

Towards INPOP07

Adjustments to Lunar Laser Ranging data

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ILRS fall workshop
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INPOP

Planetary Numerical Integration of the Paris Observatory

- motion the planets, Moon, Sun and 300 asteroids
- librations of the Moon
- orientation of the Earth

INPOP05: « copy » of DE405 (model + initial conditions and parameters)

INPOP06: improvement of the dynamical model (asteroids, Earth orientation)

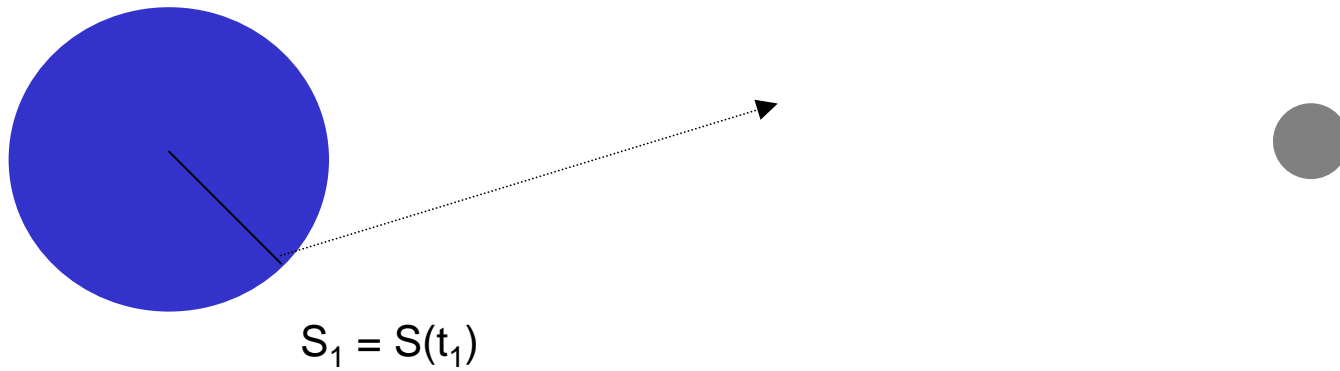
+ fitted to planetary observations (Agnès Fienga)

+ fitted to the Earth-Moon distance of DE405

INPOP07: fitted directly to LLR data

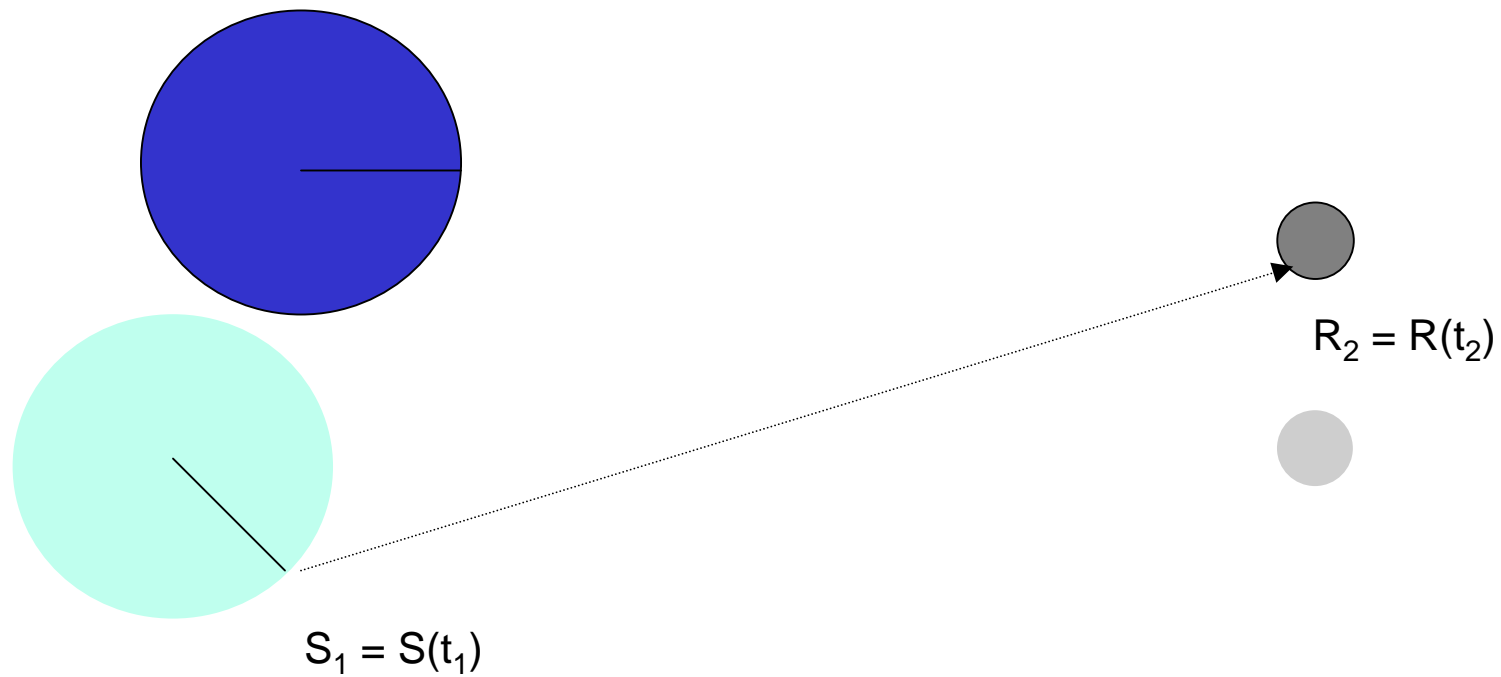
LLR observation

Light time between a station (3) on the Earth and a reflector (4) on the Moon



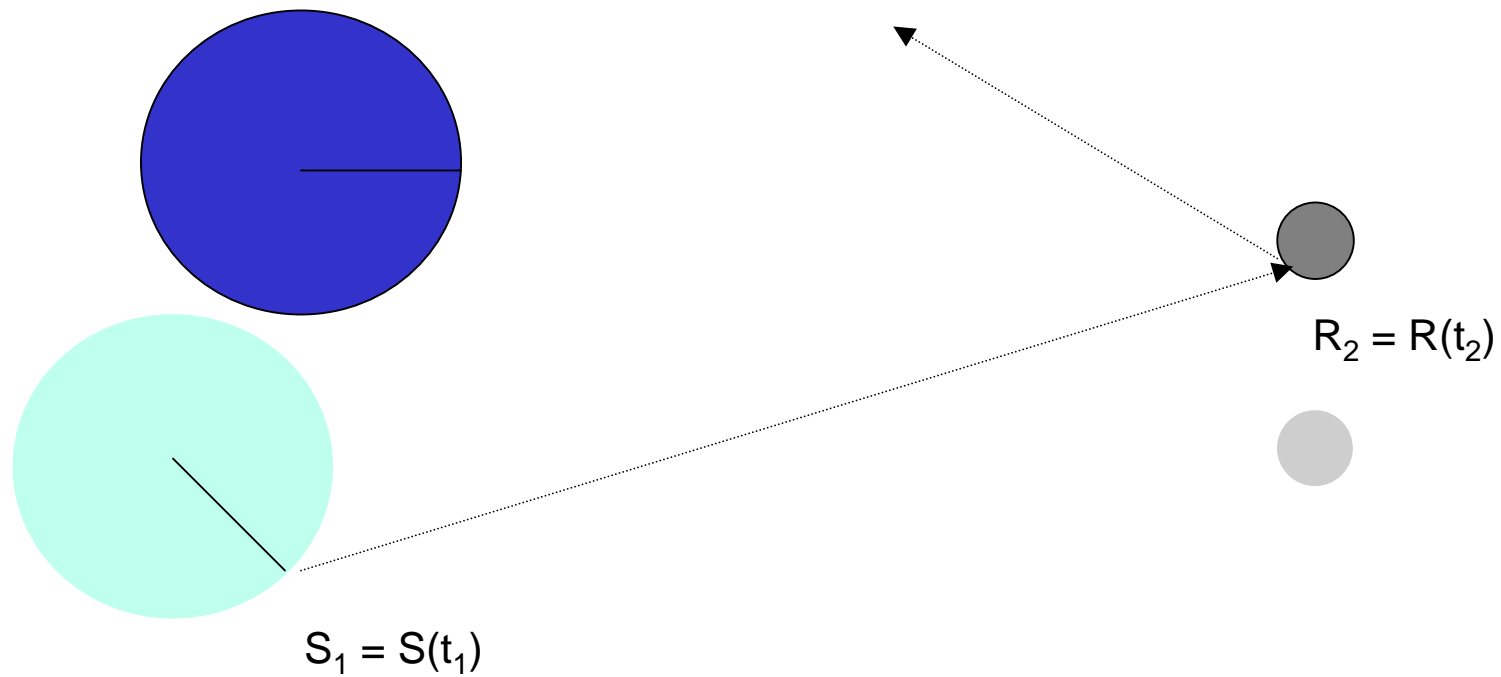
LLR observation

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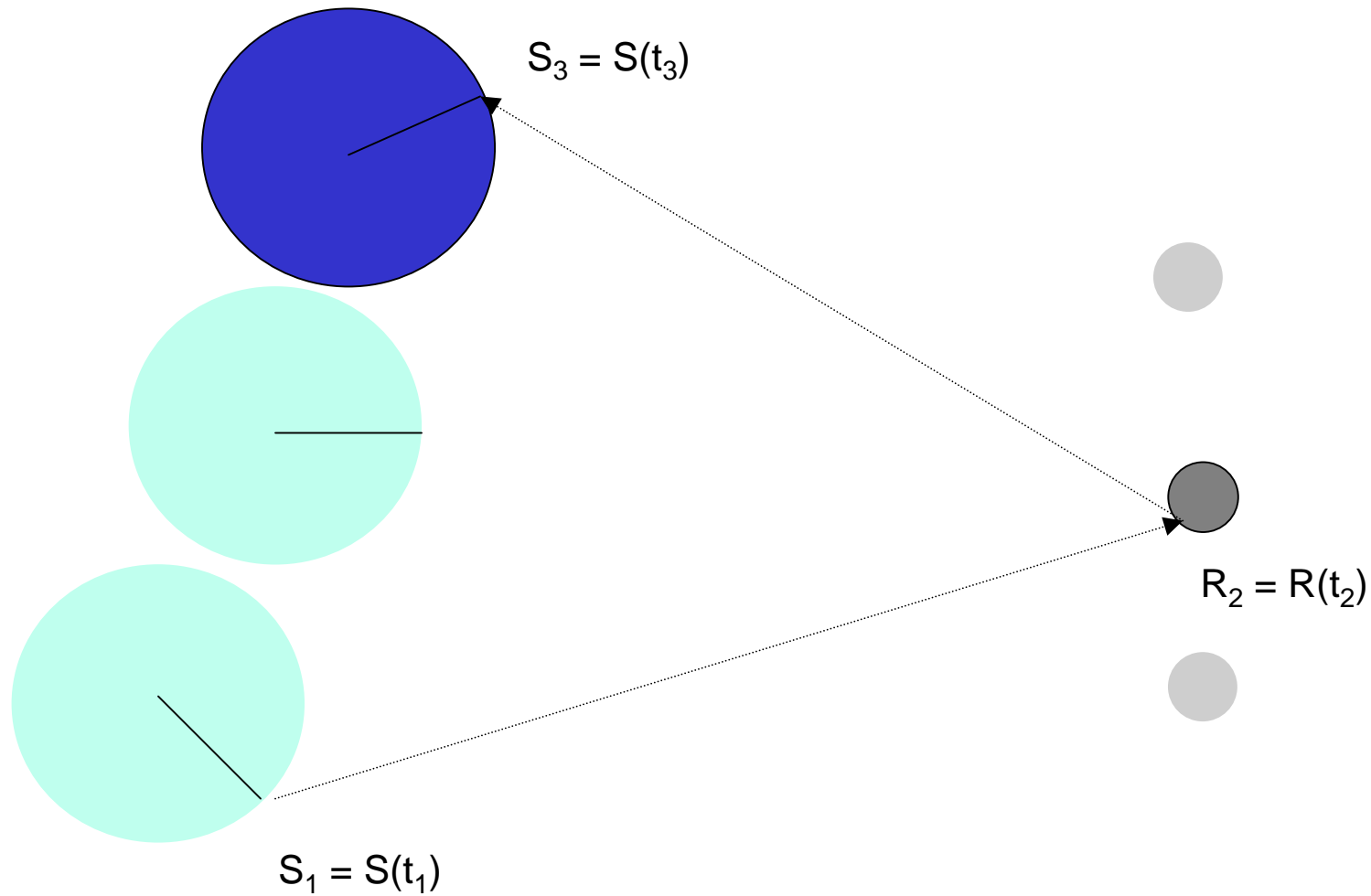
LLR observation

Light time between a station (3) on the Earth and a reflector (4) on the Moon



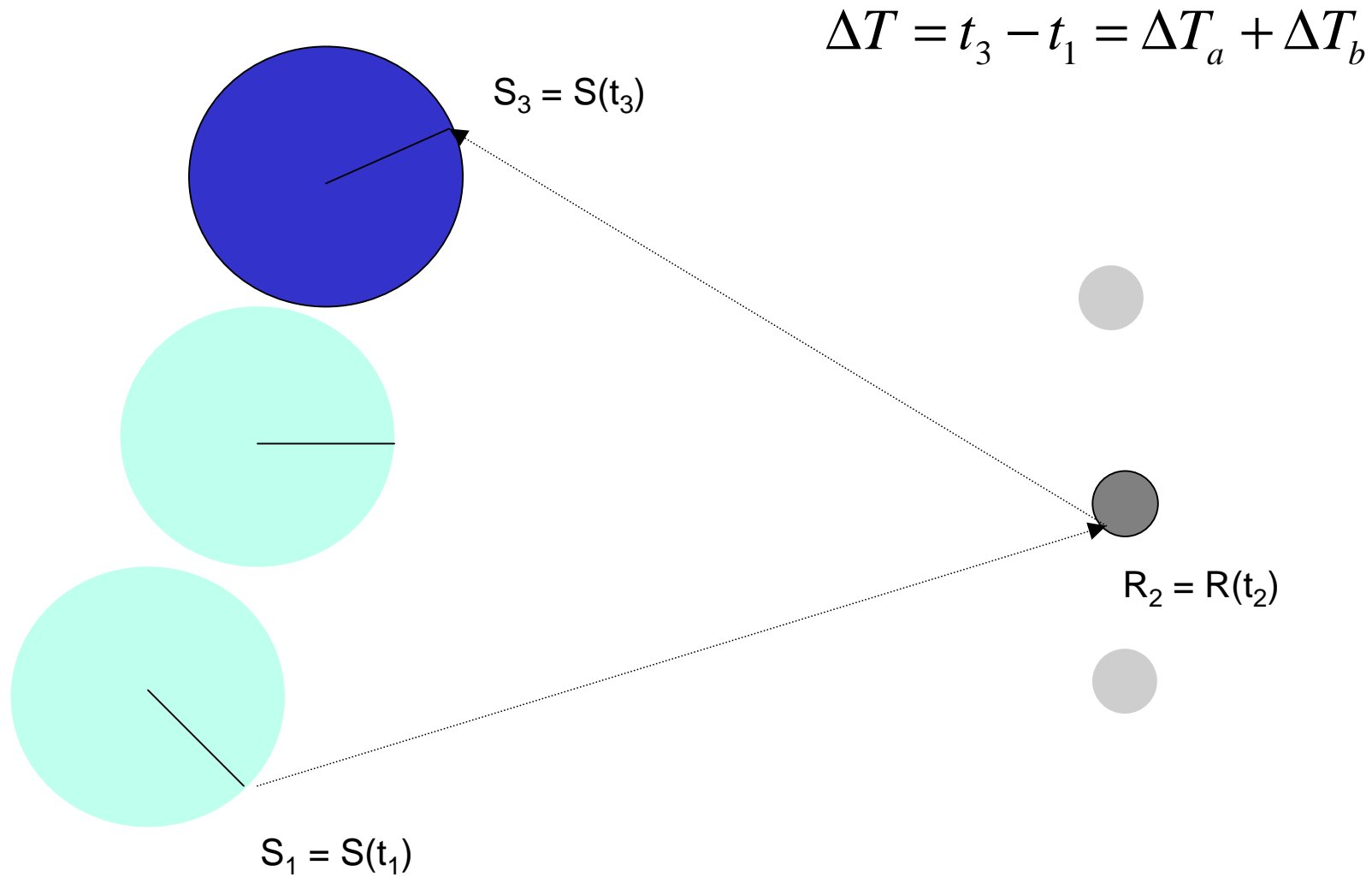
LLR observation

Light time between a station (3) on the Earth and a reflector (4) on the Moon



LLR observation

Light time between a station (3) on the Earth and a reflector (4) on the Moon



$$\Delta T_a = \frac{\left\| \overrightarrow{BM}_2 + \overrightarrow{M}_2\overrightarrow{R}_2 - \left(\overrightarrow{BE}_1 + \overrightarrow{E}_1\overrightarrow{S}_1 \right) \right\|}{c} + \Delta T_{GR} + \Delta T_{atm}$$

B: Solar System Barycenter (origin of the reference frame)

E: center of mass of the Earth

M: center of mass of the Moon

S: station

R: reflector

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↑
↑
 INPOP(t_2) INPOP(t_1)

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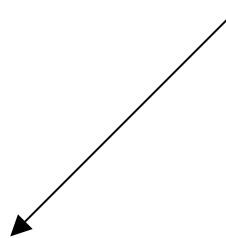
S: station

R: reflector

$$\Delta T_a = \frac{\left\| \overrightarrow{BM}_2 + \overrightarrow{M}_2 R_2 - \left(\overrightarrow{BE}_1 + \overrightarrow{E}_1 S_1 \right) \right\|}{c} + \Delta T_{GR} + \Delta T_{atm}$$

IERS Conventions 2003

- Position of the station (ITRF2000)
- Displacement due to the deformation of the Earth:
 - Plate tectonic
 - Solid tides raised by Sun and Moon (V. Dehant)
 - Polar tide
 - Atmospheric loading
 - Ocean loading
- Transformation from GTRF to GCRF (CIP + C04 EOP series)
- Transformation from GCRF to BCRF

$$\Delta T_a = \frac{\left\| \overrightarrow{BM}_2 + \overrightarrow{M}_2\overrightarrow{R}_2 - \left(\overrightarrow{BE}_1 + \overrightarrow{E}_1\overrightarrow{S}_1 \right) \right\|}{c} + \Delta T_{GR} + \Delta T_{atm}$$


Williams & al., 1996

- relative positions of Sun, station and reflector
- relative positions of Earth, station and reflector
- Post newtonian parameter γ

$$\Delta T_a = \frac{\left\| \overrightarrow{BM}_2 + \overrightarrow{M}_2R_2 - \left(\overrightarrow{BE}_1 + \overrightarrow{E}_1S_1 \right) \right\|}{c} + \Delta T_{GR} + \Delta T_{atm}$$

Marini & Murray, 1973

- position of the station (ϕ, H)
- true elevation of the reflector
- meteorological conditions (P, T, %)
- laser wavelength

Time scales

Earth orientation (sideral time)

UT1



EOP C04 series

Time of observation



Leap of second

TAI



Offset 32.184s

Earth orientation (CIP)

TT



Fairhead & Bretagnon, 1990

INPOP

T_{eph} , « TDB »

Time scales

Earth orientation (sideral time)

UT1

EOP C04 series

Time of observation

UTC

Leap of second

TAI

Offset 32.184s

Earth orientation (CIP)

TT

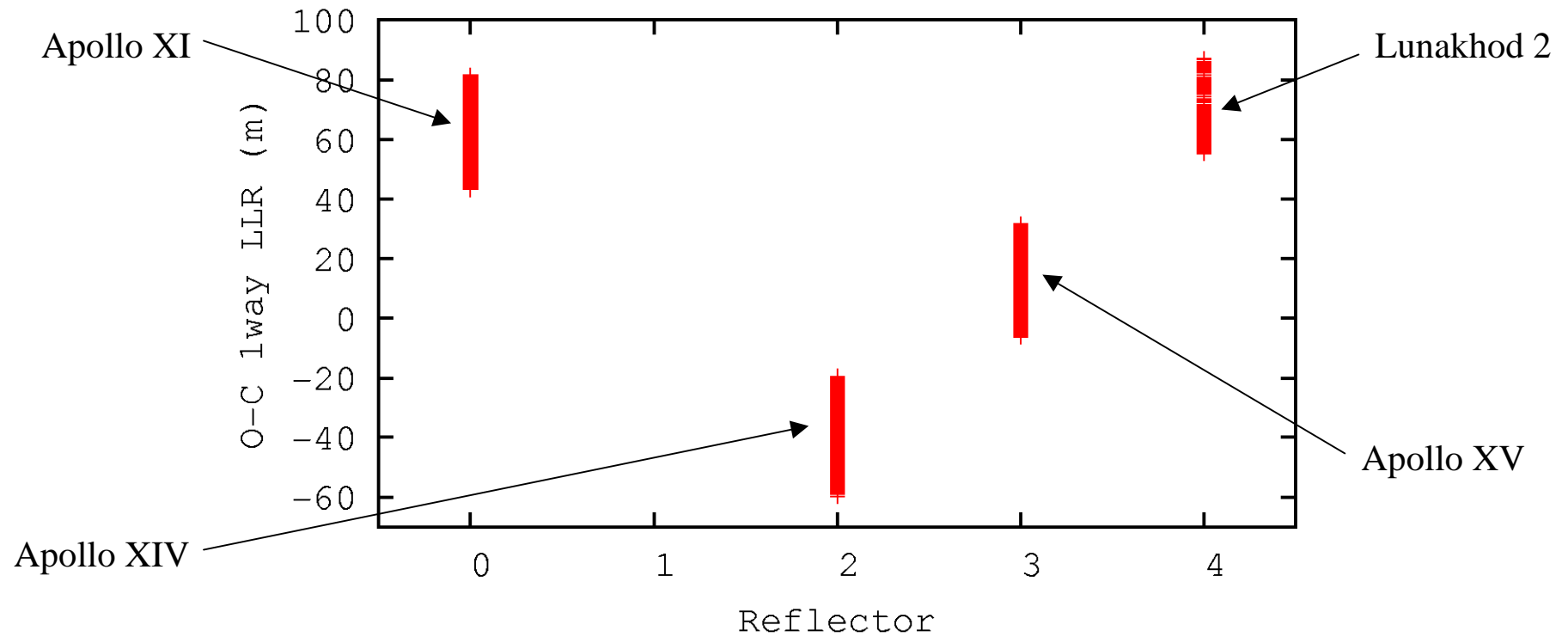
Fairhead & Bretagnon, 1990

INPOP

T_{eph} , « TDB »

IAU 2006 Resolution 3

INPOP06 residuals by reflector

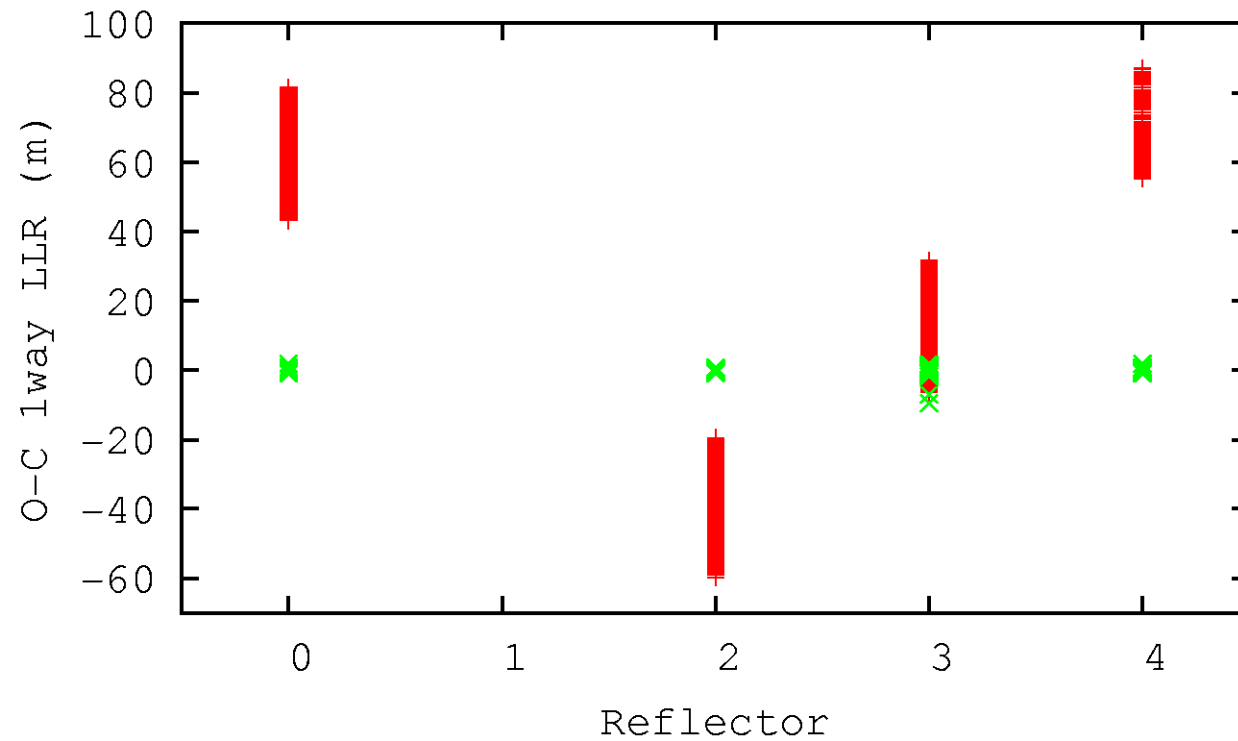


Grasse data, from 1988 to 2005 (8441 observations)

INPOP06 residuals

by reflector, **before** and **after** adjustments

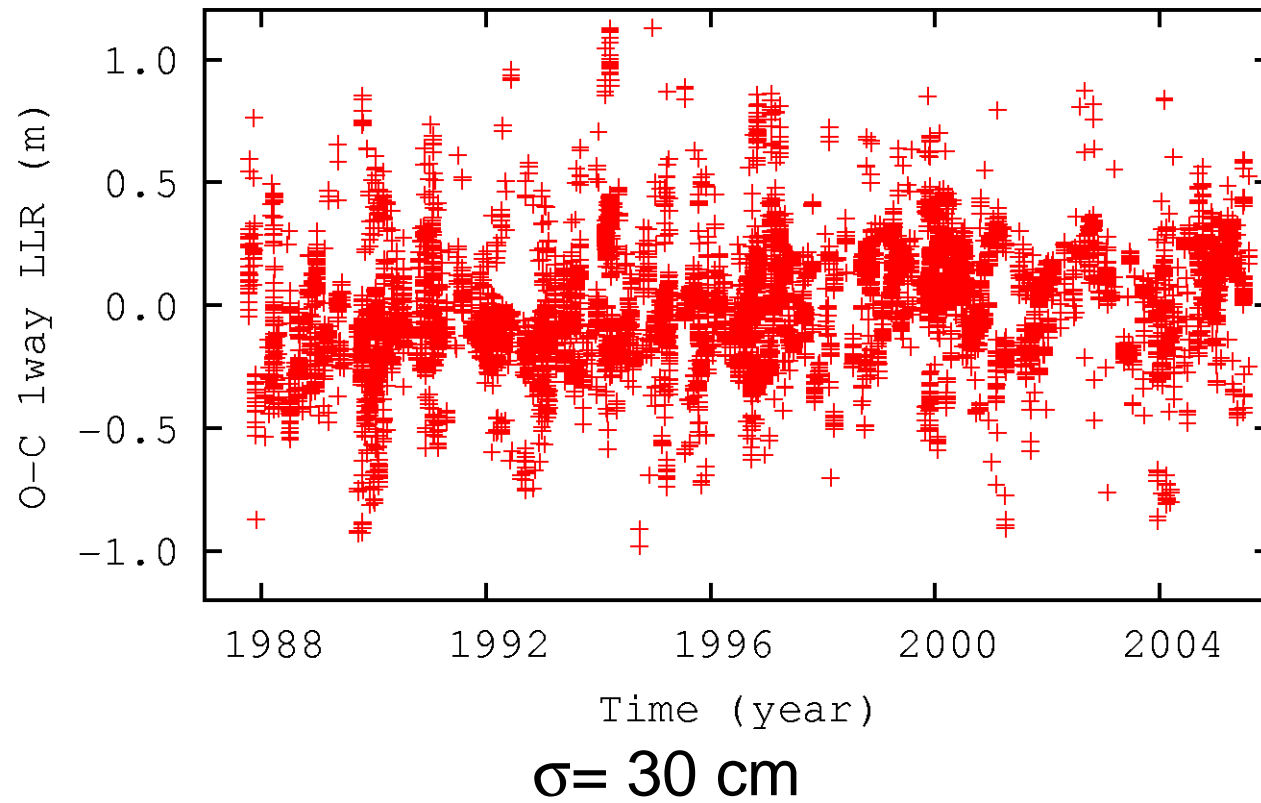
(positions of reflectors and Grasse station)



INPOP06 residuals

(best solution, positions of reflectors fitted)

Grasse data from 1987 to 2005



INPOP07 (*work in progress*)

Adjustments:

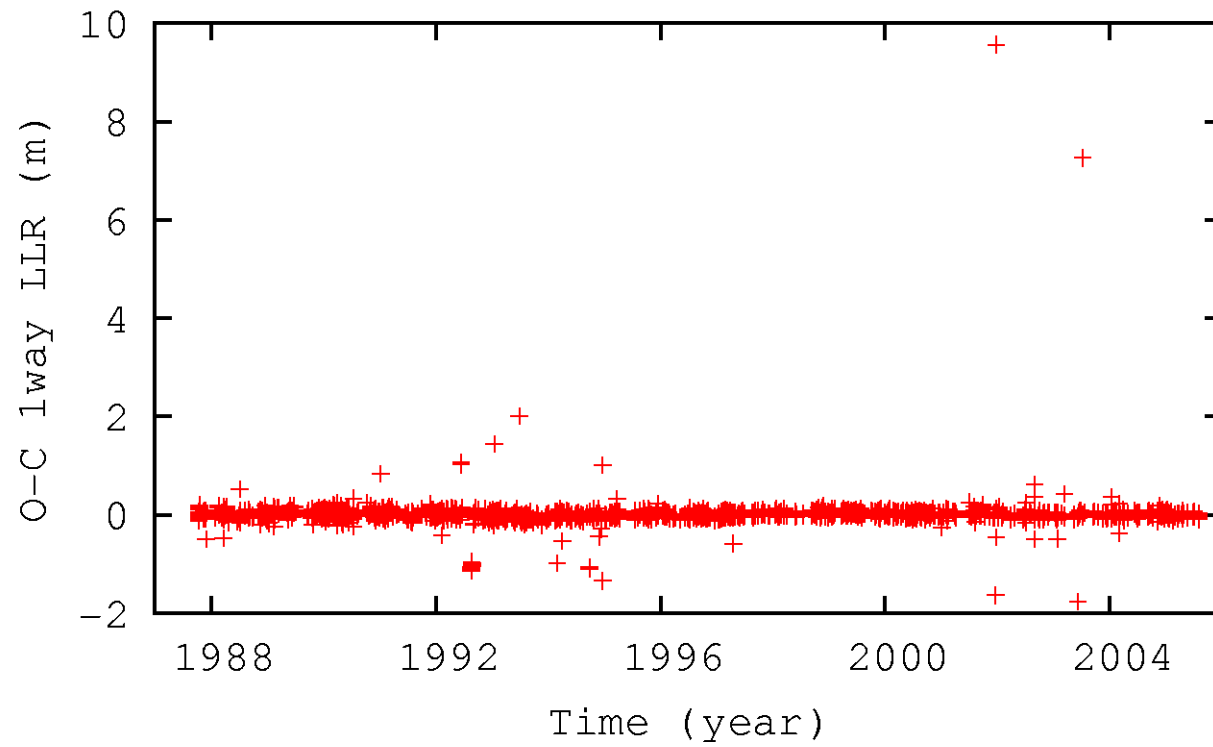
- Selenocentric positions of reflectors (12)
- Geocentric position of the station (3)
- Initial conditions for the Earth-Moon vector (6)
- Initial conditions for libration angles (6)
- Time delays (3), lunar Love numbers (3) and potential coefficients (18), C/MR^2 , offset

→ 53 parameters

Fit only on Grasse data from 1987 to 2005

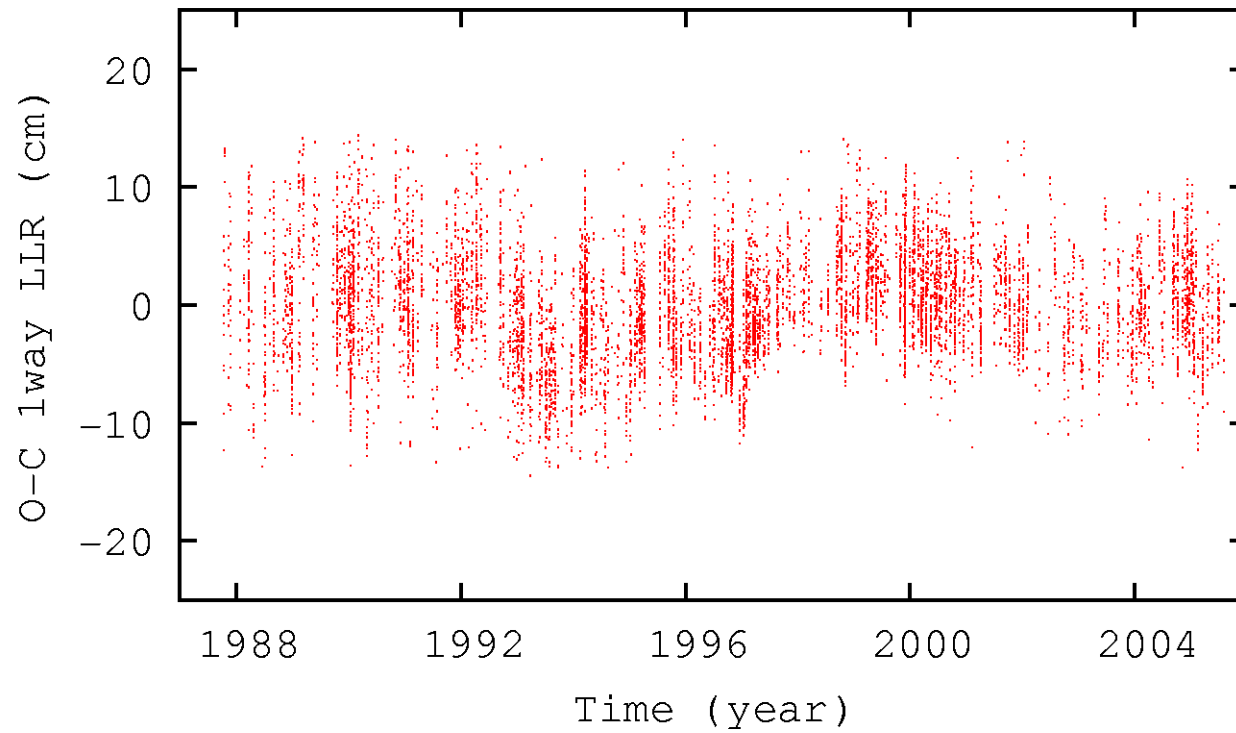
INPOP07 residuals

all Grasse data from 1987 to 2005



INPOP07 residuals

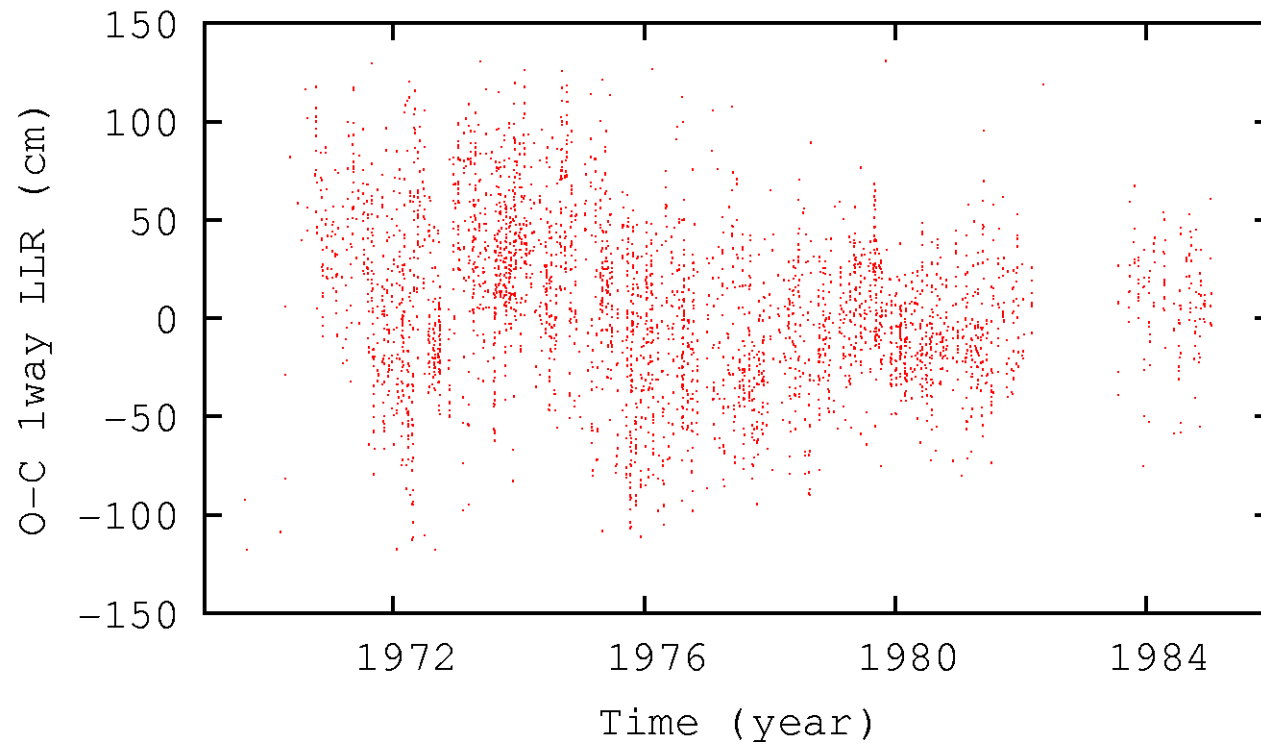
outliers $>3\sigma$ rejected (179/8441)



$\sigma = 4,64$ cm

INPOP07 residuals

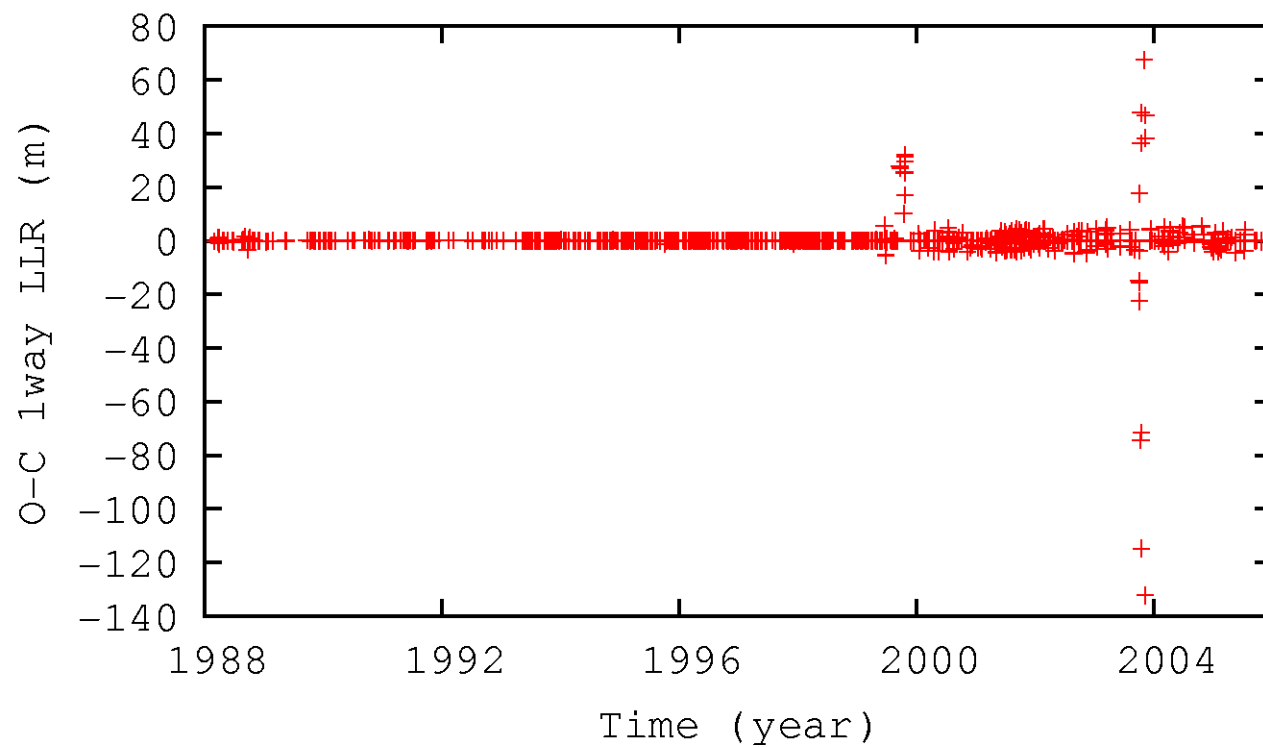
Projection on Mac Donald data
from 1969 to 1985



$$\sigma = 42 \text{ cm}$$

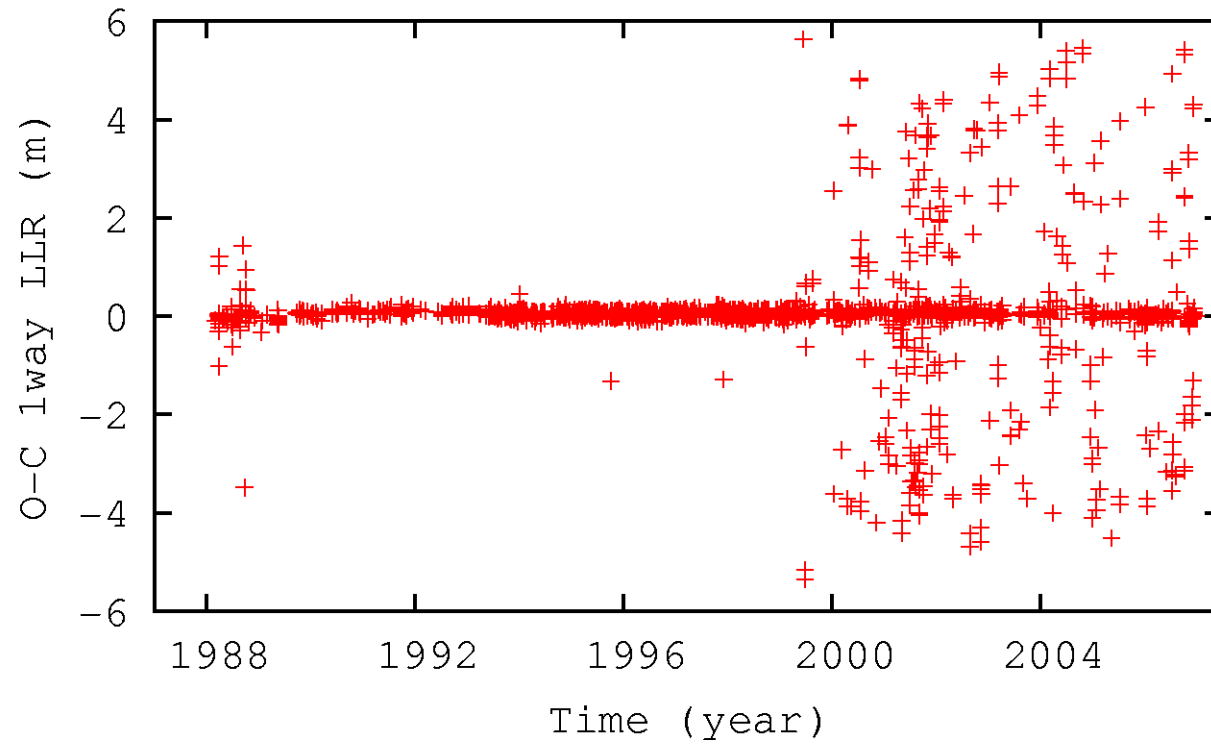
INPOP07 residuals

Projection on Mac Donald data
from 1988 to 2006



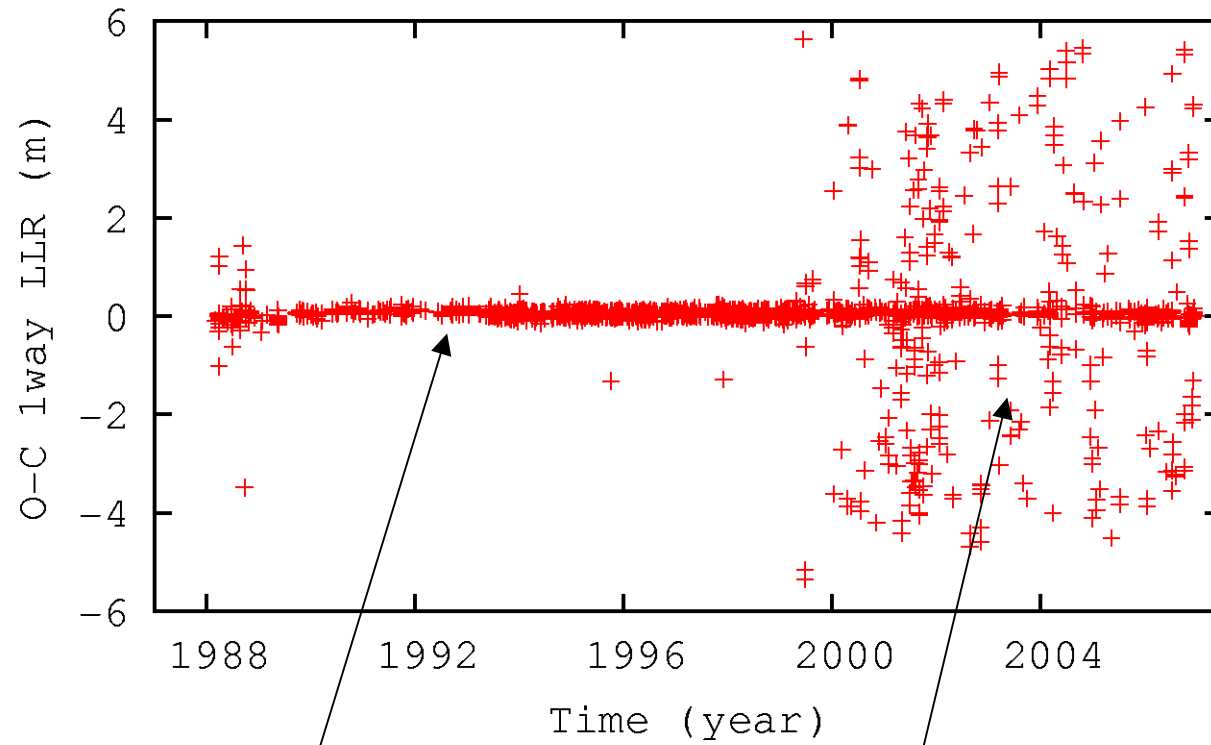
INPOP07 residuals

Projection on Mac Donald data
from 1988 to 2006



INPOP07 residuals

Projection on Mac Donald data
from 1988 to 2006



$\sigma = 4,7 \text{ cm}$

$\sigma = 110 \text{ cm}$