1 Introduction

In this document the method is described to derive a radio-aligned Gamma-ray pulsar lightcurve. The algorithm is implemented in COMPASS task **PULRGL**.
Starting point is the selection of an appropriate pulsar radio ephemeris from the Princeton catalogue for the pulsar under study. The Princeton catalogue can be accessed by *anonymous* FTP from site "*pup-psr.princeton.edu*". The directory "*gro*" contains the regularly updated pulsar ephemeris file "*psrtime.dat*". The meaning of the several column entries are described in the file "*13mar91.msg*" and is shown below :

```
PSR     Pulsar name in 1950 coordinates (for consistency with prior usage)
RA      Right Ascension in J2000 coordinates (hh mm ss.sss)
DEC     Declination in J2000 coordinates (sdd mm ss.ss)
MJD1,2  First and last dates for valid parameters (MJD)
t0geo   Infinite-frequency geocentric UTC arrival time of a pulse (MJD)
        Note: the integer part of t0geo is the barycentric (TDB) epoch
        of RA, DEC, f0, f1,and f2
f0      Pulsar rotation frequency (s**(-1))
f1      First derivative of pulsar frequency (s**(-2))
f2      Second derivative of pulsar frequency (s**(-3))
RMS     Root-mean-square radio timing residual, in milliperiods
O       Observer code
B       Blank for single pulsars, "*" for binaries.
```

This file also contain a paragraph with the warning :

DO NOT trust the geocentric pulse arrival times yet! More particularly, do not use them to compare gamma ray phases with radio phases, without direct contact with the radio observer(s). Many subtle issues arise in getting such an alignment correct, and specific cases will need to be discussed in detail. More generally, when we get to the point of analyzing real signals and drawing scientific conclusions from them, I would urge GRO investigators to contact the radio observers for more detailed and carefully calibrated ephemerides, with error bars.

However, for the well-established Gamma-ray pulsars Crab (PSR B0531+21) and Vela (PSR B0833-45), which are monitored daily, corrections to the *geocentric* UTC arrival times of the radio-pulse are listed in the file "*read.me*". Applying these corrections to t_0^{geo} it is possible to derive a reliable value of the pulsar phase corresponding to radio-phase zero using the selected pulsar ephemeris evaluated at nominal epoch (*integer* part of t_0^{geo} is the barycentric TDB epoch).

2 Definitions and relations between timescales

JD	Julian Date; day 0 starts at 12:00 noon UTC on 01-01-4713 BC
MJD	Modified Julian Date (= JD - 2400000.5)
TJD	Truncated Julian Date (= JD - 2440000.5)
SSB	Solar System Barycentre
TAI	International Atomic Time [unit SI seconds]
TDB	Barycentric Dynamical Time;used as time-scale of ephemerides referred to barycentre of the solar system
TDT	Terrestial Dynamical Time
UTC	Coordinated Universal Time

UTC_TO_TAI	Increment to obtain TAI from UTC; this is an *integer* number : number of *leap* seconds
TAI_TO_TDT	Increment to obtain TDT from TAI; fixed value of $32.^s184$
TDT_TO_TDB	Increment to obtain TDB from TDT
R_s	Schwarzschild radius of the Sun [$0.49254909 \times 10^{-5}$ lightseconds]
ν	Frequency of pulsar
$\dot{\nu}$	First time derivative of pulsar frequency
$\ddot{\nu}$	Second time derivative of pulsar frequency

The timescale relations are shown below :

$$
\begin{array}{llll}
UTC\_TO\_TAI & = TAI - UTC & = N_{leap} & (1) \\
TAI\_TO\_TDT & = TDT - TAI & = 32.^s184 & (2) \\
TDT\_TO\_TDB & = TDB - TDT & & (3) \\
UTC\_TO\_TDB & = TDB - UTC & = N_{leap} + 32.^s184 + TDT\_TO\_TDB & (4) \\
E_{tut} & = UTC\_TO\_TDB & & (5)
\end{array}
$$

The number of leap seconds (N_{leap}) can be determined from table 1.

from JD	Date	to JD	Date	N_{leap}
2441317.5	01/01/1972	2441499.5	30/06/1972	10
2441499.5	01/07/1972	2441683.5	31/12/1972	11
2441683.5	01/01/1973	2442048.5	31/12/1973	12
2442048.5	01/01/1974	2442413.5	31/12/1974	13
2442413.5	01/01/1975	2442778.5	31/12/1975	14
2442778.5	01/01/1976	2443144.5	31/12/1976	15
2443144.5	01/01/1977	2443509.5	31/12/1977	16
2443509.5	01/01/1978	2443874.5	31/12/1978	17
2443874.5	01/01/1979	2444239.5	31/12/1979	18
2444239.5	01/01/1980	2444786.5	30/06/1981	19
2444786.5	01/07/1981	2445151.5	30/06/1982	20
2445151.5	01/07/1982	2445516.5	30/06/1983	21
2445516.5	01/07/1983	2446247.5	30/06/1985	22
2446247.5	01/07/1985	2447161.5	31/12/1987	23
2447161.5	01/01/1988	2447892.5	31/12/1989	24
2447892.5	01/01/1990	2448257.5	31/12/1990	25
2448257.5	01/01/1991	2448804.5	30/06/1992	26
2448804.5	01/07/1992	2449169.5	30/06/1993	27
2449169.5	01/07/1993	2449534.5	30/06/1994	28
2449534.5	30/06/1994	....	....	29

Table 1 : Number of leap seconds as function of JD

The *TDT_TO_TDB* term reflects the effect due to the variations of the gravitational potential around Earth's orbit and has a sinusoidal shape with amplitude of ±1.6 ms. An equivalent name encountered in CGRO pulsar software for the *UTC_TO_TDB* term is E_{tut}.

3 Literature

`ApJ 345:434-450,1989`	`Further experimental tests of relativistic gravity using the binary pulsar PSR 1913+16`	`J.Taylor & J.Weisberg`
`COM-TN-SYS-DAT-004`	`Having a really good time`	`H.Steinle`
`COM-TN-SSD-PUL-431`	`Having a good barycentric time`	`K.Bennett & M.Busetta`
`PUL-AL-004`	`Computation of SSB times`	`R.Buccheri`

4 Description of the method

The method to determine the arrival time of the radio-pulse at the SSB from t_0^{geo} (and possible corrections to it) is analogous to the method descibed in PUL-AL-004. However, in this case the Solar System Barycentre (SSB) vector components consist now of the pure Earth-SSB components while in the PUL-AL-004 case the CGRO spacecraft-SSB vector components are used (obtained by adding the spacecraft position vector (from *-OAD-* dataset) to the Earth-SSB vector). The precise procedure is described below :
The t_0^{geo} value is converted from MJD to JD and splitted up in an *integer* and *fractional* part :

$$i_{t_0^{geo}} = \mathrm{int}(t_0^{geo}) + 2400000 + 1 \tag{6}$$

$$f_{t_0^{geo}} = t_0^{geo} - \mathrm{int}(t_0^{geo}) - 0.5 \tag{7}$$

The fractional part is corrected by the correction value $\mathcal{C}_p$ as given in the "*read.me*" file and properly converted from milliseconds to days (divide by 1000 × 86400). This means that $f_{t_0^{geo}} \rightarrow f_{t_0^{geo}} + \mathcal{C}_p$ and we have in total :

$$f^{cor}_{t_0^{geo}} = f_{t_0^{geo}} + \mathcal{C}_p \tag{8}$$

$$t^{geo}_{0,cor}[\mathrm{JD}] = i_{t_0^{geo}} + f^{cor}_{t_0^{geo}} \tag{9}$$

$$t_0^{nom}[\mathrm{JD}] = \mathrm{int}(t_0^{geo}) + 2400000.5 \tag{10}$$

The t_0^{nom}[JD] term defined in (11) specifies the nominal epoch in Julian Days of the pulsar ephemeris. The integer fraction $i_{t_0^{geo}}$ is used to find the proper record in the JPL DE200 based solar system ephemeris dataset (*-EPH-*), in which the Earth-SSB vector - ,Earth-SSB velocity -, Sun-SSB vector components and finally the *TDT_TO_TDB* value are stored for every Julian day between 9-12-1988 (JD 2447505) and 10-01-2001 (JD 2451920). The fractional part is subsequently used to evaluate the required vector components at the exact time (a Taylor series expansion at $i_{t_0^{geo}}$ is formed using the Taylor components as read from the *-EPH-* file). Now we are in a position to determine the arrival time of the radio-pulse at the SSB from :

$$t_0^{ssb}[\mathrm{JD}] = t^{geo}_{0,cor}[\mathrm{JD}] + 32.^{s}184 + N_{leaps}(i_{t_0^{geo}}, f^{cor}_{t_0^{geo}}) + TDT\_TO\_TDB(i_{t_0^{geo}}, f^{cor}_{t_0^{geo}}) + \mathcal{D} \tag{11}$$

The term denoted by $\mathcal{D}$ is composed of the (pulsar position dependent) travel-time delay factor $\mathcal{D}_t$ and Shapiro delay term $\mathcal{D}_s$ in the form $\mathcal{D} = \mathcal{D}_t - \mathcal{D}_s$. The $\mathcal{D}_t$ term is given by :

$$\mathcal{D}_t = \mathcal{E}_x \cdot \mathcal{P}_x + \mathcal{E}_y \cdot \mathcal{P}_y + \mathcal{E}_z \cdot \mathcal{P}_z \tag{12}$$

The $\mathcal{P}_{x,y,z}$ components are the (x,y,z) components of the pulsar given by :

$$\begin{aligned} \mathcal{P}_x &= \cos(\delta_{2000}) \cdot \cos(\alpha_{2000}) \\ \mathcal{P}_y &= \cos(\delta_{2000}) \cdot \sin(\alpha_{2000}) \\ \mathcal{P}_z &= \sin(\delta_{2000}) \end{aligned} \tag{13}$$

,while the $\mathcal{E}_{x,y,z}$ components are the (x,y,z) components of the Earth-SSB vector evaluated in a J2000 defined frame. The $\mathcal{D}_s$ term is calculated from :

$$\mathcal{D}_s = -2 \cdot R_s \cdot \ln(1 + \cos\theta) \tag{14}$$

with θ the pulsar-Sun-Earth angle given by :

$$\cos\theta = \left(\frac{\vec{\mathcal{P}} \cdot (\vec{\mathcal{E}} - \vec{\mathcal{S}})}{|\vec{\mathcal{E}} - \vec{\mathcal{S}}|}\right) \tag{15}$$

$\vec{\mathcal{S}}$ in (15) specifies the Sun-SSB vector. A (not to scale) picture of situation is depicted in figure 1.

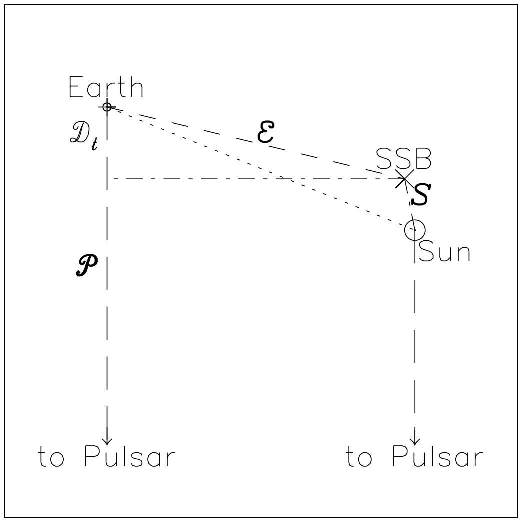

Fig. 1 : Schematic representation of situation

The $\mathcal{D}_s$ term is of the order of microseconds, while $\mathcal{D}_t$ is of the order of seconds and can in principle be ignored in practice!
Next,the time difference Δt is calculated between t_0^{ssb}[JD] from equation (11) and the nominal epoch t_0^{nom}[JD] as defined in (10).
Finally ,the value of Δt is substituted in the formula calculating the phase Φ of the pulsar :

$$\Phi_{radio} = \mathrm{mod}(\nu \cdot \Delta t + 1/2 \cdot \dot{\nu} \cdot \Delta t^2 + 1/6 \cdot \ddot{\nu} \cdot \Delta t^3, 1.) \tag{16}$$

to obtain radio-phase zero at nominal epoch. Using this value as offset in the pulsar lightcurve generated according to (16) yields a radio-aligned Gamma-ray pulsar lightcurve.

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