Absolute Timing of the USA Experiment Using Pulsar Observations

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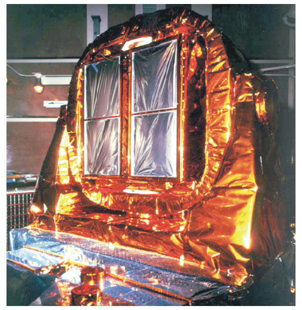
Introduction

Absolute timing observations of the Crab Pulsar (PSR B0531+21) have the capability of revealing significant information about the physics and geometry of the pulsar emitting region by comparing the shape and time delays between the pulses emitted at different wavelengths. However, before this can be attempted, one must first be certain that the calibrations of the instruments and the details of measuring absolute arrival times is well understood. Here we present observations of the Crab Pulsar with two X-ray, one radio, and one optical telescope, each of which expects to be accurate to of order 10 microseconds. However, the measured arrival times disagree by hundreds of microseconds. When comparing measurements made at different wavelengths, this could be due to calibration errors or could be a real physical effect. But, in the case of the two X-ray measurements only a time calibration or data processing errors are possible. We describe our measurements, data processing, and possible sources of systematic errors.

The USA Experiment


The USA instrument.

The Unconventional Stellar Aspect (USA) Experiment was one of nine experiments aboard the *Advanced Research and Global Observation Satellite* (*ARGOS*) which was launched on 23 February 1999. USA was a collimated proportional counter X-ray telescope with 1000 cm^2 of effective area, sensitive to photons in the energy range 1–15 keV (see Ray et al. 2001 for a more detailed description). A unique feature of USA is that all photon events are time tagged by reference to an onboard GPS receiver allowing precise absolute time and location determination.

USA had two standard telemetry modes, event and spectral. In event mode, the arrival time and energy information is stored for each photon detected. There are two submodes of event mode providing 32 μs time with 16 pulse height channels and 2 μs time with 8 pulse height channels respectively. Data may be output in event mode at either 40 or 128 kbps, providing maximum count rates of 1400 or 8000 events per second for 32 μs time or 1100 or 6450 events per second for 2 μs time. In spectral mode, a full resolution energy spectrum (48 channels) is generated every 10 milliseconds. Because of the polar orbit of ARGOS, data come in four low background segments per orbit limiting the maximum possible continuous observation to ~25 minutes.

Results

The arrival times measured were fitted to a model using the Princeton TEMPO pulsar timing package (Taylor et al., Taylor & Weisberg 1989). TEMPO reads a file of arrival times, optionally converts them into the solar system barycenter frame and does a least squares fit to a timing model and outputs the residuals from the best-fit model. The top figure at right shows all of our measured TOAs from November 1999 through January 2000. We describe the various features of the plot in the following.

The red crosses and cyan triangles represent the Jodrell Bank radio TOAs at 610 MHz and 1396 MHz respectively. The radio data represent the baseline for comparison to the other wavelengths. The timing model used in this figure is derived from fitting all of the radio data. We generated our own model covering this range rather than using one of the three relevant lines in the published Jodrell Bank monthly ephemeris (Lyne et al.). The ephemeris we used had a constant dispersion measure (DM) and a non-zero frequency (F0), frequency derivative (F1) and frequency second derivative (F2) of :

F0 (s^{-1}):	29.84670409339285200
F1 (s^{-2}):	-3.746098445932E-10
F2 (s^{-3}):	1.019126284E-20
DM (pc/cm^3)	56.767
Epoch MJD	51527.0 (TDB)

The high frequency data (1396 MHz) were rather sparse, having only 7 observations during these three months. We chose the DM such that the high frequency data aligned with the contemporaneous low frequency data. The delay of a pulse with respect to one at infinite frequency is DM / (2.410331821E-4 ν^2) where DM is in pc/cm^3 and ν is in MHz. This corresponds to a delay of 632,935 μs at 610 MHz and 120,850 μs at 1396 MHz. The green asterisks are the fiducial arrival times published in the Jodrell Bank Monthly Ephemeris for November, December and January. The radio TOAs show a wander around the smooth timing model as they always do for this young pulsar with a large amount of timing noise. Increasing the number of non-zero frequency derivatives doesn't do much to improve the fit.

The blue squares are the USA arrival times. These appear to lag the radio by a relatively constant amount, while following the wandering of the radio pulse. The purple plus signs are the RXTE single bit data and the gold circles are the RXTE event data. Both modes of the RXTE data are consistent with each other indicating that we are able to fit offsets to a precision of much less than a bin (the single bit data have bin sizes of 250 μs). Although they are not as well sampled as the USA data, the RXTE pulses seem to lead the radio pulses by an approximately constant amount. Finally, the green circle is the one optical TOA.

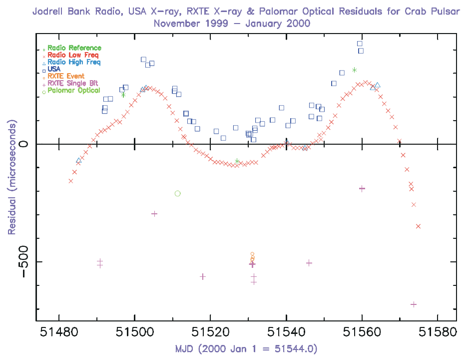
Because the two X-ray measurements appear to differ from the radio by a constant amount, we measured this offset by including fitted jumps in the timing solution between the different data sets. The radio was left fixed and the RXTE, USA, and optical each had one jump for the entire dataset. The residuals to this fit are shown in the figure below right. The constant offsets fitted were:

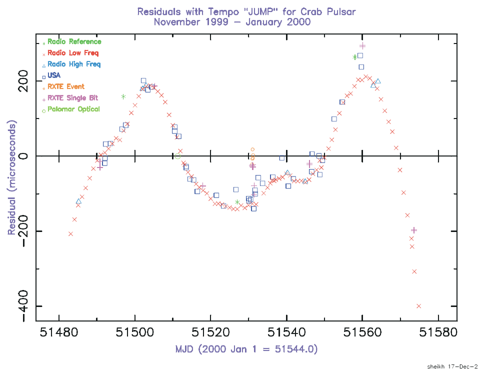
RXTE	**+533 ± 28 μs**
USA	**–108 ± 23 μs**
Palomar	**+253 ± 125 μs**

Observations

Instrument	Band	Dataset
Jodrell Bank Obs.		
Low Frequency	610 MHz	Raw TOAs Nov/99 - Jan/00
High Frequency	1396 MHz	Raw TOAs Nov/99 - Jan/00
RXTE		
EVENT	15–60 keV	P40090-01-01-00
SINGLE_BIT	2–15 keV	P40090-01-01-00
SINGLE_BIT	2–7 keV	P40093-01-{14 to 20}-00
USA	1–15 keV	Crab_Pulsar_HR Nov/99 - Jan/00
Palomar	V Band	Raw binned data


The ARGOS launch on 23 February 1999.





Data Processing

The data processing required to produce TOAs depended on the particular instrument; however, we attempted to use as much common software as possible to reduce the number of places instrument-specific processing errors could be introduced. In particular, we adopted a standard position for the Crab Pulsar that was used in all analysis. The reference position of the Crab Pulsar was chosen from the Jodrell Bank August 13, 2002 Reference Notes (Lyne et al.) published value of
RA = 05h 34m 31.97232s
Dec = 22d 00' 52.0690"
All coordinates are epoch J2000.0 and we adopted the solar system ephemeris DE200 (Standish 1982).

To do our timing analysis, we compared times of arrival (TOAs) of the peak of the main pulse as measured by each different instrument. We used the same template profile for fitting both X-ray data sets and the optical data. This template was aligned to have the peak of the main pulse (as determined by the centroid of the central few bins of the peak) at phase 0.0 (see Figure at right). The radio TOAs were determined using a triangular profile with peak at phase 0.0. For all data except the radio data we followed a similar procedure to determine TOAs.

For the space-based observations, the photon or bin times were first reduced to the arrival time at the solar system barycenter using the axBary FTOOL by A. Rots. The data were then folded at the barycentric pulse period to produce profiles. TOAs were generated by fitting for the time delay required to align the profile with the template profile (Taylor 1992).

For the ground-based optical data, the binned data were folded at the topocentric pulse period and a topocentric TOA was determined using the same template as the X-ray data. These topocentric TOAs were then fed into TEMPO with an observatory code corresponding to the telescope's geocentric location.

Jodrell Bank Radio Data

The radio data were taken as part of the Jodrell Bank pulsar group's long term monitoring of the Crab pulsar which provides a monthly ephemeris of the Crab Pulsar to the community (Lyne et al.). We used the TOAs that go into the monthly ephemeris directly so no further data reduction was necessary before importing the TOAs into TEMPO. TOAs were obtained at 610 MHz and 1396 MHz. The observatory clock has been referenced to GPS since 1996.

RXTE X-ray Data

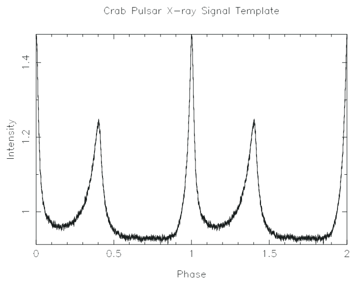
We used public RXTE data which were taken with several different EDS modes: Single Bit Mode (250 μs resolution), Event Mode (16 μs resolution) and Event Mode (2 μs resolution). The RXTE onboard clock is calibrated (and the spacecraft position is determined) using the USCCS technique via TDRSS. The expected timing accuracy is about 2 μs and the quoted position accuracy is 3 km (C. Markwardt, private comm.).

USA X-ray Data

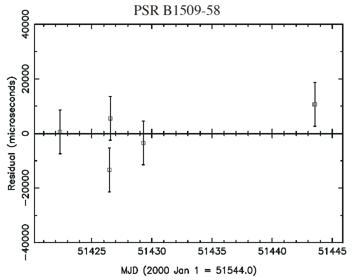
The USA data we analyzed were taken in the 32 μs resolution event mode with 16 energy channels from 1–15 keV. We used 41 observations of the Crab Pulsar, each of which was about 10 minutes in duration and produced a single TOA. Times of the USA events are referenced to an onboard GPS receiver. The receiver had difficulty maintaining lock so all data used in this work were selected for times when the GPS receiver reported good lock indicating that the clock should be accurate to within a few microseconds of UTC.

Palomar Optical Data

The V-band optical data were taken at Palomar Observatory using a custom detector that produced binned data at a time resolution of 20 microseconds starting at 1999 Nov 29 07:32:41 UTC (exactly). The times are referenced to UTC using a GPS receiver. The observation duration was about 4.5 hours.



Template profile used for creating arrival time measurements. The phase of the main peak has been aliged to phase 0.0 so that arrival times correspond to the peak of the main pulse. Two cycles are shown for clarity.



In principle, observations of other pulsars can be used to confirm the offset measured between USA and RXTE. In particular, both satellites observed PSR B1509-58 in September 1999. The plot above shows the USA TOAs measured during that month as compared to a published radio ephemeris. The agreement is excellent to within a few percent of a pulse period, but unfortunately the errors are still 8 ms which is much larger than the few hundred microsecond error we are looking for. The combination of low signal to noise and relatively long pulse period (150 ms) for this pulsar make it not useful for this purpose.

Discussion

At this point we can not draw any conclusions about the relationship between the X-ray pulse and the radio pulse since one experiment finds and X-ray lag and the other finds that the X-ray leads the radio. Previous authors (Rots et al 1998) have performed an independent analysis of the RXTE data and found that the X-ray pulse leads the radio by 300 ± 50 μs. We find a similar result from our analysis of RXTE data, but a very different result from the USA Experiment. This discrepancy must be resolved before physical conclusions can be drawn. We now consider several possible error sources:

* Energy dependence of the X-ray pulse profile. This must be considered because of the difference in X-ray energy sensitivity of RXTE and USA. However, this appears not to be a factor since the RXTE data show only small differences between the 2-15 keV data and the 15-60 keV data. Other authors have also reported no energy dependence up to 100 keV.

* Dispersion measure errors. The DM of the Crab varies by about 0.01 pc/cm^3 per month. An error of this magnitude would cause an offset of 110 μs in the 610 MHz data. But, our multiwavelength data allow a determination of the DM to an accuracy of considerably better than that, and this would not explain the difference between the two X-ray measurements.

* Satellite position errors. The satellite position at the time of reception of a photon goes into the conversion of times to the solar system barycenter (SSB). A position error would correspond directly to a time error. Both RXTE and USA have estimated position errors of a few km which would correspond to a timing error of 10s of microseconds. An unknown larger position error would very likely have a time dependence at the satellite orbital period, whereas the observed offsets appear constant over months or longer.

* Errors in barycentering the data. We have checked the barycentering code used for the X-ray data (all based on axBary by A. Rots) against the Princeton TEMPO code and found that, for the same inputs, the barycentric corrections are equal to better than 1 μs.

* Timestamp errors. Either (or both) satellites could have an undiscovered (but constant) error in the time stamping of their photon events, or in the data processing that assigns times to photons. These errors are naturally much more difficult to find since the relative timing for each instrument will be good but there will be a fixed offset.

* Software errors. Although we minimized the number of different software packages used in processing, it is possible that there is an error somewhere that affects RXTE differently than USA and introduces a time offset.

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