Technical requirements for autonomous space craft navigation using radio pulsars

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Overview

1. Determination of space-time locations, background
2. Radio pulsar TOA measurement principles
3. Radio Noise Background
4. Pulsar Spectrum
5. Pulse widths and Radio Frequency: Dispersion, Scattering, Jitter
6. Properties of real timing pulsars
7. Optimal receiver frequency and antenna sizes
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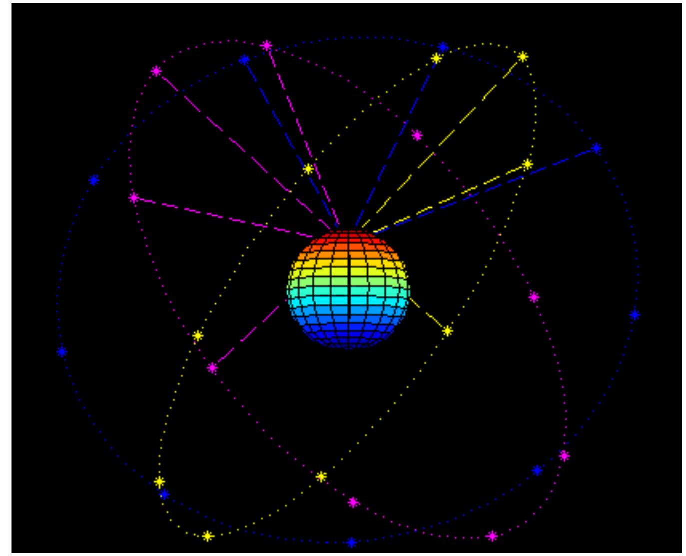
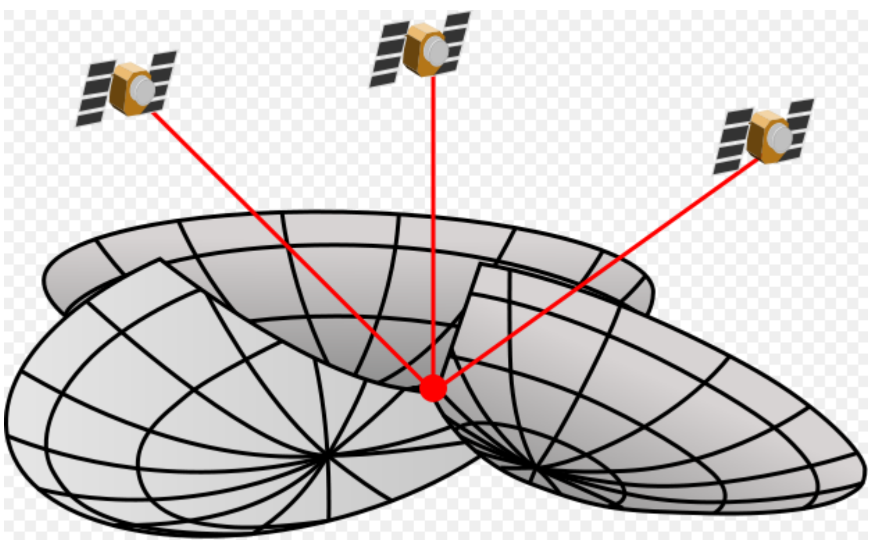
10. Summary and conclusions

Terrestrial Satellite Navigation

Satellite navigation is usually understood as the determination of the **4-position** (longitude, latitude, height, time) of an object from the **arrival time** of **radio signals** emitted by a number (>4) of satellites.



http://commons.wikimedia.org/wiki/File:Galileo_sat_constallation.gif



http://de.wikipedia.org/wiki/Globales_Navigationssatellitensystem#/media/File:GPS_Spheres.svg

Satellites transmit their position and time

The intersection of three spheres with radii

$$R=c(t_{rec}-t_{em})$$

defines the location of the receiver.

Clock correction needs fourth satellite

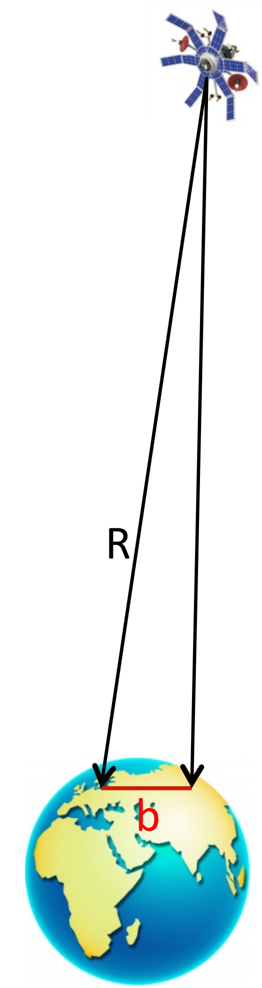
Satellite Positions

Reference system: **Earth**

Satellite positions are regularly updated and corrected via

- precise orbit calculations
- ranging measurements

made from the earth and transmitted to the satellite



Ranging accuracies depend on
time resolution δt and relative baseline accuracies $\delta b/b$

$$\delta R \propto 2 \cdot R \cdot \frac{\delta b}{b} + \frac{1}{2} c \cdot \delta t$$

with $\delta b/b$ becoming the dominant factor for large distances,

Example: δb=1 cm, b=5000 km, δt =1µs and R = 10 AU ➔ **δR≈ 6km**

Baseline effects begin to dominate when R> 0.25 AU or 37 Mill. km

Deep Space Satellite Positions

Reference system: **Solar Barycentre**

Satellite positions may be regularly updated and corrected via time of arrival (TOA) measurements of pulsed signals from distant beacons

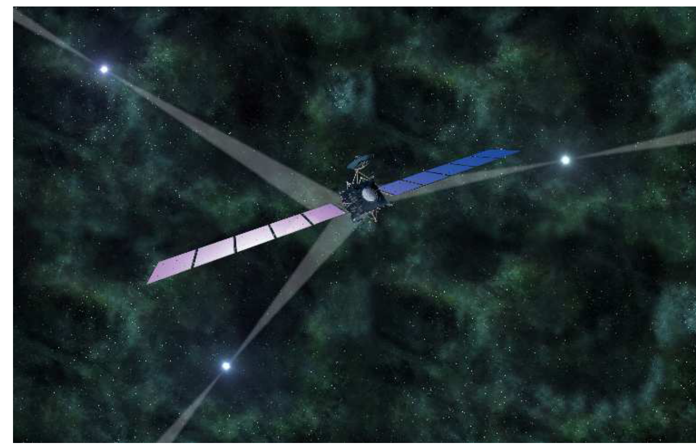
Position accuracies depend only on time resolution δt

There are 7 independent variables that describe the trajectory of the spacecraft w.r.t. the solar barycentre:

- 3 spatial coordinates X,Y,Z,
- 3 velocity components V_x, V_y, V_z
- the time t

An accuracy of δR=1 km corresponds to a timing error of 3.3 µs.

➔For three position coordinates we require a
timing accuracy of < 2 µs
➔ for at least four pulsars
➔ updated once per hour



Becker et al. 2013

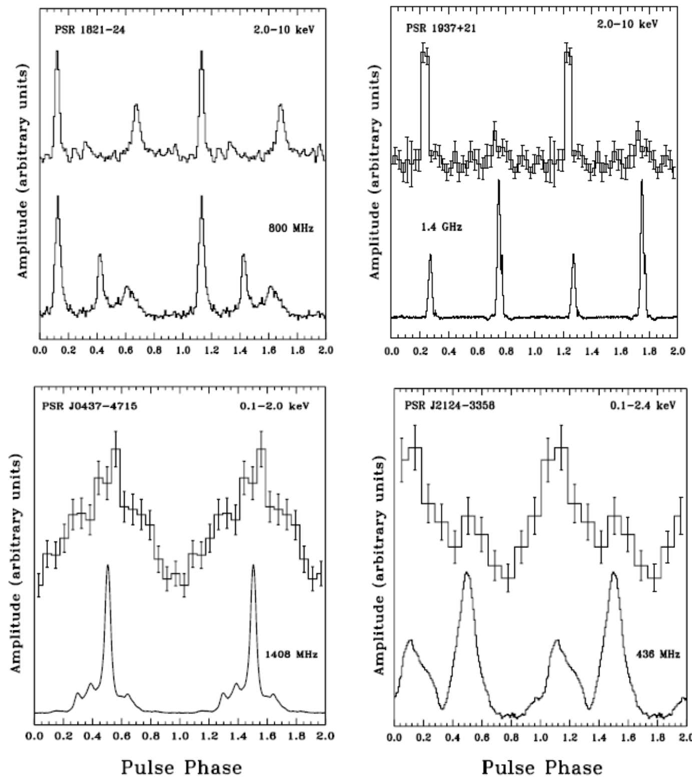
Celestial Beacons

Using celestial references for navigation is not new:

•**Optical emission** from **stars** is regularly used for the control of satellite orientation in space

Pulsars have regular pulsed emissions on radio and X-ray wavelengths

pulse arrival times (TOAs) may be predicted from **ephemeris data** based on the past TOA measurements.



Becker et al. 2013

•**Radio pulsars** for satellite navigation first by

Downs, G. S. :

"Interplanetary Navigation Using Pulsating Radio Sources," NASA Technical Reports **1974**

•Antenna: only three dipoles

•ν= 200 MHz, $\Delta\nu$=200 MHz,   **t_{int}=24 h**

Δt=20-60 ms   **δR=60-180 km**

•**X-ray pulsars**: Chester, T., Butman, S. (**1981**) , I.S. Sheik et al. (2004)

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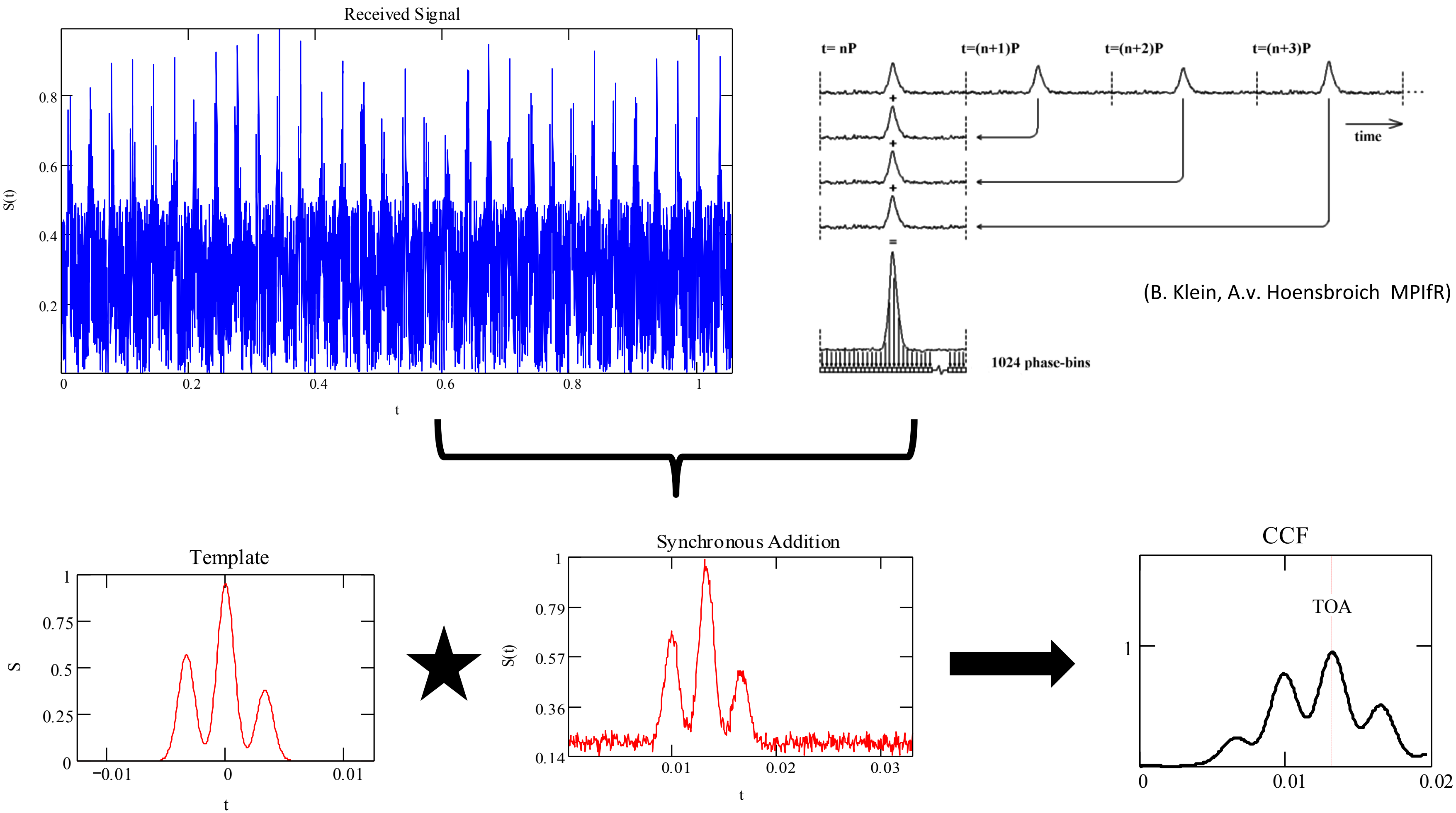
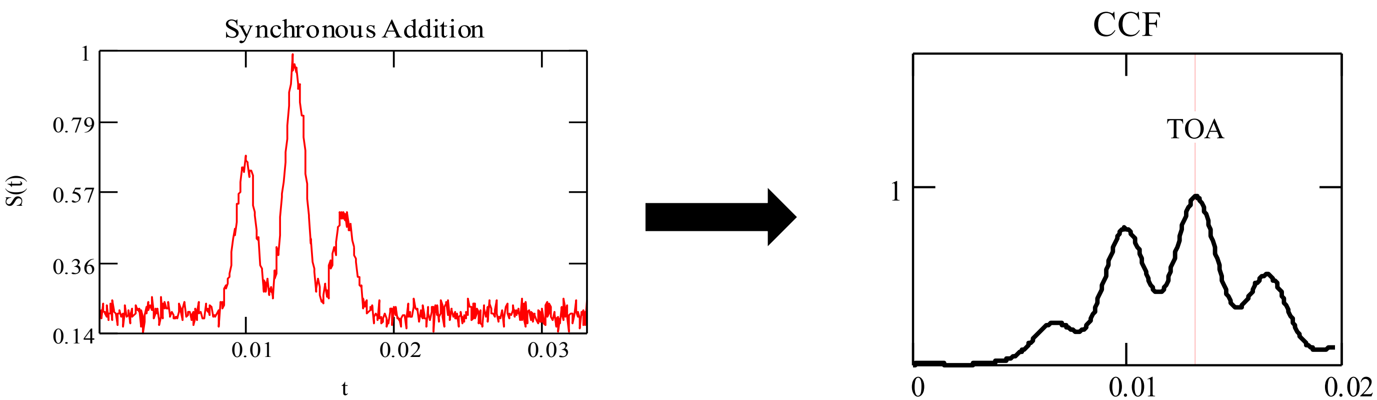
TOAs from received signals

Pulse arrival times are usually measured using cross-correlations between a **template profile** and the received **synchronously averaged radio profile.**



Factors Limiting TOA Precision



Signal to Noise Ratio & profile width determine TOA errors σ_t.

Gaussian profile :

(Hagen et al. 2007)

$$\sigma_t = (2\cdot\pi\cdot\ln(2))^{-\frac{1}{4}} \cdot \sqrt{\frac{w}{\delta t}\cdot\frac{N}{S}}$$

For best

1. S/N: ➔ strong source, high gain antenna, low noise receiver, low gal. Noise
2. w: ➔ source with narrow pulse width

S, N, w depend strongly on frequency, requiring careful optimisation!

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System Noise

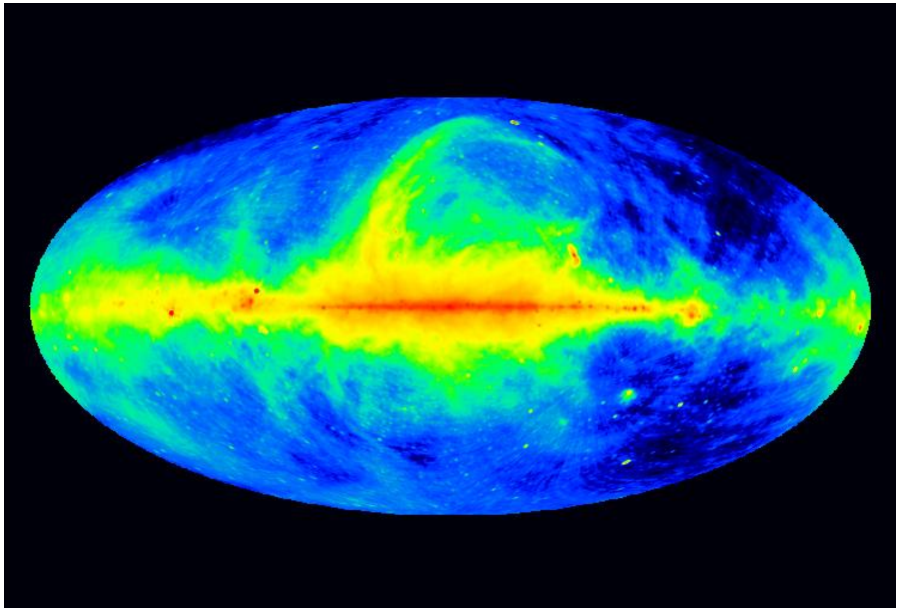
In spectral flux density units (Jy): $$S_{sys}(\nu) := \frac{2 \cdot k \cdot \left(T_{rec} + T_{sky}(\nu)\right)}{\varepsilon_{ant} \cdot A_{ant}}$$

- $\varepsilon_{ant} A_{ant}$ **??** → antenna size must be optimised!

- $T_{rec} \approx 100$ K (non-cryogenic!)

- T_{sky} depends on ν and celestial coordinates

Radio Sky at 408 MHz



(C.G.T. Haslam et al. 1974, MPIfR)

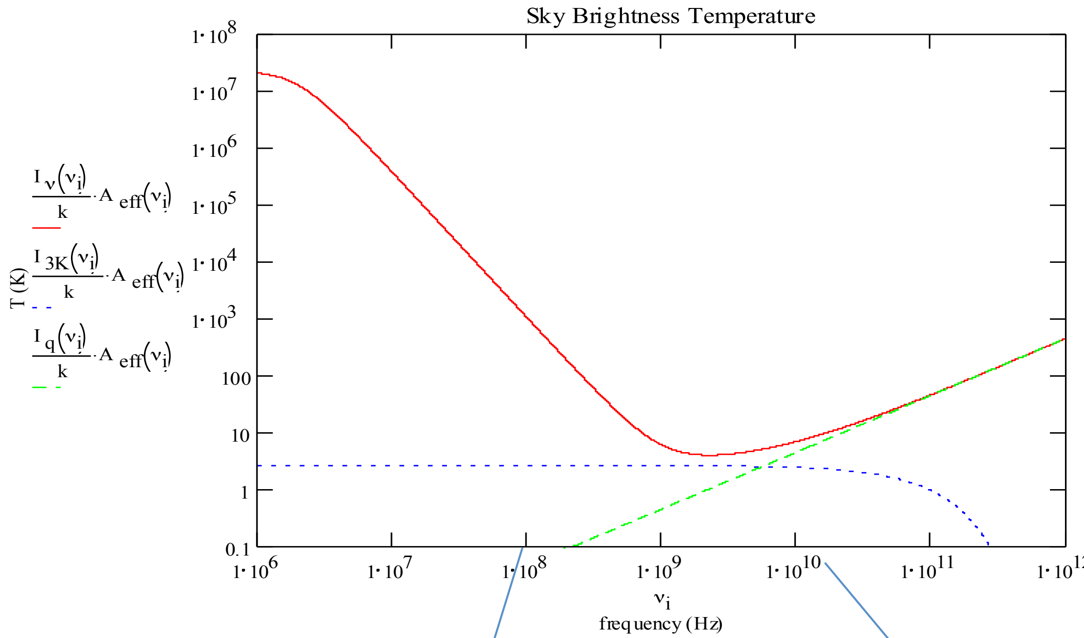
Noise Background Model

Contributions from

- Galactic &
  extra-galactic synchroton radiation
  (Cane 1979, Ellington 2005)

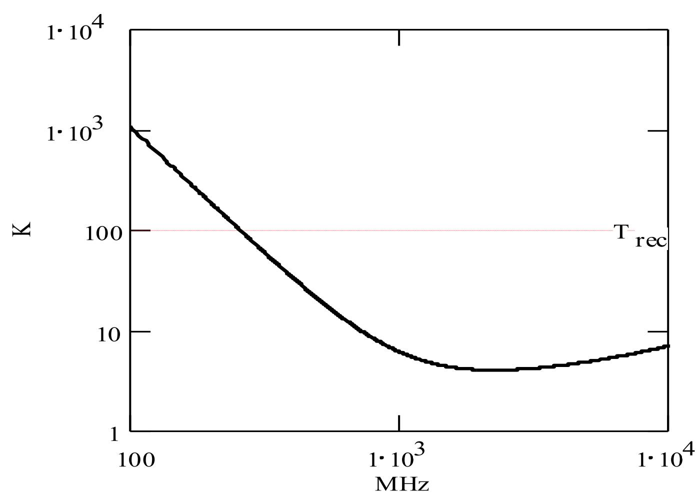
- 3 K background radiation
  (Planck Law)

- Quantum noise



Background noise has shallow minimum around 2 GHz.

➔ favours L-Band frequencies (1-2 GHz)



Radiometric S/N

Effective r.ms. noise level per time bin δt using a receiver bandwidth $\Delta\nu$, with n_{per} periods and n_{pol} polarisations averaged : (Dicke, 1949)

$$\sigma_{rec} = \frac{2\cdot k\cdot\left(T_{rec} + T_{sky}\right)}{\varepsilon_{ant}\cdot A_{ant}\cdot\sqrt{n_{pol}\cdot n_{per}\cdot\delta t\cdot\Delta\nu}}$$

Combining with cross correlation precision using

$\eta=\Delta\nu/\nu$, $t_{int}=n_{per}\cdot P$, $n_{pol}=2$ as well as $S_{peak}=S\cdot(P/w)$

yields:

$$\sigma_t(\nu,\eta,t_{int},w,P,S) = \frac{1}{(2\cdot\pi\cdot\ln(2))^{\frac{1}{4}}}\cdot\sqrt{\frac{w^3}{2\cdot\nu\cdot\eta\cdot t_{int}\cdot P}}\cdot\frac{S_{sys}(\nu)}{S}$$

(Similar to Cordes & Shannon, 2010)

Scaling of timing precision:

$$\sigma_t = w_{eff}^{\frac{3}{2}}\cdot P^{\frac{-1}{2}}\cdot\nu^{\frac{-1}{2}}\cdot\eta^{\frac{-1}{2}}\cdot t_{int}^{-\frac{1}{2}}\cdot\frac{S_{sys}(\nu)}{S_{psr}(\nu)}\cdot 233\cdot\mu s$$

(for P, w in ms, S_{psr} in mJy, S_{sys} in Jy)

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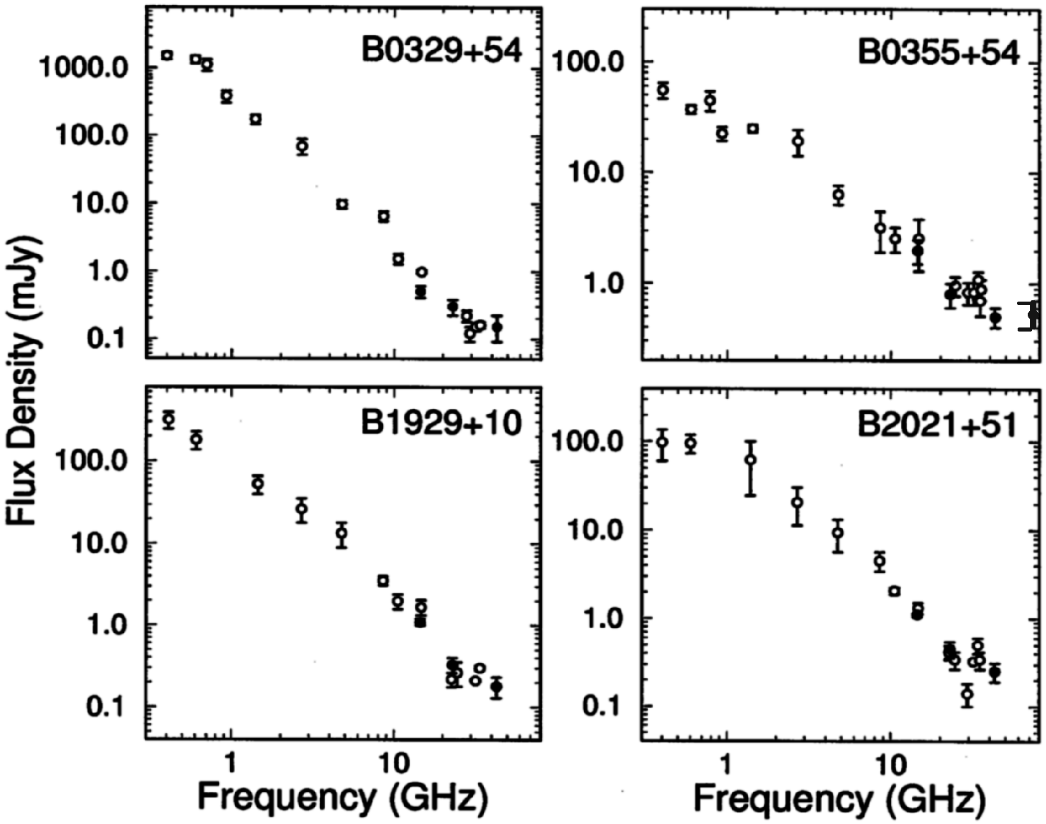
Pulsars are weak radio sources with steep spectra



(Kramer et al. 1996)

$$S \propto \nu^{\alpha_p}$$

$\alpha_p \approx -1.5 \ \ldots \ -1.9$

Average Flux density of strongest pulsars at 1.4 GHz:

$$< S > \approx 1 Jy$$

➔ N(ν)/S(ν) favours low receiver frequencies

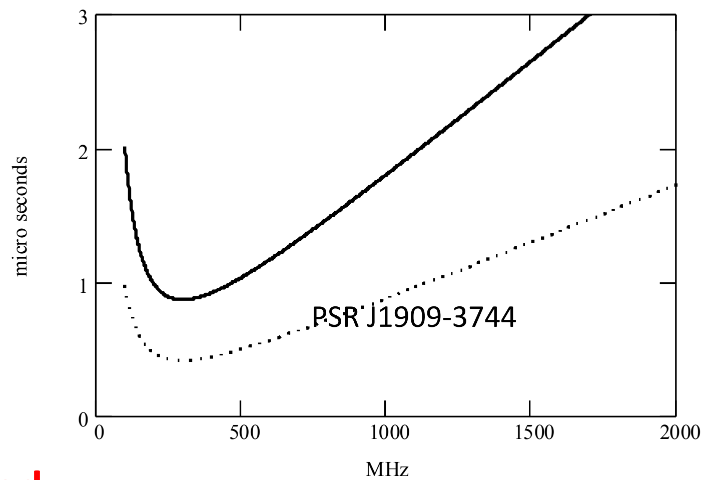
First estimate of optimal frequency

The steep power-law spectrum of pulsars and sky background require averaging over receiver bandwidth:

$$\sigma_t = \frac{w_{eff}^{\frac{3}{2}} \cdot P^{\frac{1}{2}} \cdot \nu^{\frac{-1}{2}} \cdot \eta^{\frac{-1}{2}} \cdot t_{int}^{-\frac{1}{2}}}{\varepsilon \cdot A_{ant}} \cdot \frac{1}{S_{1400}} \cdot \frac{1}{\eta \cdot \nu} \cdot \int_{\nu \cdot \left(1 - \frac{\eta}{2}\right)}^{\nu \cdot \left(1 + \frac{\eta}{2}\right)} \left(\frac{\nu}{1.4 \cdot GHz}\right)^{-\alpha_p} \cdot \left[2 \cdot k \cdot \left(T_{rec} + T_{sky}(\nu)\right)\right] d\nu$$

Although the sky background decreases significantly above 500 MHz, the steep pulsar spectrum effectively limits the TOA accuracies at higher frequencies. Function has minimum at about 300 MHz.

Example:
α_p=-1.5, εA_{ant}=150 m^2, T_{rec}=100 K, η=0.18
w=0.3 ms, P=10 ms, S_{1400}=10 mJy,



Not far from Downs 1974, but far too optimistic!

Profile width dependence on frequency has been neglected

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Interstellar dispersion broadens pulse profiles

Plasmafrequency

$$\omega_{pe} := \sqrt{\frac{n_e \cdot q_e^2}{m_e \cdot \varepsilon_0}}$$

Group velocity

$$v_g = c \cdot \sqrt{1 - \left(\frac{\omega_{pe}}{\omega}\right)^2} = c \cdot \sqrt{1 - \frac{n_e \cdot q_e^2}{4 \cdot \pi \cdot m_e \cdot \varepsilon_0} \cdot \frac{1}{\nu^2}}$$

Light travel time for a distance d:

$$\Delta t(f) = \int_0^d \frac{1}{c \cdot \sqrt{1 - \left(\frac{\omega_{pe}(s)}{\omega}\right)^2}}\, ds \approx \frac{d}{c} + \frac{1}{2} \cdot \mathrm{DM} \cdot \frac{q_e^2}{4 \cdot \pi^2 \cdot \varepsilon_0 \cdot m_e \cdot c} \cdot \frac{1}{\nu^2}$$

$$\Delta t_{\mathrm{DM}} \approx 4.1494 \cdot 10^{15} \cdot \mathrm{DM} \cdot \left(\frac{1}{\nu_1^{\,2}} - \frac{1}{\nu_2^{\,2}}\right) \mathrm{s}$$

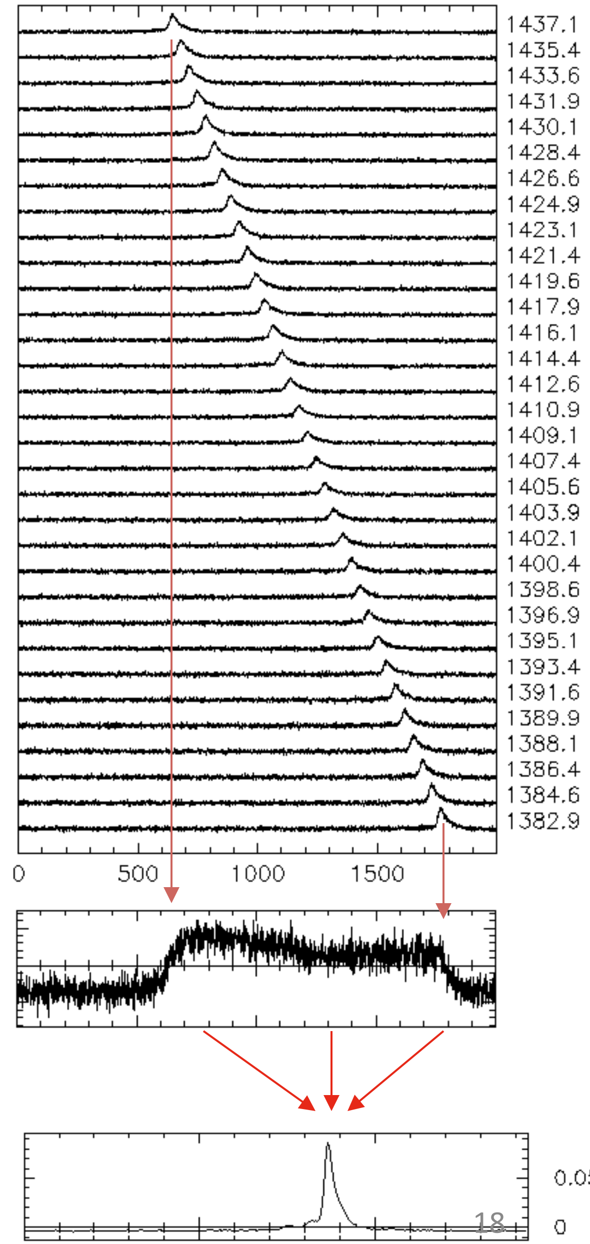
with

$$\mathrm{DM} = \int_0^d n_e(s)\, ds$$

in pc cm^{-3}

PSR J1713+0747

P = 4.57 ms, DM = 16



Dispersion broadens this profile by 2.5 ms,
but shifting the frequency channels compensates for that

De-dispersed profile at full resolution:

Frequency Evolution of Pulse Profiles

Low frequency emissions have slightly wider profiles

compared to

profiles at higher frequencies

$$w \approx \nu^{-0.2}$$

(Cordes & Shannon, 2001)

PHILLIPS & WOLSZCZAN

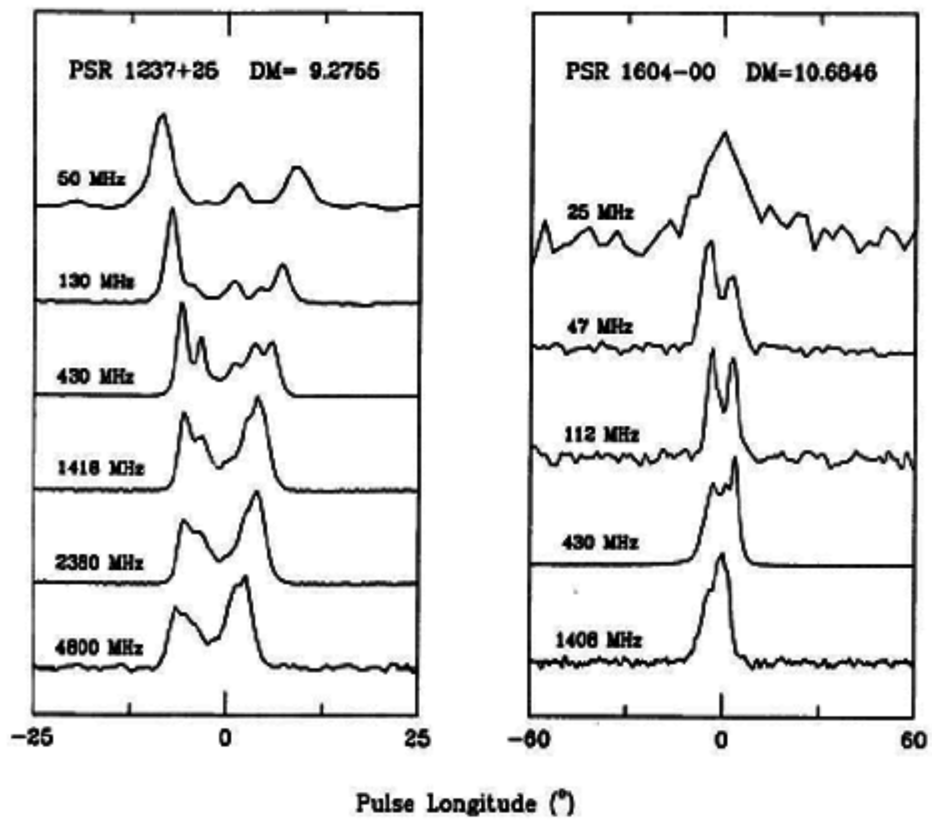
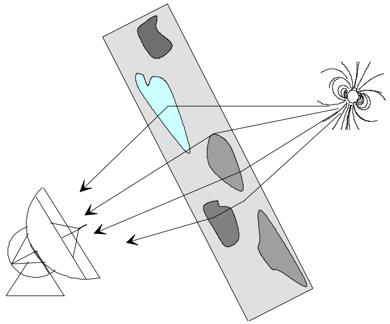


FIG. 4.—Time-aligned multifrequency profiles of PSR 1237+25 and PSR 1604−00

Phillips & Wolszan, 1992

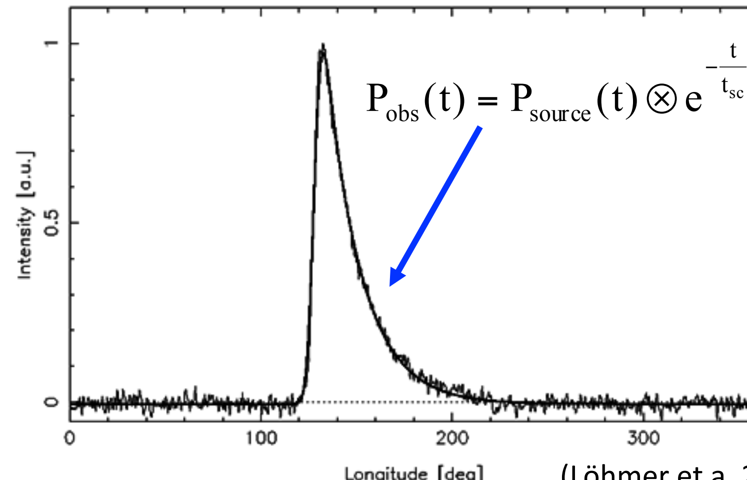
➔ Preference for high receiver frequencies (> 100 MHz)

Pulse Broadening by Interstellar Scattering I

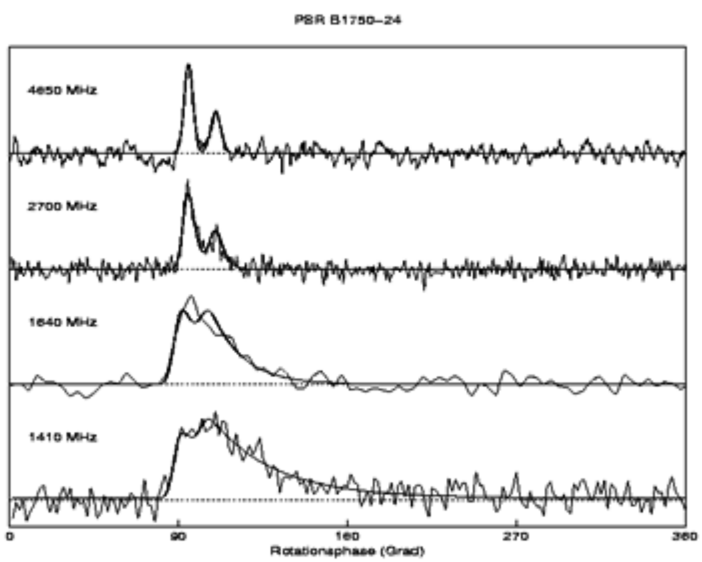


On its way from the source the pulsar signal is scattered by inhomogeneities in the interstellar medium and propagates on multiple paths and acquires multiple phases.

Because of their multiple scattering the affected profiles show an exponential tail with a typical scattering timescale τ_{sc}.



(Löhmer et a. 2001)



Pulse scatter is frequency dependent!

Described by power law $\tau_{sc} \approx \nu^{-\beta}$ with β ranging from 3 – 4.4.

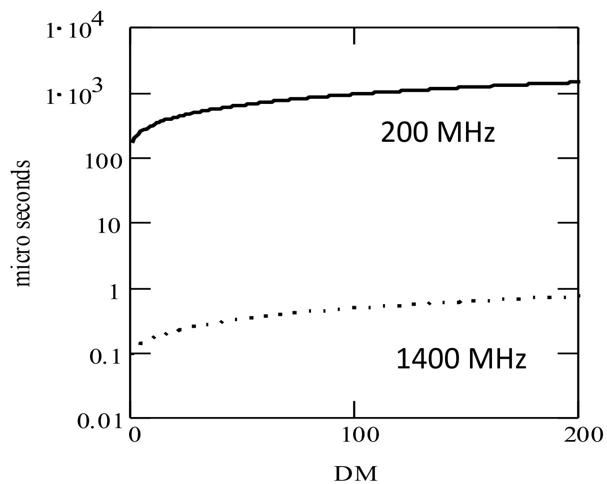
(O. Löhmer, PhD Thesis, 2002)

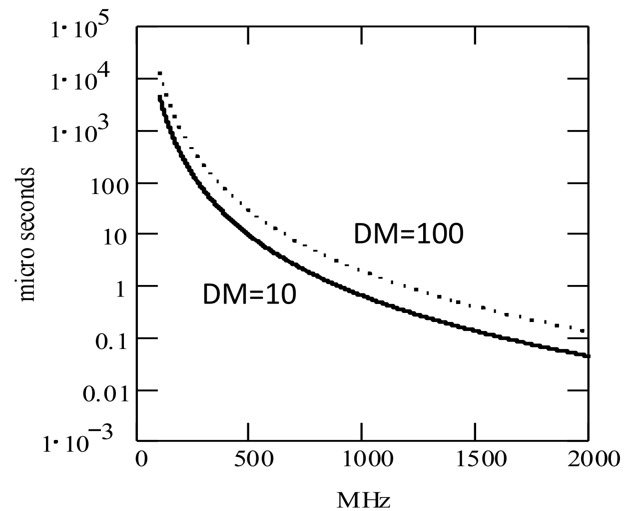
Pulse Broadening by Interstellar Scattering II

The broadening depends on the electron column density of the ISM expressed through the dispersion measure DM and on frequency.

Empirical fit for average pulsar (Bhat et al. 2004):

$$\tau_d(DM,\nu) := 10^{\left[\left(-6.46 + 0.154\log(DM) + 0.107\log(DM)^2\right) - 3.86\log\left(\frac{\nu}{GHz}\right)\right]} \cdot s$$





➔ Preference for low DM and high receiver frequencies

Pulse Broadening by Pulse Jitter

Individual single pulses have very different shapes.

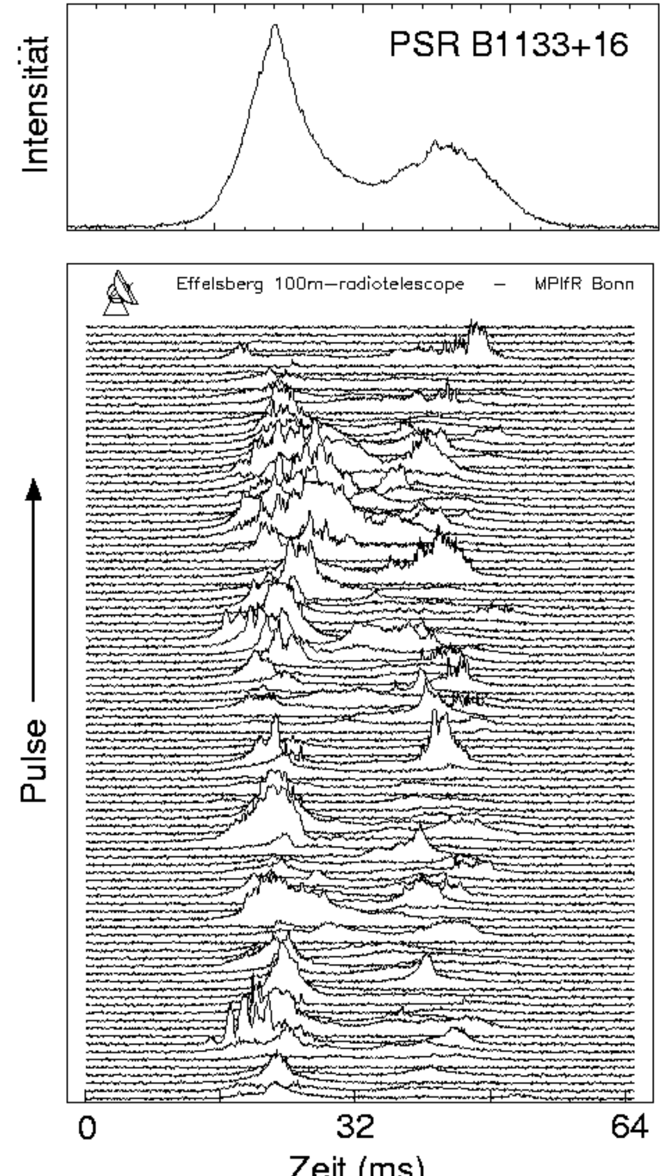
Only the average profile is stable.

Jitter caused by averaging over the intrinsic pulse to pulse variability.

- Proportional to pulse width w,
- Decreases with number of pulses averaged
- Decreases with frequency

$$\sigma_J(w_{eff}, P, t_{int}, \nu) := 0.28 \cdot \mu s \cdot \frac{w_{eff}}{ms} \cdot \left(\frac{t_{int}}{P \cdot 10^6}\right)^{-\frac{1}{2}} \cdot \left(\frac{\nu}{1.4 \cdot GHz}\right)^{-0.2}$$

(Cordes & Shannon, 2001)



➔ favours short period pulsars and long integration times, small effect for long integrations

Short Overview and combination of all effects

1. S/N related effects:

- Noise background favours L-Band frequencies (1-2 GHz)
- pulsar spectrum favours low receiver frequencies

➔ Optimum for T_{rec}=100 K at 300 MHz

2. Pulse width dependencies

- Profile evolution ($\approx\nu^{-0.2}$) implies small preference for high receiver frequencies
- Scattering ($\approx\nu^{-3.9}$) gives strong preference for high frequencies, close sources
- Dispersion can be compensated
- Pulse jitter ($\approx\nu^{-0.2}$) is a small effect for long integrations of short period pulsars

➔ all effects increase timing errors and favour higher frequencies

Final form of frequency dependence to be evaluated by averaging over bandwidth:

$$\sigma_t = \frac{P^{-\frac{1}{2}} \cdot \eta^{\frac{-3}{2}} \cdot \nu^{\frac{-3}{2}} \cdot t_{int}^{\frac{-1}{2}}}{\sqrt{2}} \cdot \int_{\nu\cdot\left(1-\frac{\eta}{2}\right)}^{\nu\cdot\left(1+\frac{\eta}{2}\right)} \frac{S_{sys}(\nu)\cdot\left(w+\tau_d(DM,\nu)\right)^{\frac{3}{2}}}{S_{psr}(\nu)} \cdot \left(\frac{\nu}{1.4\cdot GHz}\right)^{0.3} d\nu + \sigma_J\left(w,P,t_{int},\nu\right)$$

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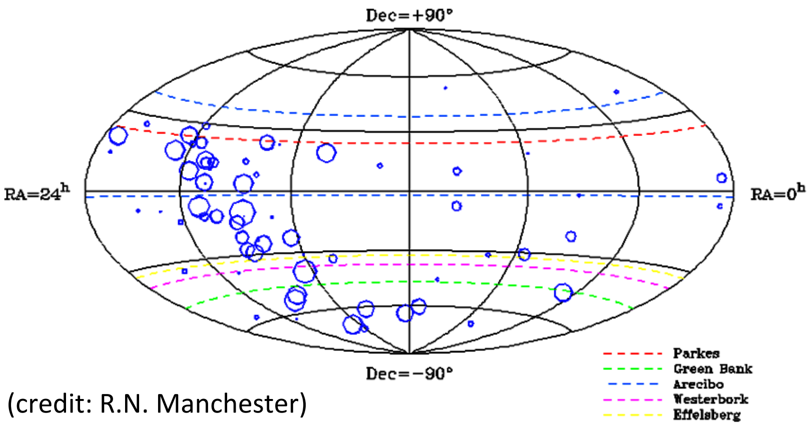
Properties of known good radio timing pulsars



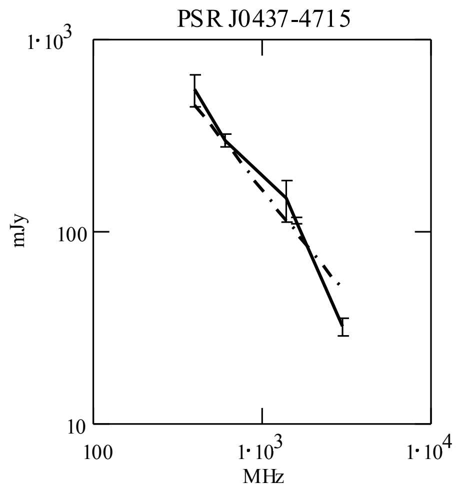
(credit: R.N. Manchester)

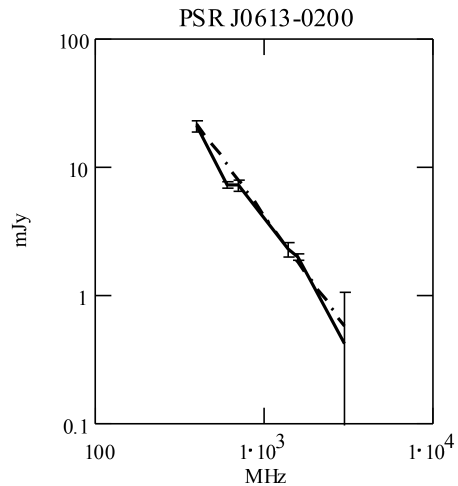
Many ms-psr are known and used for precision timing in the search for gravitational waves.

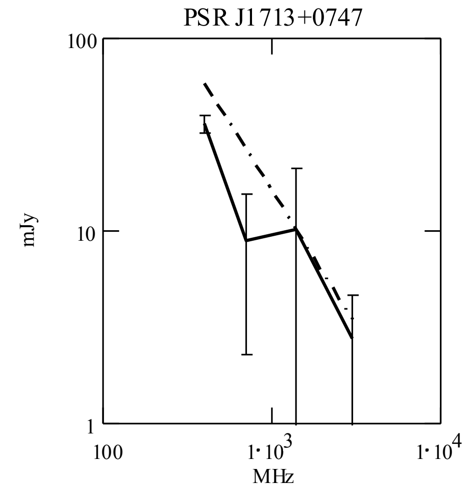
Characteristic data for some good timing sources from ATNF Catalogue:

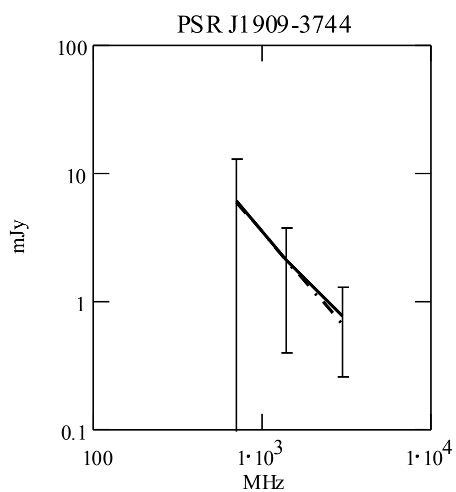
PSR	P (ms)	W_{50} (ms)	$-\alpha_p$	DM	S_{400} (mJy)	S_{600} (mJy)	S_{700} (mJy)	S_{1400} (mJy)	S_{1600} (mJy)	S_{3000} (mJy)
J0437-4715	5.8	0.141	1.1	2.6	550	600	406	149	115	32
J0613-0200	3.06	0.462	1.8	38	20	7.3	7.2	2.3	2.0	0.42
J1024-0719	5.16	0.521	1.9	6.5	4.6	4.2	5.4	1.5	0.88	0.37
J1713+0747	4.5	0.11	1.4	16	36		8.9	10.2		2.74
J1744-1134	4.08	0.137	1.8	3	18	16	7.8	3.1	1.7	0.7
J1824-2452A	3.0	0.98		120	40		10.6	2.0		0.33
J1909-3744	2.95	0.044	1.5	10.4			6.1	2.1		0.77
B1937+21	1.6	0.038		71	240		63	13.2		1.55

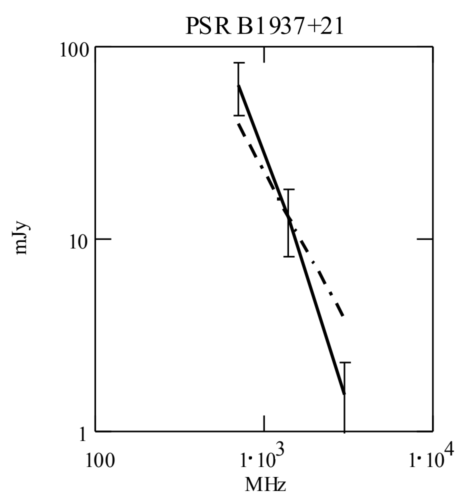
Empirical Pulsar Spectra











- Timing errors depend strongly on radio flux
- Power law assumption is often unrealistic
- Good flux measurements are crucial for reliable estimates of timing errors.

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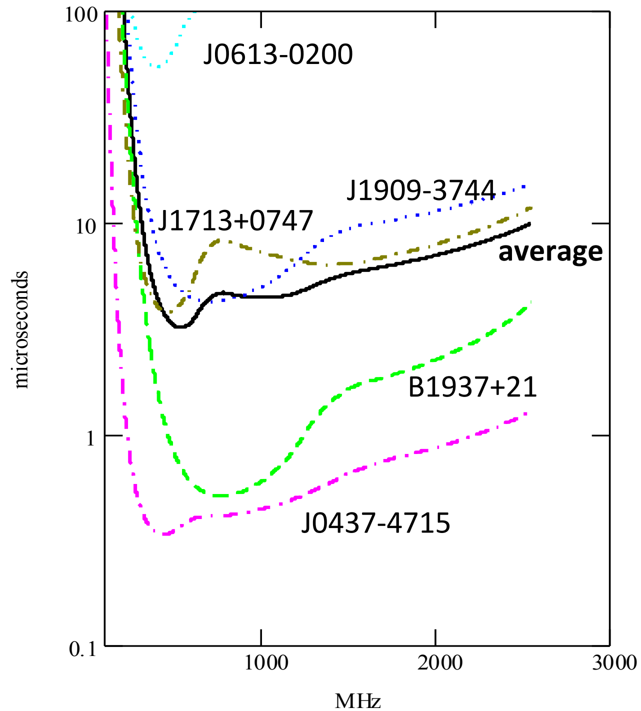
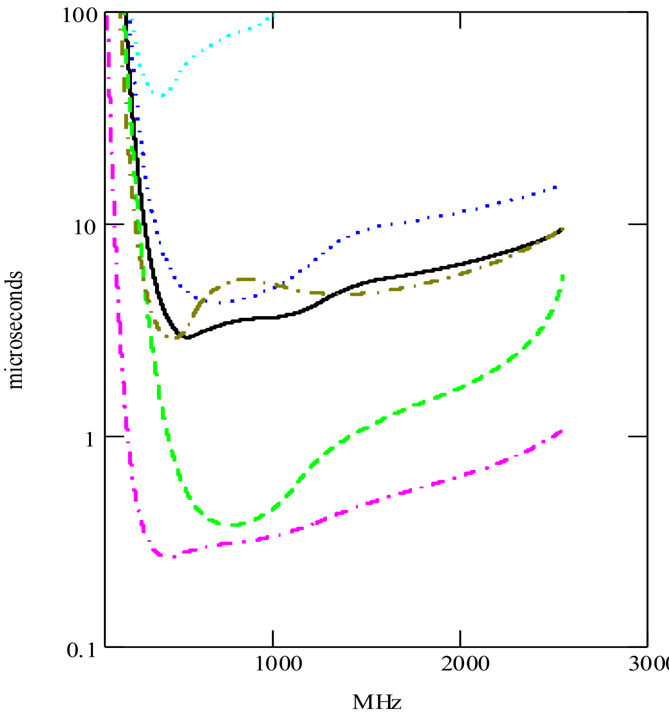
TOA precision for selected pulsars using a small antenna

$A_{ant}=100\ m^2$, $\varepsilon=0.5$, $T_{rec}=100\ K$, $t_{int}=3600\ s$

$\eta=0.25$



$\eta=0.5$



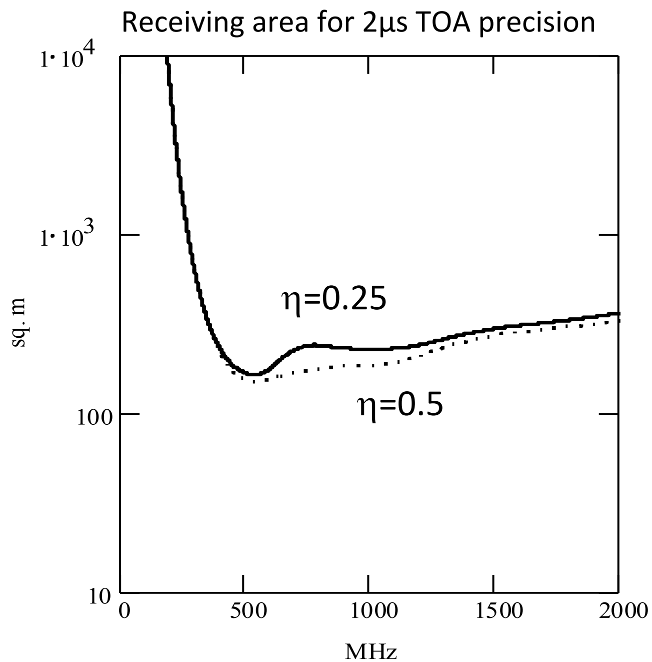
Black: average using J1909-3744, B1937+21, J0437-4715 and J1713+0747

Min. $\sigma_t=3.2\mu s$ for $\eta=0.25$ **ν=538 MHz $\Delta\nu$=134.5 MHz**

$\sigma_t=2.9\mu s$ for $\eta=0.5$ ν=543 MHz $\Delta\nu$=271 MHz ➔ **no advantage for high η**

Minimum receiving area

TOA errors $\sigma_t \propto S_{sys} \propto \frac{1}{A_{ant}}$ hence $A_{ant} = \frac{c \cdot \sqrt{3}}{\delta R} \cdot \sigma_t \cdot 100 \cdot m^2$ as A_{ref}=100 m², ε=0.5



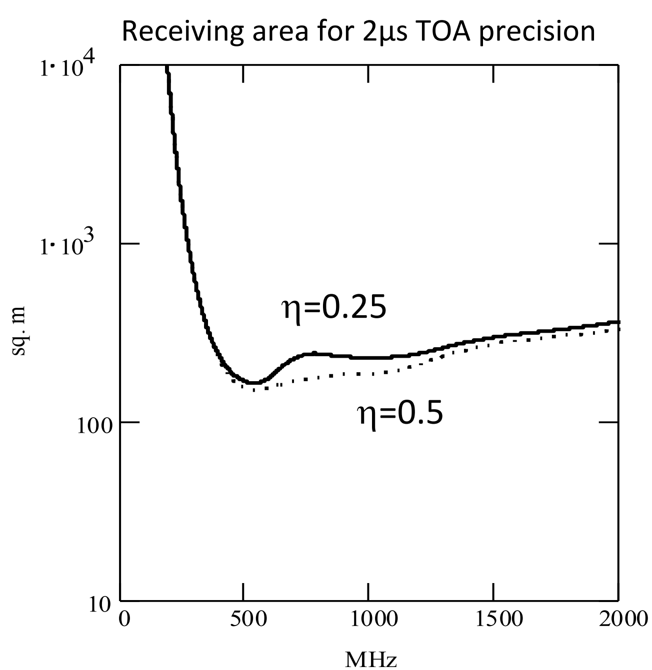
A_{min}=166 m² r_{min}=14.5 m η=0.25

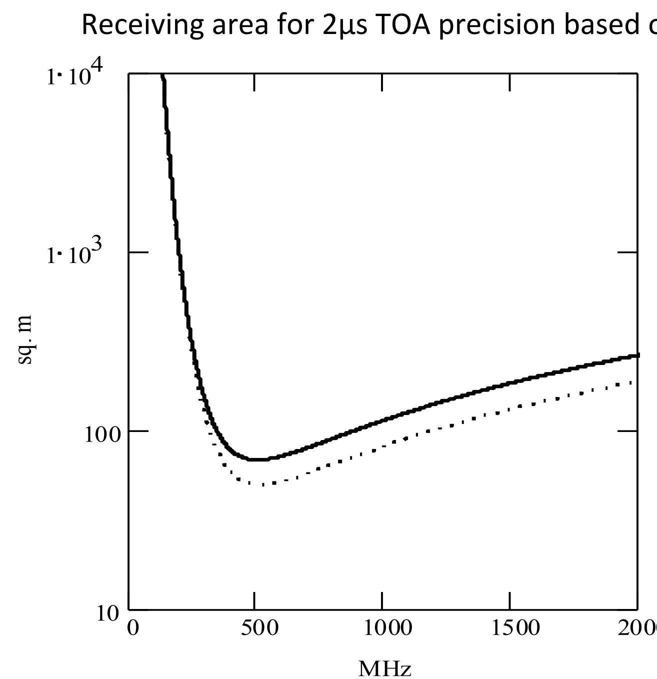
A_{min}=151 m² r_{min}=13.8 m η=0.5

$G = \frac{A_{min}}{A_{iso}} = 6780$ or 37 dBi , **HPBW ca. 1.3°**

Minimum receiving area

TOA errors $\sigma_t \propto S_{sys} \propto \frac{1}{A_{ant}}$ hence $A_{ant} = \frac{c \cdot \sqrt{3}}{\delta R} \cdot \sigma_t \cdot 100 \cdot m^2$ as A_{ref}=100 m², ε=0.5





A_{min}=166 m² r_{min}=14.5 m η=0.25

A_{min}=151 m² r_{min}=13.8 m η=0.5

A_{min}=120 m² r_{min}=12.4 m

A_{min}=87 m² r_{min}=10.4 m

$G = \frac{A_{min}}{A_{iso}} = 6780$ or 37 dBi , **HPBW ca. 1.3°**

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Antenna design considerations

- Antenna with d=15 m is large, but feasible
  (Voyager d=3.7m, RadioAstron d=10m)

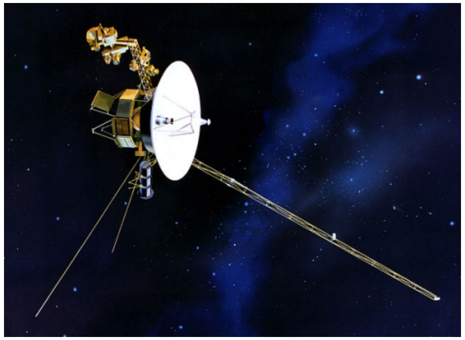
- Antenna size and weight is determined by radio flux of pulsars
  should be optimised by good knowledge of pulsar
  spectrum in 300-1000 MHz regime.

- Operation on 500 MHz with narrow bandwidth allows for larger
  surface tolerances: $\lambda/8 \approx 7$ cm.
  and light weight construction (wire mesh, printed foil)

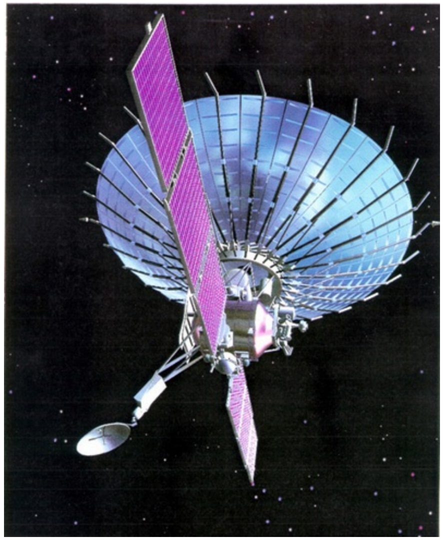
- 1° Beam needs optical attitude control (e.g. using guide stars)

- Parabolic dish points to only one source at a time,
  needs frequent movement, requires power and
  reaction mass, reliable long term operation questionable

➔Alternative:
phased array antenna can have several beams and is less
restricted in shape

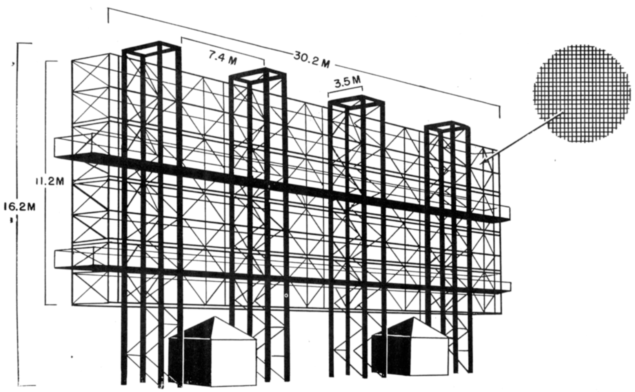


Voyager (NASA/JPL)



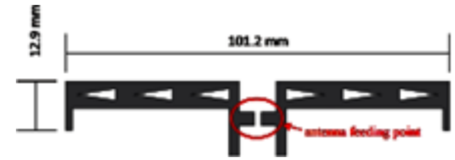
SpectR/RadioAstron
(Lebedev AstroSpace Centre)

Phased Array Antennas

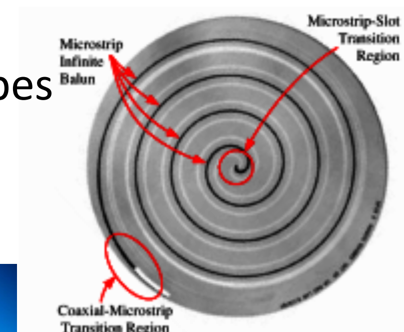


150 MHz "Mammut Hoarding radar" 1944
(US War Department - TM E 11-219)

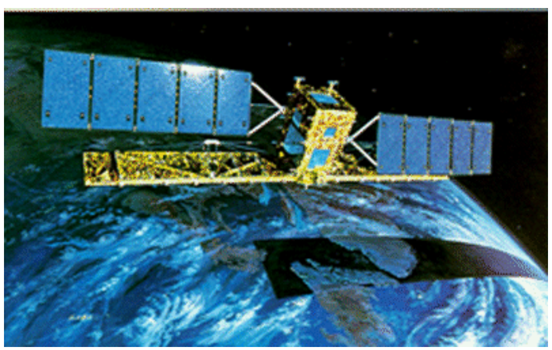
- Well established technology
- Allow large light weight constructions
- Elements can be printed
- Several simultaneous beams
- Used for satellites and space probes and radio astronomy (LOFAR, MWA)



(Zicher et al. 2013)



(Reichart 2005)



RADARSAT-1 with
15 m phased array antenna
(CSA)

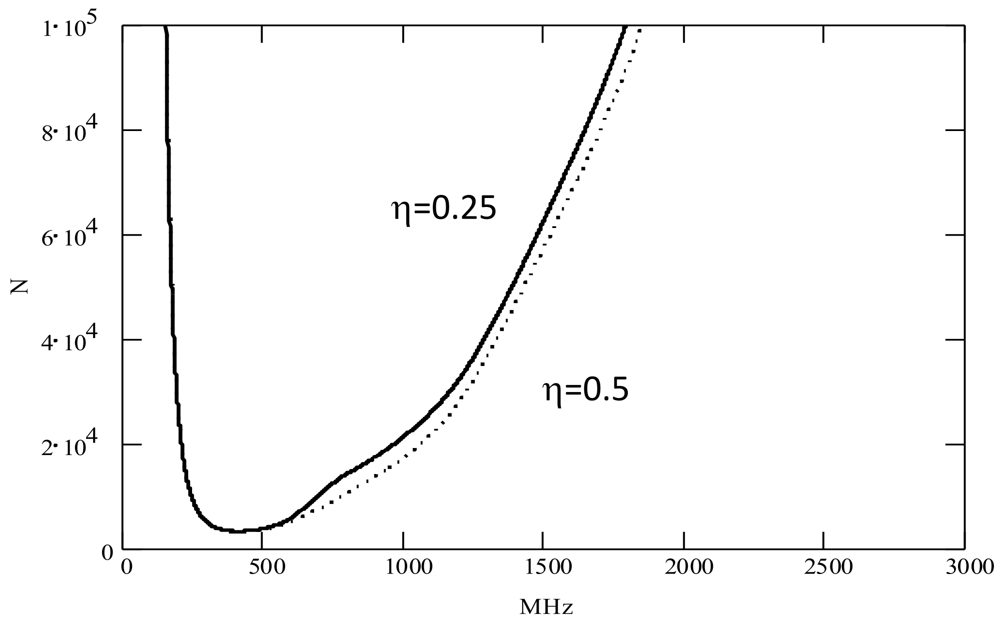
MWA 32T Tile
80-300 MHz

(Natasha Hurley-Walker)

Minimum Number of Array Elements

One may estimate the number of elements simply by dividing the effective antenna area by the effective area of e.g. a dipole

$$N_{dip} = \frac{A_{ant}}{A_{dip}} = A_{ant} \cdot \frac{8\pi}{3} \cdot \left(\frac{\nu}{c}\right)^2$$



Minimum with

N_{dip}= 3250 for ν=413 MHz

Different optimisation!

N_{dip}= 4850 for ν_{opt} = 538 MHz

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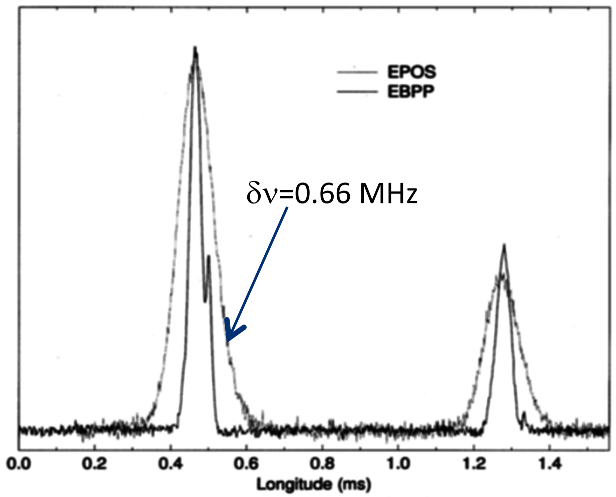
Incoherent and Coherent De-Dispersion



PSR B1937+21 P=1.56 ms DM=71 pc cm^{-3} at 1.4 GHz

- Residual filter dispersion:
  detected output from a filterbank will be broadened:

$$\delta t \cong 2 \cdot D \cdot DM \cdot \frac{\eta}{\nu^2}$$

With δt=2μs, DM=71, ν=540 MHz
➔ $\eta=10^{-6}$ or $2.5\cdot10^5$ filter channels: $\delta\nu$=540 Hz

- Filter response:
  limited $\delta t > \delta\nu^{-1} \approx 2$ ms!

- Minimum depends only on ν and DM :

$$\delta t_{min} = (2\, D \cdot DM)^{\frac{1}{2}}\ \nu^{-\frac{3}{2}} \approx 61\mu s$$

Alternative: Coherent de-dispersion
(Hankins & Rickett 1975)

Apply an all-pass filter compensating frequency and DM dependent time delays to sampled rf amplitudes before detection.

➔ Requires dedicated programmable filters and detectors for each source stream.
➔ Technical implementation around 1990 (D. Backer)

Coherent De-Dispersion: The Effelsberg-Berkeley-Pulsar Processor (EBPP)

Developed in Berkeley by Don Backer et. al.

Hybrid signal processing:

Analog splitting of bandwidth into 8 sub-bands,

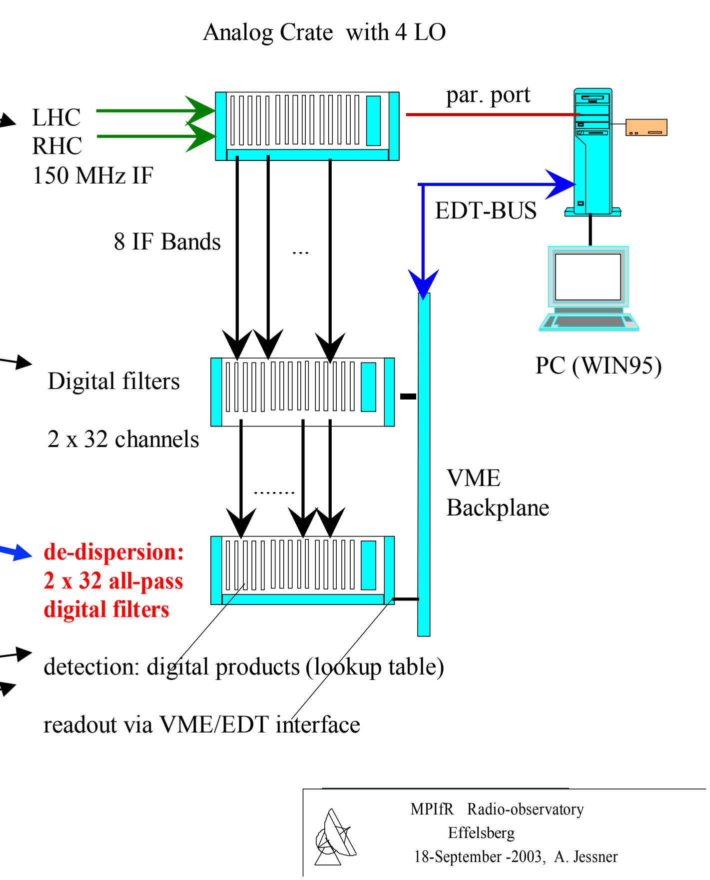
Digital splitting and filtering of each sub-band again into 8 narrow band channels

1024-tap lateral all-pass filters for dispersion compensation of individual narrow band channels

Digital signal detection via programmable lookup table.

Direct transfer of data via VME-PC interface

EBPP Coherent De-dispersing Backend



Data Processing Requirements

•Antenna output needs to be converted to baseband and digitised.

•Data rate $2\Delta\nu \approx$ 300-600 Ms/s per output

➔ hardware beam forming and combining of the two polarisations

•Total sustained data rate 1-2 Gs/s

•Major work load from **coherent de-dispersion**, but can be realised in hardware.

•Power requirements ca. 200-300 W

Summary and Conclusions

- Autonomous navigation of satellites using radio pulsars is feasible with current technology
- It can be advantageous for large deep-space probes
- The Optimal receiver frequency is in the UHF band and increases for higher position accuracy
- A Bandwidth of < 150 MHz is sufficient, wide-band systems have no net advantage
- Minimum antenna diameter > 12m, grows with accuracy and frequency
- Phased array antennas with 3000-4000 simple printed or wire dipoles may be used
- Beam forming of ≥ 4 beams in hardware within antenna structure is needed
- Coherent de-dispersion of 300 Ms/s data stream per beam dominates data processing
- Careful consideration of the spectrum of the chosen pulsar beacons and their local radio background is required before designing a realistic space navigation system

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