

Towards INPOP07

Adjustments to Lunar Laser Ranging data

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Systèmes de référence spatio-temporels
September, 18

Versions of INPOP

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

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

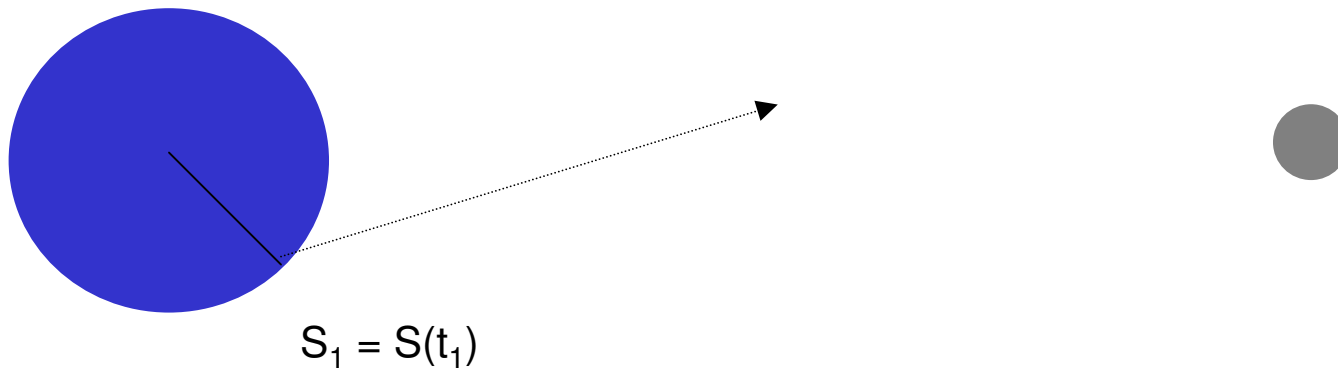
- + fitted to planetary observations (Agnès Fienga)

- + fitted to the Earth-Moon distance of DE405

INPOP07: fitted directly to LLR data

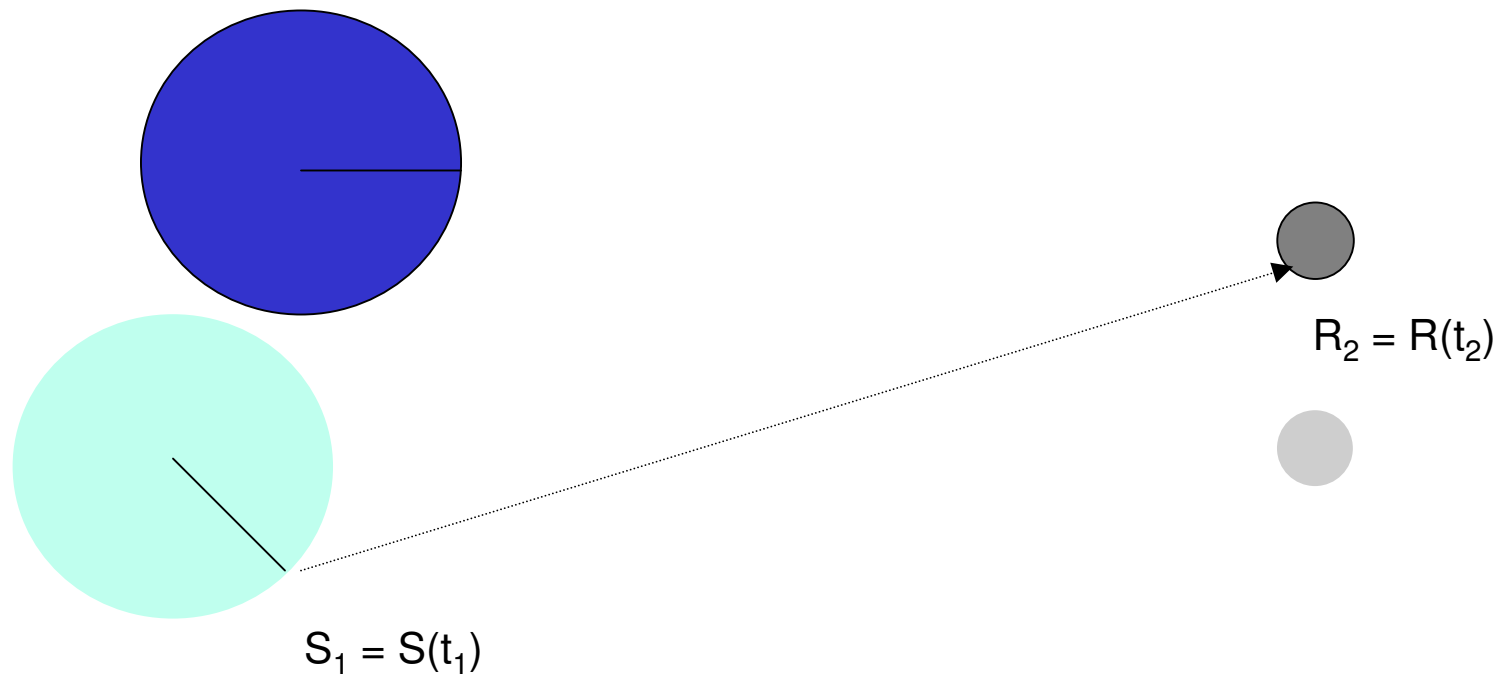
LLR observation

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



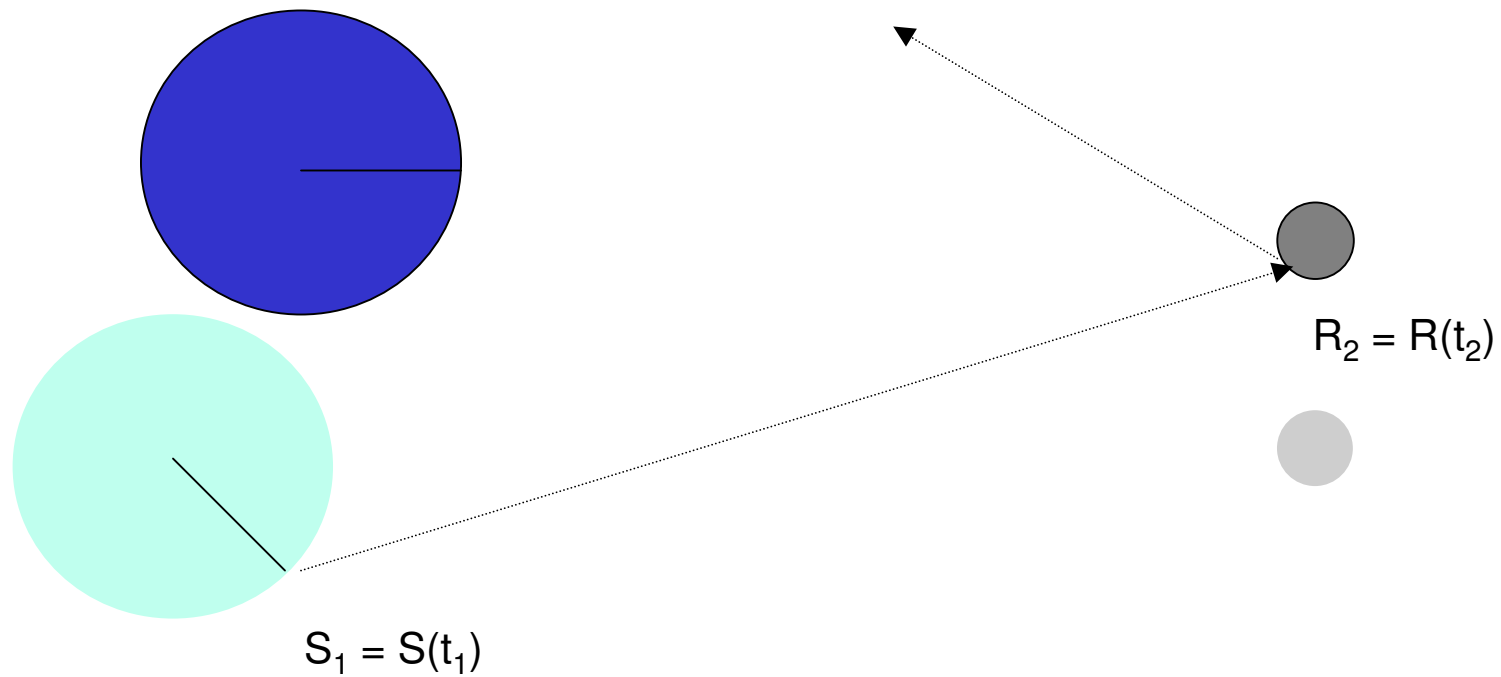
LLR observation

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



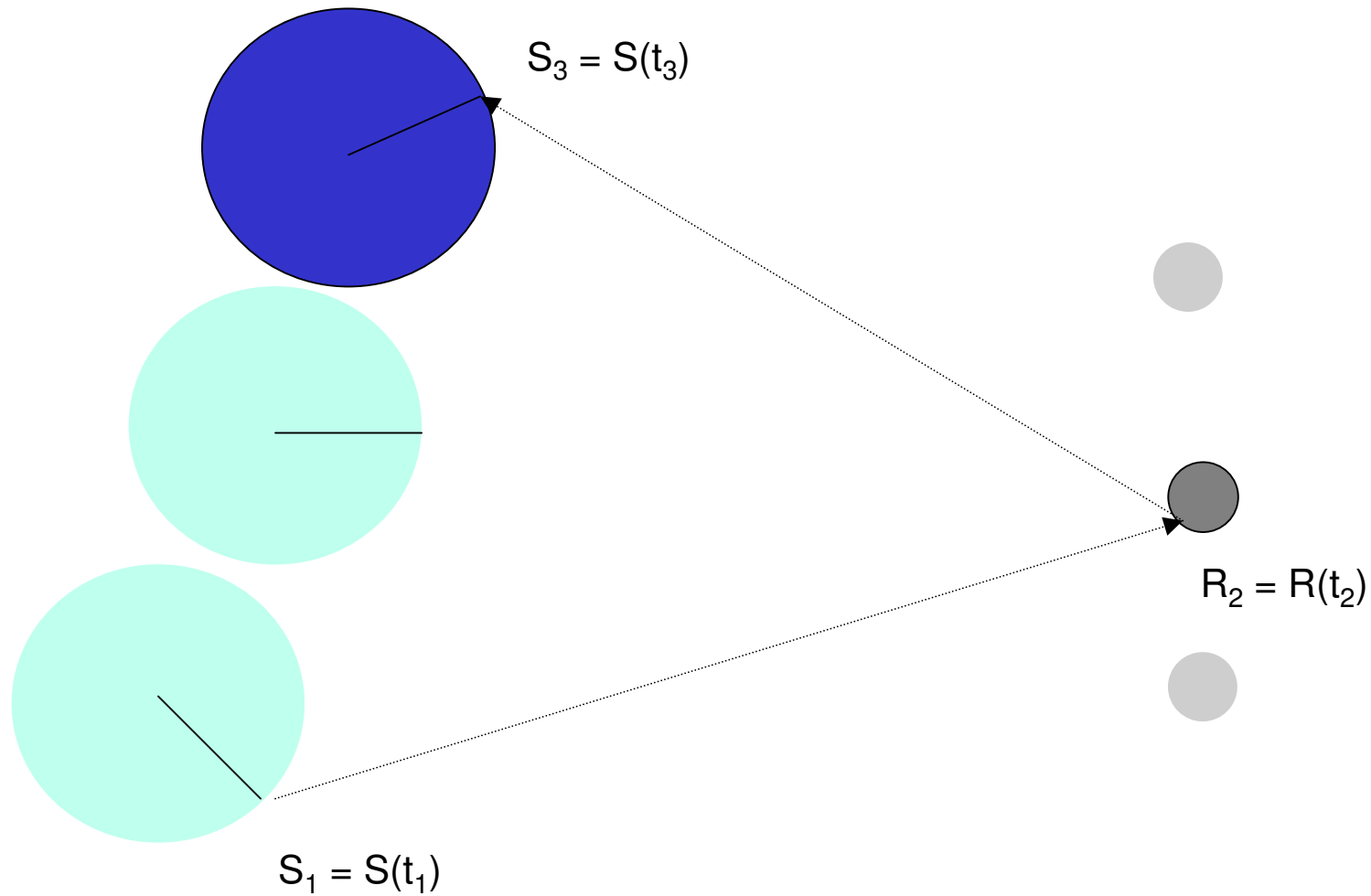
LLR observation

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



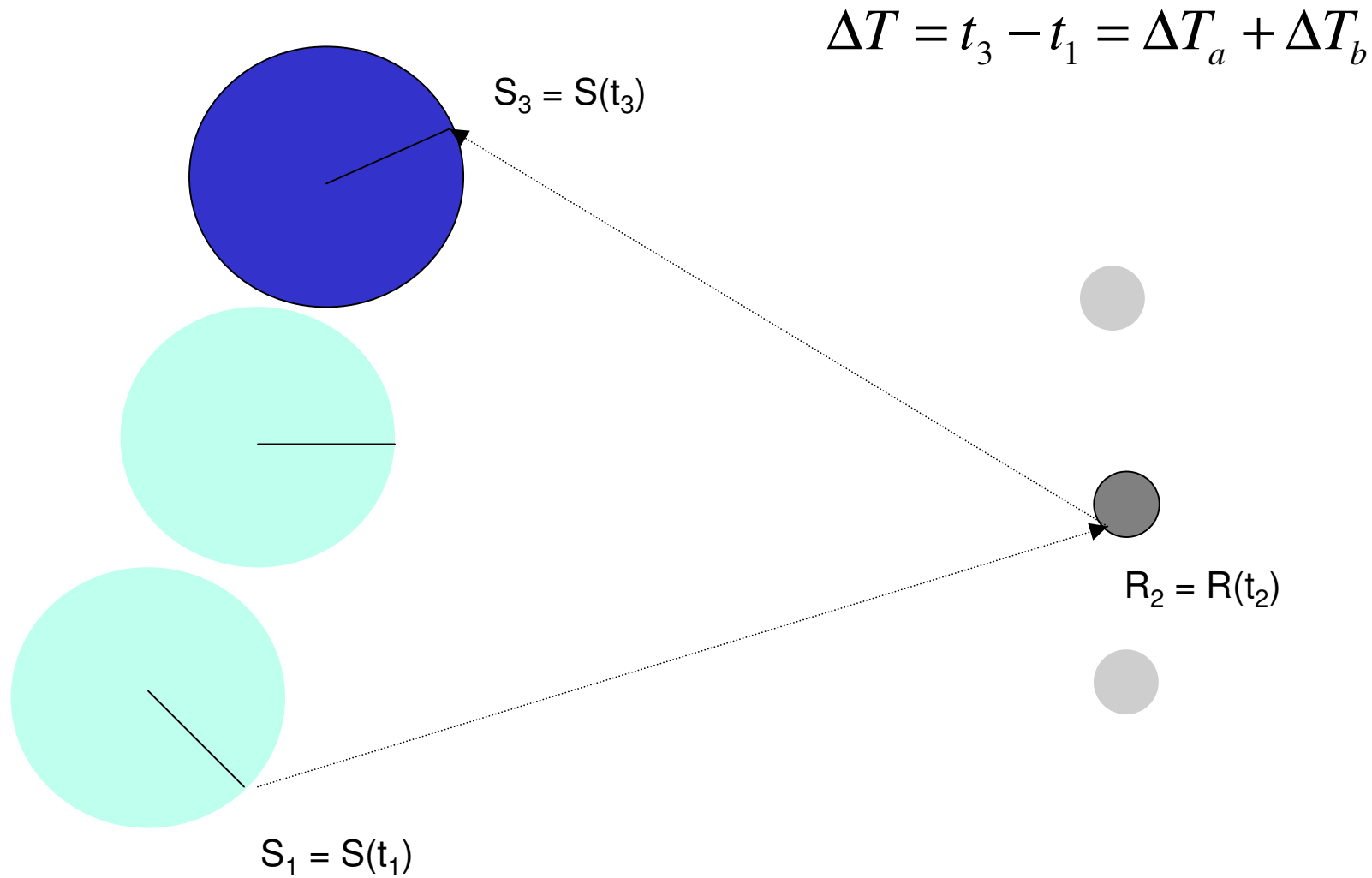
LLR observation

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



LLR observation

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



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

↑
↑
↑

INPOP(t₂)
INPOP(t₁)

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

E: center of mass of the Earth

M: center of mass of the Moon

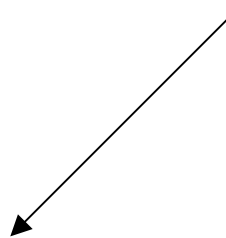
S: station

R: reflector

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

IERS Conventions 2003

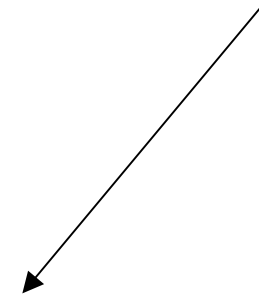
- Position of the station (ITRF2000)
- Displacement due to the deformation of the Earth:
 - Plate tectonic
 - Solid tides raised by Sun and Moon (V. Dehant)
 - Polar tide
 - Atmospheric loading
 - Ocean loading
- Transformation from GTRF to GCRF (CIP + C04 EOP series)
- Transformation from GCRF to BCRF

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


Williams & al., 1996

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

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



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

UTC

Leap of second

TAI

Offset 32.184s

Earth orientation (CIP)

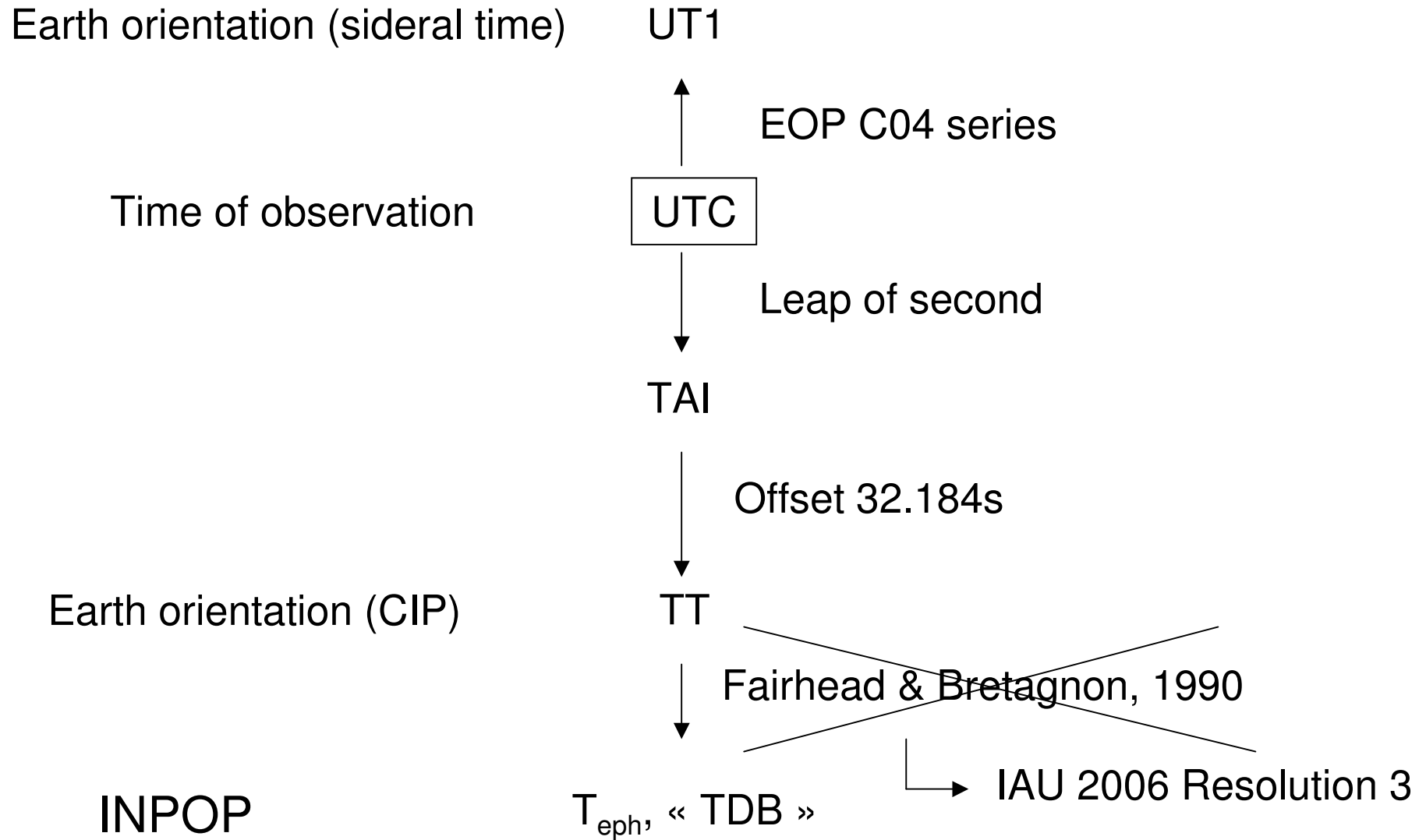
TT

Fairhead & Bretagnon, 1990

INPOP

T_{eph} , « TDB »

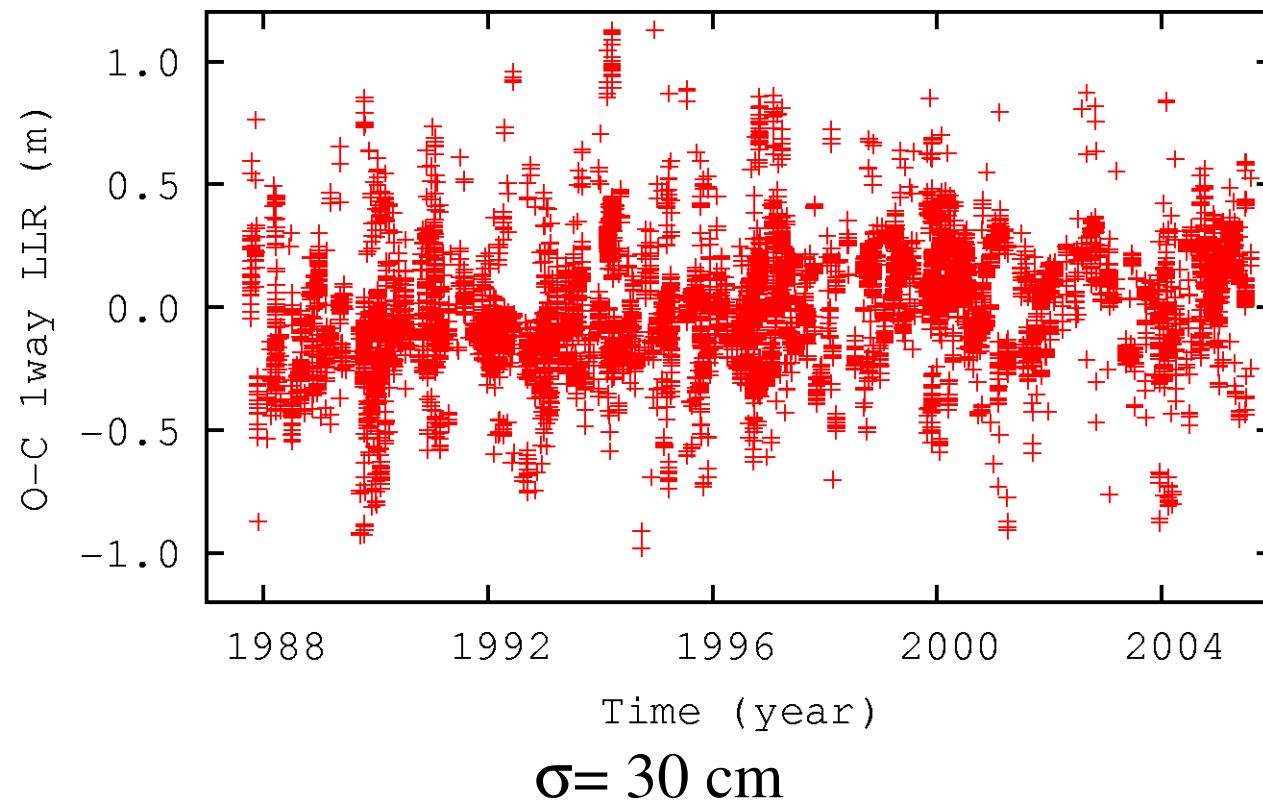
IAU 2006 Resolution 3



INPOP06 residuals

(best solution, positions of reflectors fitted)

Grasse data from 1987 to 2005



INPOP07 (*work in progress*)

Adjustments:

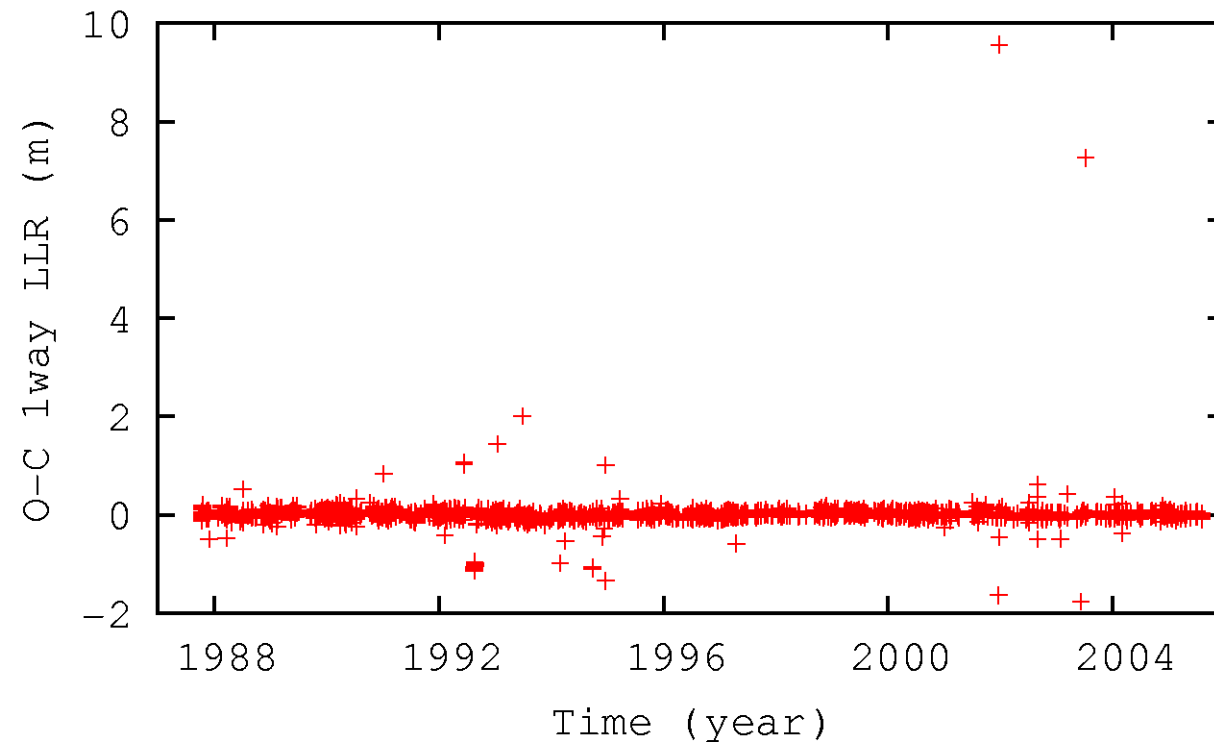
- Selenocentric positions of reflectors (12)
- Geocentric positions of the station (3)
- Initial conditions for the Earth-Moon vector (6)
- Initial conditions for libration angles (6)
- Time delays (3), lunar Love numbers (3) and potential coefficients (18), C/MR^2 , offset

→ 53 parameters

Fit only on Grasse data from 1987 to 2005

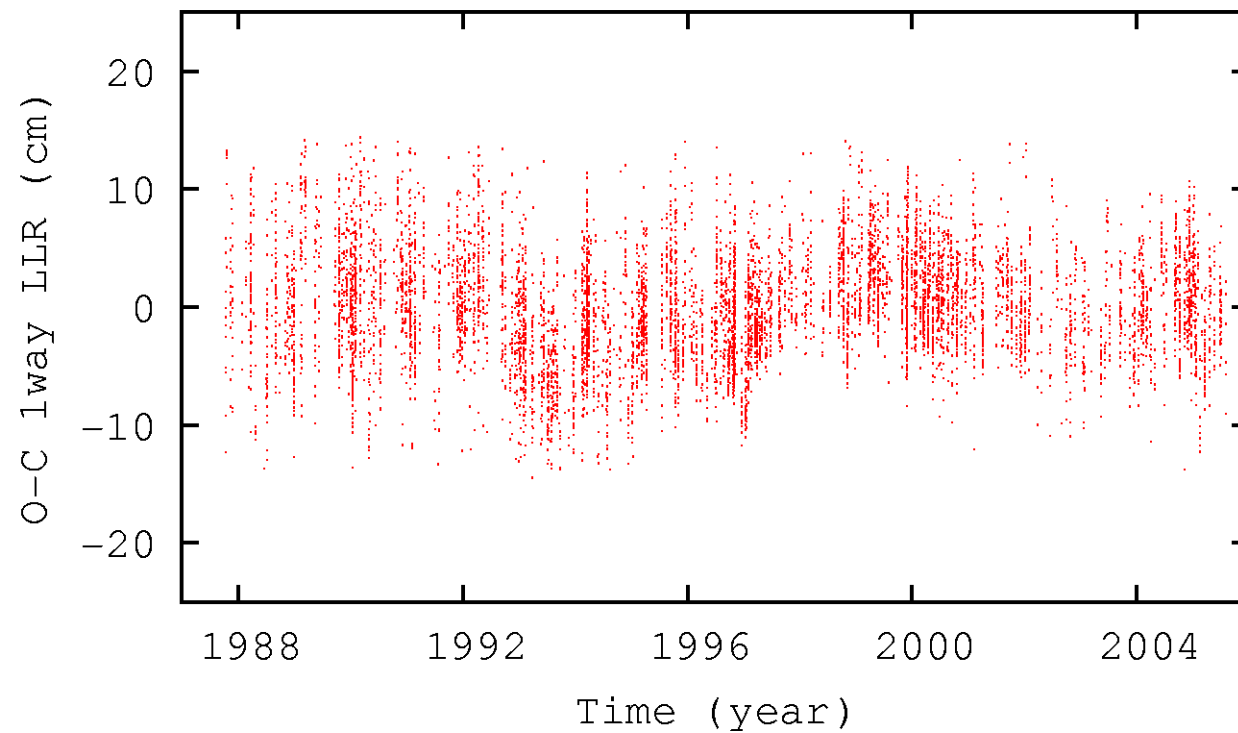
INPOP07 residuals

all Grasse data from 1987 to 2005



INPOP07 residuals

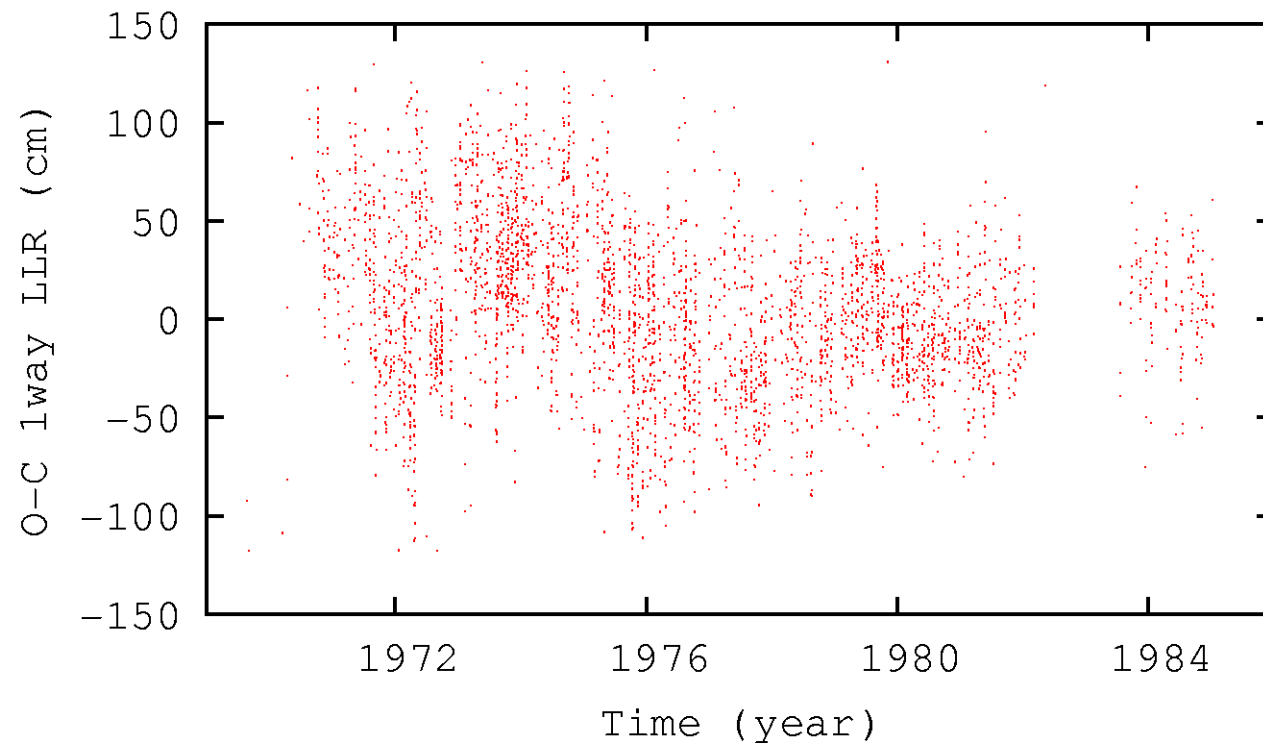
outliers $>3\sigma$ rejected (179/8441)



$$\sigma = 4,64 \text{ cm}$$

INPOP07 residuals

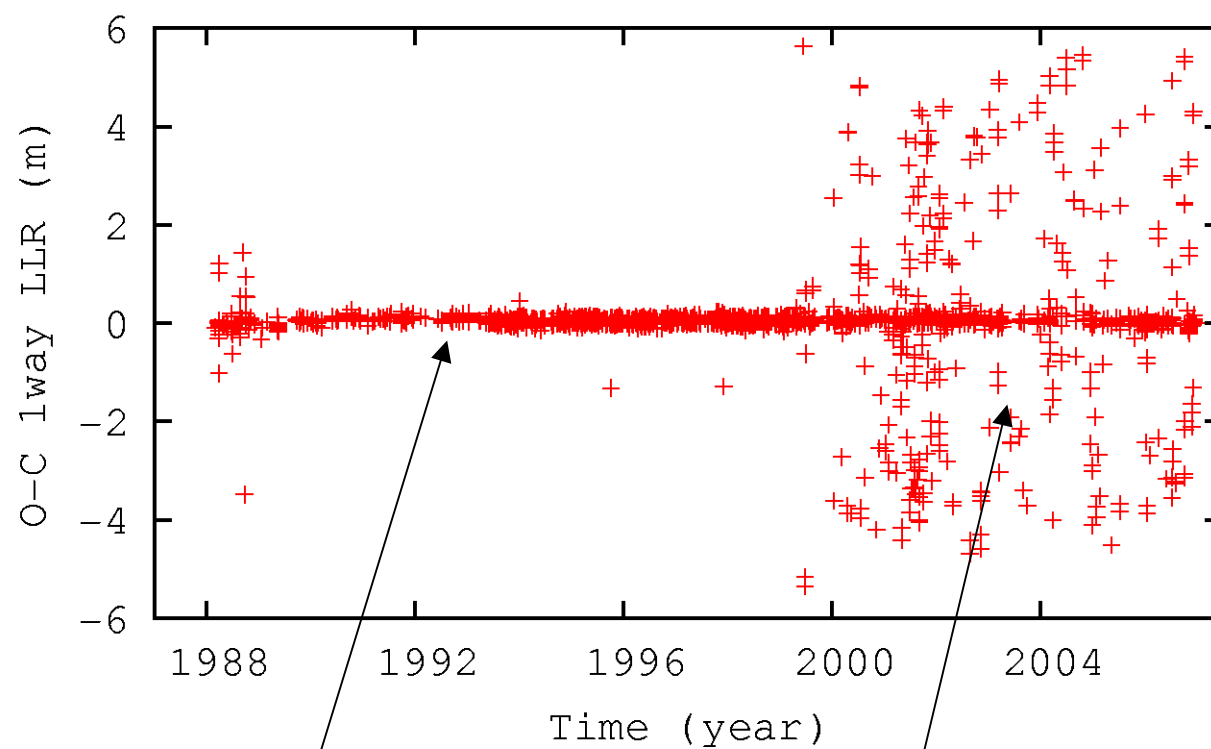
Projection on Mac Donald data
from 1969 to 1985



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

INPOP07 residuals

Projection on Mac Donald data
from 1988 to 2006



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

$\sigma = 110 \text{ cm}$