REPORT ON A STABLE NEW PULSAR

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ABSTRACT

A pulsar has been discovered which not only has a very rapid pulsing period of 1.6 milliseconds and a narrow pulse width of ~70 microseconds, but also appears to be an isolated and very stable object. Monitoring has so far shown no signs of the instabilities or "glitches" which reduce the utility of many pulsars as precise time references. Study of this "millisecond pulsar" therefore yields, in principle, a time reference of greater stability than any other known. However, its utility as a possible laboratory reference is presently limited to about 1 microsecond due to systematic errors in the corrections for numerous time transfer and solar system effects. The prospects for improving these corrections and for using the millisecond pulsar both as a time reference and to improve our knowledge of solar system parameters appear very good.

INTRODUCTION

The serendipitous discovery of pulsars in 1967 by Jocelyn Bell (Bell-Burnell, 1983) with the Cambridge University interplanetary scintillation array (Hewish et al., 1968) confirmed the very long standing prediction of the existence of neutron stars (Baade and Zwicky, 1934) and provided one of the most exciting discoveries of modern astrophysics. Since that time, even though detailed theoretical models of the emission processes still are not completely satisfactory, the gross theoretical properties of pulsars have been relatively well defined and the observational aspects have been explored in great detail (see, e.g., Manchester and Taylor, 1977). They are rotating neutron stars, presumably left as the stellar remnants of supernova explosions. They are born within about 80 pc of the galactic plane and, because they are relatively short lived (~2 x 10^6 yr), remain strongly concentrated to the plane during their visible lifetimes in spite of their relatively high individual velocities (~200 km s^{-1}) (Figure 1). Essentially all pulsars are known only as radio objects and the individual pulse profiles vary strongly from object to object (Figure 2), often showing a second or "interpulse," with an average pulse period of ~1 second (Figure 3). Only three pulsars are known to pulse in optical light (PSR0531+21 in the Crab Nebula, PSR0833-45 in the Vela supernova remnant, and PSR0540-693 in the Large Magellanic Cloud) and only one of these (the Crab Nebula pulsar) has been found to pulse in all wavelength bands from high energy gamma rays to low frequency radio waves. Several pulsars have been found to be members of binary systems (with one

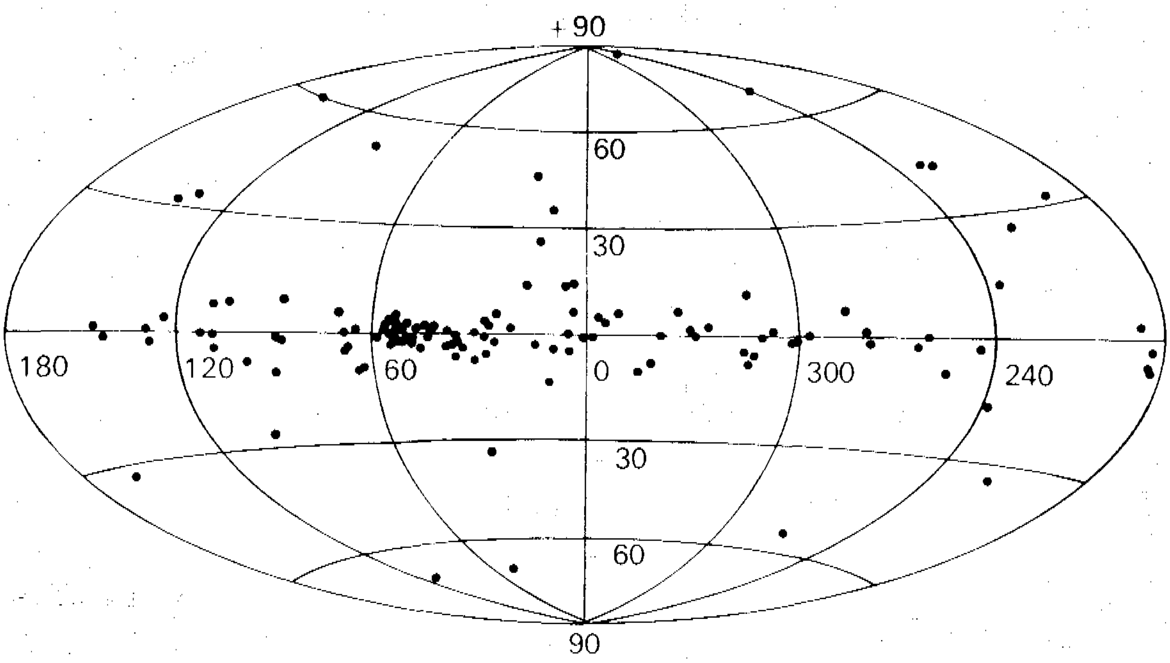

Figure 1. Distribution of pulsars in galactic coordinates, plotted on a Hammer equal area projection. [Used from Manchester and Taylor, 1977 (Figure 1-5, p. 10), with permission.]

Table 1: General Properties of Pulsars[a]

<Birth /z/>	~ 80 pc
<Present /z/>	~153 pc
<Transverse /v/>	~214 km s^{-1}
Density (for 3 mJy)	~ 25 kpc^{-2}
Number known	~150
Number in Galaxy	~1-3 x 10^{5}
<Characteristic age> $(P/2\dot{P})$	~4.3 x 10^{6} yr
<True age>	~1-2 x 10^{6} yr
<Lifetime>	~ 4 x 10^{6} yr
Birthrate in Galaxy	~2.2 x 10^{-4} yr^{-1} kpc^{-2} ~1/25 yr

[a] Manchester and Taylor, 1977

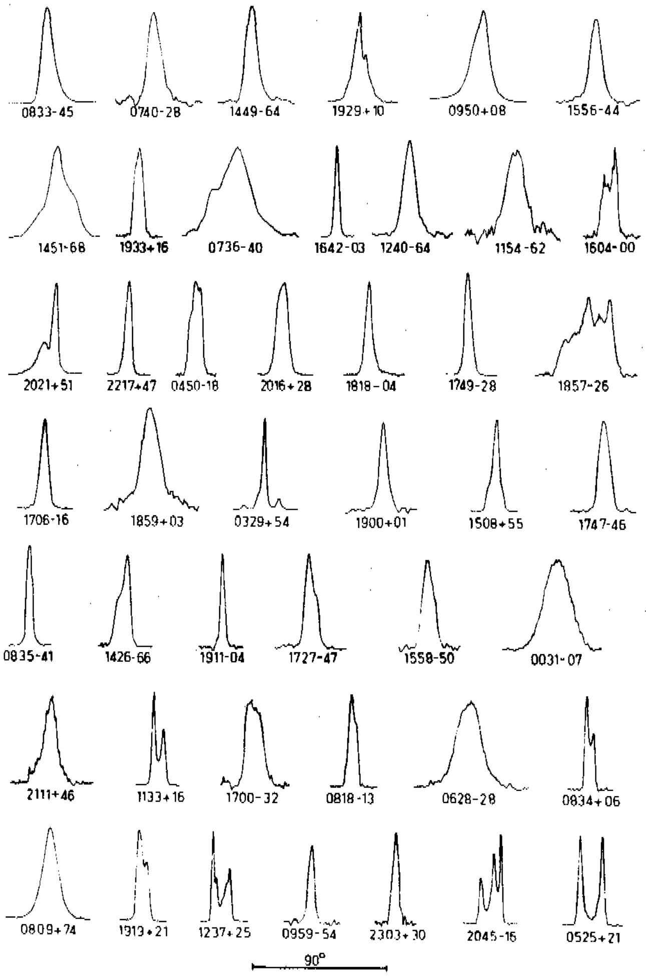

Figure 2. Integrated pulse profiles for 45 pulsars, all plotted on the same longitude scale (a 90° bar is given at the bottom of the figure). These profiles were recorded at frequencies between 400 and 650 MHz and are arranged in order of increasing pulse period. [Used from Manchester and Taylor, 1977 (Figure 2-1, p.14), with permission.]

of these, PSR1913+16, being particularly interesting because it shows the first direct evidence for energy loss from a system due to gravitational radiation [Hulse and Taylor, 1975]), but most appear to be isolated objects. (For a summary of general pulsar properties, see Table 1 and Manchester and Taylor, 1977.)

Although these massive and rapidly spinning neutron stars were recognized almost immediately as holding out the promise of being extremely accurate and stable frequency references, experience has shown that this promise is not fulfilled for the majority of objects. Not only do most pulsars have relatively slow periods of ~1 second and relatively broad pulse profiles making precise timing difficult, but also many of them exhibit unpredictable "glitches" in their periods as the surface of the neutron star occasionally

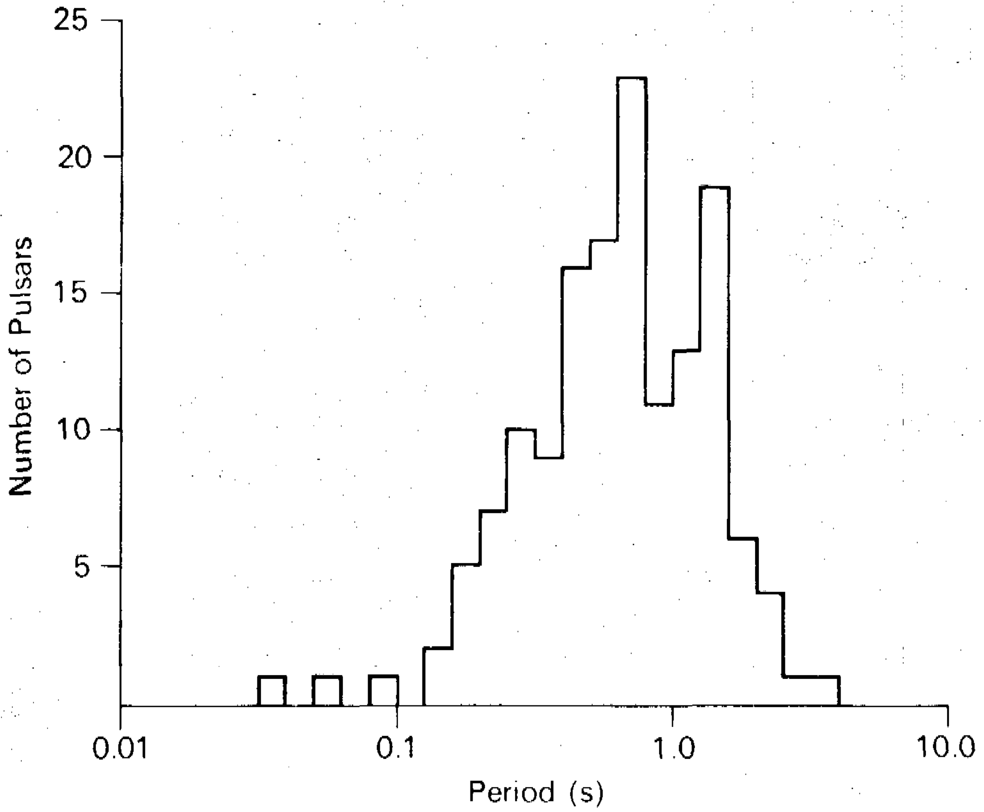

Figure 3. Distribution of pulsar periods. [Used from Manchester and Taylor, 1977 (Figure 1-4, p. 9), with permission.]

Table 2: Measured Parameters of PSR1937+21[a]

Period (s)	0.0015578064488724 ± (2×10^{-16})
Period derivative (s/s)	(1.05110 ± .00008) x 10^{-19}
Second period derivative (s^{-1})	$<10^{-29}$
Right ascension (1950.0)	19h37m28.74600s ± 0.00003s
Declination (1950.0)	21°28'01.4606" ± 0.0010"
Proper motion in R.A.	-0.3 ± 0.4 milliarcsec yr^{-1}
Proper motion in Dec.	-1.4 ± 1.0 milliarcsec yr^{-1}
Epoch at barycenter	2445303.2731658 JED
Assumed dispersion	2.94788 x 10^{17} Hz
Distance	5 kpc
Q	$>3 \times 10^{19}$
Characteristic age ($P/2\dot{P}$)	2 x 10^{8} yr
Surface magnetic field	5 x 10^{8} Gauss

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[a] Davis et al., 1985

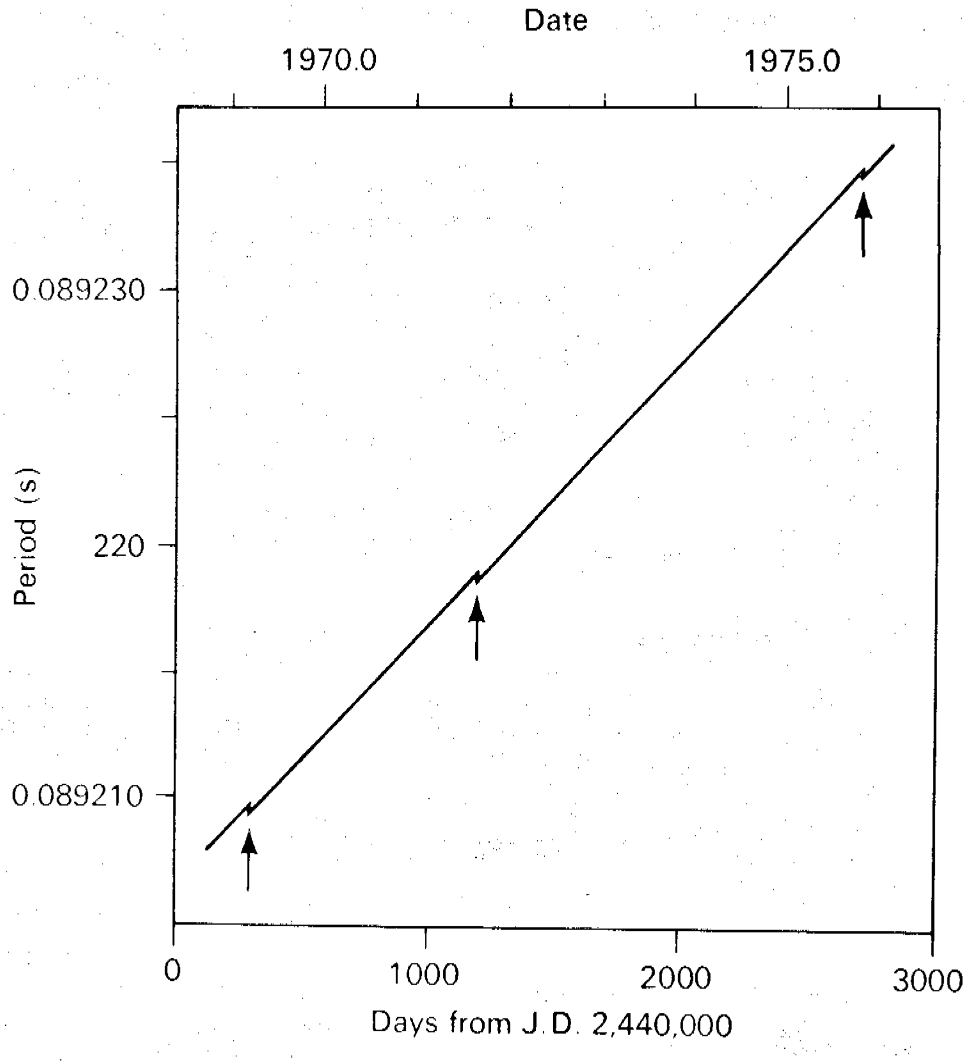

Figure 4. Variations in the period of the Vela pulsar, PSR0833-45, from 1968 to 1976, showing three discontinuous steps in the regular increase of the period. [Used from Manchester and Taylor, 1977 (Figure 6-4, p. 114), with permission.]

readjusts itself to the decreasing centrifugal force as the star slows its spin with time (see, e.g., Figure 4). However, one pulsar, known as the "millisecond pulsar" because of its very short pulse period of only 1.6 milliseconds, has been found which so far exhibits none of these defects. It has a short pulse period, a narrow pulse profile, a small slowdown rate, is isolated, and has no detectable glitches in more than three years of measurements.

PSR1937+21

The observable properties of PSR1937+21 have recently been discussed by Davis et al. (1985) and are summarized in Table 2. After over three years of data collection, the millisecond pulsar appears to remain a very high Q rotator with a stability unattainable with any other known celestial or terrestrial

Table 3: Contributions to Observed Pulse Arrival Times[a, b]

Origin	Model magnitude (microsec)	Estimated error (microsec)
Pulsar		
Spin	$3 \times 10^{13} t$	-----
Spindown	$3 \times 10^{4}\ t^{2}$	-----
Timing noise	-----	$0.01\ t^{3/2}$
Propagation at 1.4 GHz		
Interstellar medium	1.5×10^{5}	0.5 t
Interplanetary medium	0.4	<0.4
Ionosphere	-----	<0.04
Troposphere	-----	<0.01
Clocks and corrections		
UT(AO)-UT(JUP)	1	0.5
UT(JUP)-UT(USNO)	1	0.2
UT(USNO)-TAI(USNO)	50	0.0
Errors in TAI(USNO)	-----	0.3 t
Reduction to barycenter		
Observatory to center of Earth	2×10^{4}	0.01
Earth to barycenter	4×10^{8}	0.6 t
TAI-TDB	1,600	0.1
Gravitational propagation delay	20	<0.1
Parallax of pulsar	-----	0.06

[a] Davis _et al._, 1985

[b] For each of the named contributions to pulse arrival times, the left-hand column gives an indication of the magnitude of the effect currently included in the model and the right-hand column gives an estimate of the errors caused by having ignored it or having modelled it imperfectly. Times, t, are measured in years. AO stands for Arecibo Observatory and JUP for the Loran station at Jupiter, Florida. TAI stands for International Atomic Time and TDB for Barycentric Dynamic Time.

frequency references. This is shown in Figure 5 which plots the fractional stability of various types of oscillators against measurement interval. As stated by Davis _et al._ (1985) "...it (is) clear that over time scales of the order of one year, radio astronomical observations of PSR1937+21 can provide a standard of time that is competitive with any other available standard." However, in spite of its great stability and promise as a long term time reference, PSR1937+21 is not easily useful as a possible laboratory standard. At present, corrections for Solar System dynamical and relativistic effects dominate the errors and limit the timing accuracy to approximately one microsecond. The

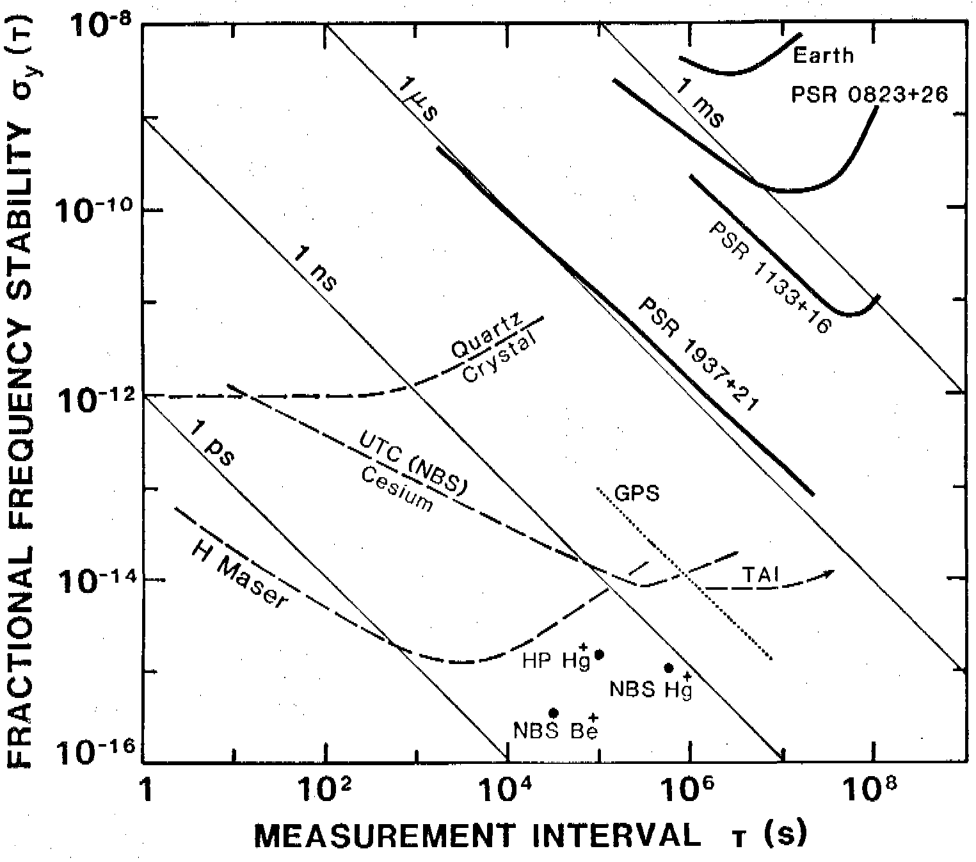

Figure 5. Measured frequency stability for PSR1937+21 over intervals from 30 minutes to 256 days. For comparison purposes, stability curves representative of several types of oscillators and other celestial rotators are also plotted (Backer and Hellings, 1986).

various error sources affecting the measurements along with estimates of their approximate magnitudes are listed in Table 3. There is the hope, however, that most of these error sources can be removed or reduced with further observation and modelling. [For example, time transfer via the Global Positioning System (GPS) satellites to the Arecibo Observatory is now available to ~10 nanoseconds.] This will lead not only to more accurate timing measurements, but will provide a better definition of the parameters needed to calculate Barycentric Dynamic Time (TDB).

Obviously, the corrections needed to derive laboratory time from pulsars would be more easily defined if a number of pulsars with stability similar to that of the millisecond pulsar were available for study. However, among the objects so far discovered, none is as useful as a precise time reference. A pulsar with a 6.1 millisecond period is known, but it is considerably fainter and has a much broader pulse profile, both effects leading to a much poorer definition of its "time mark." Another fast pulsar (~59 millisecond period) which appears to be very stable, the "binary" pulsar, yields a precision of ~25 microseconds for a 2 hour measurement but is also very weak with a broad pulse profile (D.C. Backer, 1985, private communication). Thus, until new and ongoing searches yield further stable examples for study, the millisecond pulsar will remain the best "cosmic clock" available. For a more extensive presentation of the properties of the millisecond and other pulsars and their timing properties, Backer (1985) has recently presented a discussion of the subject and a review article by Backer and Hellings (1986) is in press.

ACKNOWLEDGMENTS

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QUESTIONS AND ANSWERS

MARK WEISS, NATIONAL BUREAU OF STANDARDS:
Has the millisecond pulsar observed any star quakes?

MR.WEILER:
None so far.

MR. WEISS:
In how much time?

MR. WEILER:
Three years. The Crab has one every year or two, so it is more stable than that.

ROBERT DOUGLAS, NATIONAL RESEARCH COUNCIL OF CANADA:
How many free parameters are fit to the clock model that you are using?

MR. WEILER:
You would have to ask one of the afficionados, Joe Taylor at Princeton or Don Backer at U.C. Berkely or Mike Davis at Arecibo. I just simply don't know.

MR. DOUGLAS:
Order of magnitude?

MR. WEILER:
Nope. I am not a specialist on this subject and am giving the paper for Ken Johnston.

DAVID ALLAN, NATIONAL BUREAU OF STANDARDS:
The main terms, of course, are the terms associated with the ephemeris of the earth. At the symposium on the millisecond pulsar and Ron Hellings used about a nine term fit for the earth ephemeris. The clock itself is a separate issue and with cesiums involved it is a drift free system, so it only has two terms, the frequency offset term and the time term.

ROBERT FRUEHOLZ, THE AEROSPACE CORPORATION:
If one were to look exclusively for this pulsar, would it be possible to use something smaller than than the radio astronomy type of antenna? Say a satellite of some sort?

MR. WEILER:
No, the frequencies at which they observe are not particularly disturbed by the ionosphere or the atmosphere. They tend to observe at 1.4 GHz which is a nice medium frequency; high enough so that the ionosphere doesn't bother you and low enough that the atmosphere doesn't bother you. Basically the pulsar is weak and to get good signal to noise to pin down your phase on the pulse to get a decent timing tick needs the collecting area of Arecibo. It can certainly be detected with smaller antennas, but I think that you would need at least a twenty five meter antenna with a state of the art cold receiver to be able to get any sort of reasonable accuracy or to detect it at all. The pulsar can be detected by the 100 meter at Bonn, but that is the largest fully steerable antenna in the world. So with a three meter satellite antenna you would have no chance, and going outside the earth's atmosphere doesn't give you any advantage.

INDECIPHERABLE QUESTION FROM THE AUDIENCE:

MR.WEILER:
Yes, it is broad band, but they tend to have very steep spectra, so the higher frequency you go to gives higher gain, but they get weak very fast. You have to stick to the lower frequencies and, since they are so weak to start with, you have to have large collecting areas. You have a limit of, say, twenty degrees Kelvin in the receiver temperature.

DONALD SULLIVAN, NATIONAL BUREAU OF STANDARDS:
Are other observatories following this particular object?

MR. WEILER:
Not in detail. It is essentially the property of this group of the fourth reference. They have the best equipment and the most experience. Mike Davis himself is at Arecibo. They are able to follow it and track the phase and keep the timing. They are unique with their activities with the millisecond pulsar.