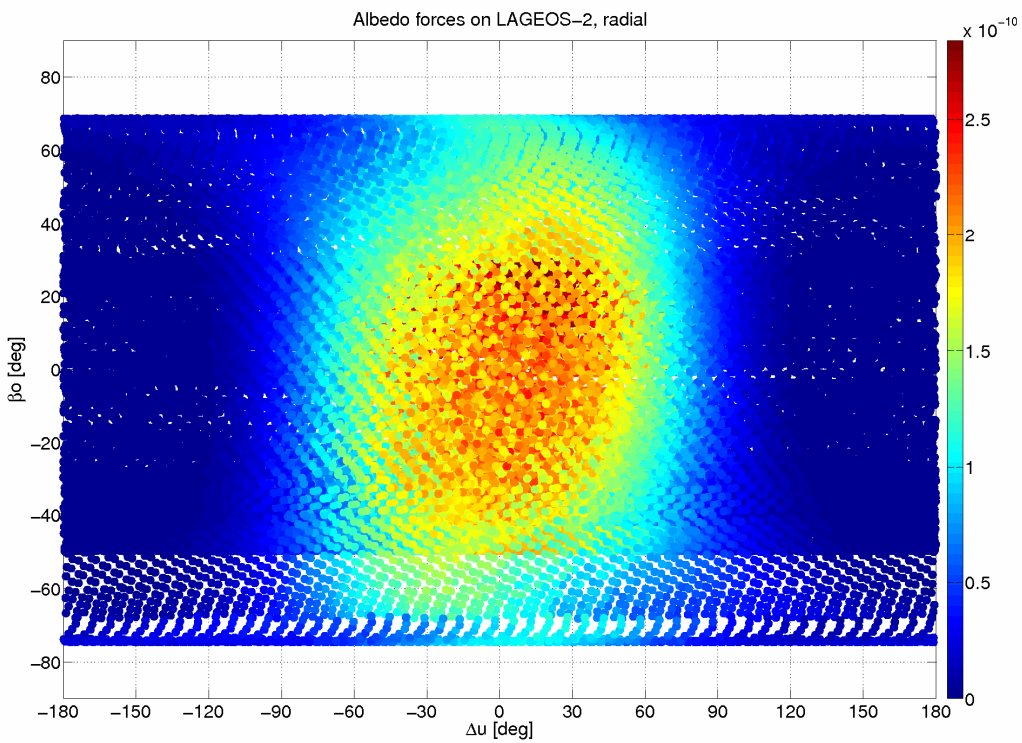
β ... Elevation of the Sun above the orbital plane

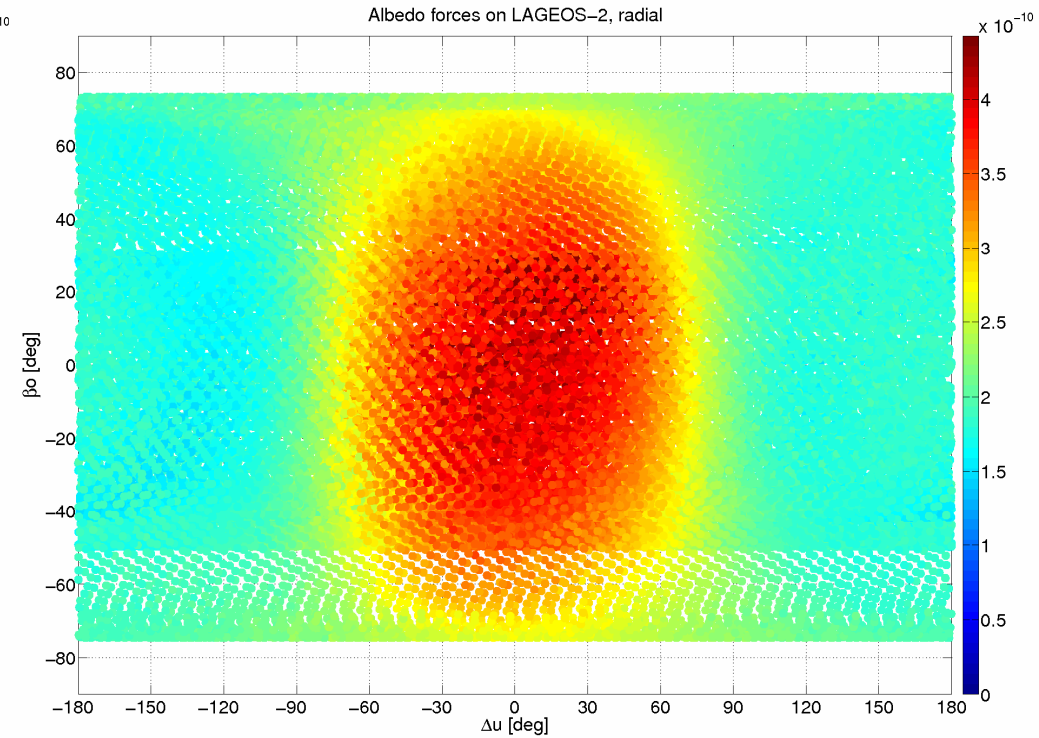
Δu ... Argument of latitude (satellite – Sun)



Acceleration due to albedo in radial direction

LAGEOS-2



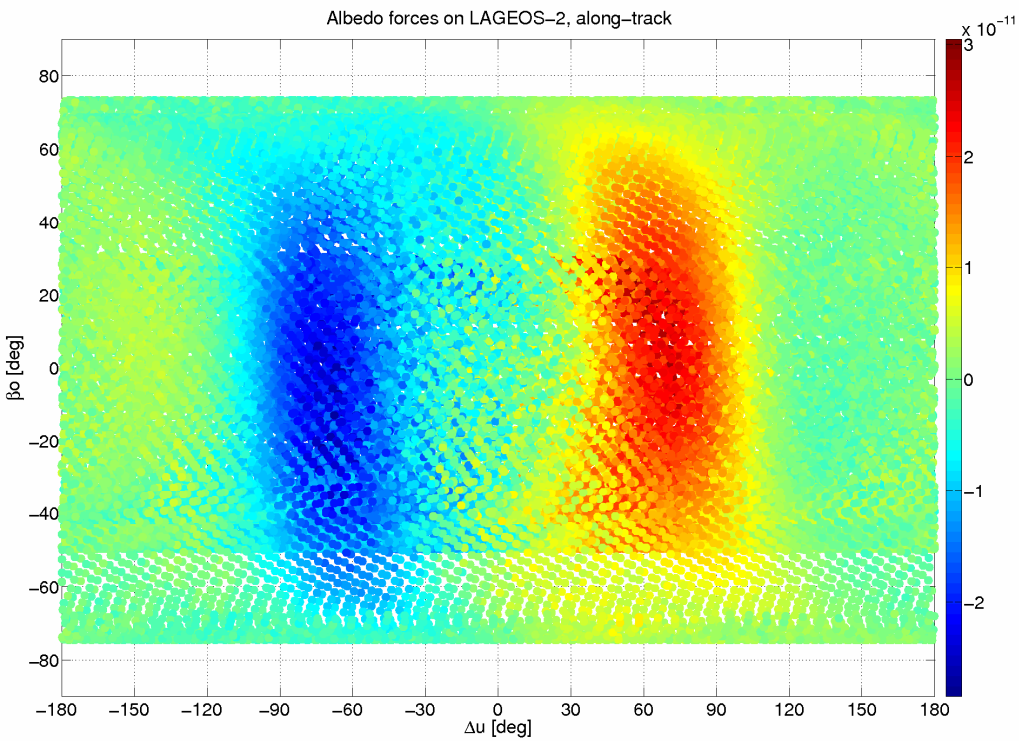


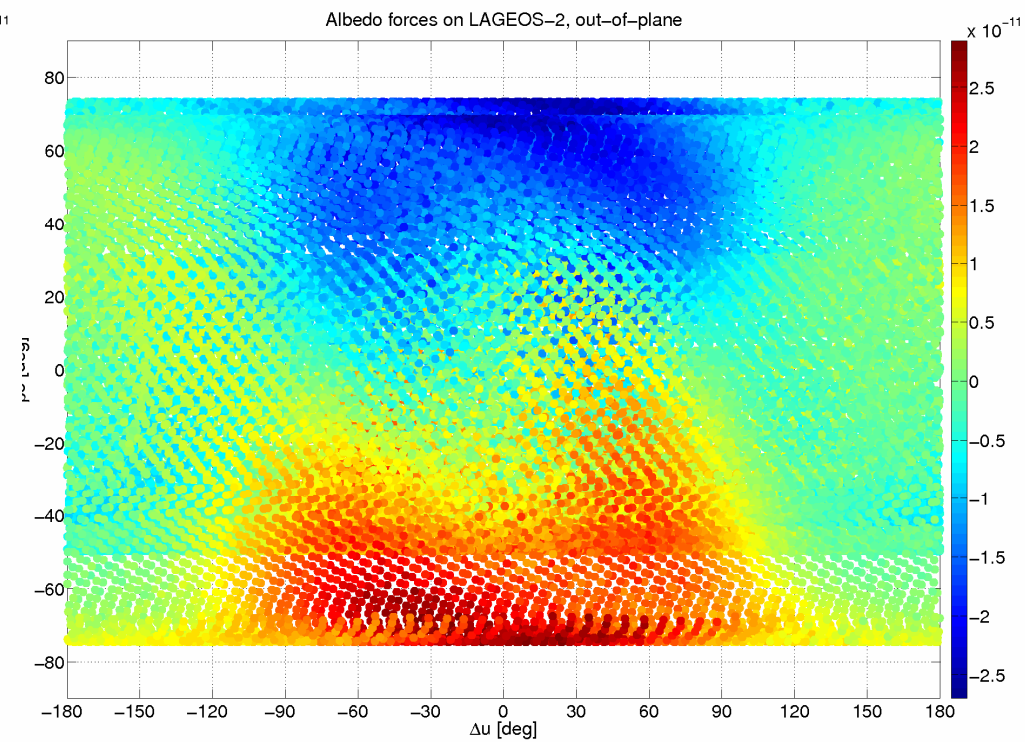
Reflectivity only

Reflectivity and emissivity

Acceleration due to albedo

LAGEOS-2

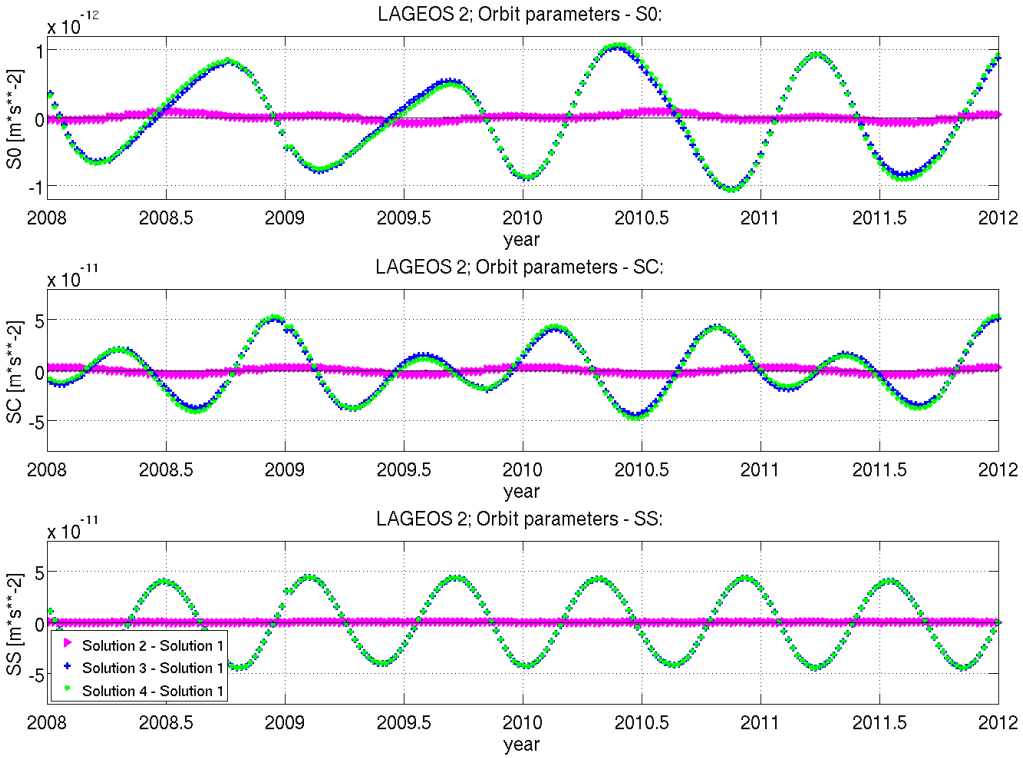


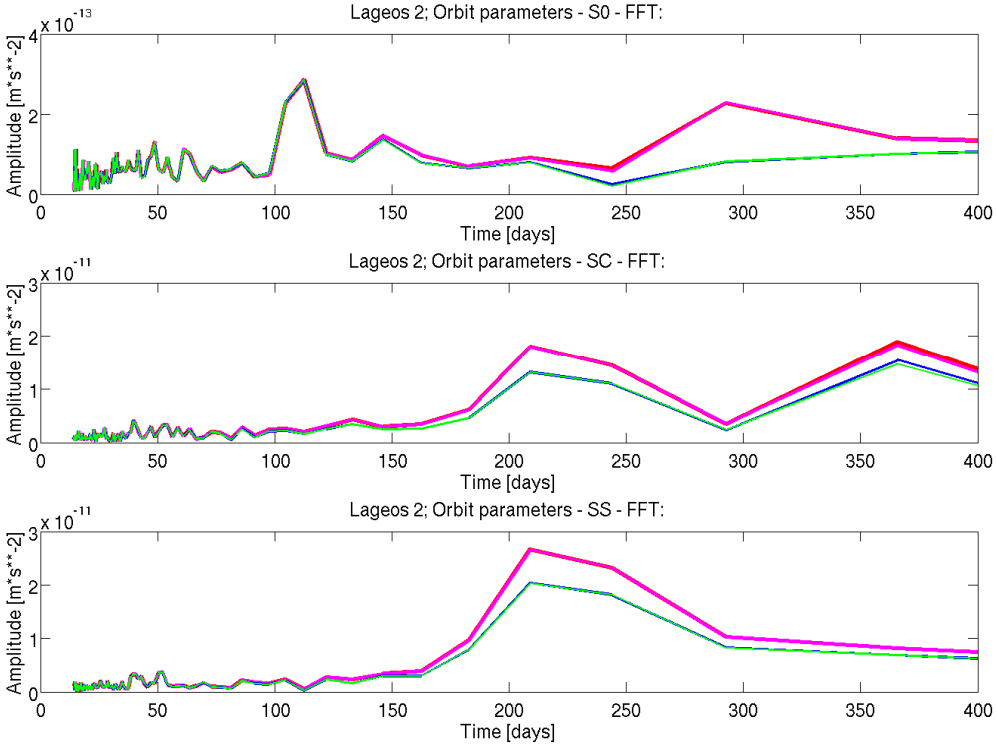


Reflectivity and emissivity: along-track

Reflectivity and emissivity: out-of-plane

Impact of albedo on LAGEOS-2 orbit





Differences of empirical accelerations in along-track w.r.t. Solution 1

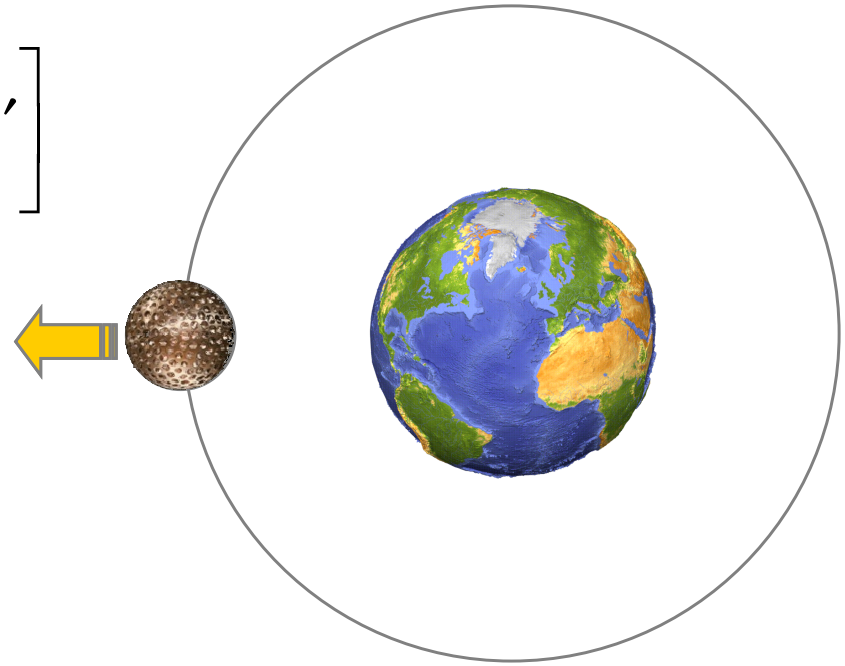
	Emissivity	Reflectivity
Solution 1	NO	NO
Solution 2	YES	NO
Solution 3	NO	YES
Solution 4	YES	YES

Impact of albedo on LAGEOS-2 orbit

$$n_c = n + \frac{1-e^2}{n\,a\,e}\left[\left(\cos v - 2e\frac{r}{p}\right)R' - \left(1+\frac{r}{p}\right)\sin v\, S'\right]$$

$$n_c = n - 2\frac{r}{n\,a^2}R' = n - \frac{2}{n\,a}R'$$

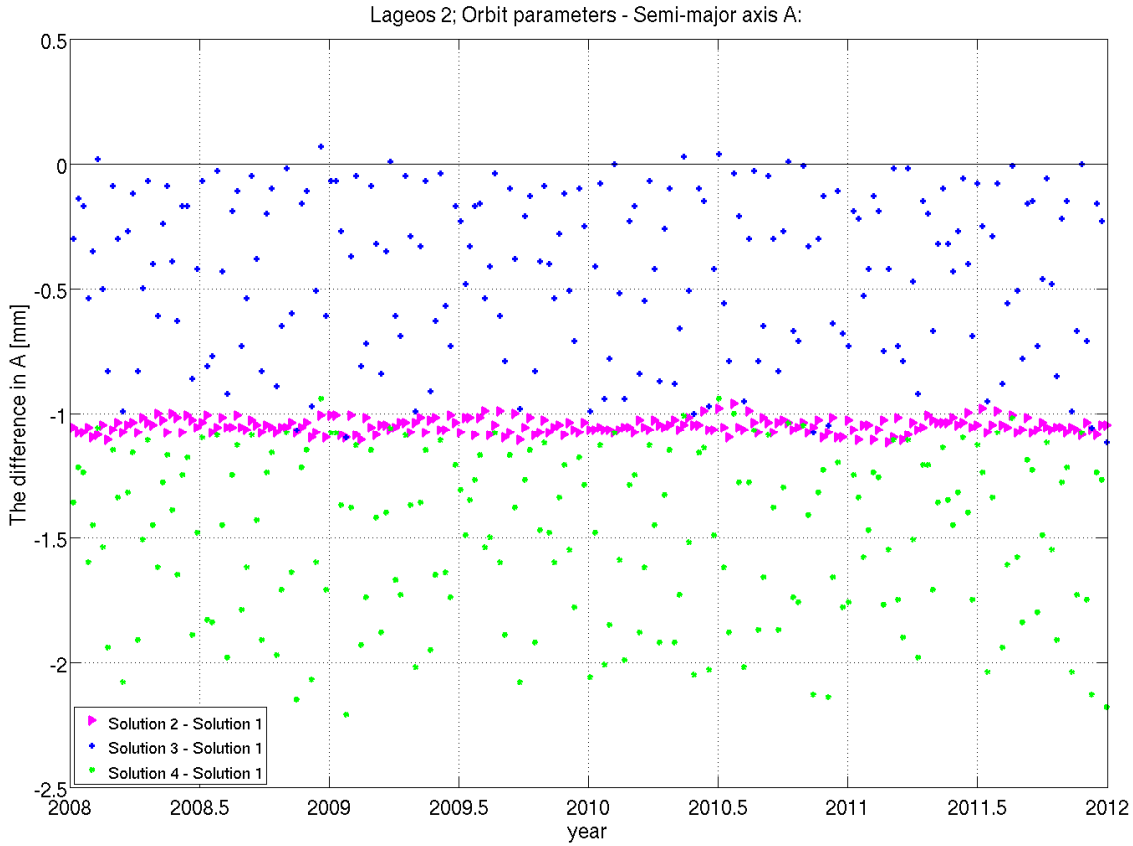
$$n^2 a^3 = GM$$



Albedo introduces a force in an opposite direction to the Earth's gravitational attraction

	Emissivity	Reflectivity
Solution 1	NO	NO
Solution 2	YES	NO
Solution 3	NO	YES
Solution 4	YES	YES

Impact of albedo on LAGEOS-2 orbit

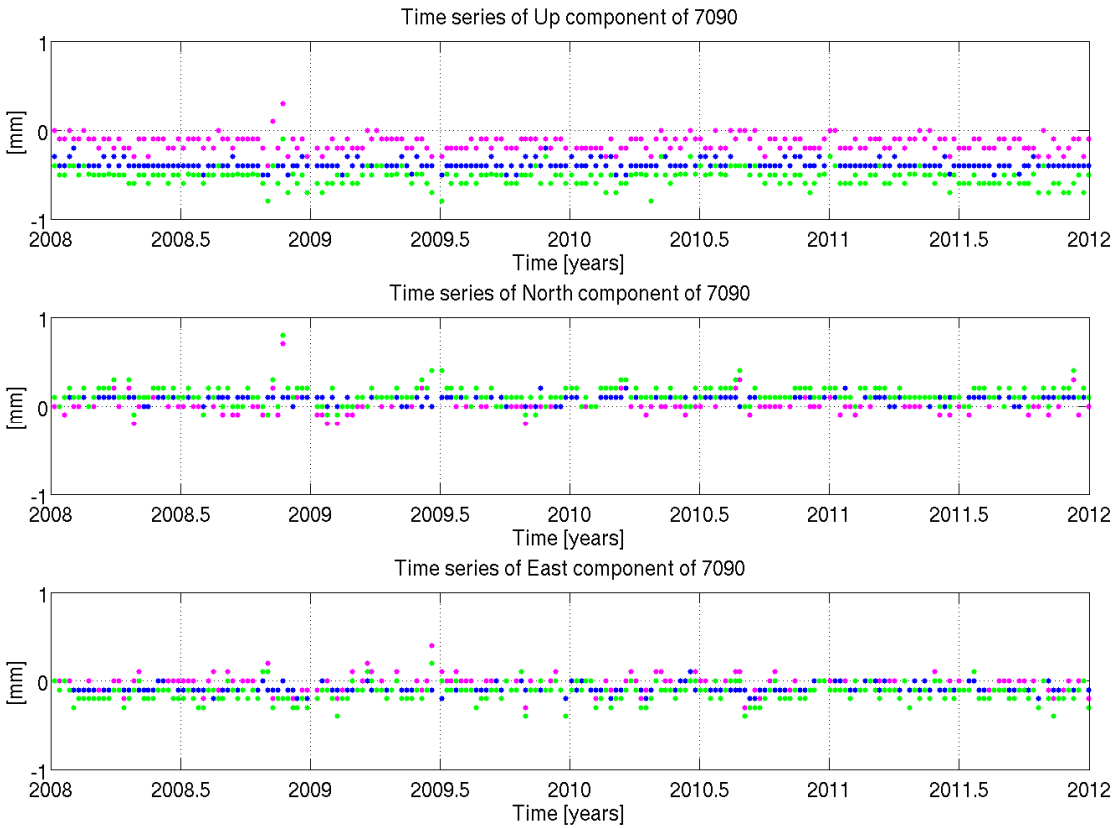


Differences of semi-major axis w.r.t. Solution 1

In total LAGEOS orbits are diminished due to albedo by about 1.5 mm

	Emissivity	Reflectivity
Solution 1	NO	NO
Solution 2	YES	NO
Solution 3	NO	YES
Solution 4	YES	YES

Impact of albedo on station coordinates



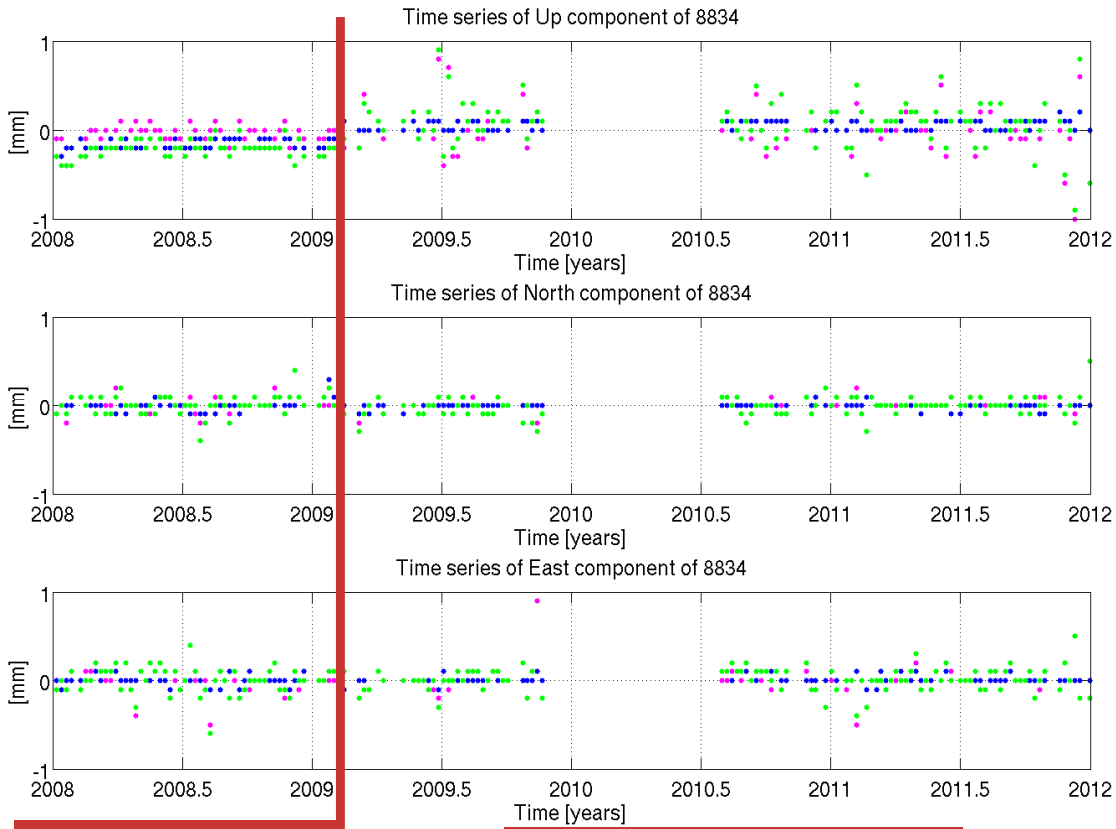
Differences of station coordinates w.r.t. Solution 1

Yarragadee

A shift in up component of -0.2 mm due to emissivity and -0.4 mm due to albedo reflectivity

	Emissivity	Reflectivity
Solution 1	NO	NO
Solution 2	YES	NO
Solution 3	NO	YES
Solution 4	YES	YES

Impact of albedo on station coordinates



No range bias

Range bias estimated

Differences of station coordinates w.r.t. Solution 1

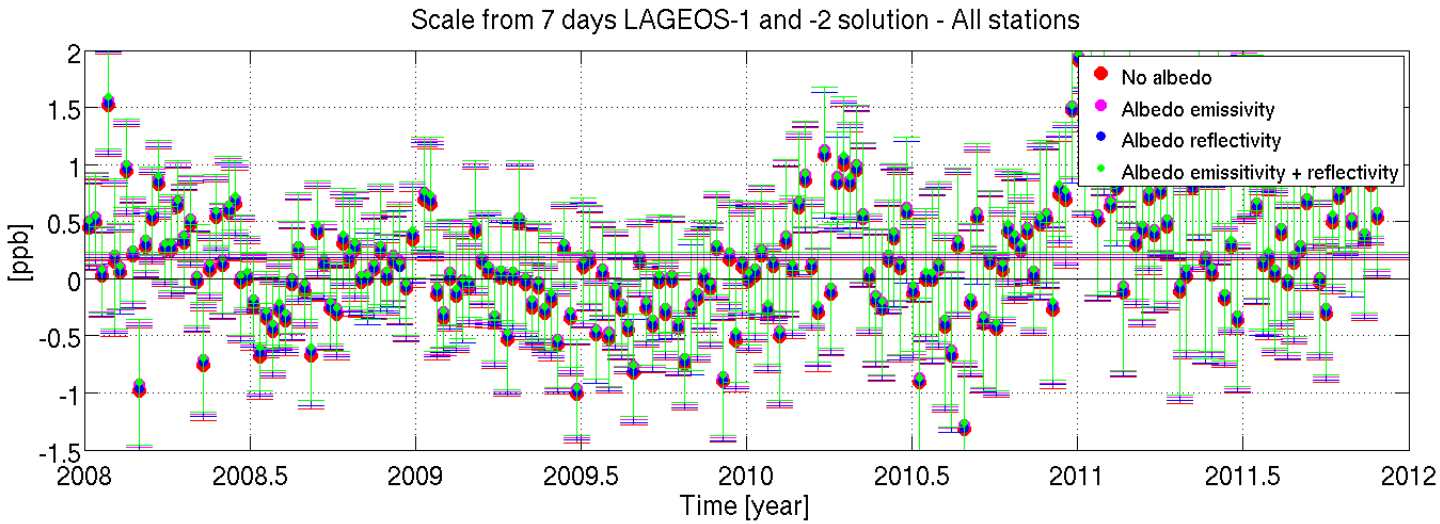
Wettzell

	Emissivity	Reflectivity
Solution 1	NO	NO
Solution 2	YES	NO
Solution 3	NO	YES
Solution 4	YES	YES

A range bias absorbs the impact of albedo

Impact of albedo on scale

Scale differences w.r.t. ITRF2008



	Mean bias	
	Scale [ppb]	Std dev [ppb]
Solution 1	0.16	0.54
Solution 2	0.21	0.54
Solution 3	0.18	0.54
Solution 4	0.23	0.54

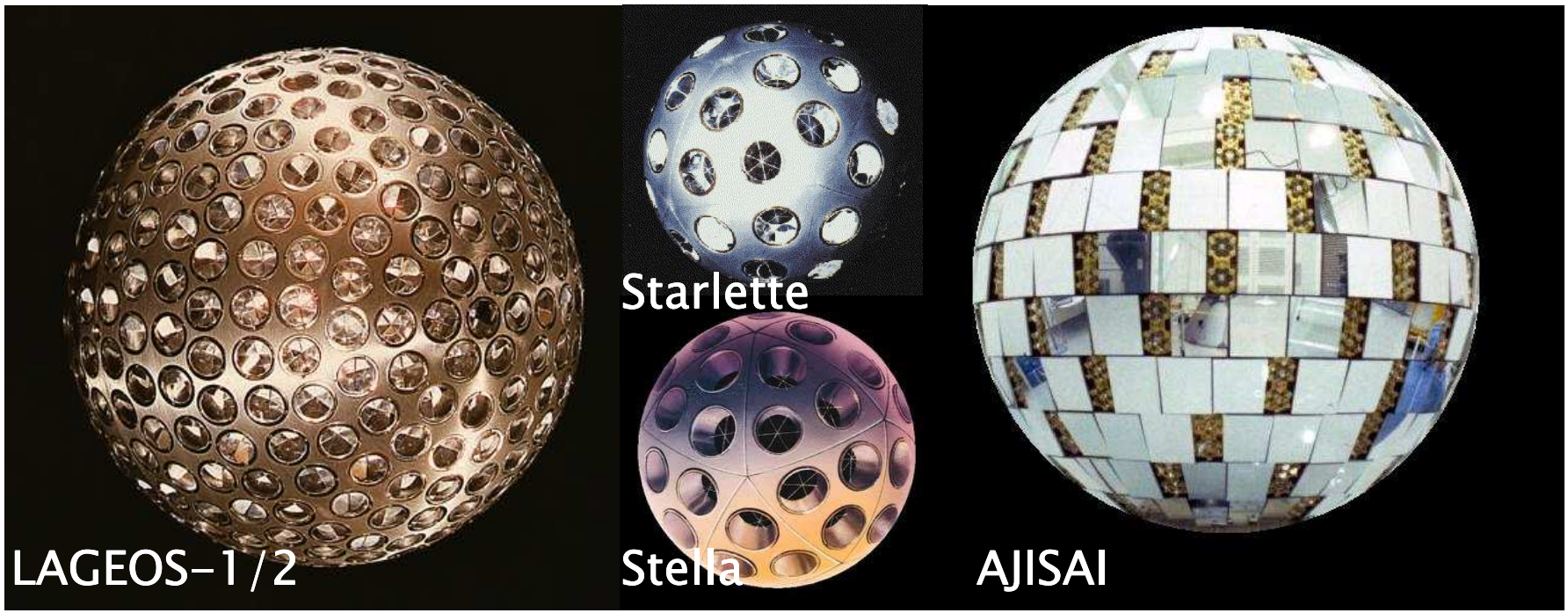
	Emissivity	Reflectivity
Solution 1	NO	NO
Solution 2	YES	NO
Solution 3	NO	YES
Solution 4	YES	YES

Multi-satellite solution

Multi-satellite solution

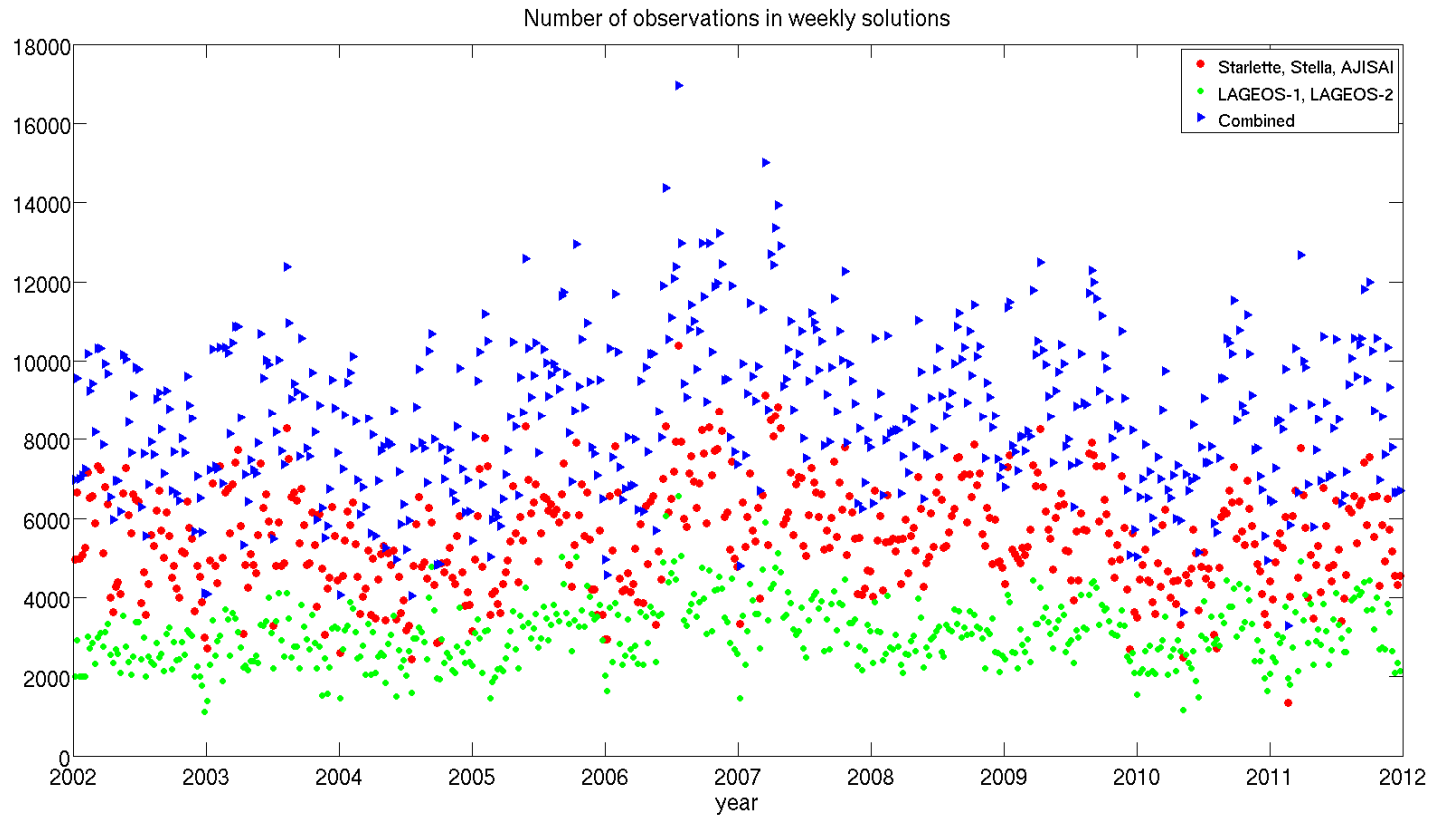
Current International Laser Ranging System's (ILRS) products:

- LAGEOS-1/2 & Etalon-1/2 solutions only,
- On average ~3000 normal points to LAGEOS-1/2 and ~300 normal points to Etalon-1/2 per week,
- The impact of Etalon-1/2 on the solution is virtually negligible



Multi-satellite solution

- Some of the SLR stations do not observe LAGEOS, e.g., Helwan, Egypt (7831), Mendeleevo, Russia (1870)



	LAGEOS-1	LAGEOS-2	AJISAI	Starlette	Stella
No of normal points per week	1500	1500	3000	1600	800

	LAGEOS-1/2	LEO	Combined
No of stations per week	19.8	21.1	22.4

Why LEO satellites are neglected?

It is more difficult to model Starlette, Stella, AJISAI (LEO) orbits, because of:

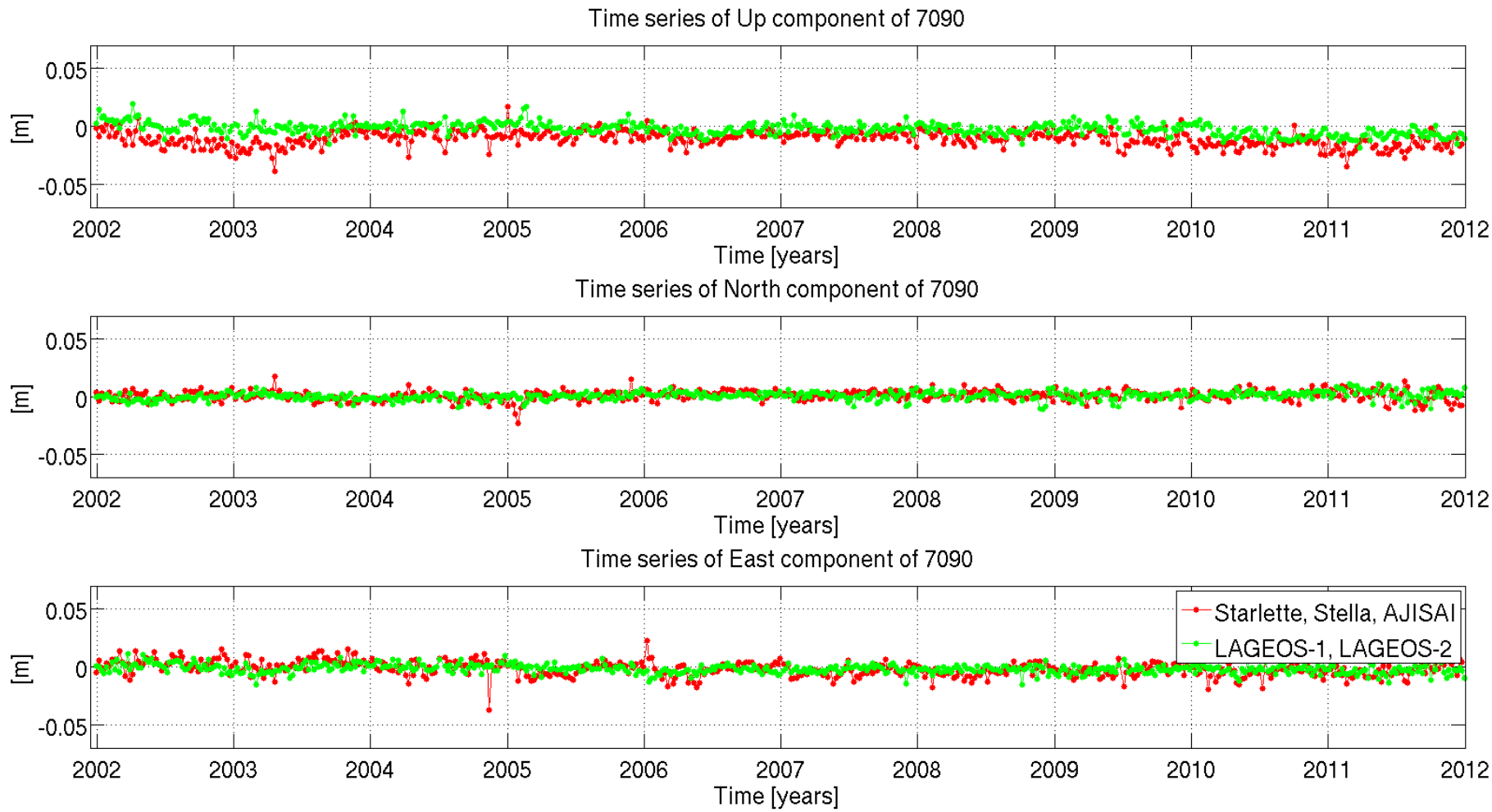
- higher sensitivity to the Earth gravity field and to the temporal variations of the gravity field,
- uncertainties in air drag models and variations of air density in the high atmosphere,
- deficiencies of SLR station-specific Center-of-Mass corrections (CoM), due to different laser systems used in SLR stations.

Solution set-up

In the Starlette, Stella, and AJISAI (LEO) 7-day solutions we apply the air drag NRLMSISE-00 model with fixed scaling factors and we estimate:

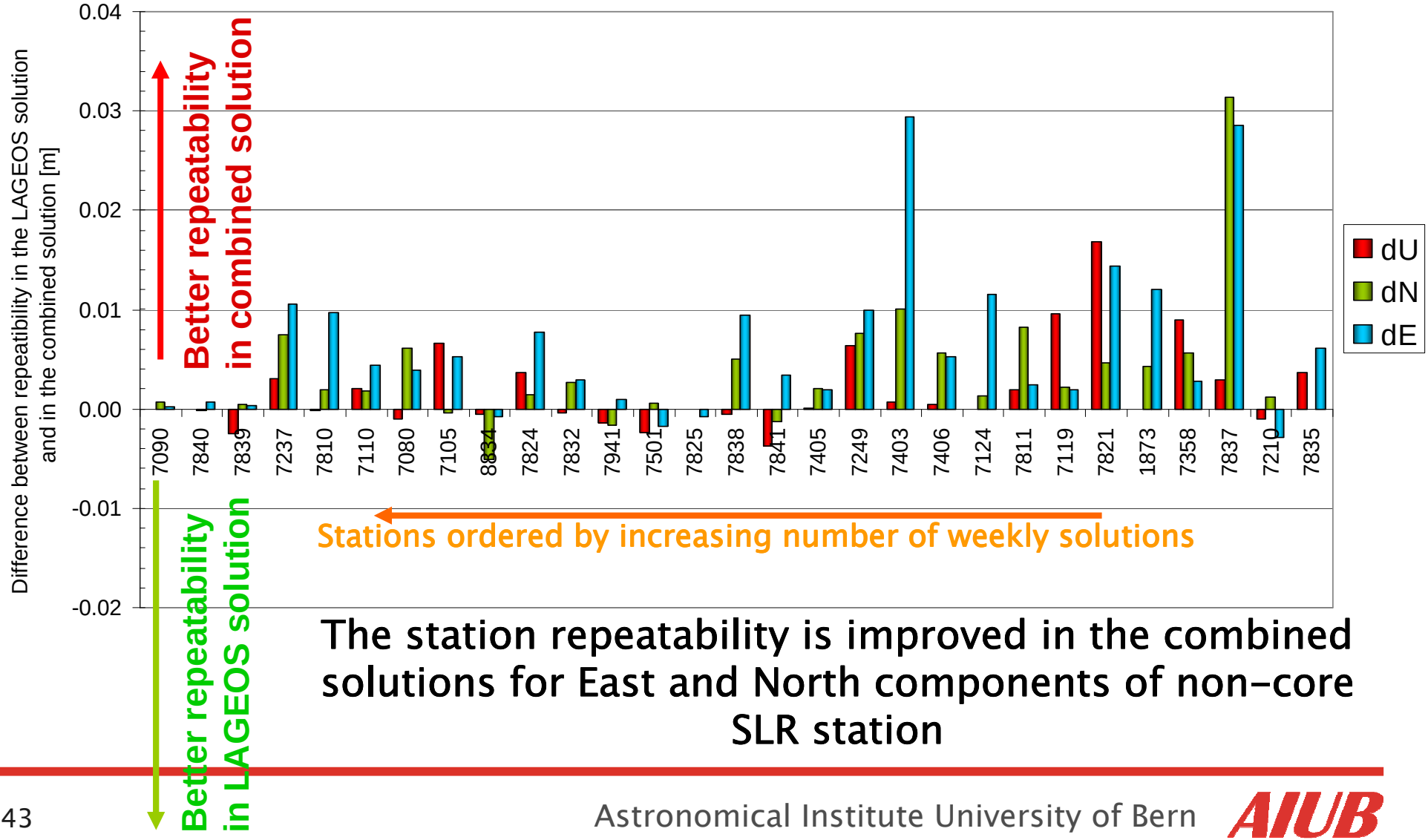
- Orbits:
  - six osculation elements (daily)
  - constant (S0) and OPR sine and cosine terms (SS/SC) in along-track (daily),
  - OPR sine and cosine terms (WS/WC) in out-of-plane (daily),
  - pseudo-stochastic pulses in along-track (every revolution period) -> similar to CHAMP/GRACE/GOCE orbit solutions
- station coordinates (one set per 7-day arc),
- range biases (for all satellites and all stations, one set per 7-day arc),
- gravity field coefficients up to degree/order 4/4 (one set per 7-day arc),
- Piece Wise Linear (PWL) pole coordinates and Length-of-Day (one set at the daily boundary).

Results: Station coordinates



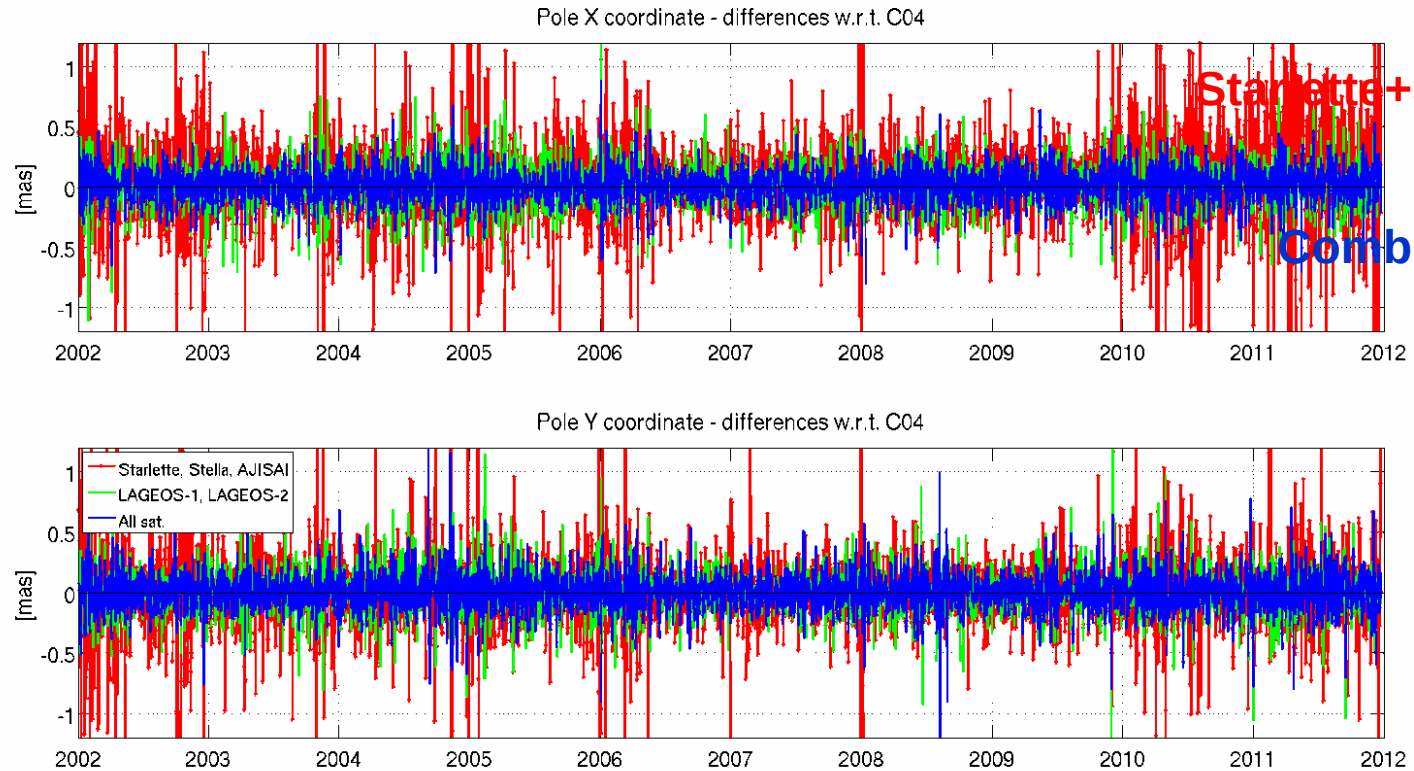
Results: Station coordinates

Station coordinate repeatability
in LAGEOS-1/2 and the combined solutions



The station repeatability is improved in the combined solutions for East and North components of non-core SLR station

Results: Earth Rotation Parameters (w.r.t. IERS C04)



Starlette+Stella+AJISAI

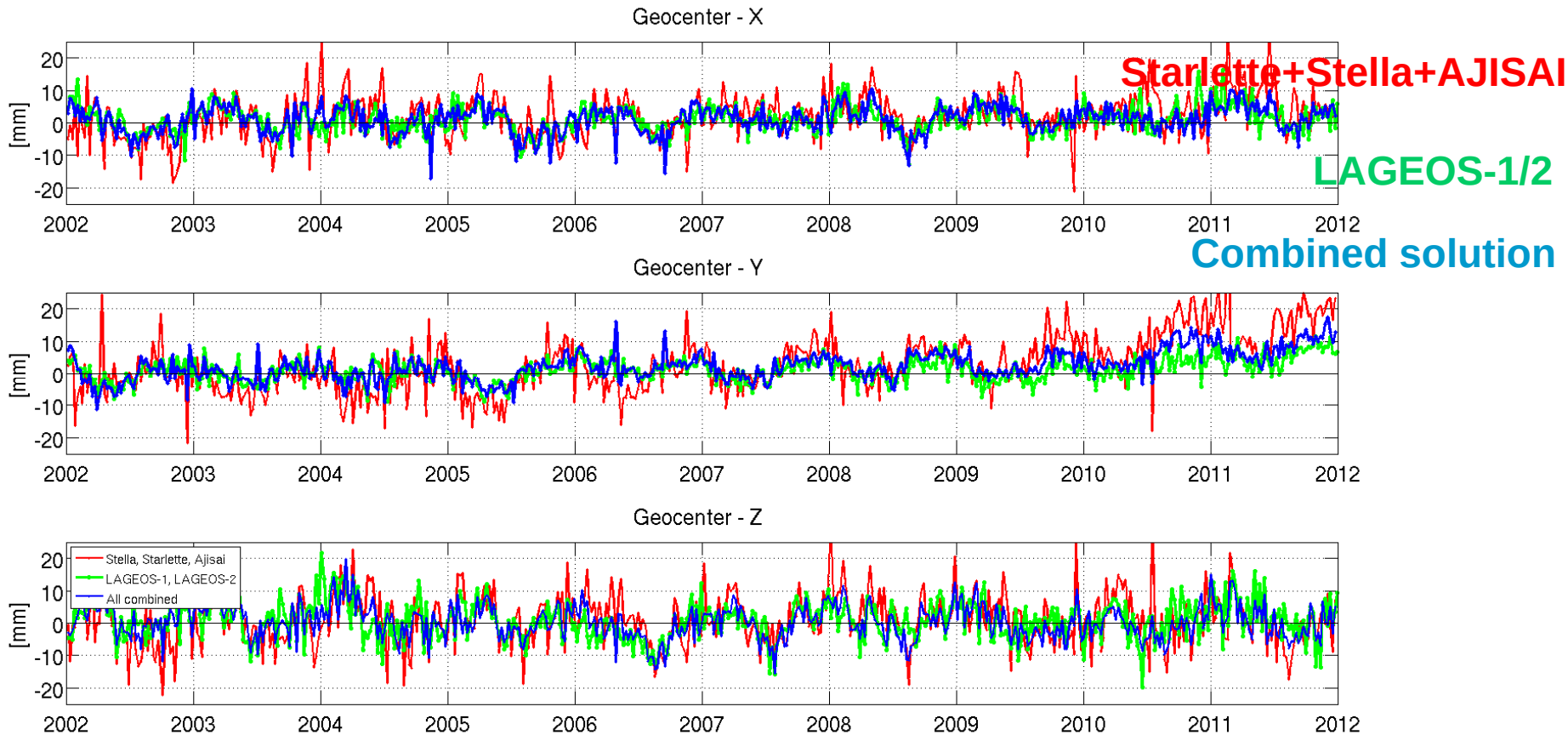
LAGEOS-1/2

Combined solution

		Starlette, Stella, Ajisai	Lageos -1/2	Combined solution
Mean bias	X pole	57.7 µas	4.1 µas	6.4 µas
	Y pole	-8.7 µas	-8.0 µas	-8.5 µas
	LOD	-3.6 µs	6.1 µs	6.3 µs
Weighted RMS	X pole	269.8 µas	160.0 µas	148.9 µas
	Y pole	218.1 µas	155.2 µas	140.3 µas
	LOD	106.5 µs	57.0 µs	56.3 µs

7% for X pole
10% for Y pole

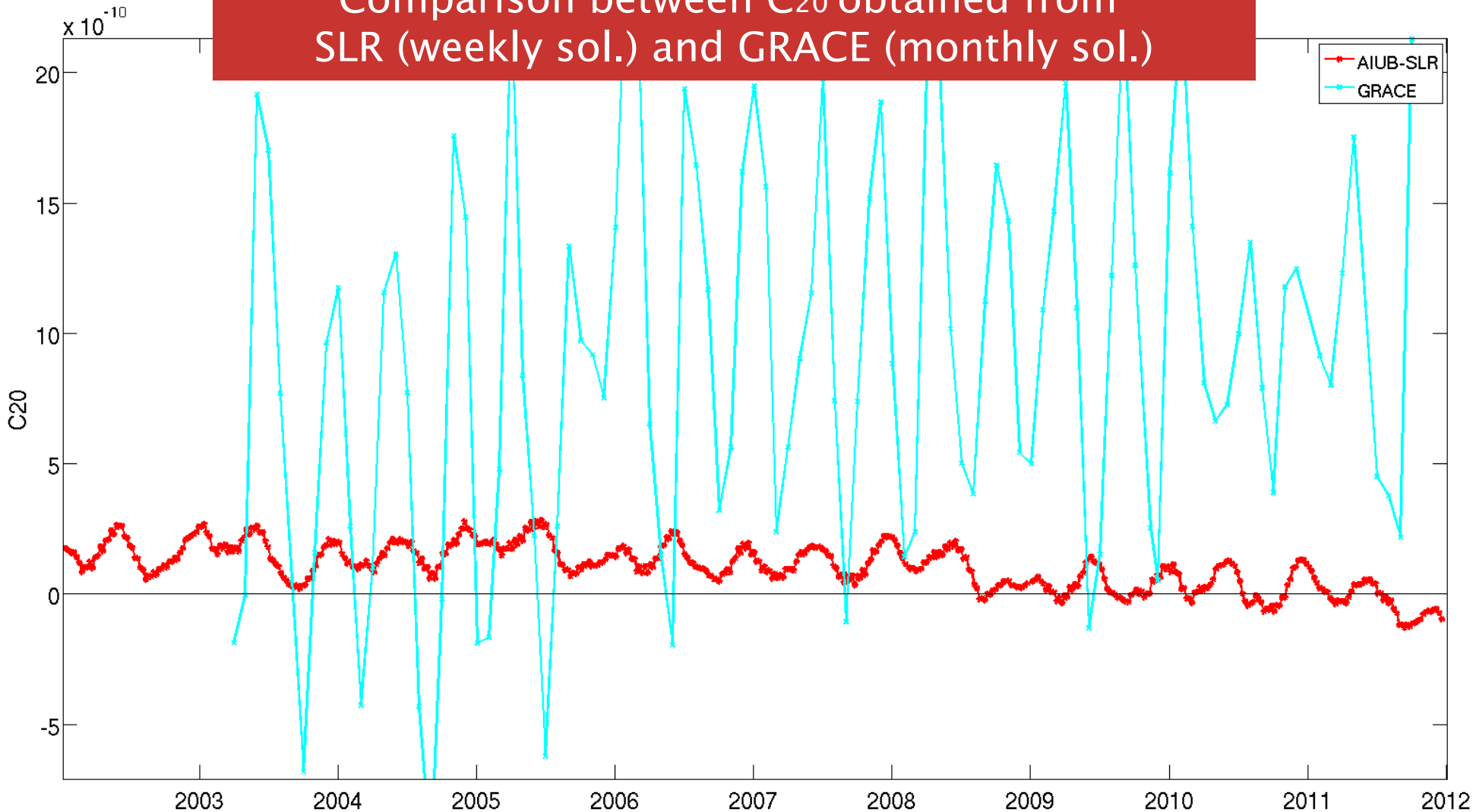
Results: Geocenter



	X			Y			Z		
	LEO	LAGEOS	LEO+ LAGEOS	LEO	LAGEOS	LEO+ LAGEOS	LEO	LAGEOS	LEO+ LAGEOS
RMS	6.67	4.02	4.23	9.06	3.67	4.56	7.97	**5.99**	**5.33**
Amplitude of annual signal	2.97	2.99	3.40	5.28	2.49	2.94	4.68	3.64	4.13

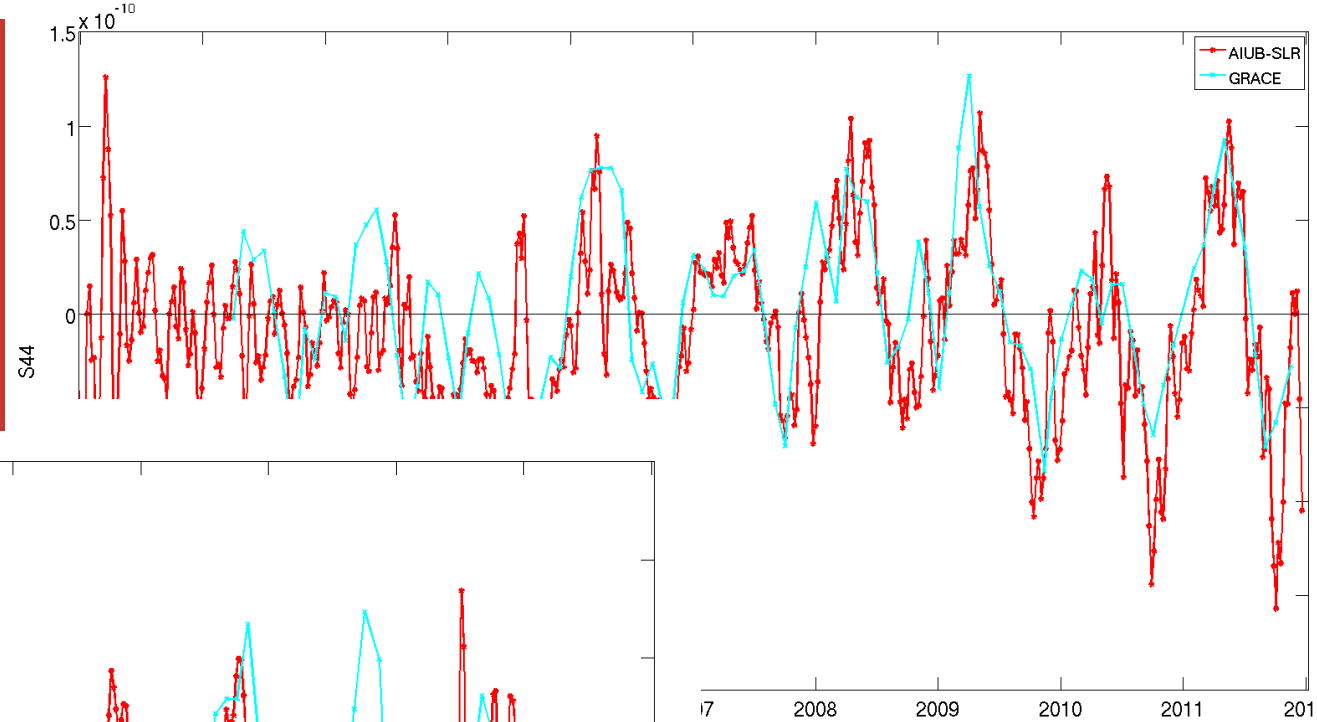
Results: Gravity field coefficients

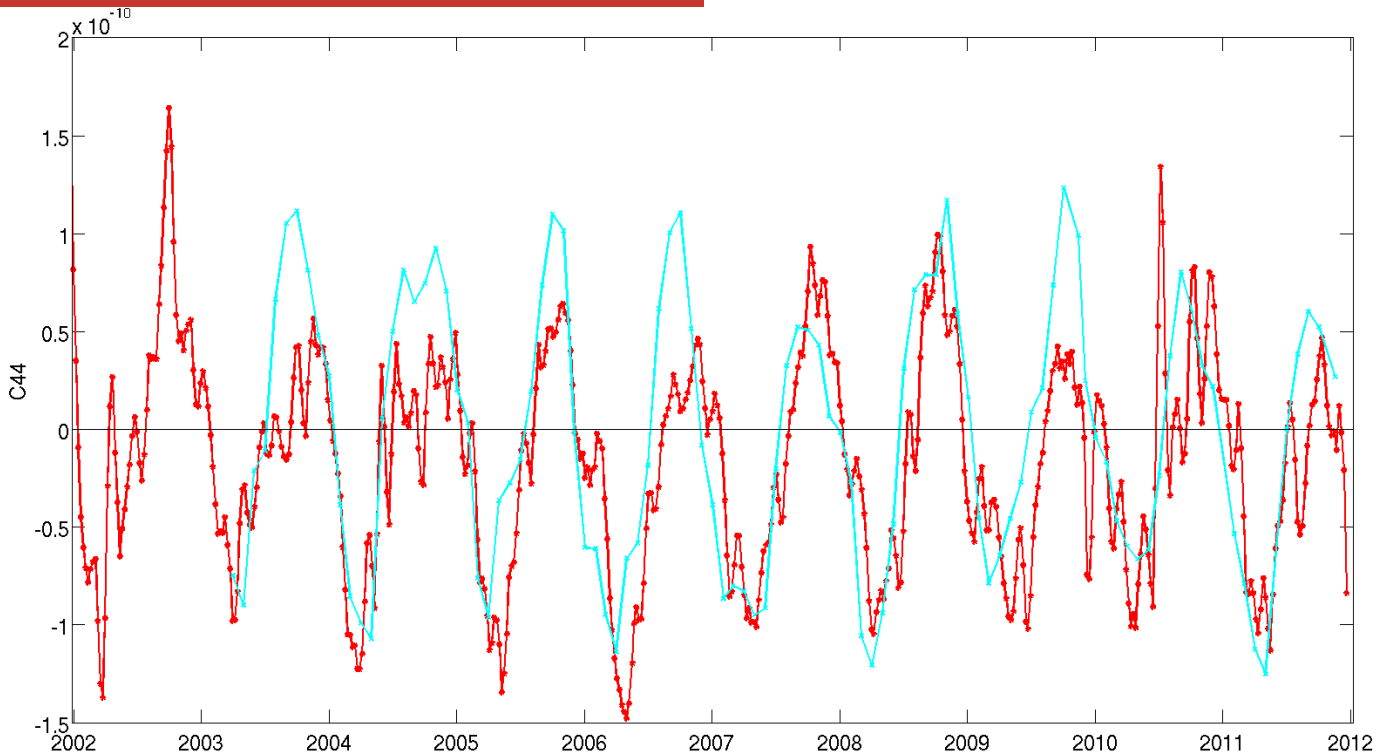
Comparison between C_{20} obtained from SLR (weekly sol.) and GRACE (monthly sol.)



Results: Gravity field coefficients

SLR observations of geodetic satellites are still a very efficient tool for the determination of low gravity field harmonics





Summary

- Special handling of non-gravitational forces is important in order to achieve orbits of the highest precision,
- Thermal effects and atmospheric drag cause a decay of satellites‘ semi-major axes,
- Earth Albedo has an impact on SLR-derived scale,
- LAGEOS-only solutions can be improved by combining with lower geodetic satellites,
- Low spherical can be well established using SLR observations of geodetic satellites.

Thank you for your attention

Astronomical Institute, University of Bern, Switzerland

Special acknowledgments to:

- AIUB: Daniela Thaller, Adrian Jäggi, Rolf Dach, Christian Baumann, Gerhard Beutler, et al.,
- Swiss National Science Foundation for the financial support within the SNF Project 200021E-131228

ETH Zurich, 14.11.2012