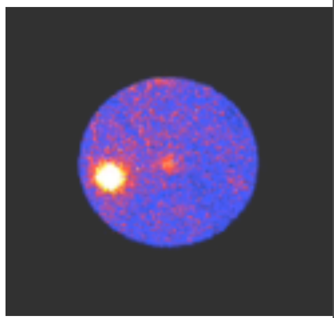
Time frames, leap seconds and GPS

Andy Shearer

Centre for Astronomy

NUI, Galway



How important is absolute timing accuracy...... I

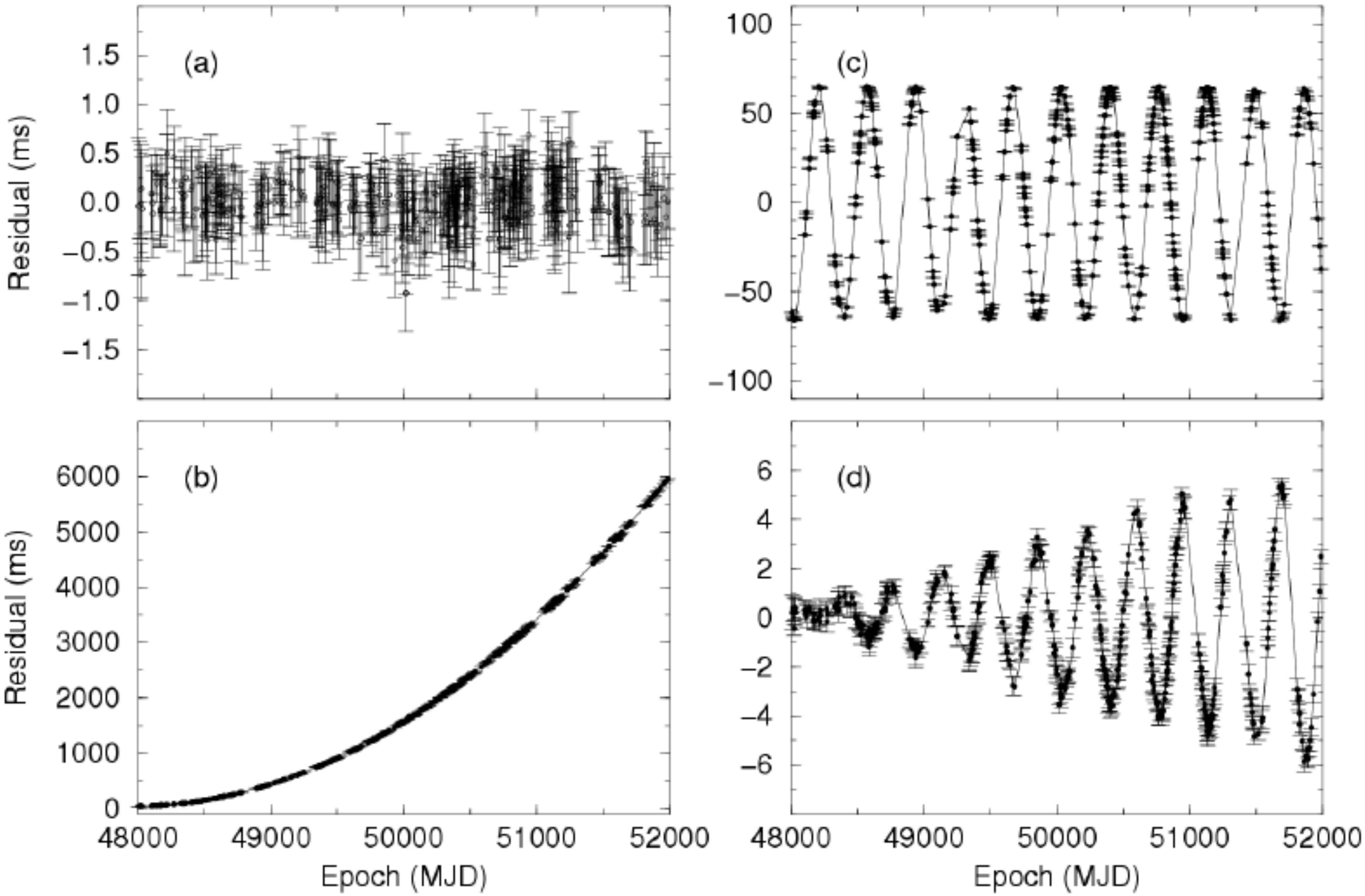


Figure 2: Pulsar timing examples. Panel (a) shows a "good" timing solution with no unmo
effects. The sinusoidal ripple in Panel (c) indicates an error in position. Panel (b) shows an
error in the frequency derivative ($f = d\phi/dt$ so $\dot{f} = d^2\phi/dt^2$). Panel (d) shows unmodele
pulsar proper motion. From Lorimer and Kramer, 2005.

How important is absolute timing accuracy...... II

important enough for particle physicists ....

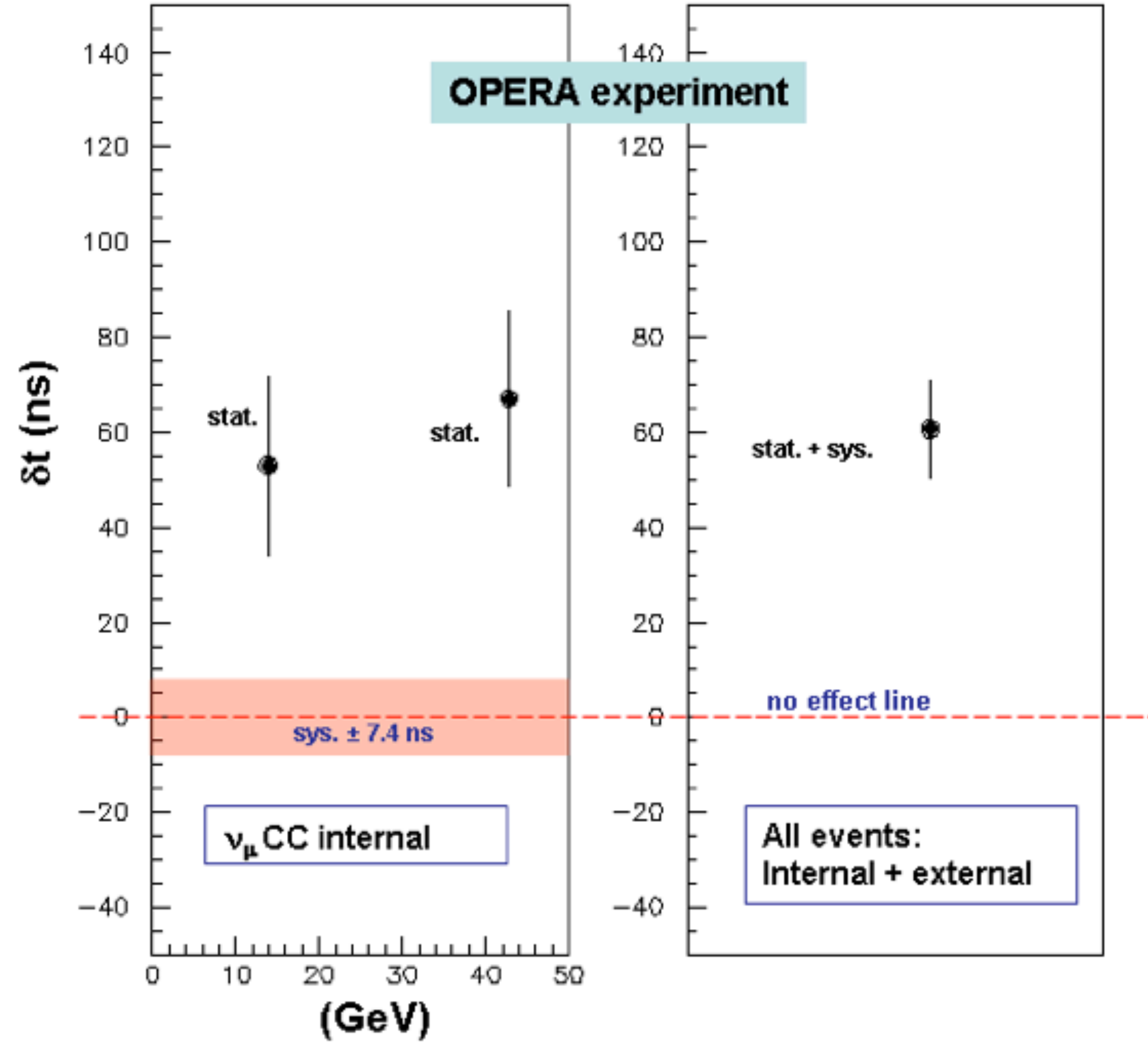


Fig. 13: Summary of the results for the measurement of δt. The left plot shows δt as a function of the energy for ν_μ CC internal events. The errors attributed to the two points are just statistical in order to make their relative comparison easier since the systematic error (represented by a band around the no-effect line) cancels out. The right plot shows the global result of the analysis including both internal and external events (for the latter the energy cannot be measured). The error bar includes statistical and systematic uncertainties added in quadrature.

NUI G
OÉ Ga

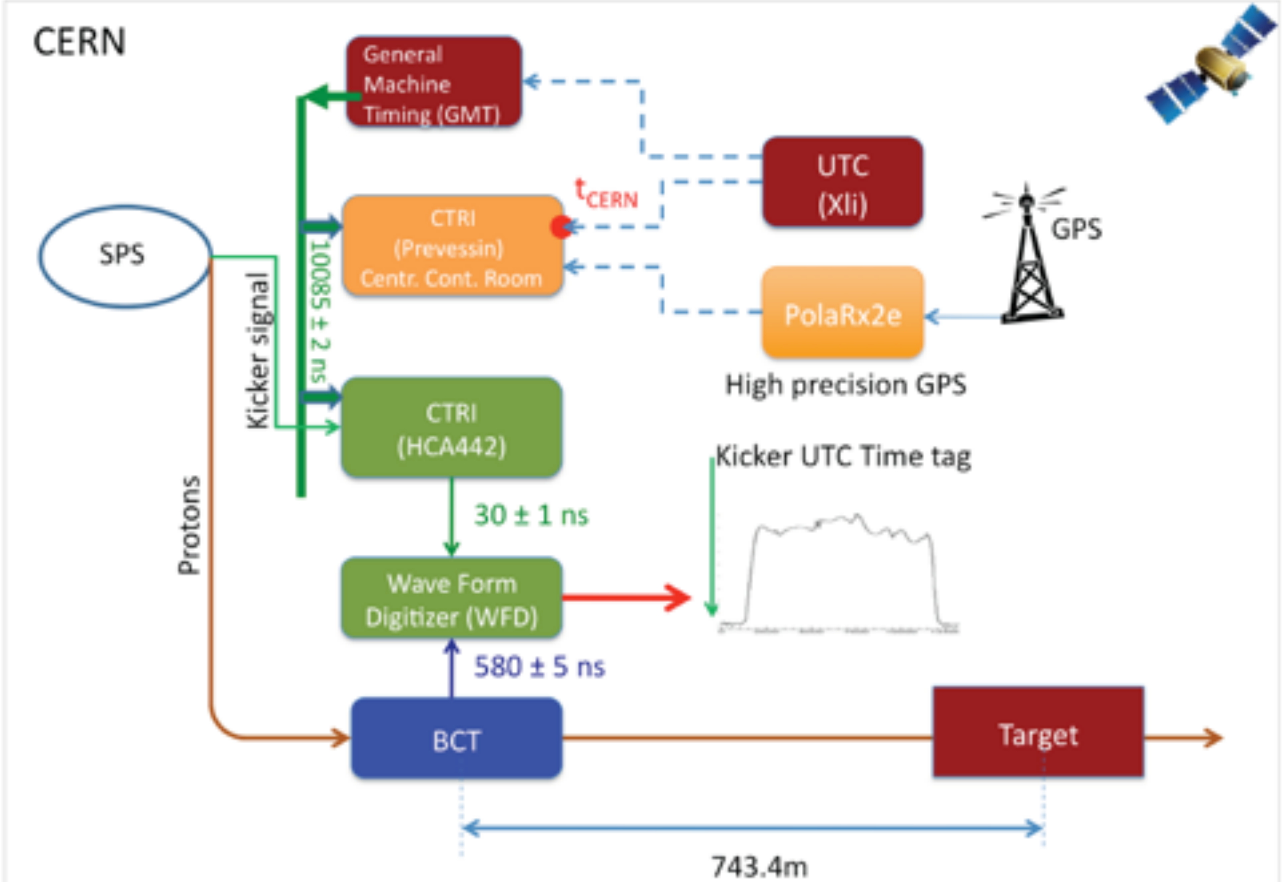


Fig. 3: Schematic of the CERN SPS/CNGS timing system. Green boxes indicate detector time-response. Orange boxes refer to elements of the CNGS-OPERA synchronisation system. Details on the various elements are given in Section 6.

Opera Timing

Table 2: Contribution to the overall systematic uncertainty on the measurement of

Systematic uncertainties	ns
Baseline (20 cm)	0.67
Decay point	0.2
Interaction point	2.0
UTC delay	2.0
LNGS fibres	1.0
DAQ clock transmission	1.0
FPGA calibration	1.0
FWD trigger delay	1
CNGS-OPERA GPS synchronisation	1.7
MC simulation for TT timing	3.0
TT time response	2.3
BCT calibration	5.0
Total sys. uncertainty (in quadrature)	**7.4**

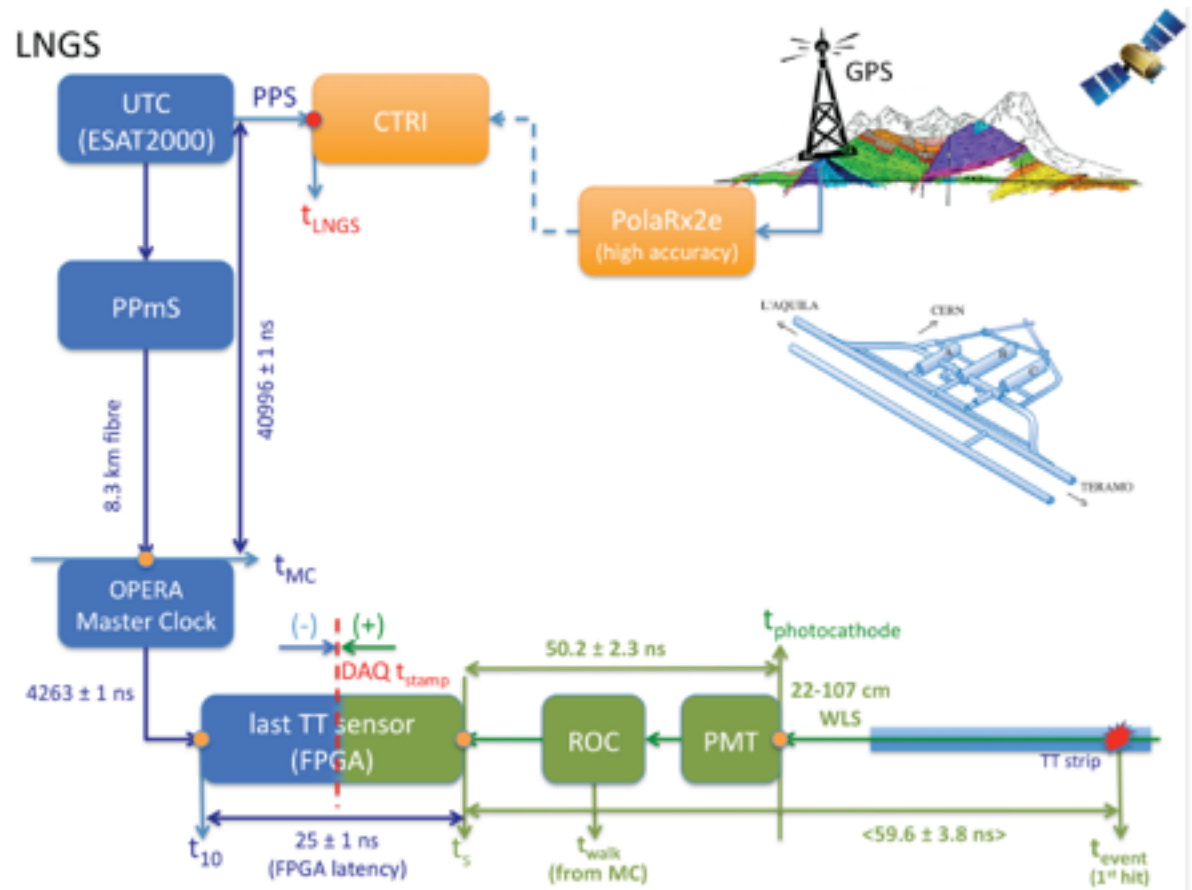


Fig. 6: Schematic of the OPERA timing system at LNGS. Blue delays include elements of the time-stamp distribution; increasing delays decrease the value of δt. Green delays indicate detector time-response; increasing delays increase the value of δt. Orange boxes refer to elements of the CNGS-OPERA synchronisation system.

PolaRx - performance

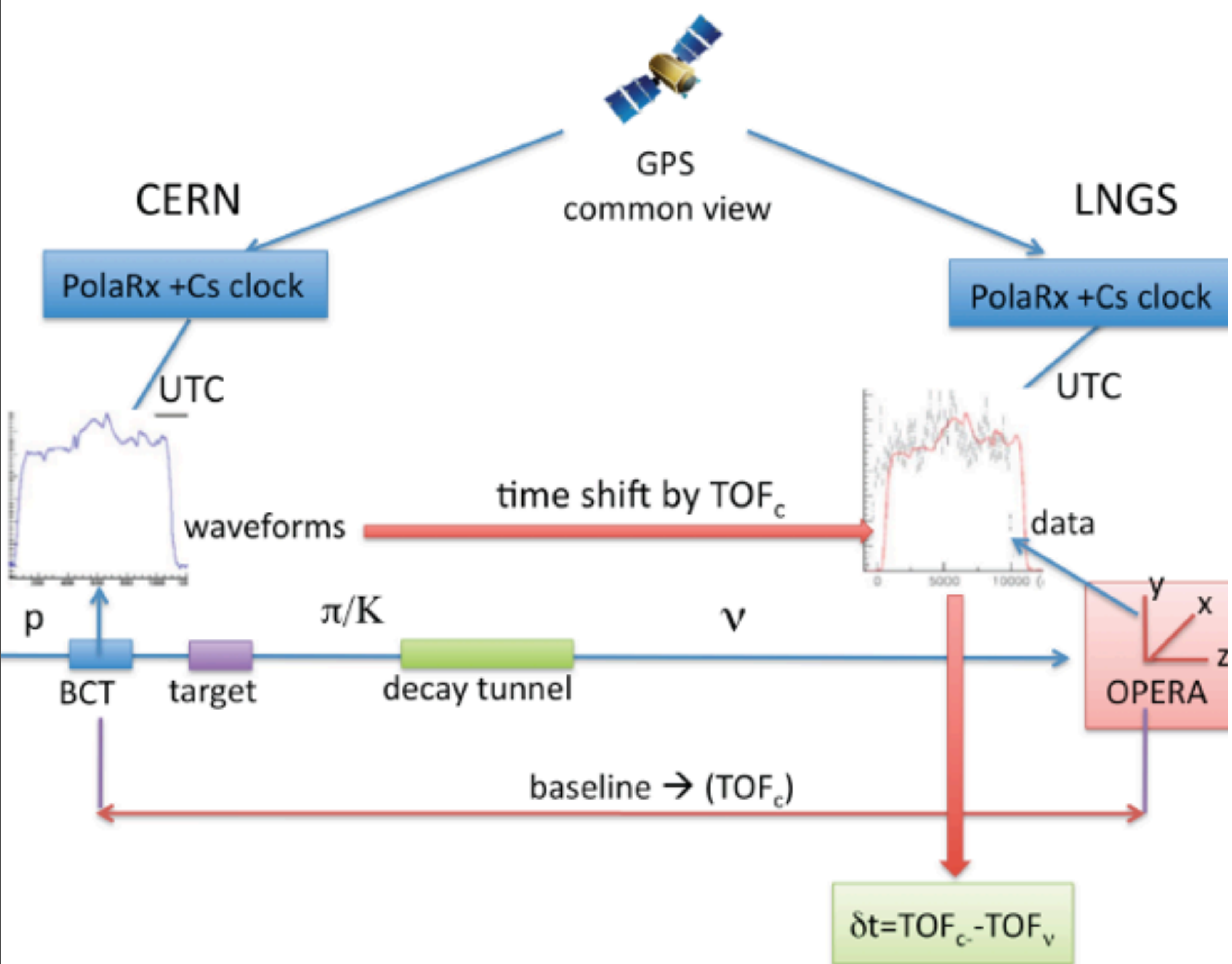


Fig. 5: Schematic of the time of flight measurement.

PERFORMANCE

Position accuracy[1,2]

	Horizontal[3]	Vertical[3]
Standalone	1.1 m	1.9 m
SBAS	0.7 m	1.2 m
DGPS	0.6 m	1.1 m

RTK performance[1,5]

Horizontal accurary[3]	1 cm + 1ppm
Vertical accuracy[3]	2 cm + 2ppm
Average time to fix[5]	7 sec
Availability[5]	> 99,8 %

Velocity Accuracy[1,2]

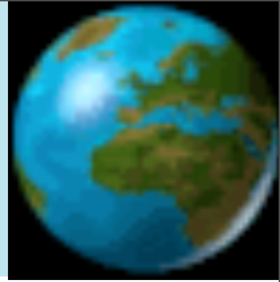
	Horizontal[3]	Vertical[3]
Standalone	1.5 mm/sec	2.8 mm/sec

Maximum Update rate	10 Hz
Latency	< 50 msec

Time accuracy[1,2]

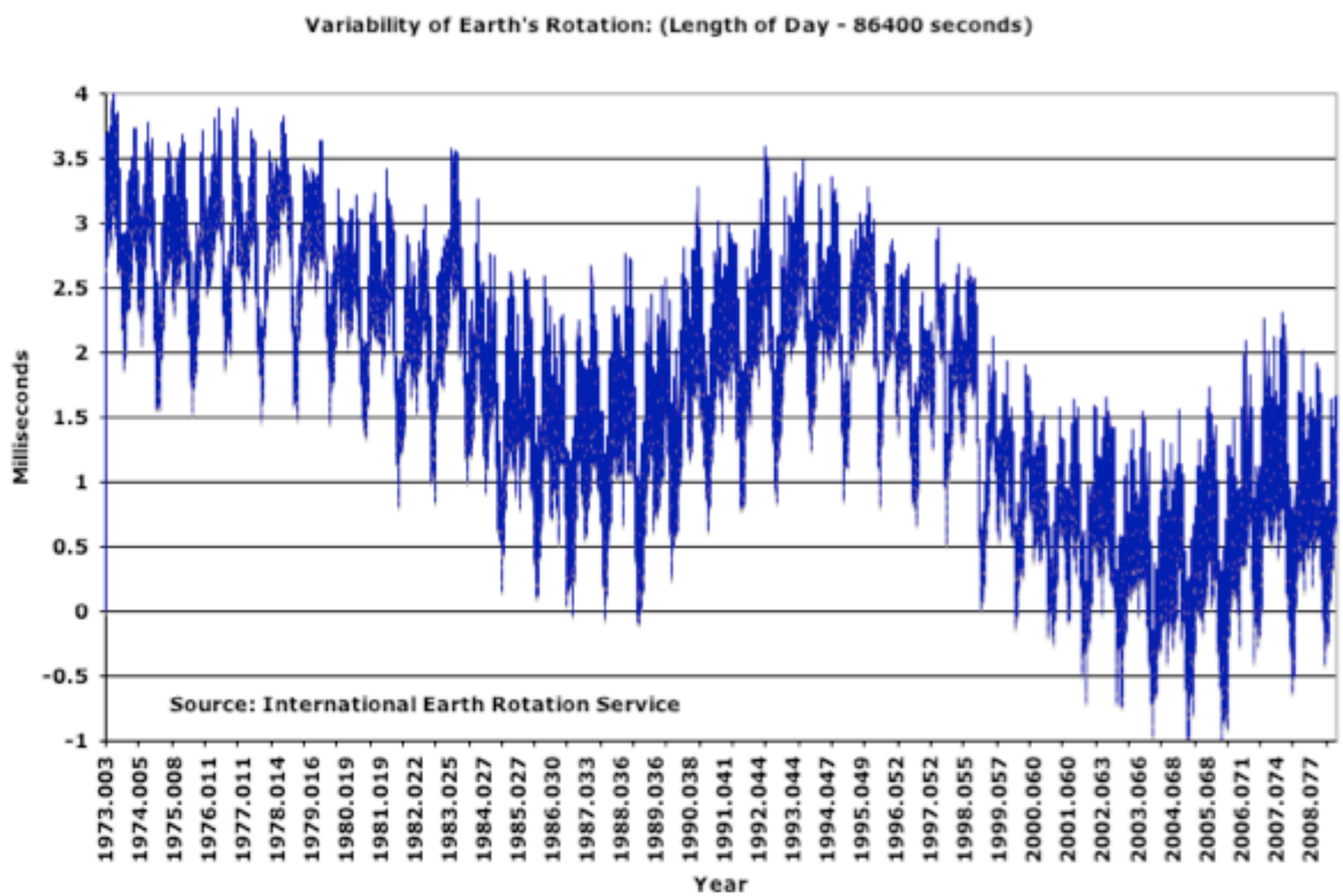
1PPS	20 nsec

What is the problem?



- We are observing on
  - a moving platform - elliptical orbit around the sun
  - a rotating platform - the Earth spins
  - in a variable gravitational field - Sun and planets ...
- This presents a few problems, particularly for pulsar observers
- Does it really matter?

US Naval Observatory :
Earth Orientation
Department.



Formal definitions - time
from Klioner et al, 2009, IAU Sym. 261

- According to ISO (1993, definition 1.1), **quantity** is an attribute of a phenomenon, body or substance that may be distinguished qualitatively and determined quantitatively. A value (of a quantity) is defined as the magnitude of a particular quantity generally expressed as a ***unit*** of measurement multiplied by a number (ISO 1993, definition 1.18)
- The official definition of the concept of "**unit**" is given by ISO (1993, definition 1.7): a unit (of measurement) is a particular quantity, defined and adopted by convention, with which other quantities of the same kind are compared in order to express their magnitudes relative to that quantity.
- The official definition of the SI **second** can be found in (BIPM 2006):The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium 133 atom

(Old unit : The ephemeris second is the fraction 1/31,556,925.9747 of the tropical year for 1900 January 0 at12 hours ephemeris time)

Formal definitions - time

from Klioner et al, 2009, IAU Sym. 261

In the framework of General Relativity, one should distinguish between observable (or measurable) and coordinate quantities. A measurable quantity has dimension, a unit, and gets a numerical value after comparison with its unit. Its value is independent of the choice of theory and reference systems.

A coordinate quantity has dimension, cannot be measured directly but can get a numerical value after computation from observables with proper theoretical (relativistic) Units of relativistic time scales and associated quantities 3 relations. Its numerical value is usually followed by "second", "meter" or some combination according to its dimension and the system of units used for the observables. Its value depends on the choice of theory (General Relativity in present IAU Resolutions) and reference systems.

Time Frames : Soffel et al, ApJ, 126, 2606

THE ASTRONOMICAL JOURNAL, 126:2687–2706, 2003 December

THE IAU 2000 RESOLUTIONS FOR ASTROMETRY, CELESTIAL MECHANICS, AND METROLOGY IN THE RELATIVISTIC FRAMEWORK: EXPLANATORY SUPPLEMENT

M. SOFFEL,[1] S. A. KLIONER,[1] G. PETIT,[2] P. WOLF,[2] S. M. KOPEIKIN,[3] P. BRETAGNON,[4] V. A. BRUMBERG,[5] N. CAPITAINE,[6] T. DAMOUR,[7] T. FUKUSHIMA,[8] B. GUINOT,[6] T.-Y. HUANG,[9] L. LINDEGREN,[10] C. MA,[11] K. NORDTVEDT,[12] J. C. RIES,[13] P. K. SEIDELMANN,[14] D. VOKROUHLICKÝ,[15] C. M. WILL,[16] AND C. XU[17]
Received 2002 August 9; accepted 2003 July 2

theoretical considerations. In the notes to the third recommendation, the relation of TCB to TDB is given as

$$\mathrm{TCB} - \mathrm{TDB} = L_B \times (\mathrm{JD} - 2{,}443{,}144.5) \times 86{,}400\,,$$
$$L_B \approx 1.550505 \times 10^{-8}\,. \qquad (6)$$

TABLE 1

CONSTANTS RELATING THE MEAN RATES OF DIFFERENT RELATIVISTIC TIME SCALES

Constant	IAU 1991 (s s^{-1})	IAU 2000 (s s^{-1})	IAU 2000 (ms yr^{-1})
L_C	1.480813×10^{-8}	$1.48082686741 \times 10^{-8}$	467.313
L_G	6.969291×10^{-10}	$6.969290134 \times 10^{-10}$	21.993
$L_B \equiv L_C + L_G - L_C L_G$	1.550505×10^{-8}	$1.55051976772 \times 10^{-8}$	489.307

NOTE.—Both the values adopted by the IAU 1991 recommendations and the IAU 2000 resolutions are given. As an illustration, the IAU 2000 values are also given in milliseconds per Julian year.

Some definitions - taken from http://tycho.usno.navy.mil/systime.html

- **Atomic Time** , with the unit of duration the *Systeme International (SI) second* defined as the duration of 9,192,631,770 cycles of radiation corresponding to the transition between two hyperfine levels of the ground state of cesium 133. **TAI** is the International Atomic Time scale, a statistical timescale based on a large number of atomic clocks.
- **Universal Time (UT)** is counted from 0 hours at midnight, with unit of duration the *mean solar day*, defined to be as uniform as possible despite variations in the rotation of the Earth.
  - **UT0** is the rotational time of a particular place of observation. It is observed as the diurnal motion of stars or extraterrestrial radio sources.
  - **UT1** is computed by correcting UT0 for the effect of polar motion on the longitude of the observing site. It varies from uniformity because of the irregularities in the Earth's rotation.
- **Coordinated Universal Time (UTC)** differs from TAI by an integral number of seconds. UTC is kept within 0.9 seconds of UT1 by the introduction of one-second steps to UTC, the **"leap second."** To date these steps have always been positive.

Some definitions - taken from http://tycho.usno.navy.mil/systime.html

- **Dynamical Time** replaced *ephemeris time* as the independent argument in dynamical theories and ephemerides. Its unit of duration is based on the orbital motions of the Earth, Moon, and planets.
  - **Terrestrial Time (TT)**, (or Terrestrial Dynamical Time, **TDT**), with unit of duration 86400 SI seconds on the geoid, is the independent argument of apparent *geocentric* ephemerides. TDT = TAI + 32.184 seconds.
  - **Barycentric Dynamical Time (TDB)**, is the independent argument of ephemerides and dynamical theories that are referred to the *solar system barycenter*. TDB varies from TT only by periodic variations.
- **Geocentric Coordinate Time (TCG)** is a *coordinate time* having its spatial origin at the center of mass of the Earth. TCG differs from TT as: TCG - TT = Lg x (JD -2443144.5) x 86400 seconds, with Lg = 6.969291e-10.
- **Barycentric Coordinate Time (TCB)**is a *coordinate time* having its spatial origin at the solar system barycenter. TCB differs from TDB in rate. The two are related by: TCB - TDB = iLb x (JD -2443144.5) x 86400 seconds, with Lb = 1.550505e-08.

Some definitions - taken from http://tycho.usno.navy.mil/systime.html

- **Sidereal Time**, with unit of duration the period of the Earth's rotation with respect to a point nearly fixed with respect to the stars, is the hour angle of the vernal equinox.

- **Julian Day Number** is a count of days elapsed since Greenwich mean noon on 1 January 4713 B.C. The Julian Date is the Julian day number followed by the fraction of the day elapsed since the preceding noon. This talk started at JD 2,455, 845.7917

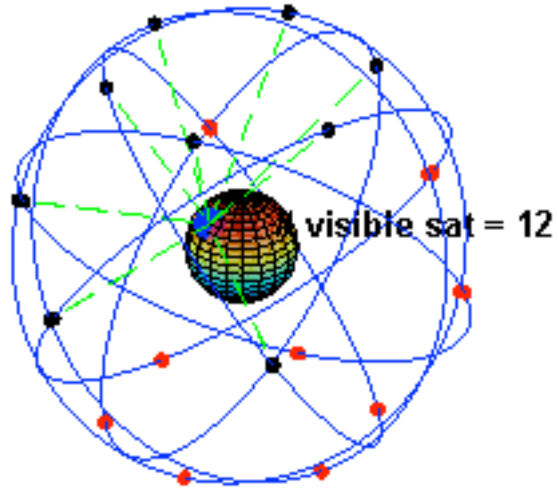
- **Modified Julian Date (MJD)** MJD = JD - 2,400,000.5 (i.e. starts and midnight)

Leap Seconds

- Added on January 1st or July 1st
- See US Naval Observatory website for latest changes

```
1991 JAN  1 =JD 2448257.5  TAI-UTC=  26.0       S + (MJD - 41317.) X 0.0      S
1992 JUL  1 =JD 2448804.5  TAI-UTC=  27.0       S + (MJD - 41317.) X 0.0      S
1993 JUL  1 =JD 2449169.5  TAI-UTC=  28.0       S + (MJD - 41317.) X 0.0      S
1994 JUL  1 =JD 2449534.5  TAI-UTC=  29.0       S + (MJD - 41317.) X 0.0      S
1996 JAN  1 =JD 2450083.5  TAI-UTC=  30.0       S + (MJD - 41317.) X 0.0      S
1997 JUL  1 =JD 2450630.5  TAI-UTC=  31.0       S + (MJD - 41317.) X 0.0      S
1999 JAN  1 =JD 2451179.5  TAI-UTC=  32.0       S + (MJD - 41317.) X 0.0      S
2006 JAN  1 =JD 2453736.5  TAI-UTC=  33.0       S + (MJD - 41317.) X 0.0      S
2009 JAN  1 =JD 2454832.5  TAI-UTC=  34.0       S + (MJD - 41317.) X 0.0      S
```

GPS - Global Positioning Satellites



- Military based system - now civilian
- 2 forms
  - Normal GPS - typical accuracy 14 ns, receiver dependent
  - Differential GPS - GPS plus terrestrial radio beacons - accuracy ~ 1ns
- GPS time set to UTC in 1980 - see USNO web site
- Other systems include
  - Galileo : EU
  - GLONASS : Russian

Pulsar timing : probably the most difficult

$$\Delta t = \Delta_C + \Delta_A + \Delta_{E_\odot} + \Delta_{R_\odot} + \Delta_{S_\odot} - D/f^2 + \Delta_{VP} + \Delta_B, \quad (1)$$

- see Hobbs et al, MNRAS, 369, 655 (2006) and Lorimar and Kramer - Handbook of Pulsar Astronomy

PSRB 0531+21
RAJ 05:34:31.9723211771976
DECJ 22:00:52.0691783694112
PEPOCH 55180.0000001333683030679822 8.391099e-11
F0 2.9728942504225436e+01 9.322426e-10
F1 -3.7144351634185121e-10 4.495249e-15
F2 1.1047696322534057e-20
F3 -6.0000000000000023e-31
POSEPOCH 53254.0000000000000000
DM 5.6823752598038659e+01 7.707162e-04
DM1 -7.1124158761698542e-01 1.089199e-01
START 55175.9479189596677315
FINISH 55184.9241623203488416
EPHEM DE200

Pulsar timing requirements

$$\Delta t = \Delta_C + \Delta_A + \Delta_{E_\odot} + \Delta_{R_\odot} + \Delta_{S_\odot} - D/f^2 + \Delta_{VP} + \Delta_B, \quad (1)$$

Δt = pulsar arrival time correction

Δ_c = clock error, including GPS errors

corrects for deviations away from GCT

Δ_A = atmospheric propagation delays

$\Delta_{E_\odot}$ = Solar System Einstein delay - gravitational

and Earth's motion

$\Delta_{R_\odot}$ = Roemer delay - translation between observatory

Solar System Barycentre

$\Delta_{S_\odot}$ = Shapiro delay - delay due to space curvature

around Solar System bodies

D/f^2 = Dispersion and other frequency dependent delays

$\Delta_{VP}\Delta_B$ = Secular delays due pulsar velocity and orbits

Table 2. Corrections and their typical sizes for phenomena
TEMPO2.

Correction	Typical value/range
Observatory clock to TT	1 µs
Hydrostatic tropospheric delay	10 ns
Zenith wet delay	1.5 ns
IAU precession/nutation	~5 ns
Polar motion	60 ns
ΔUT1	1 µs
Einstein delay	1.6 ms
Roemer delay	500 s
Shapiro delay due to Sun	112 µs
Shapiro delay due to Venus	0.5 ns
Shapiro delay due to Jupiter	180 ns
Shapiro delay due to Saturn	58 ns
Shapiro delay due to Uranus	10 ns
Shapiro delay due to Neptune	12 ns
Second-order Solar Shapiro delay	9 ns
Interplanetary medium dispersion delay	100 ns[b]
ISM dispersion delay	~1 s[b]

[a]Earlier precession/nutation model implemented.
[b]Observing frequency- and pulsar-dependent, typical value fo
listed.

Shapiro delay - from Hobbes et al

$$\Delta t = \Delta_C + \Delta_A + \Delta_{E_\odot} + \Delta_{R_\odot} + \Delta_{S_\odot} - D/f^2 + \Delta_{VP} + \Delta_B,$$

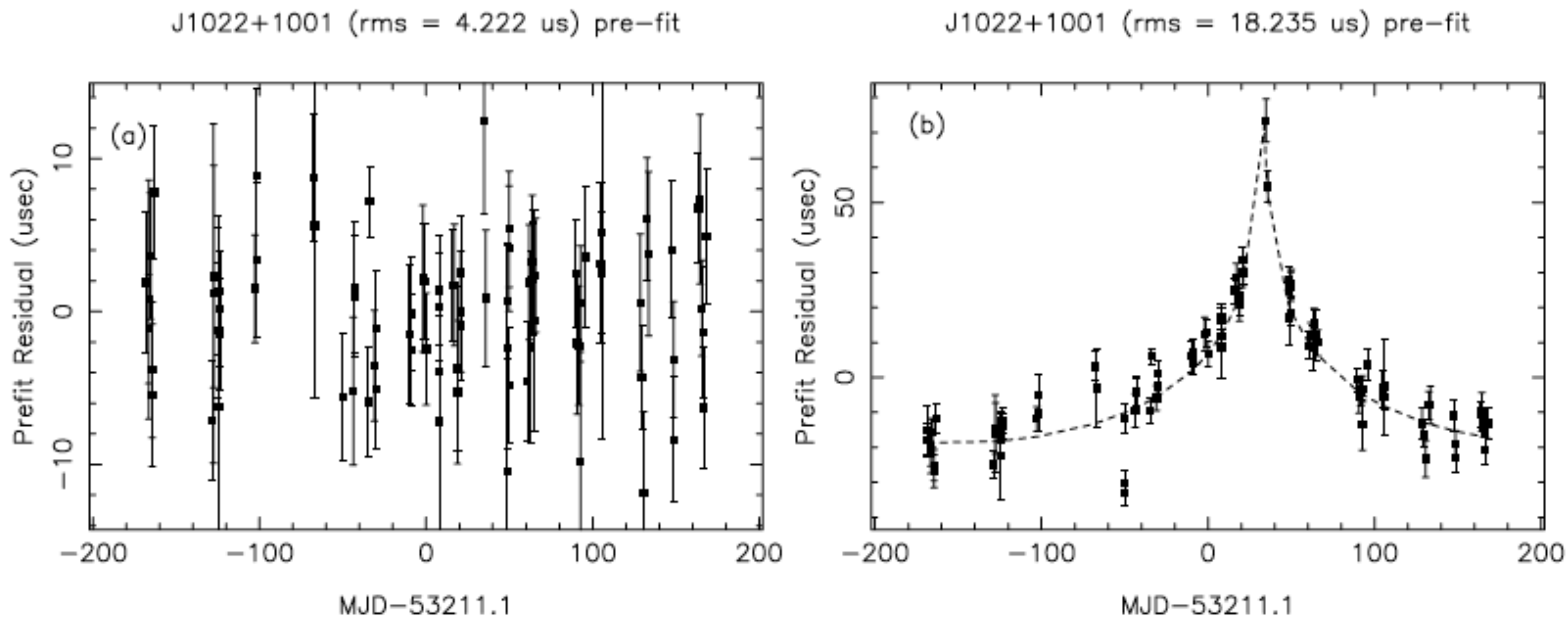
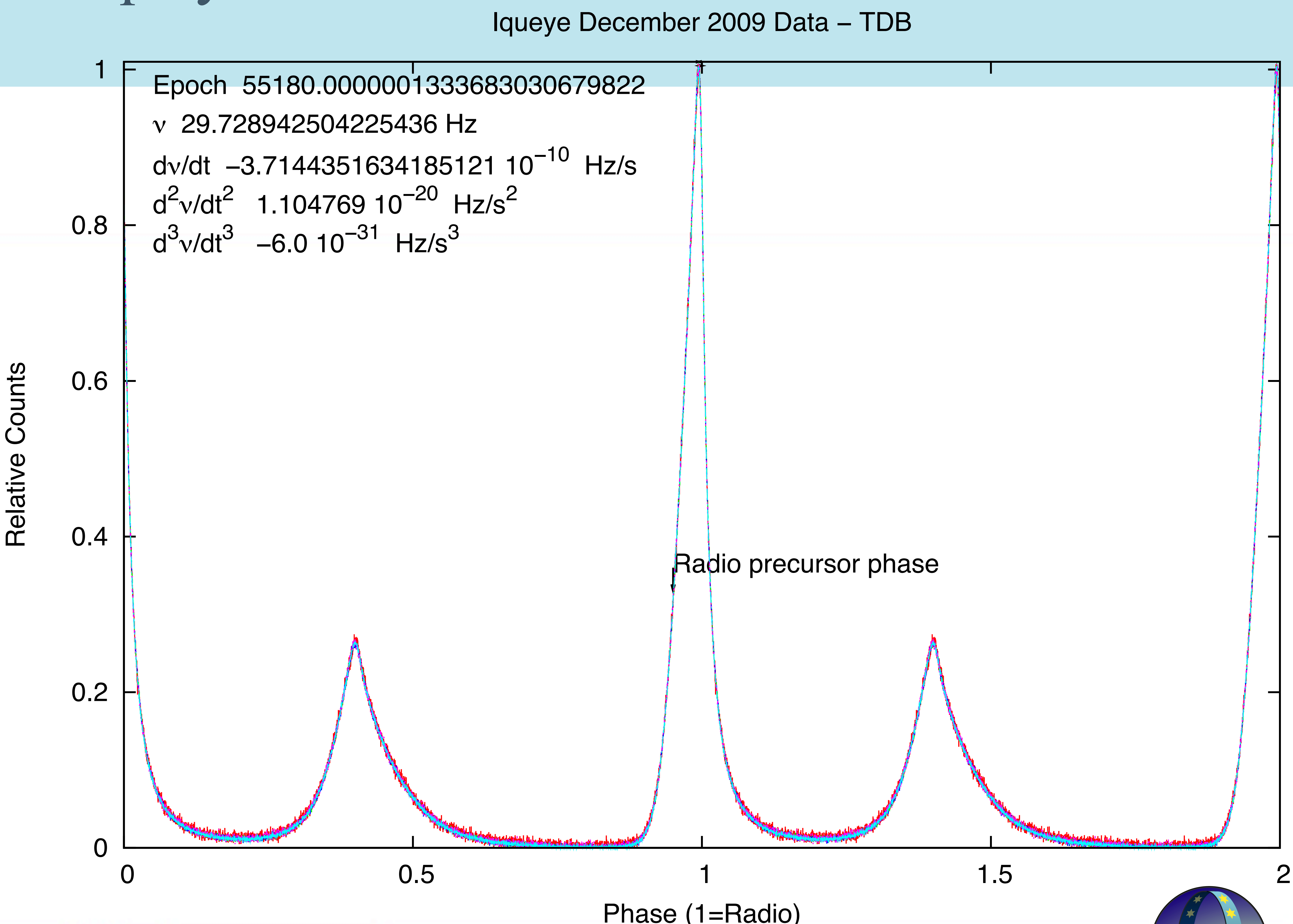


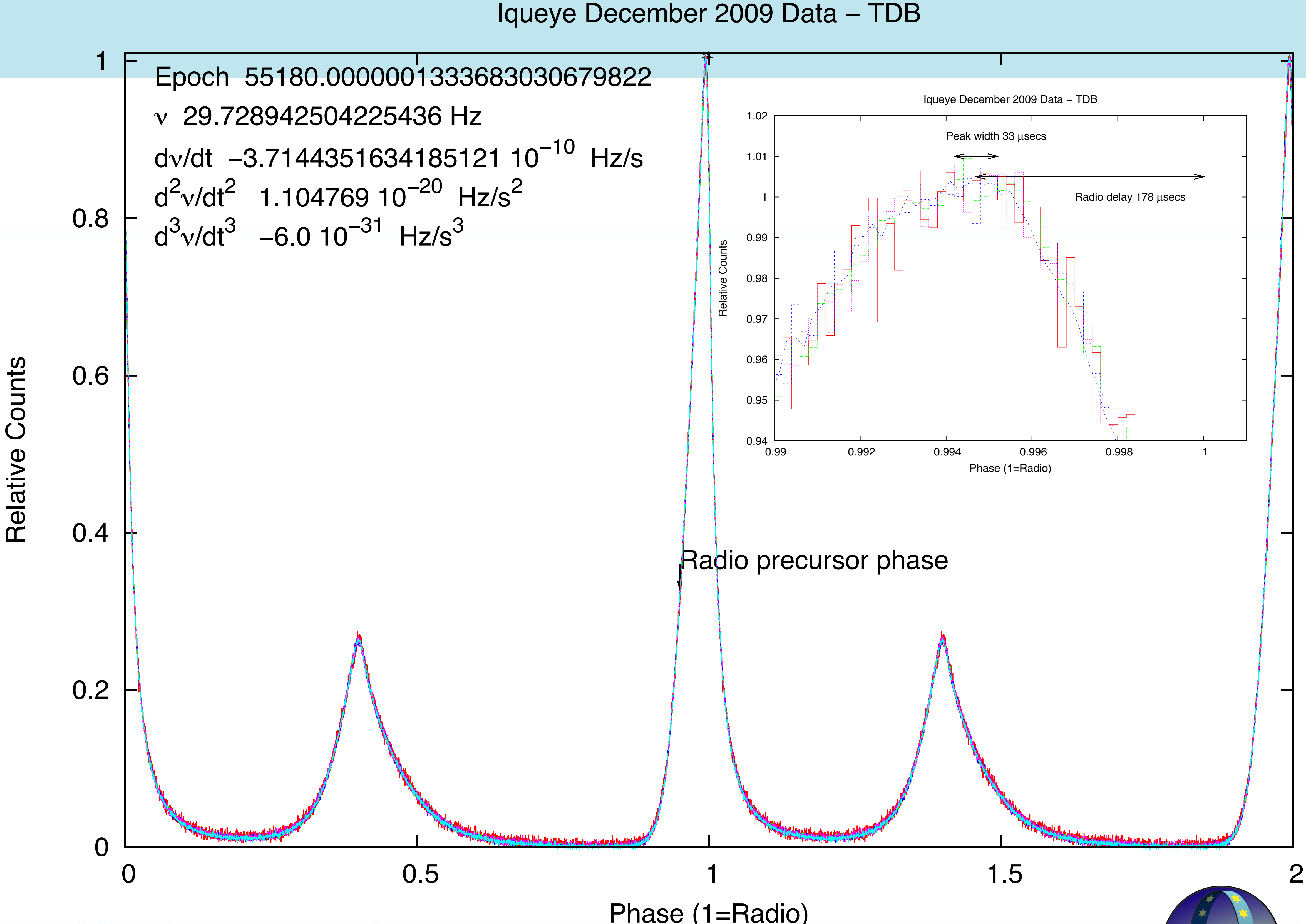
Figure 7. The timing residuals, in μs, for PSR J1022+1001, (a) after fitting for the pulsar's parameters and (b) without removal of the Solar system Shapir delay. This plot was created using the PLK plug-in for TEMPO2 (note, the original PLK plotting package incorrectly plotted the uncertainties on the residuals; th errors were a factor of 2 too small).

Iqueye Data



see Susan Collins' poster

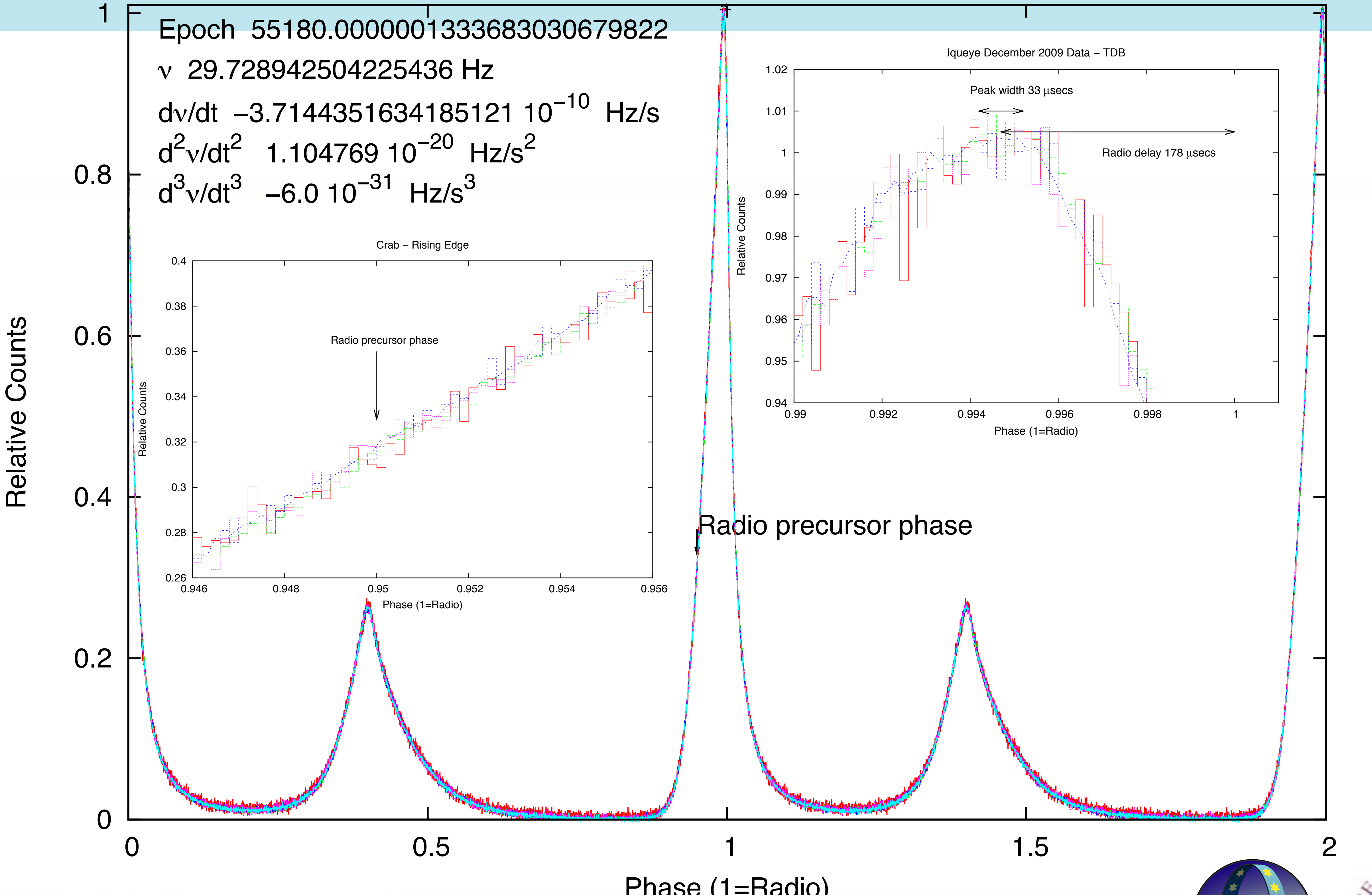
Iqueye Data



Iqueye - Istanbul 2011

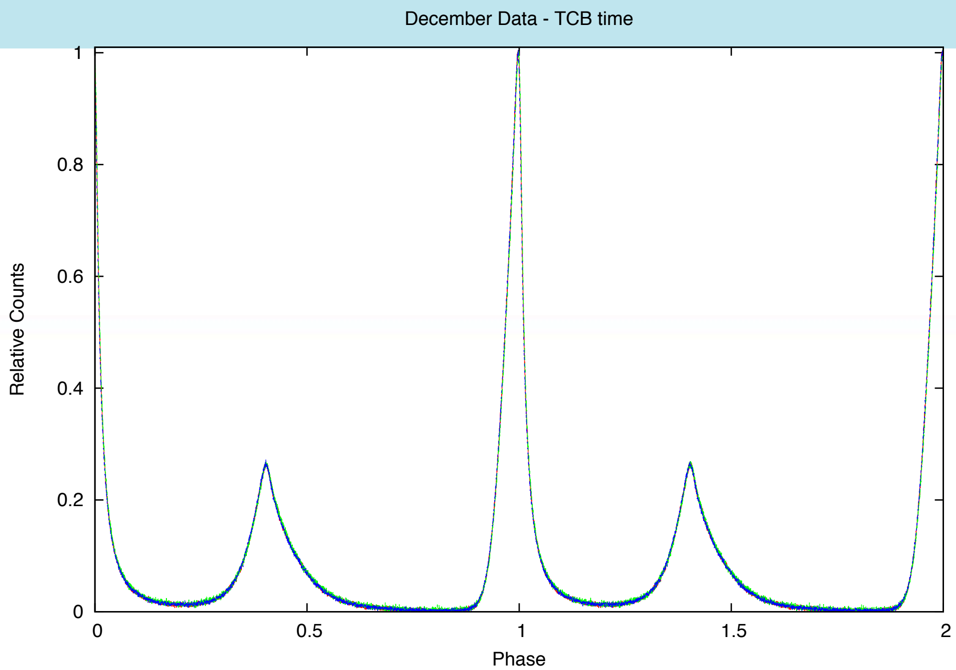
see Susan Collins' poster

Iqueye Data

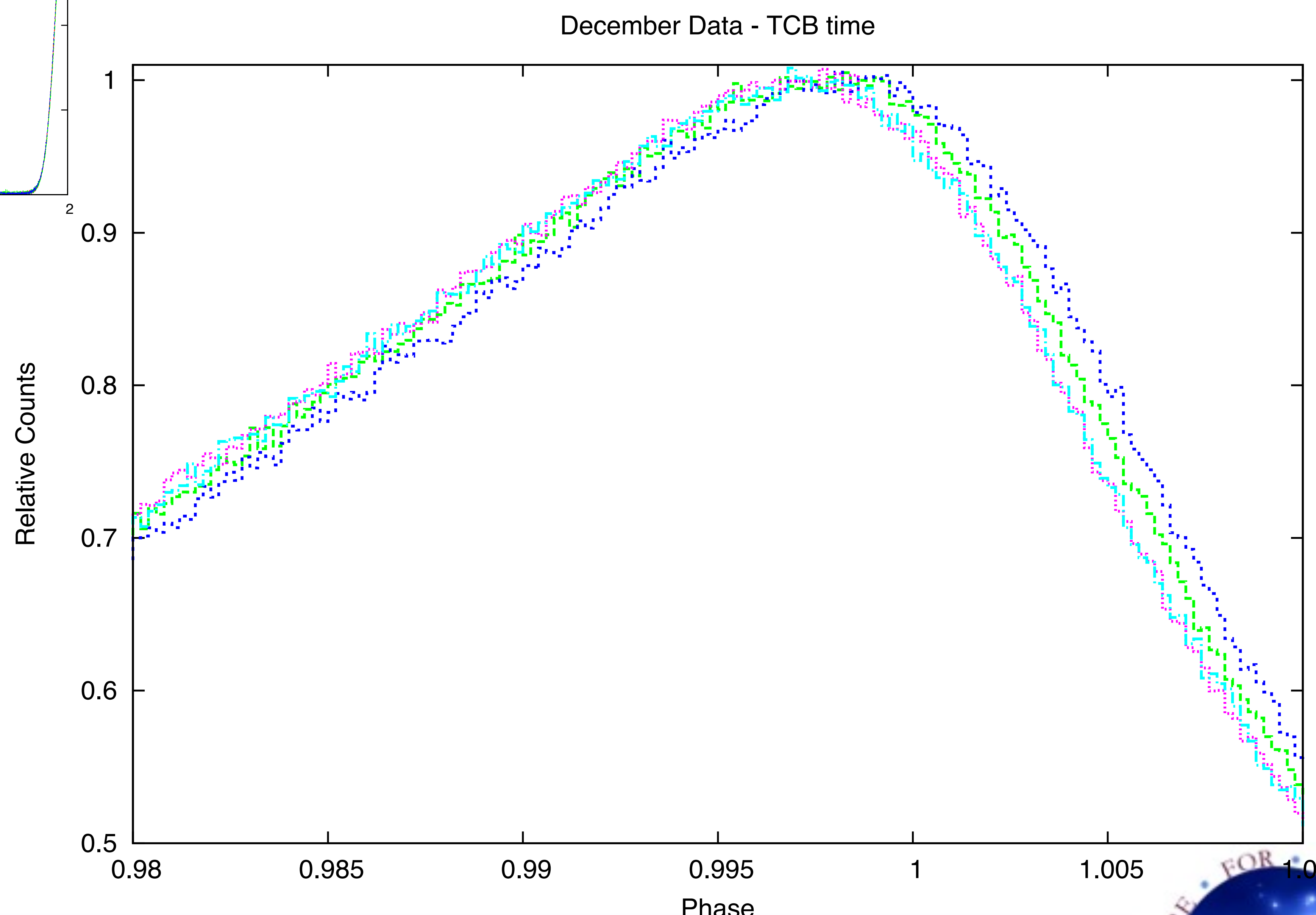


see Susan Collins' poster

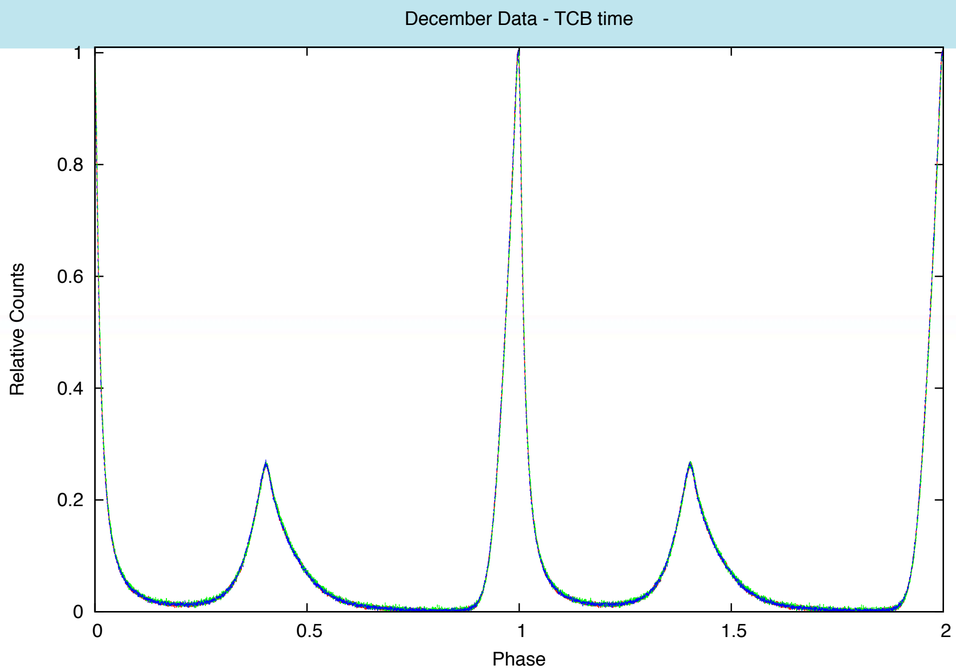
TDB vs TCB - if you get it wrong ....

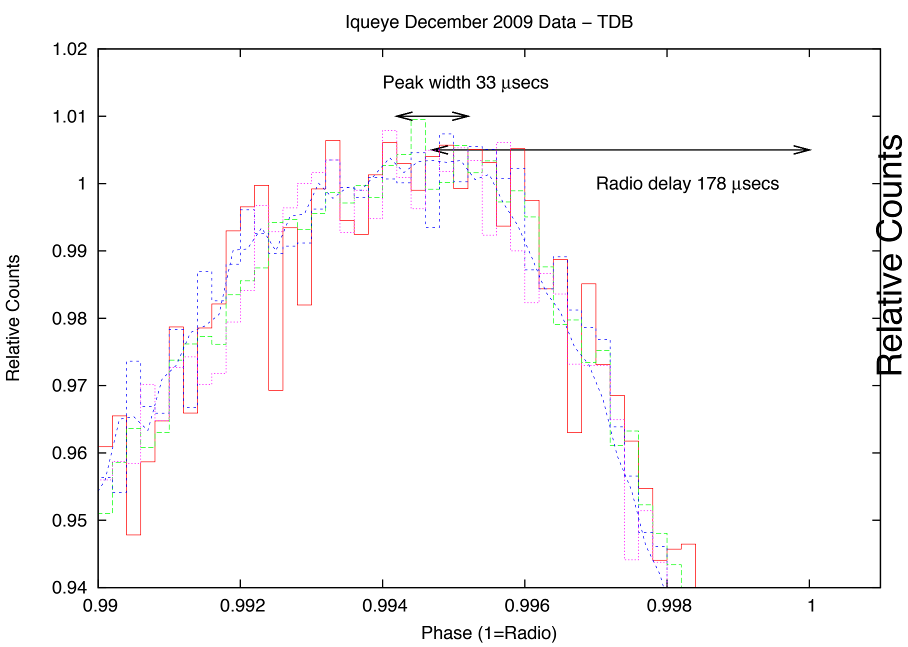


Barycentring TCB
Ephemeris TDB

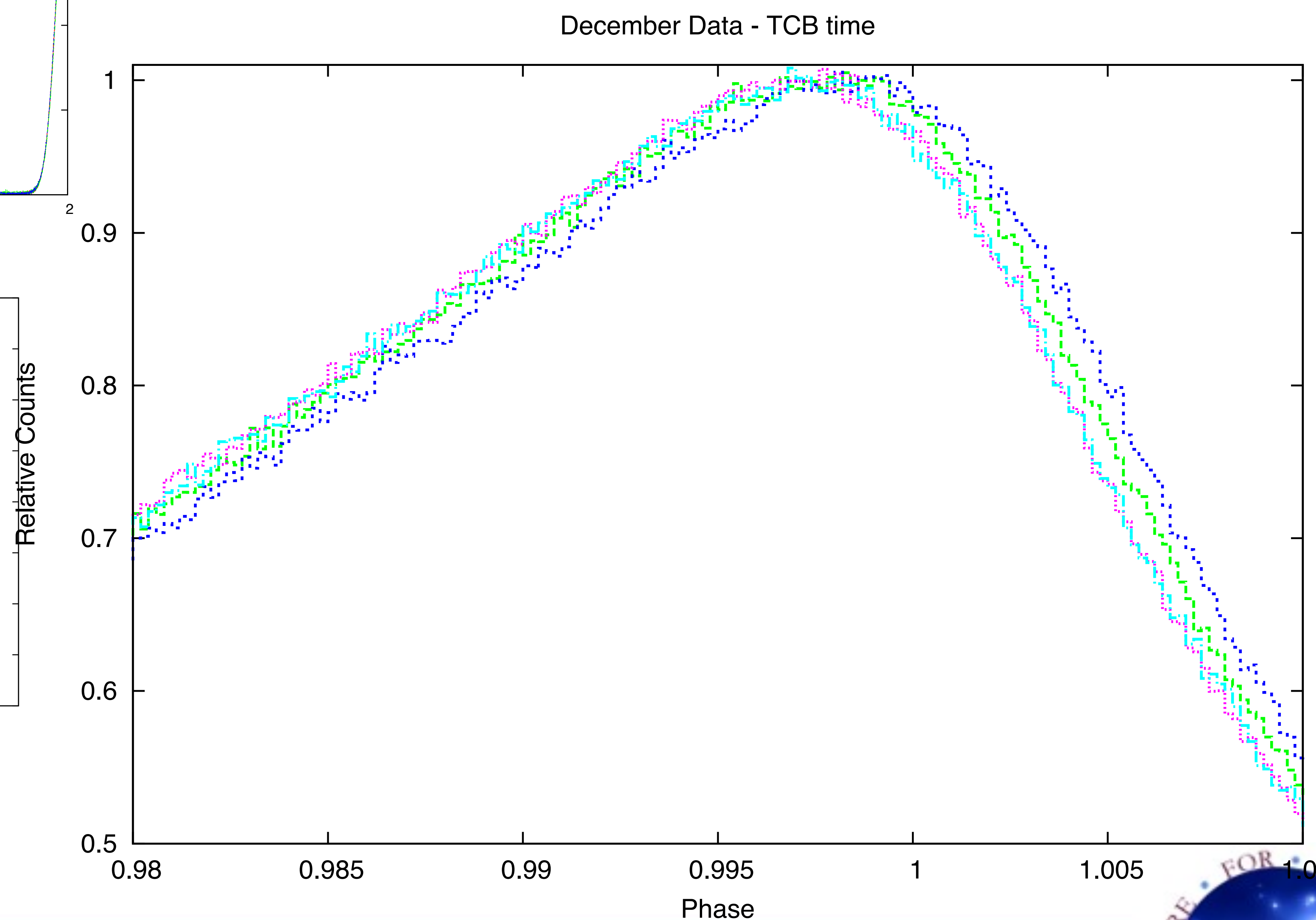


TDB vs TCB - if you get it wrong ....





Barycentring TCB
Ephemeris TDB



Conclusions

- Different time frames and systems taken into account in *tempo2*
- Be careful of differences between TDB and TCB