Navigation Using X-Ray Pulsars

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Approximately one-dozen X-ray pulsars are presently known which emit strong stable pulses with periods of 0.7 to ~1000 s. By comparing the arrival times of these pulses at a spacecraft and at the Earth (via an Earth-orbiting satellite), a three-dimensional position of the spacecraft can be determined. One day of data from a small (~0.1 m^2) on-board X-ray detector yields a three-dimensional position accurate to ~150 km. This accuracy is independent of spacecraft distance from the Earth. Present techniques for determining the two spacecraft coordinates other than range measure angles and thus degrade with increasing spacecraft range. Thus navigation using X-ray pulsars will always be superior to present techniques in measuring these two coordinates for sufficiently distant spacecraft. At present, the break-even point occurs near the orbit of Jupiter. The Crab pulsar can also be used to obtain one transverse coordinate with an accuracy of ~20 km.

I. Introduction

At present, as spacecraft are targeted farther from Earth, it becomes increasingly difficult to measure the transverse spacecraft coordinates (the two other than range). Fundamentally, present techniques measure the angular coordinates of a spacecraft and hence the positional uncertainty of the spacecraft grows linearly with distance. Thus navigation to the outer planets and beyond will be limited by these large uncertainties unless a better measurement tool is used.

We present in this article a promising new technique that involves comparing the arrival times of pulses from X-ray pulsars at a spacecraft and at the Earth. The positional accuracy given by this technique is independent of distance from the Earth. Only a small (~0.1 m^2) X-ray detector need be carried by the satellite. This is in sharp contrast to navigation using radio pulsars, which give more precise times but require impractically large antennas on the spacecraft.

II. Details

Several relevant parameters of the known X-ray pulsars are given in Table 1, as well as the parameters of the Crab pulsar, which is a radio pulsar (an entirely different beast) that is also detectable in X-rays. There are two major classes of X-ray pulsars – "steady" and transient sources. The transient sources are detectable only at (usually) irregular intervals – for example, perhaps for only 30 days – and then are below detection limits for a year or more. Thus only the "steady" sources can be relied upon for navigation. Unfortunately, even the "steady" sources sometimes turn off for about a month. This can occur at regular intervals, as for Her X-1 which is detectable for 10 days and then undetectable (except briefly) for 25 days, or the off period can be irregular, as for Cen X-3 and SMC X-1. Nonetheless, this should cause little problem, both because it is unlikely that all usable sources would be off simultaneously, and also because the long transit times necessary on deep space voyages allow some short gaps in the measurements of some coordinates.

The pulses from X-ray pulsars are largely sinusoidal, with only a little power in the lower harmonics and no power in the higher harmonics. This is quite unlike radio pulsars, which pulse for only ~10% of their periods. Thus the time of arrival accuracy is given by how well the phase of a sinusoidal pulse can be measured, and not by the arrival of any sharp feature in the pulse.

Taking Her X-1 as an example, 20 seconds of data taken by the UHURU satellite, with a detector area of 0.1 m^2, determined arrival times accurate to 0.03 s (Ref. 1), which gives a positional measurement good to 10,000 km in the direction toward the X-ray pulsar. One full day of measurements would beat the error down to $10{,}000 \text{ km} \sqrt{20 \text{ s}/86{,}400 \text{ s}} = 150$ km. Both SMC X-1 and Cen X-3 are similar to Her X-1, and would give comparable positional accuracies. Thus these three pulsars would suffice to give a three-dimensional spacecraft position. Figure 1 shows the geometry of these three pulsars, referenced to the ecliptic plane.

Of course, with ranging, only two pulsars are needed for a good three-dimensional position. The other short-period pulsars can provide more information when they are pulsing. Even the long-period pulsars give positional measurements which are only slightly worse because they tend to have more harmonic content in their pulses, and thus timing accuracies do not degrade as badly as linearly with pulse period.

The Crab pulsar, with its period of only 0.033 s and its low duty cycle pulse, gives much more precise arrival times, and is always detectable. However, a larger detector would be required to take full advantage of this resolution. With a small detector, again 0.1 m^2, the time resolution should be ~10 times better than for Her X-1. Unfortunately, the Crab pulsar is in the ecliptic plane and thus cannot give any information about the spacecraft coordinate perpendicular to the ecliptic plane. Of course, except when the spacecraft lies along the direction to the Crab, such timing observations will measure one transverse spacecraft coordinate in the ecliptic plane.

Because the pulse periods of X-ray pulsars (and radio pulsars) are derived from the rotation of a neutron star, the period is very stable. Typically, $\dot{P}/P \sim 10^{-11}$, except for some of the long-period X-ray pulsars, which can have $\dot{P}/P \sim 10^{-4}$. The most important source of timing error on the spacecraft will therefore come from the spacecraft clock itself. Fortunately, any drift of the spacecraft clock can be treated as an additional unknown, if it is important enough, and can be found by using an additional pulsar. In that case, with ranging, three pulsars are needed for a good three-dimensional position and the determination of the spacecraft clock offset. The spacecraft clock need only be stable over the chosen integration time for an individual arrival time determination.

Finally, the positional uncertainty of the X-ray pulsars themselves can be neglected. An angular uncertainty of θ in the coordinates of a pulsar gives rise to an error of $\theta^2/2$ times the distance between the Earth and the spacecraft projected along the pulsar direction. Thus if $\theta = 5 \times 10^{-7}$ (0.1 arc sec), then the error at Saturn is less than 10 cm.

III. Discussion

Navigation using X-ray pulsars is a practical method that yields three-dimensional positions accurate to ~150 km with one day of data. It is the best practical method for sufficiently distant spacecraft, requiring only a small X-ray detector on board the spacecraft coupled with an Earth-orbiting satellite that provides the arrival of X-ray pulses at Earth. (In the last decade, there has been an average of several such satellites in orbit at any given time.)

Present positional accuracies for the transverse coordinates of a spacecraft are ~300-400 km at Saturn (Ref. 2) with ~1 day of data. Thus X-ray navigation is comparable to present techniques at roughly the orbit of Jupiter and is clearly superior at Saturn and beyond.

References

1. Fechner, W. B., and Joss, P. C., "Evidence for a 35 Day Precession in the Orbit of Hercules X-1," *Astrophys. J. Letters*, 1977, Vol. 213, p. L57.
2. Melbourne, W. G., "Navigation Between the Planets," *Scientific American*, June 1976, Vol. 234, No. 6.

Table 1. The known X-ray pulsars

Name[a]	Period, s	Peak counts/s[b]	Class[c]
3U0531 + 21 Crab pulsar	0.03	100	R
3U0115 -37 SMC X-1	0.7	28	S
3U1653 + 35 Her X-1	1.2	100	S
4U0115 + 63	3.6	70	T
3U1118 -60 Cen X-3	4.8	160	S
3U1626 - 67	7.7	10	S
OA01653 - 40	38	600	T
A0535 + 26	104	1900	T
3U1728 - 24	122	60	S
A1239 - 59	191	12	S
3U1258 - 61	272	47	S
3U0900 - 40	283	100	S
4U1145 - 61	297	72	S
A1118 - 61	405		T
3U1538 - 52	529	11	S
3U1223 - 62	696	32	S
3U0352 + 30	835	20	S

[a] The name begins with a 1- or 2-character catalogue designation, followed by the right ascension (HHMM) and the declination.
[b] 2-6 keV counts per second for a 0.1 m^2 detector.
[c] R – radio pulsar; S – steady; T – transient.

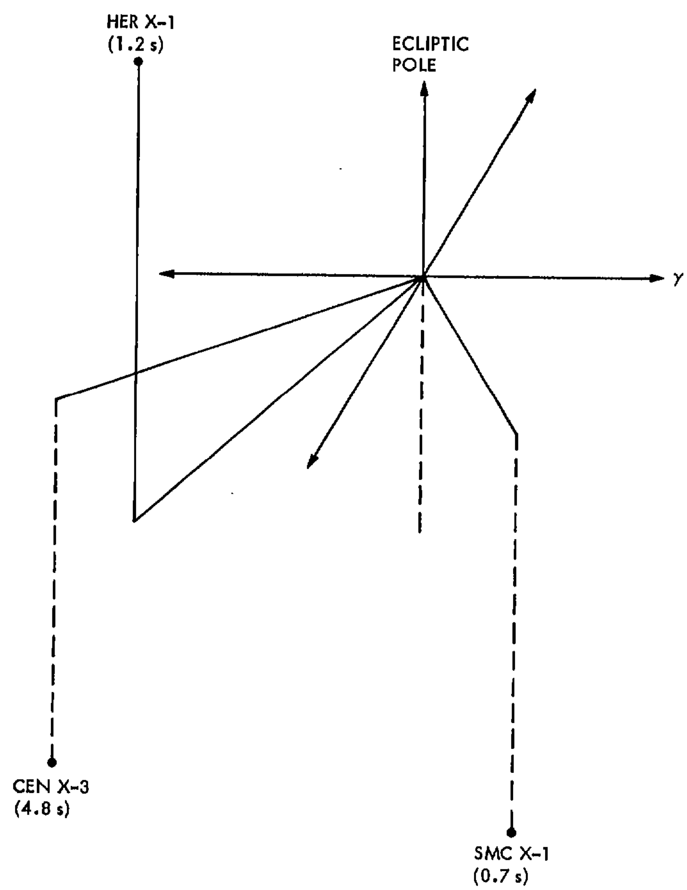

Fig. 1. Location of several X-ray pulsars relative to the ecliptic plane