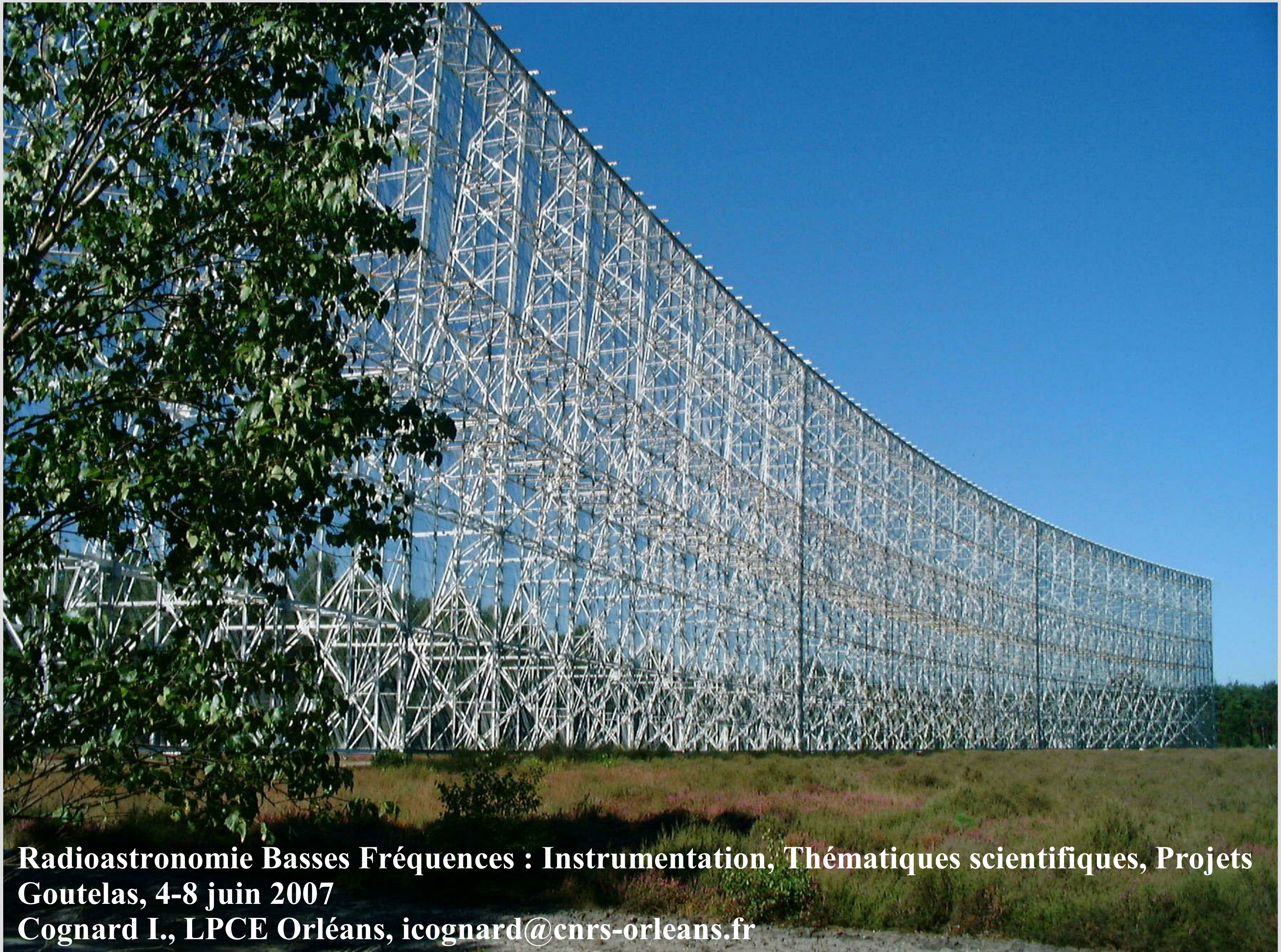
De la métrologie en radioastronomie

Metrology in radioastronomy



Radioastronomie Basses Fréquences : Instrumentation, Thématiques scientifiques, Projets
Goutelas, 4-8 juin 2007

Cognard I., LPCE Orléans, icognard@cnrs-orleans.fr

Plan

- Introduction
  - The pulsar phenomenon
  - Stellar evolution
- Interstellar Medium
  - Scattering
  - Dispersion
- Pulsar Instrumentation
  - Baseband mixing
  - Coherent dedispersion
- Observations
  - Nançay Radiotelescope
  - BON coherent dedispersor
- Pulsars TOAs
  - Timing of pulsars
  - Examples
- Conclusion

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CP 1919

August 1967
Cambridge, UK
Jocelyn Bell

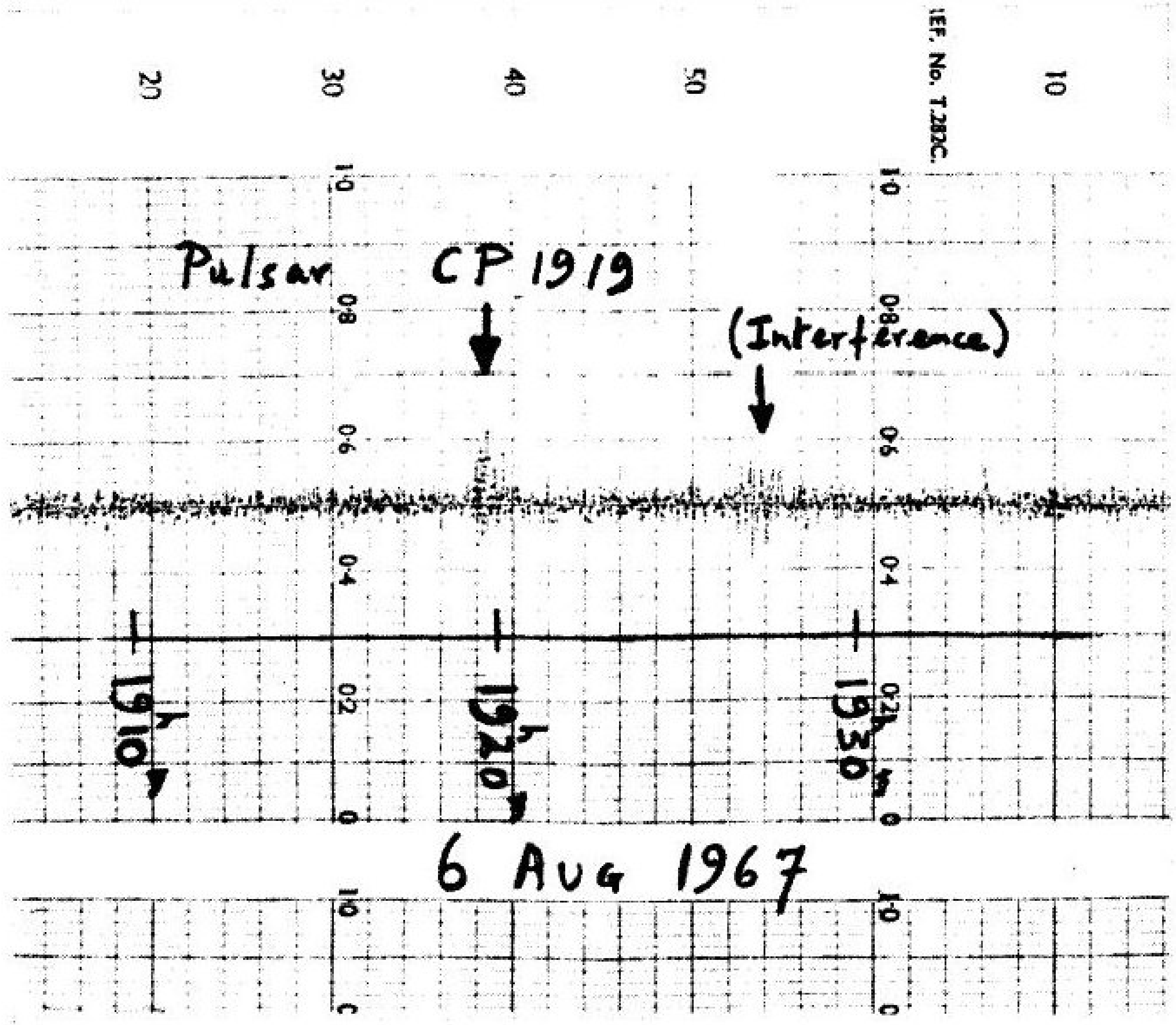


Fig. 1. The first signals from CP 1919.

a pulsar is a highly magnetized neutron star

massive star

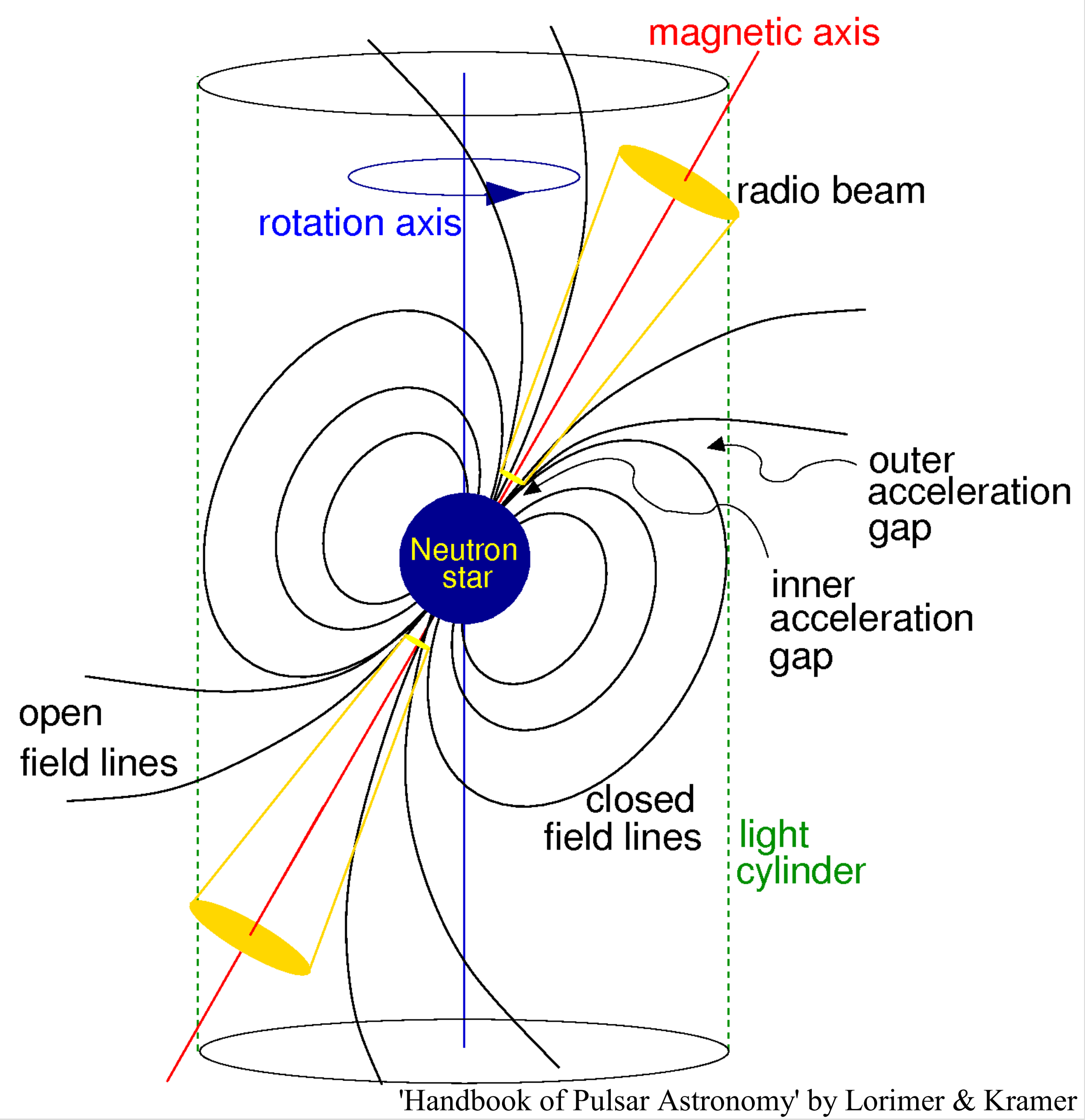
→ supernovae

→ neutron star

a neutron star +

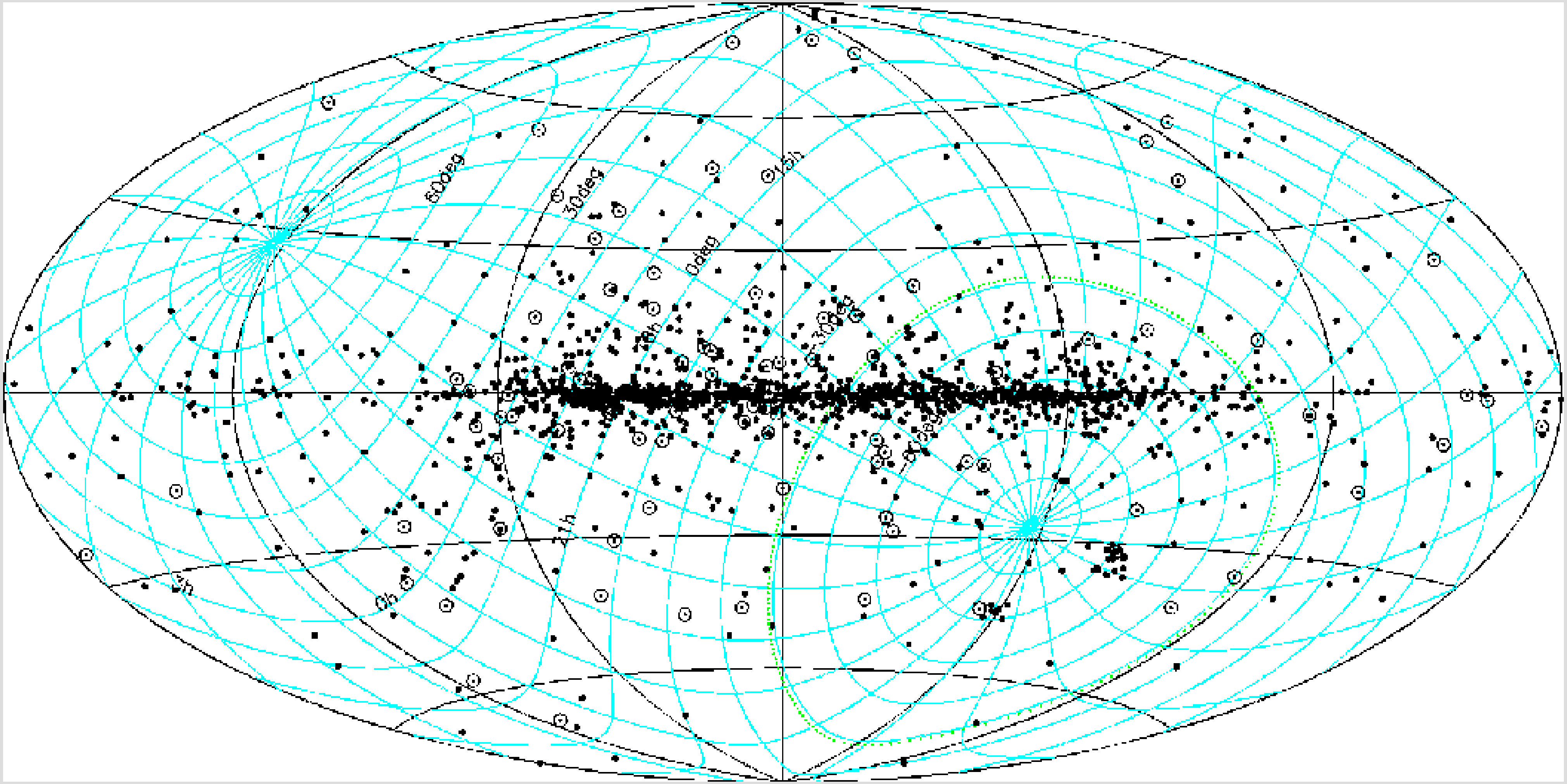
a magnetic field

→ a pulsar



'Handbook of Pulsar Astronomy' by Lorimer & Kramer

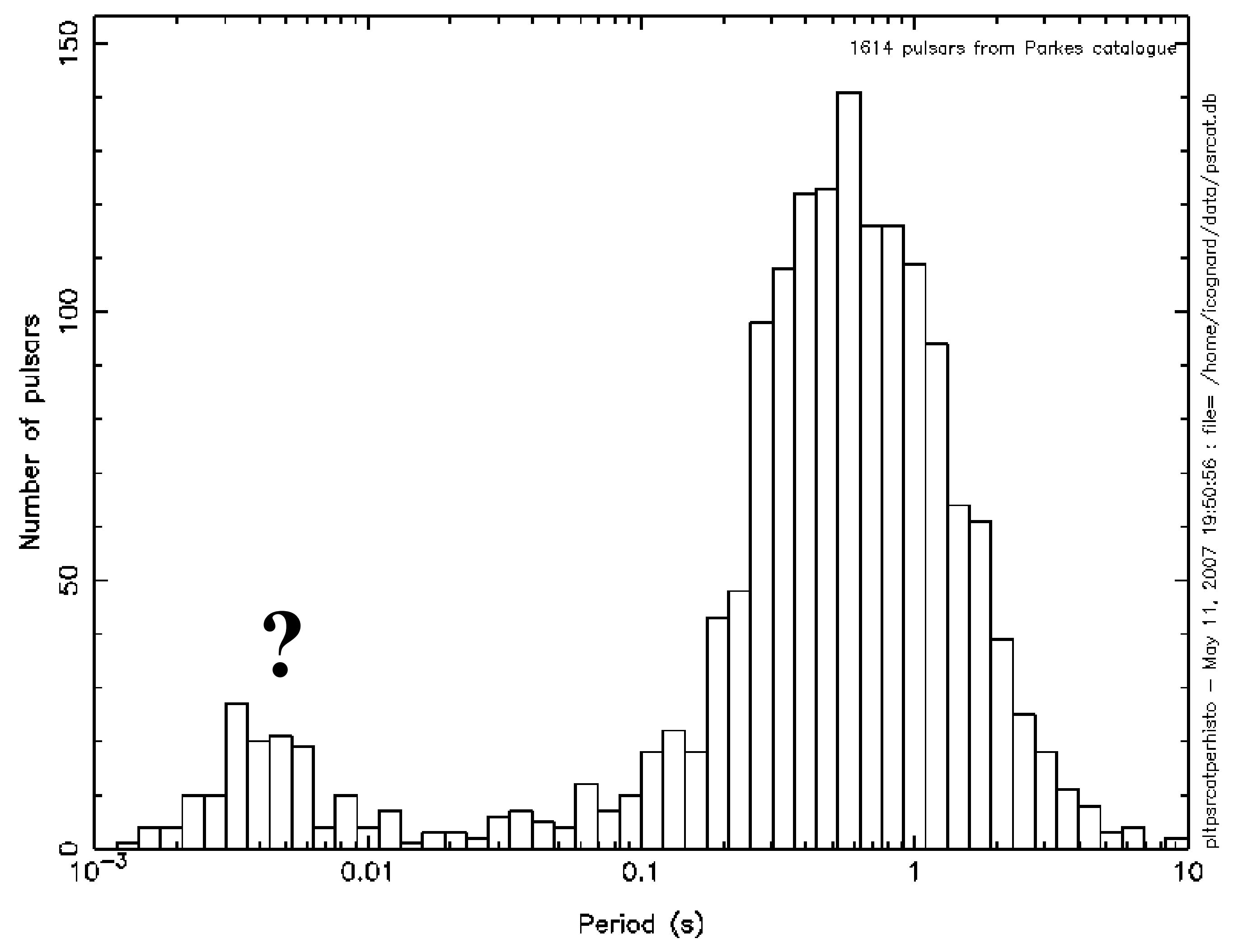
Pulsars in the Galaxy



1614 pulsars
from ATNF catalog (dot: ordinary pulsars, dot+circle: binary pulsars)

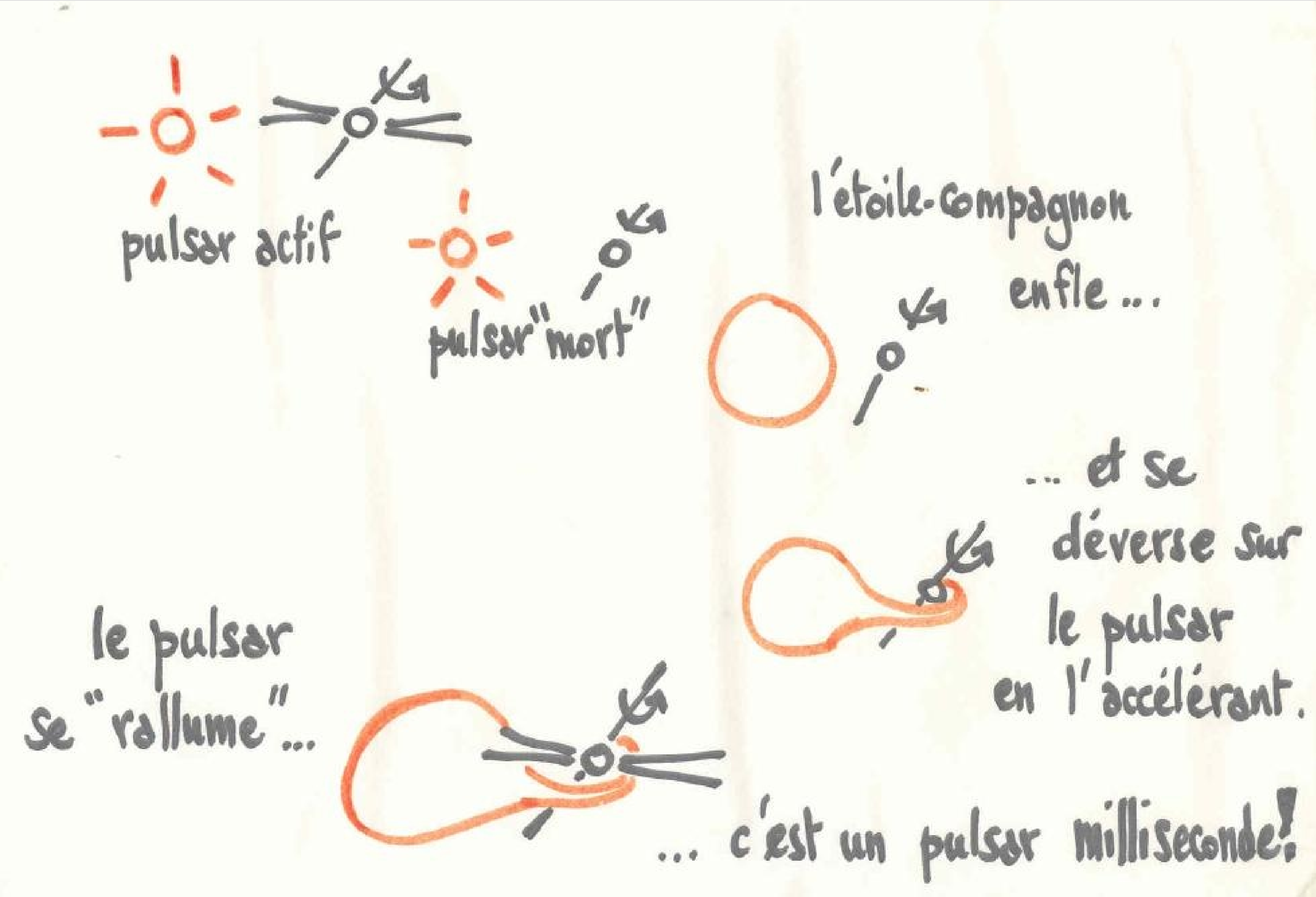
http://www.atnf.csiro.au/research/pulsar/psrcat/

Period distribution of pulsars



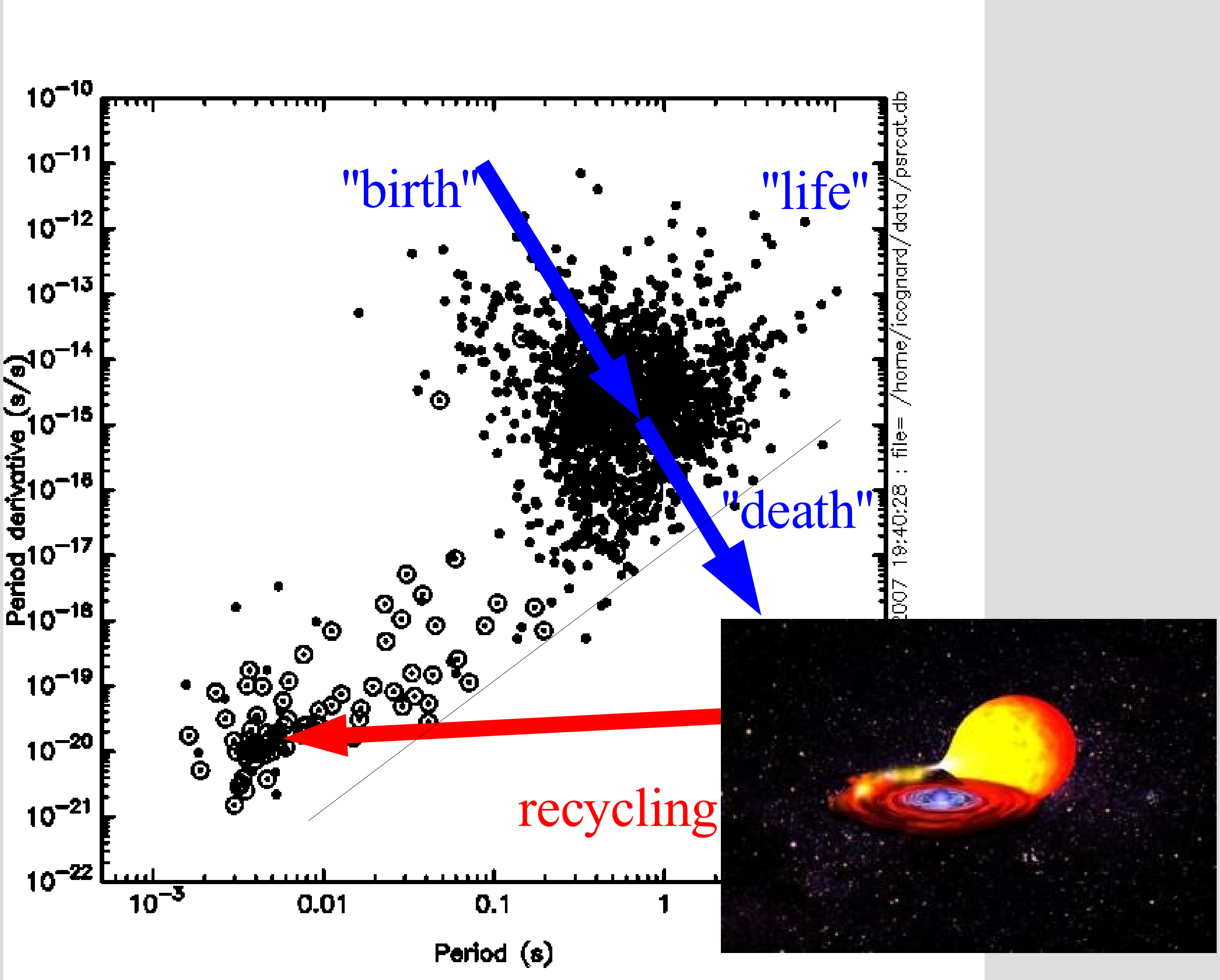
Periods of radio pulsars spans from 1.5ms to 8.5sec

Recycling...


pulsar actif
pulsar "mort"
l'étoile-compagnon enfle...
... et se déverse sur le pulsar en l'accélérant.
le pulsar se "rallume"...
... c'est un pulsar milliseconde!

Period - Period derivative diagram

(or "Hertzsprung-Russell" diagram for pulsars)



"birth"

"life"

"death"

recycling

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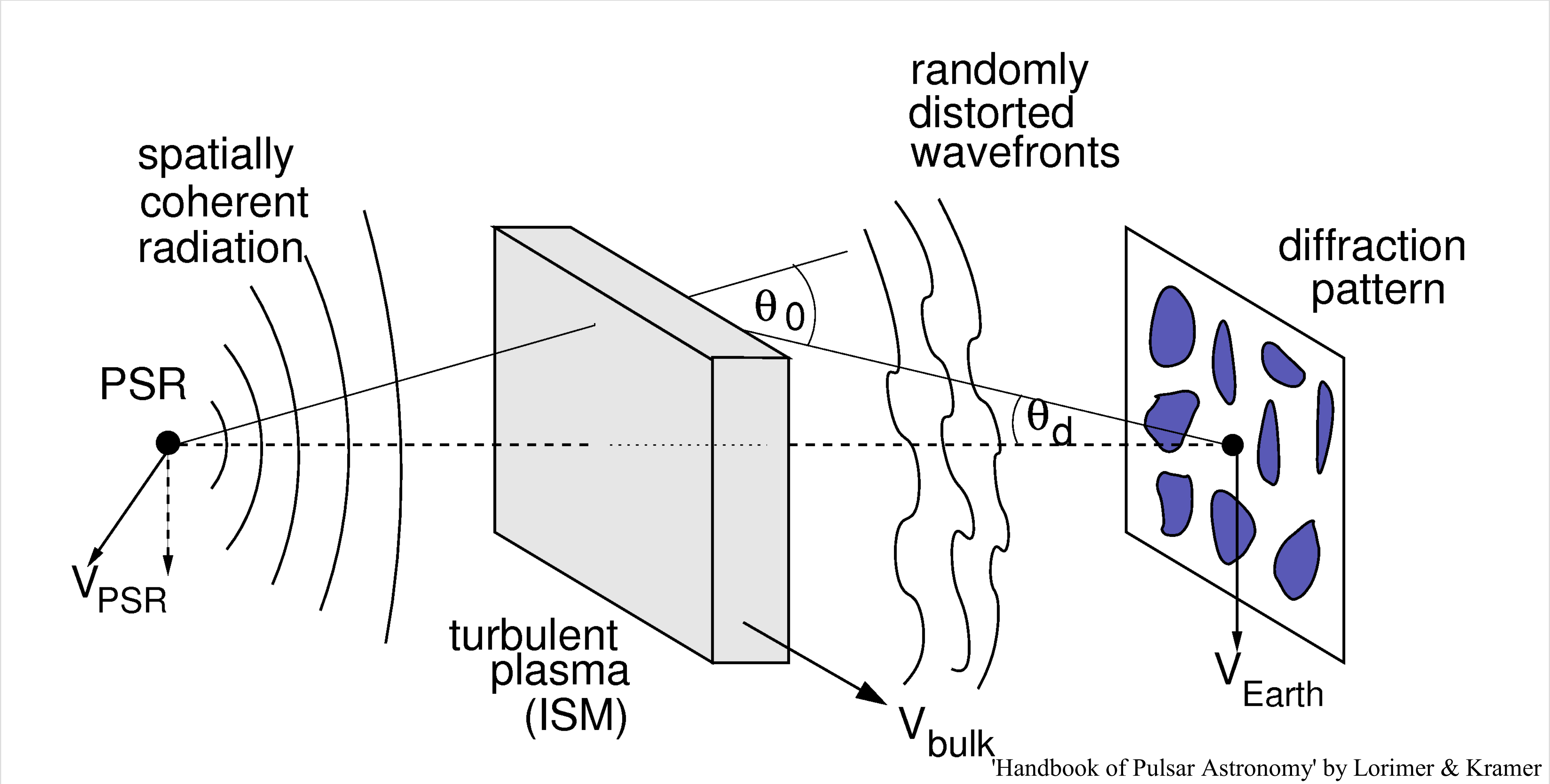
Scattering régimes

an assumption...

the turbulent medium is a **thin phase changing screen**



'Handbook of Pulsar Astronomy' by Lorimer & Kramer

Fresnel scale

$\varphi(x,y)$ is the phase change introduced by the screen at transverse position (x,y)

the amplitude received at position (X,Y) on the observer plane
is given by the **Fresnel-Kichhoff integral** (Born & Wolf, 1980)

$$\Psi(X,Y)=\frac{e^{-i\pi/2}}{2\pi r_F^2}\iint \exp\left[i\varphi(x,y)+i\frac{(x-X)^2+(y-Y)^2}{2r_F^2}\right]dx\,dy$$

where r_F is the Fresnel scale, $r_F=\sqrt{\lambda D/2\pi}$

region inside r_F contributes coherently to the integral,
while outside regions cancel because of rapid oscillations

Diffractive length scale

turbulent medium : random phase fluctuations $D_\varphi(x, y)$

described by the 'phase structure function'

$$D_\varphi(x, y) = \langle [\varphi(x'+x, y'+y) - \varphi(x', y')]^2 \rangle_{x', y'}$$

i.e. the mean square phase difference between 2 points separated by (x,y)

if Kolmogorov turbulence,

isotropic and large outer scale and small inner scale

$$D_\varphi(r) = (r / r_{diff})^{5/3}, \qquad r^2 = x^2 + y^2$$

r_{diff} is the diffractive length scale

the transverse separation for which the r.m.s. phase difference is 1 rad

... the Fried length, r_o, in optical astronomy

Scattering régimes

$r_{diff} \gg r_F$ **weak scattering**

random phase fluctuations within the first Fresnel zone are small

$r_{diff} \ll r_F$ **strong scattering**

then $D_\varphi(r_F) \gg 1$, r_F is no longer relevant
and r_{diff} is now the characteristic size of a coherent patch

For the observer in (X,Y),
there will be many points (x,y) on the scattering screen
with stationary phase...
that is **multipath propagation**

Scattering media in astronomy

	medium	wavelength	weak scattering	strong scatterring
optical	Earth's atmosphere	0.5µ	mostly	near horizon
radio	troposphere	20cm	yes	no
	ionosphere	3m	yes	sometimes
	solar wind	1m	mostly	close to the Sun
	interstellar medium	1m	no	yes

Narayan R., *Phil. Trans. R. Soc. Lond.* A (1992) 341, 151-165

Strong scattering

the spectrum of flux variations has two peaks at widely separated length scales

diffractive scintillation

a dominant peak corresponding to flux variations on lengthscales ~ r_{diff}

a large number of coherent patches scatters radiation into a diffraction cone of angle Θscatt ~ r_{ref}/D, interfering together

random interference pattern

very strict limit on the angular size :

virtually only pulsars show diffractive scintillation

refractive scintillation

a second peak corresponding to weak flux variations

on much longer lengthscales ~ r_{ref} (can be seen in term of geometrical optics)

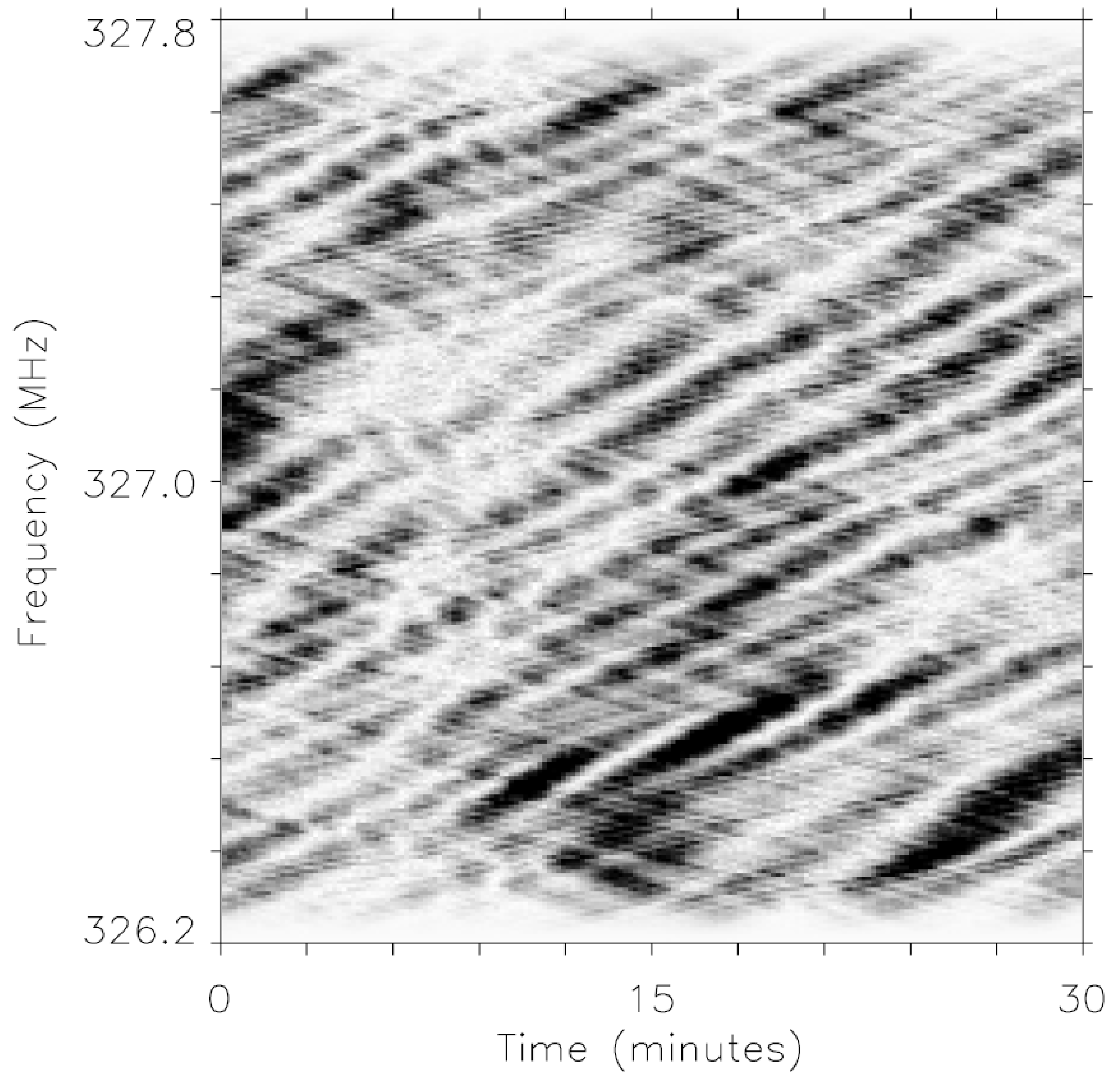
slow flux variations

modest limits on angular size :

many compacts sources shown refractive scintillation

diffractive scintillation

Dynamic spectra on
pulsar B0834+06
at Arecibo
2003 Dec 31



Dispersion induced by the ionized Interstellar Medium

The ISM is a **cold** and **ionised plasma** :

frequency-dependent **index of refraction**

$$\mu = \sqrt{(1 - (\frac{f_P}{f})^2)} \quad , \quad v_g = \mu c$$

where f is the observing radio and f_P the plasma frequency

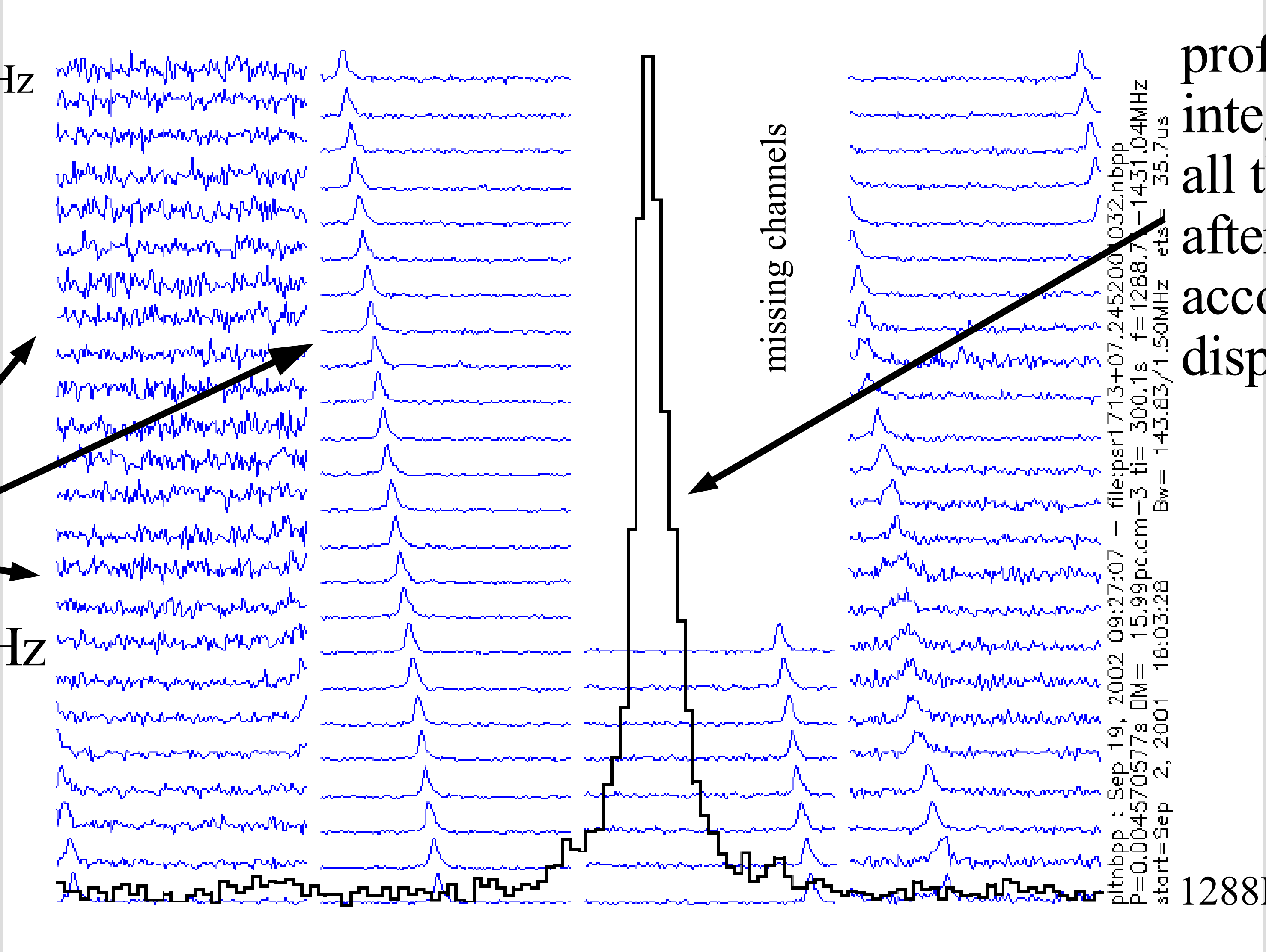
$$f_P = \sqrt{\frac{e^2 n_e}{\pi m_e}}$$

$f_P \sim 1.5$kHz with $n_e \sim 0.03$ cm^{-3}

temporal delay with respect to infinite frequency :

$$t = \int_0^d \frac{dl}{v_g} - \frac{d}{c} \equiv D \frac{DM}{f^2} \quad , \quad D \equiv \frac{e^2}{2\pi m_e c} = 4148.808\, Hz^2\, pc^{-1}\, cm^3\, s$$

Observation of pulsar PSR B1713+07 with NBPP showing dispersion and scintillation on Sep19,2002



1430MHz

profiles over 1.5MHz channels

profile integrated over all the channels after shifting according to dispersive delay

1288MHz

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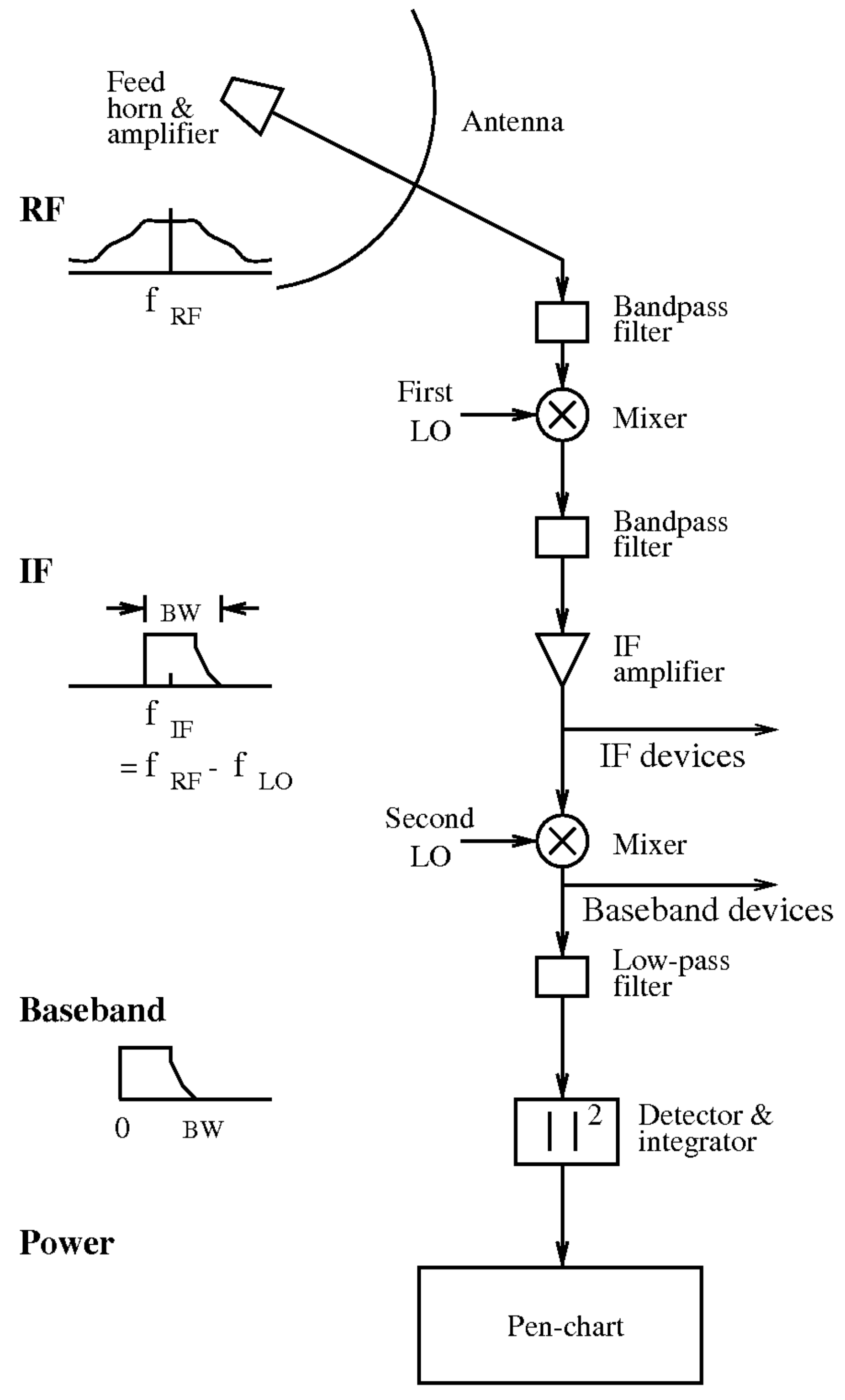
signal path in a radiotelescope

bandpass filter + mixer

IF amplifier to IF devices

mixer to baseband devices

low-pass filter
    to detection and integration
    pen-chart



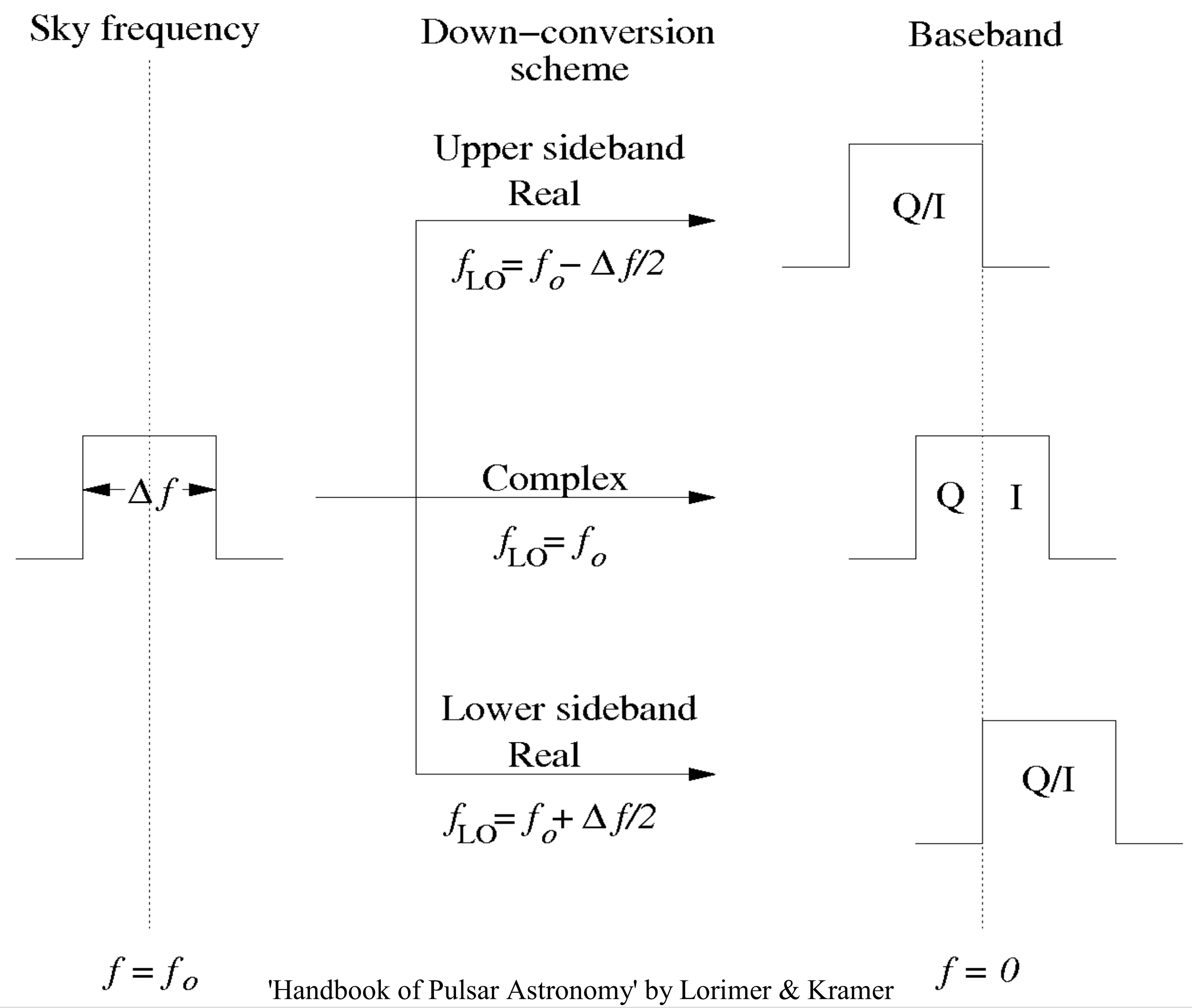
'Handbook of Pulsar Astronomy' by Lorimer & Kramer

baseband mixing

mixing can be done
 in several ways

a single LO at one end
 of the passband
 (f_o-$\Delta f/2$ or f_o+$\Delta f/2$)
 real sampled data
  rate $2\Delta f$

a pair of LOs
 in phase-quadrature
 at the middle f_o
 complex sampled data
  rate Δf twice



'Handbook of Pulsar Astronomy' by Lorimer & Kramer

ISM Transfer Function

delay in the ISM can be represented as

phase rotations depending on frequency and path length

$$\Delta \Psi = -k(f_o + f)d \quad , \quad k(f) = \frac{2\pi}{c} \mu f$$

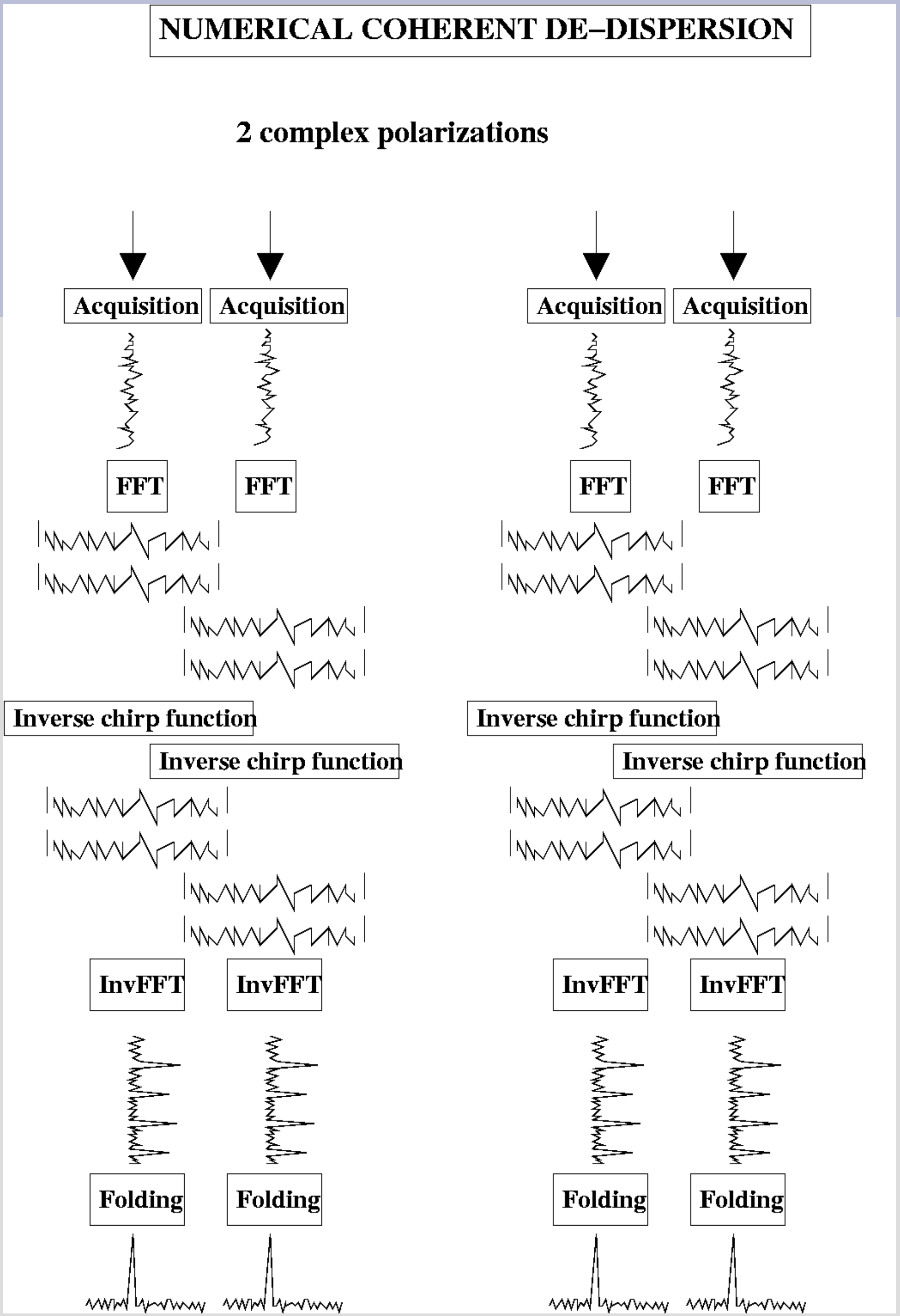
where k is the wave number

the transfer function is

$$H(f_o + f) = \mathrm{e}^{-ik(f_o + f)d} \equiv \mathrm{e}^{+i \frac{2\pi D}{(f + f_o) f_o^2} DM f^2}$$

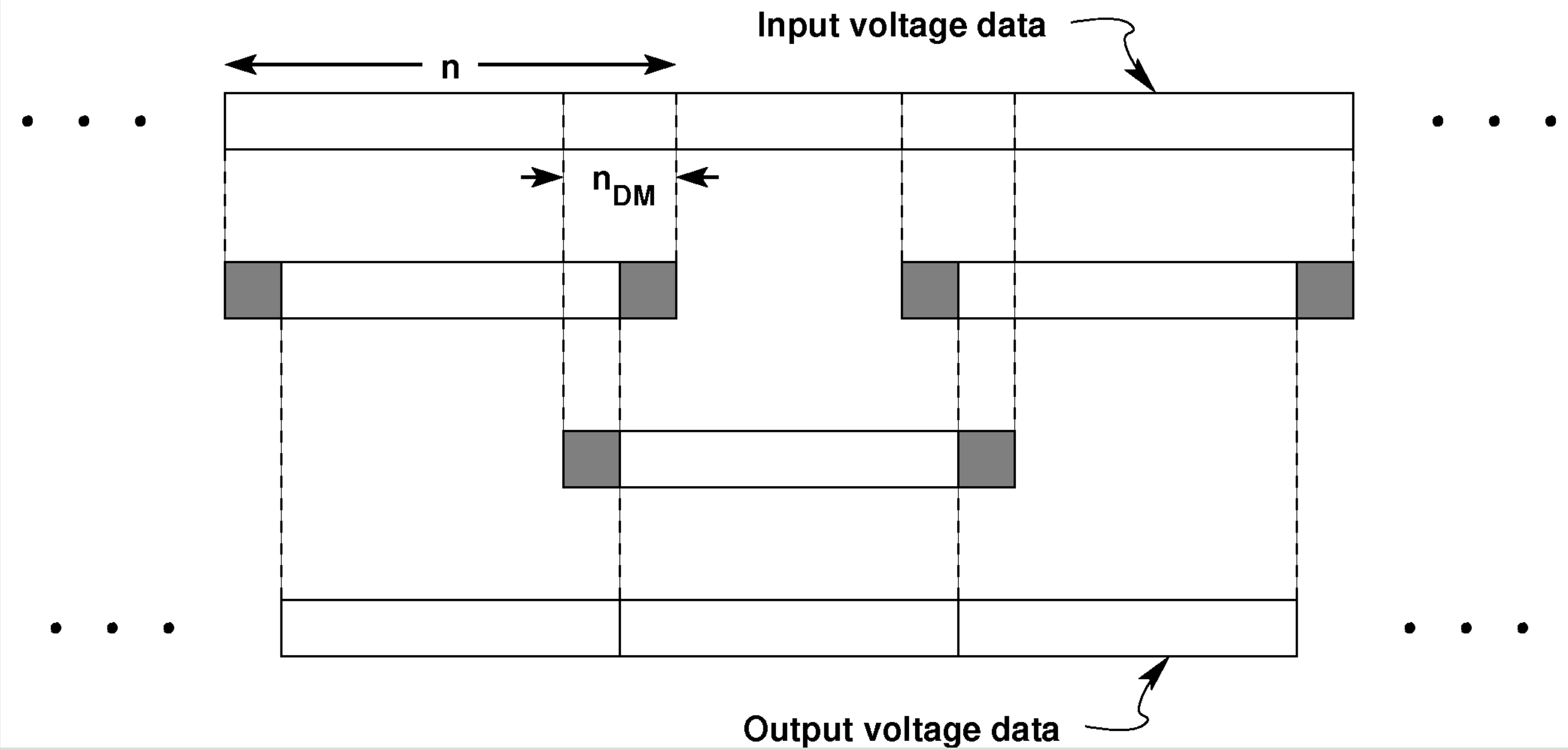
dedispersion

- a forward FFT
- multiplication by the
  inverse ISM transfer function
- a backward FFT
- folding coherently with
  varying pulsar period



dedispersion : overlap

n_{DM} is the number of samples over which the radio profile is dispersed



Two kind of pulsar instrumentation

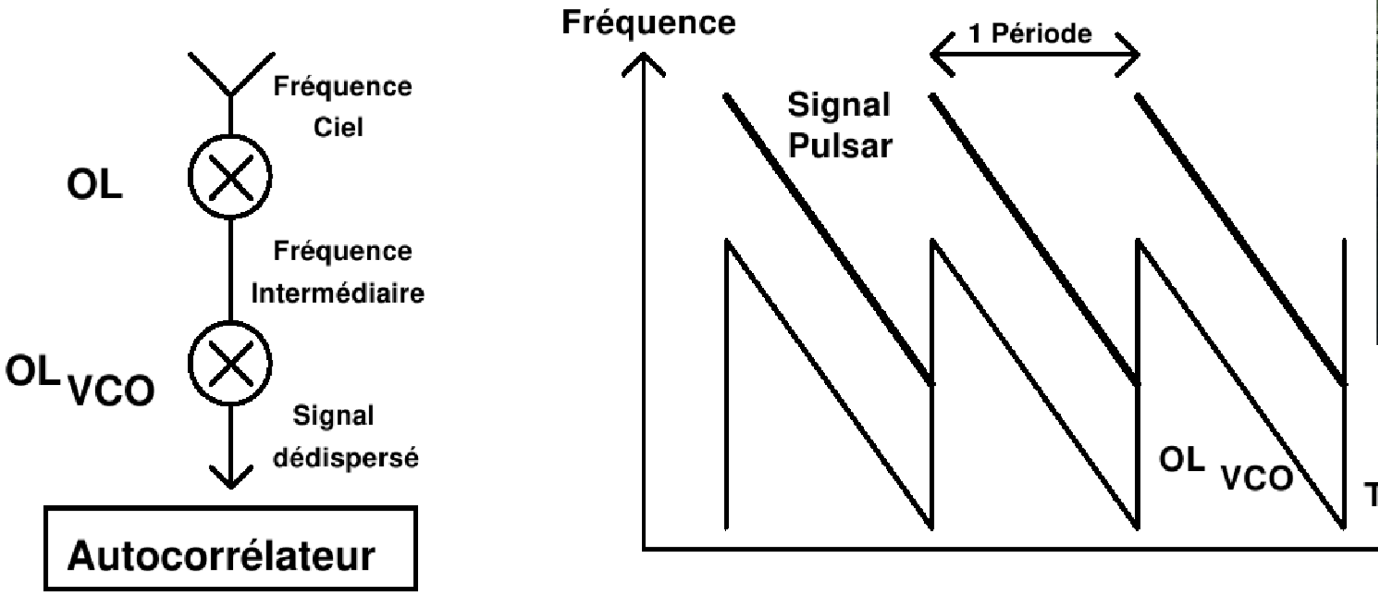
incoherent dedispersion
- done after detection
  - on averaged intensity
  - à la durée du cycle de l'onde reçue
- filterbank instrumentation

coherent dedispersion
- done before detection
  - on voltages proportional to the received electric field,
  - before any integration, signal phase is preserved
- complex sampled baseband instrumentatsion or swept LO

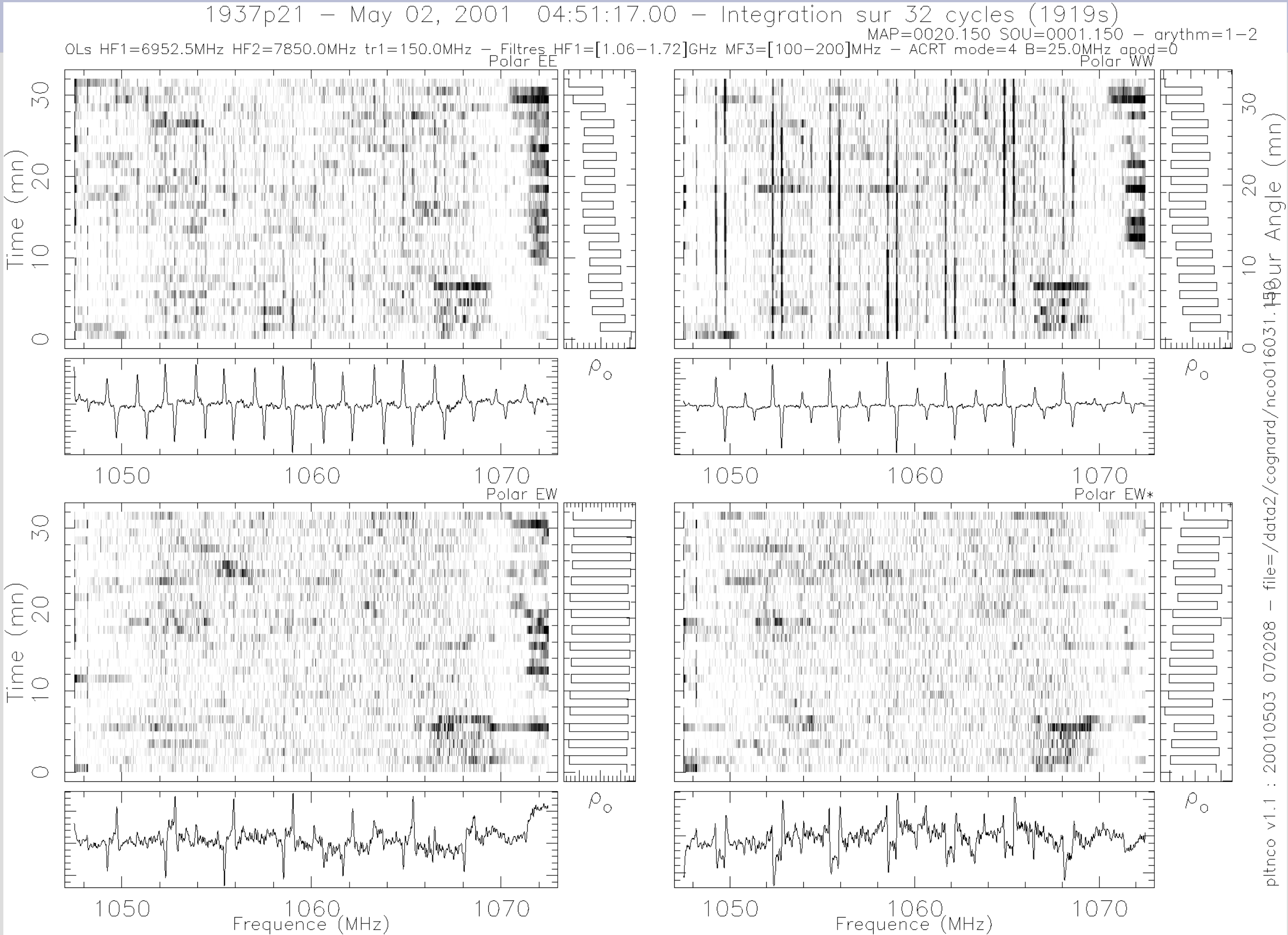
the swept LO : a special coherent instrumentation

mixing of sky signal with a swept LO emulating
the effect of the ionized ISM

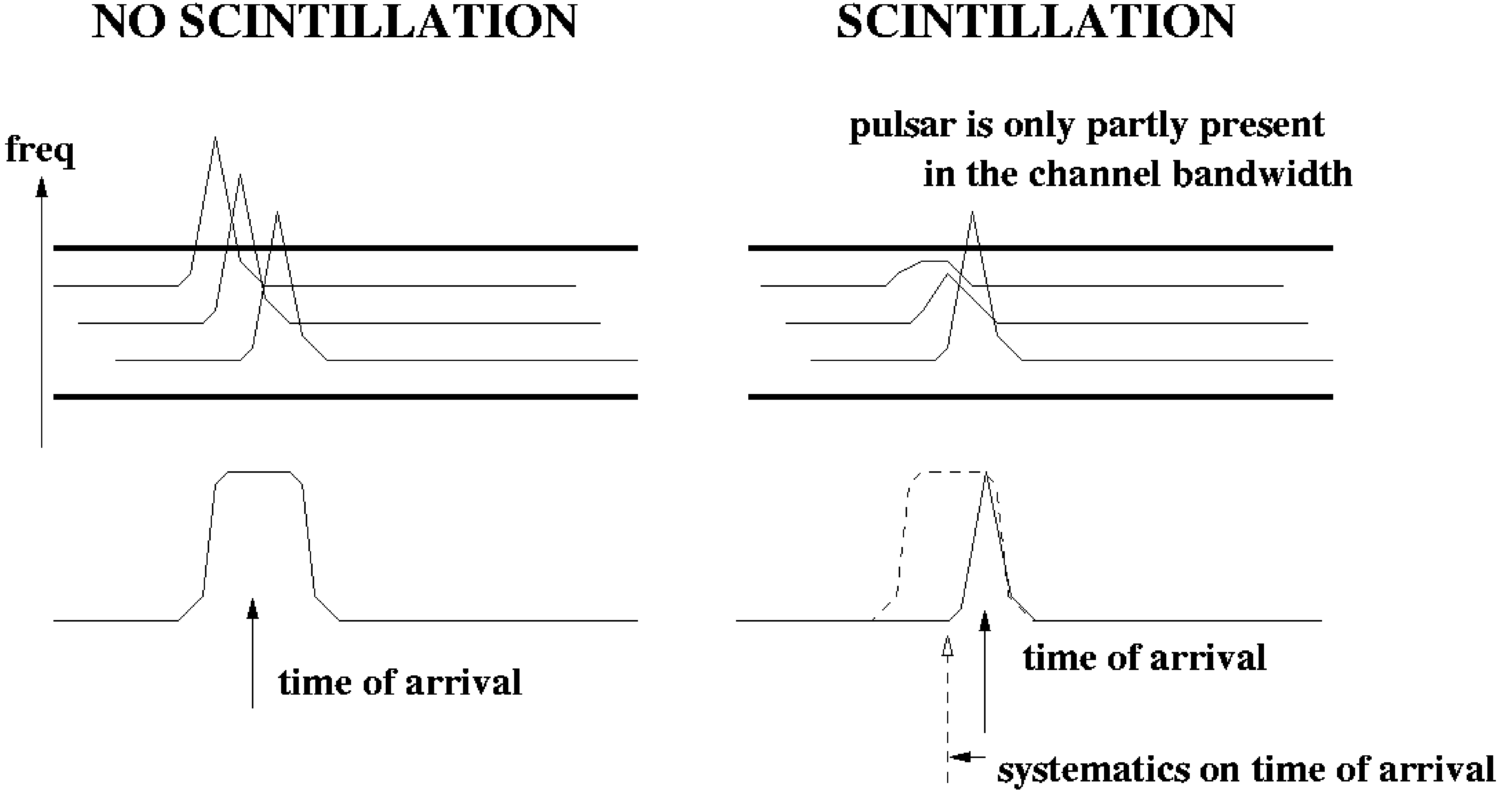
analyzing the output with a standard spectrometer



PSR B1937+21 swept LO observation



For filterbank instrumentations,
together with scintillation, the residual dispersion within channels provide systematics on times of arrival...



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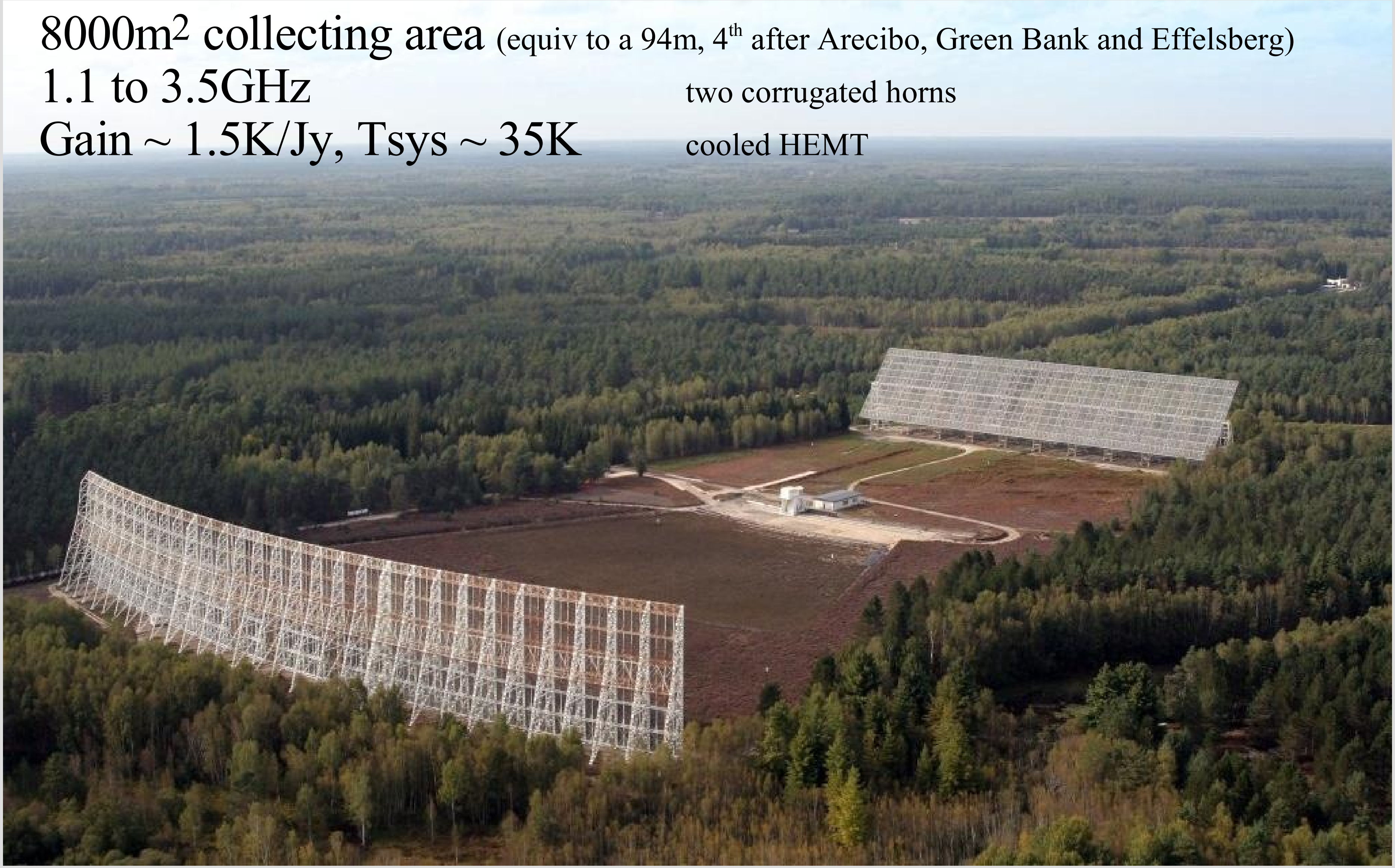
Nançay radiotelescope



$8000m^2$ collecting area (equiv to a 94m, 4th after Arecibo, Green Bank and Effelsberg)

1.1 to 3.5GHz

two corrugated horns

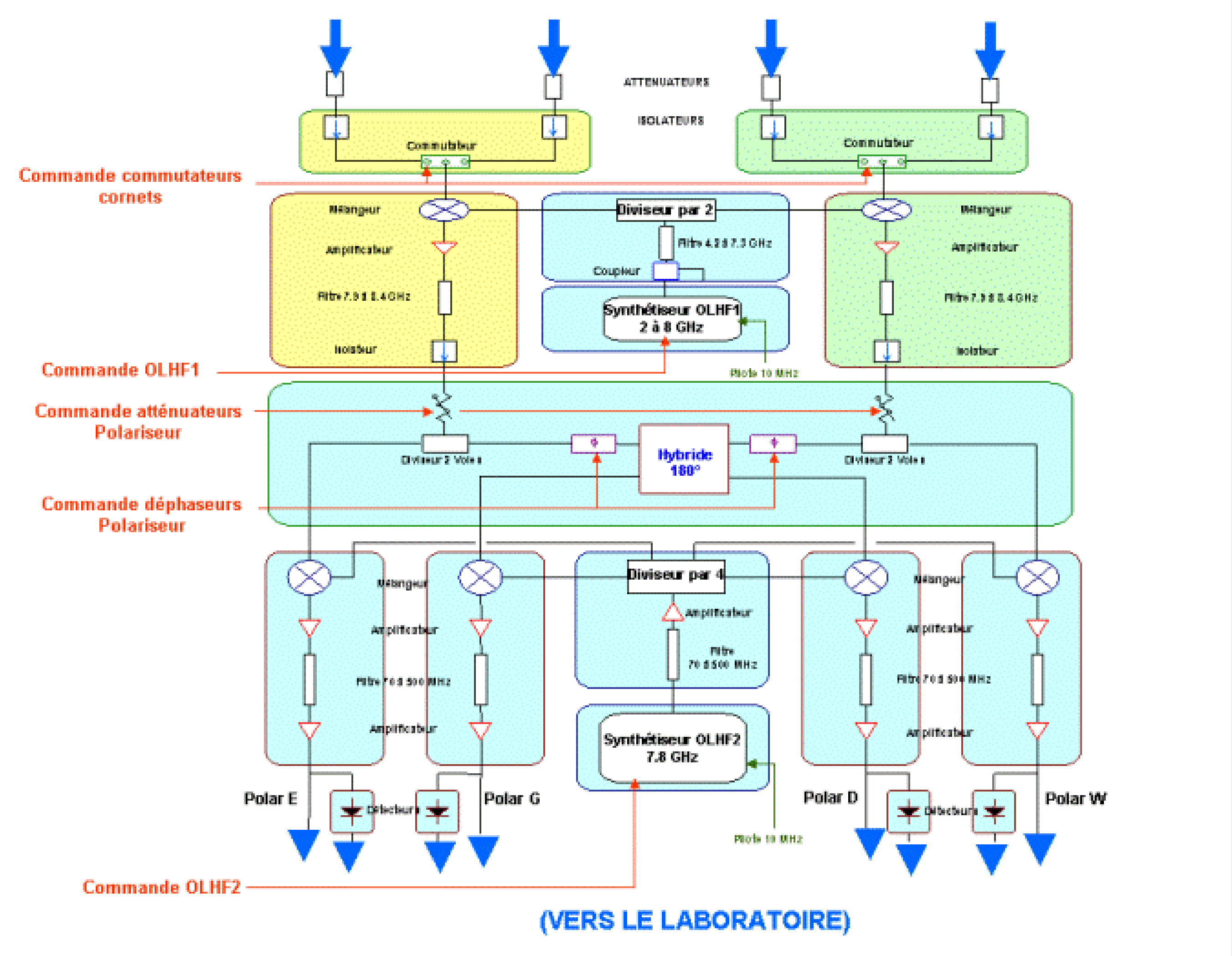
Gain ~ 1.5K/Jy, Tsys ~ 35K

cooled HEMT

Nançay radiotelescope

data path

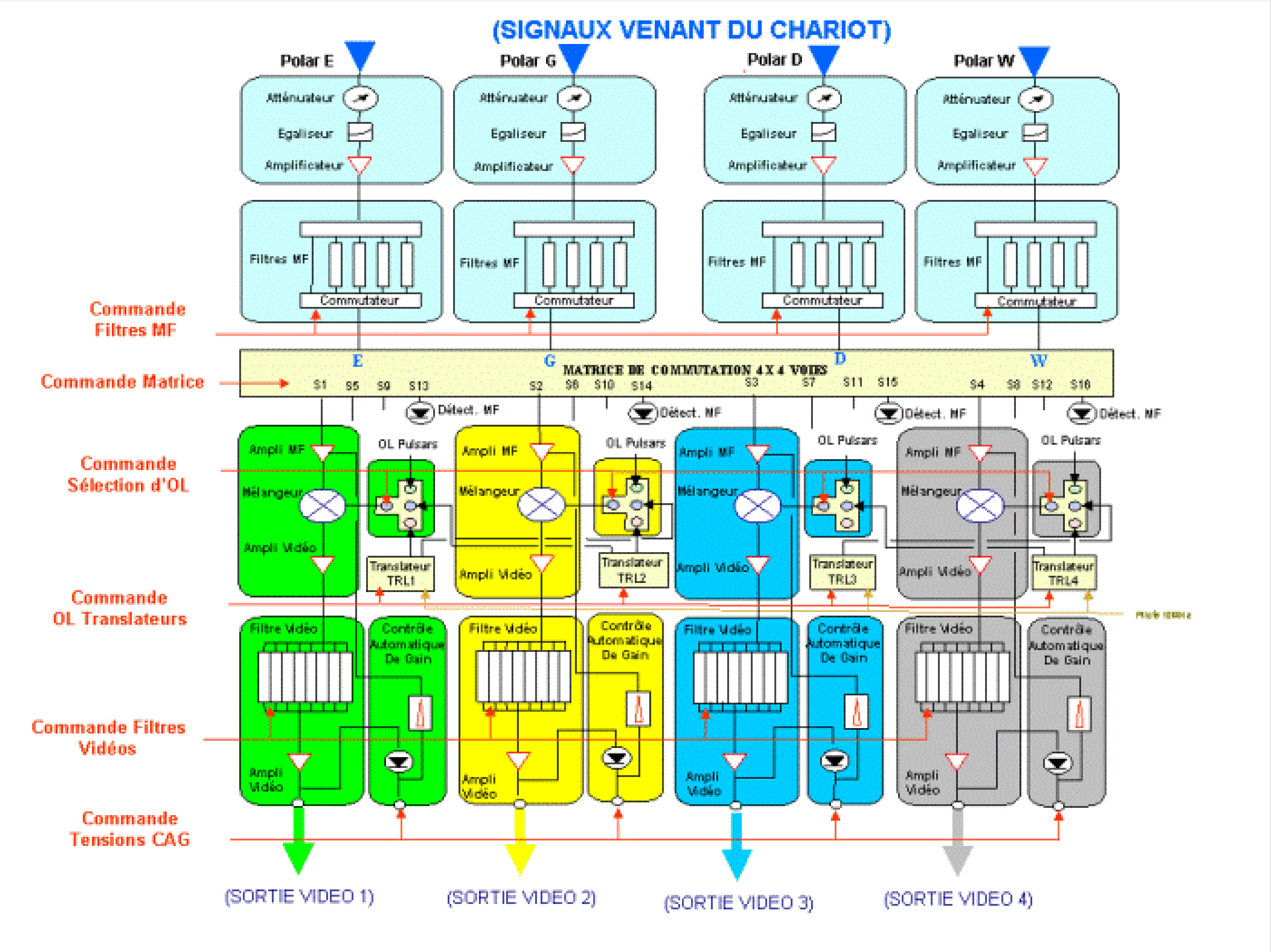
full coverage from 1.1 to 3.5GHz



Nançay radiotelescope

data path

400MHz instantaneous bandwidth



Pulsaroscope 1988-...

swept oscillator

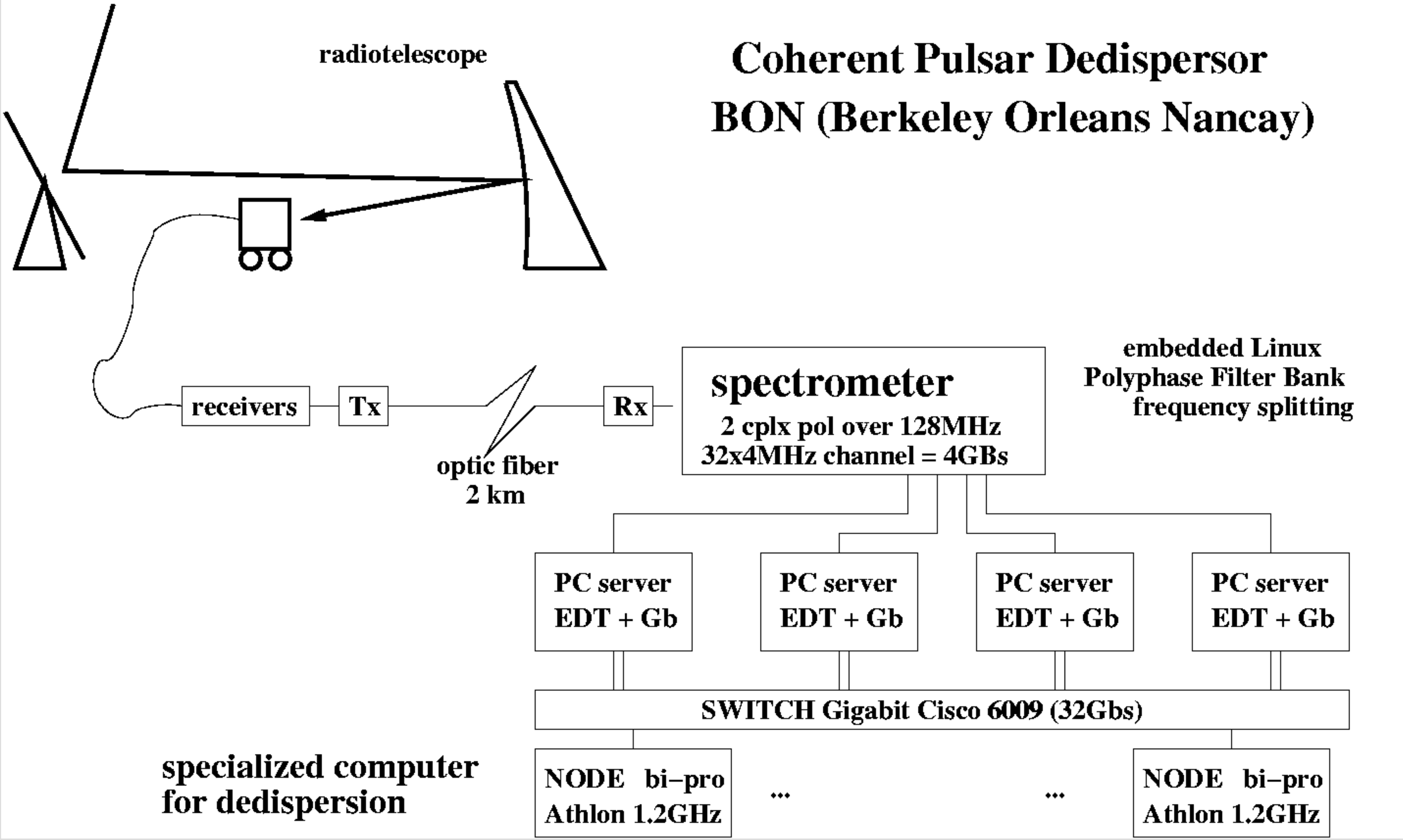
NBPP 1998-2003

(Navy Berkeley Pulsar Processor)

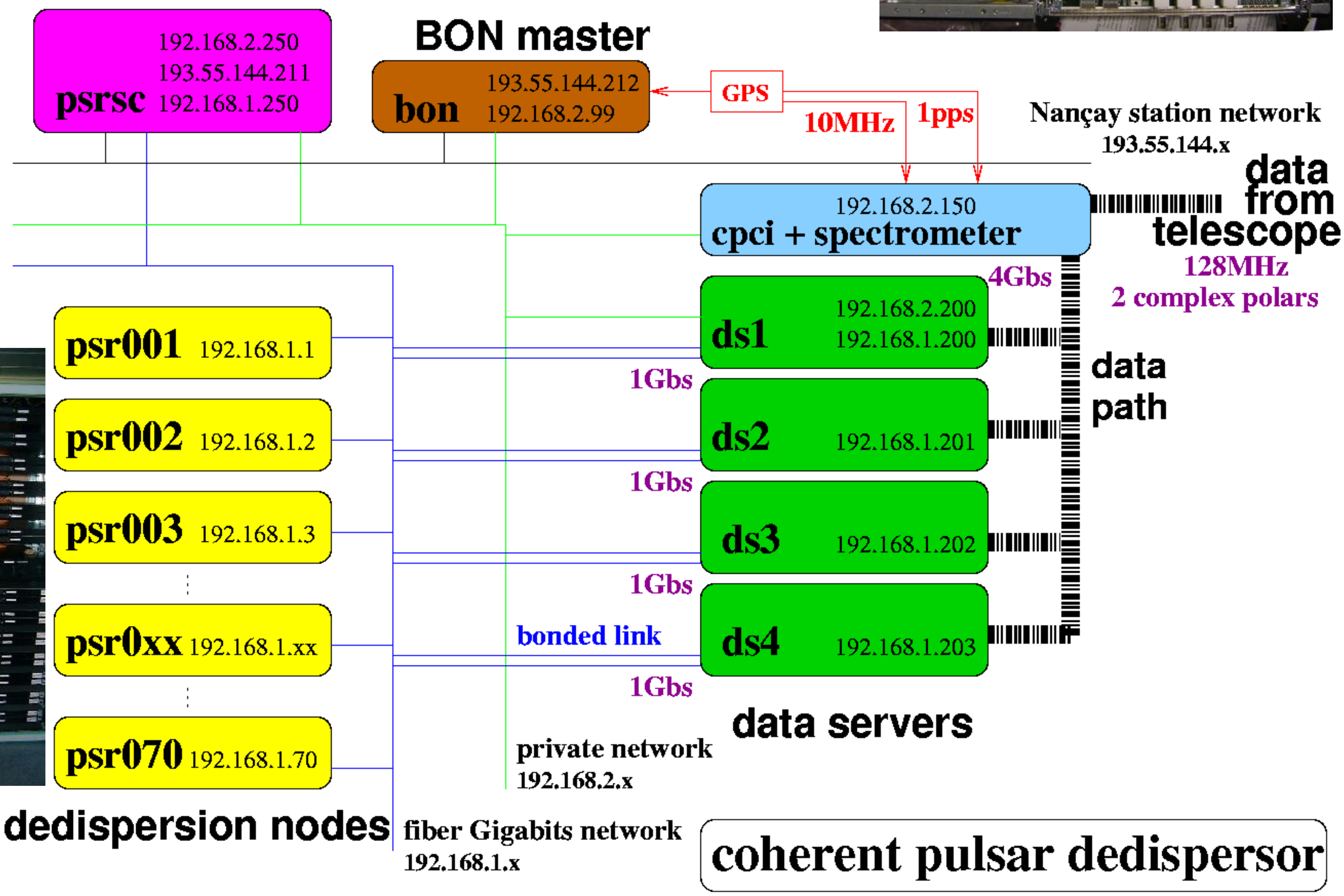
Coherent dedispersor BON 2004-...

(Berkeley-Orléans-Nançay)

BON : the coherent pulsar dedispersor at Nançay



BON : the coherent pulsar dedispersor at Nançay



BON master

psrsc
192.168.2.250
193.55.144.211
192.168.1.250

bon
193.55.144.212
192.168.2.99

GPS

10MHz

1pps

Nançay station network
193.55.144.x

cpci + spectrometer
192.168.2.150

data from telescope
128MHz
2 complex polars

4Gbs

ds1
192.168.2.200
192.168.1.200

ds2
192.168.1.201

ds3
192.168.1.202

ds4
192.168.1.203

data path

1Gbs

1Gbs

1Gbs

1Gbs

bonded link

data servers

psr001 192.168.1.1

psr002 192.168.1.2

psr003 192.168.1.3

psr0xx 192.168.1.xx

psr070 192.168.1.70

private network
192.168.2.x

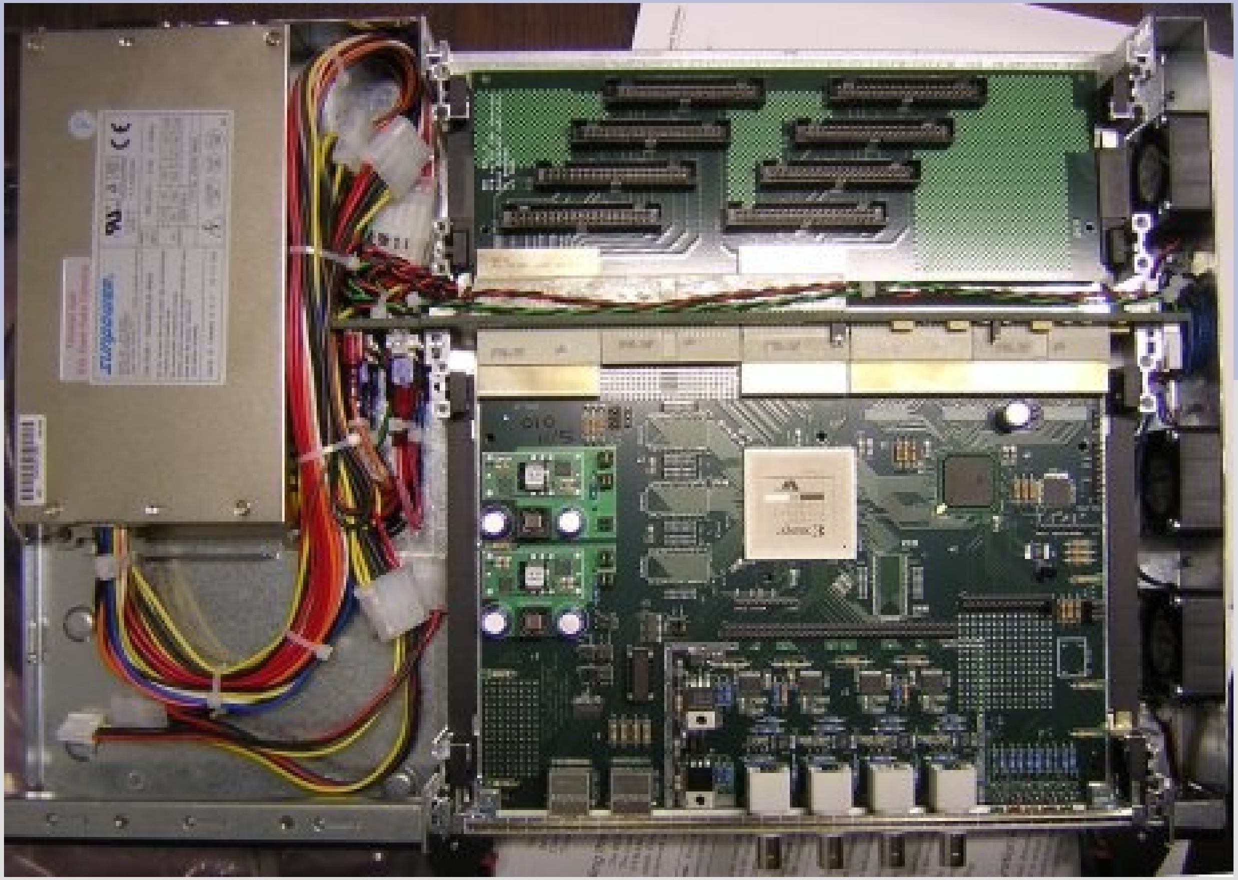
dedispersion nodes

fiber Gigabits network
192.168.1.x

coherent pulsar dedispersor

Serendip V

2 polars I,Q
sampled at 128Ms/s, 8bits
PFB : 32 4MHz channels
+
CPV5350 Motorola
embedded Linux



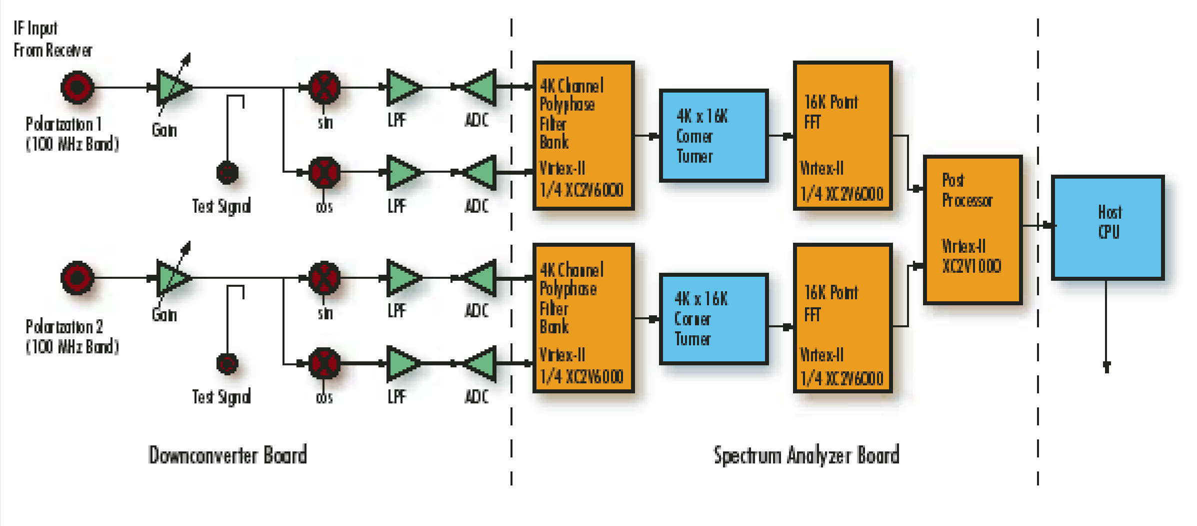
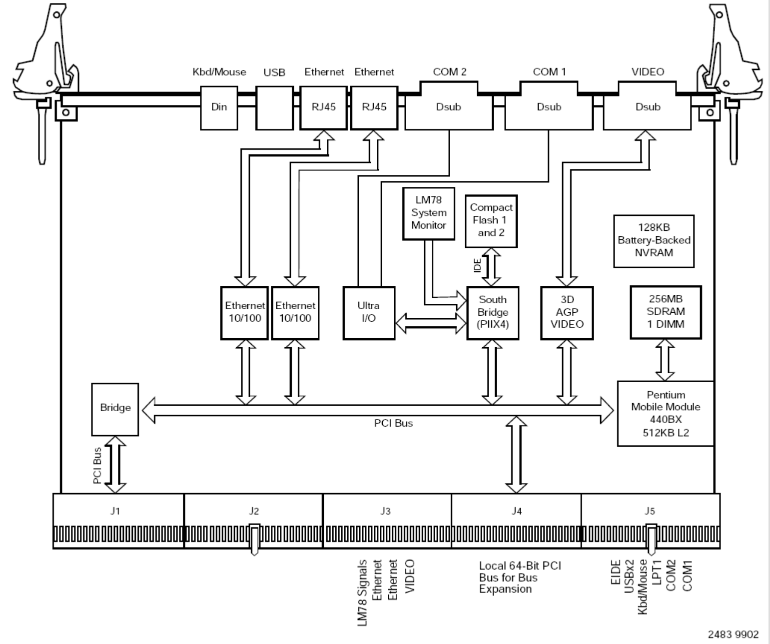


Figure 3 – SERENDIP V spectrometer module



A dedicated calculator for BON

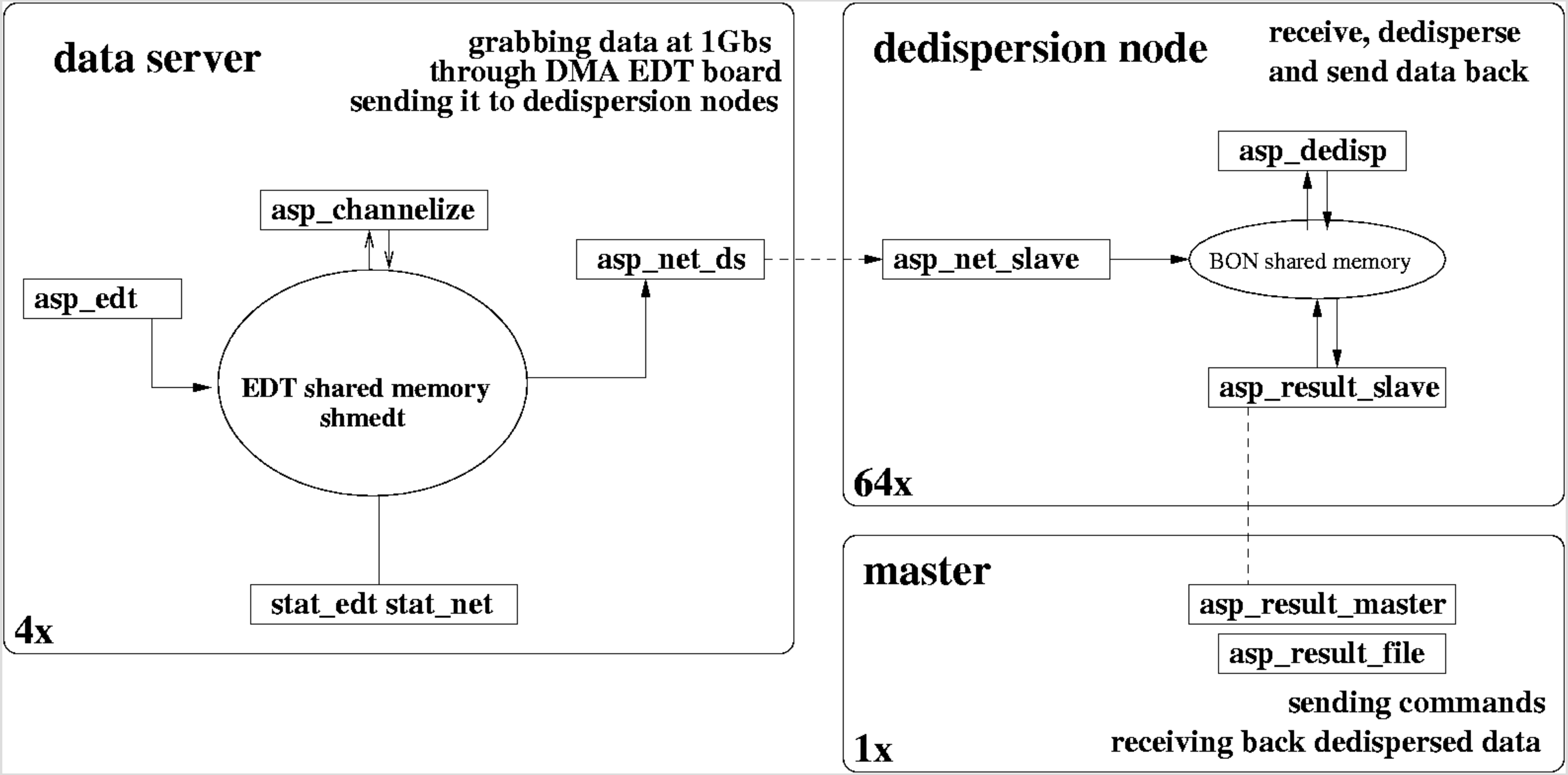
1 master bi-processor Athlon
    1.2GHz, 2Go memory

77 slaves bi-proc Athlon 1.2GHz,
    1 Go memory, 10G hard disk

Gigabit network (32GBs)
    switch Cisco 6009

operating system
    Linux, kernel 2.4.2 "optimized"

C real-time code



data server

grabbing data at 1Gbs
through DMA EDT board
sending it to dedispersion nodes

asp_channelize

asp_edt

EDT shared memory
shmedt

asp_net_ds

stat_edt stat_net

4x

dedispersion node

receive, dedisperse
and send data back

asp_dedisp

asp_net_slave

BON shared memory

asp_result_slave

64x

master

asp_result_master

asp_result_file

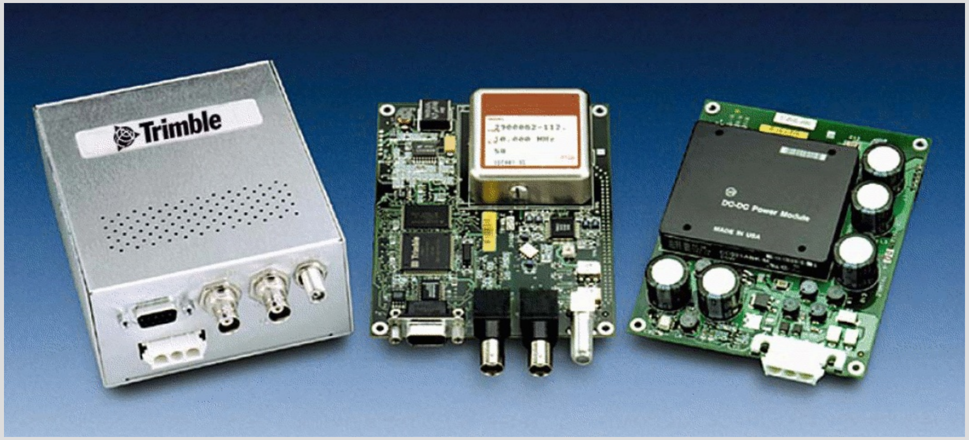
sending commands
receiving back dedispersed data

1x

a precise datation 1/3

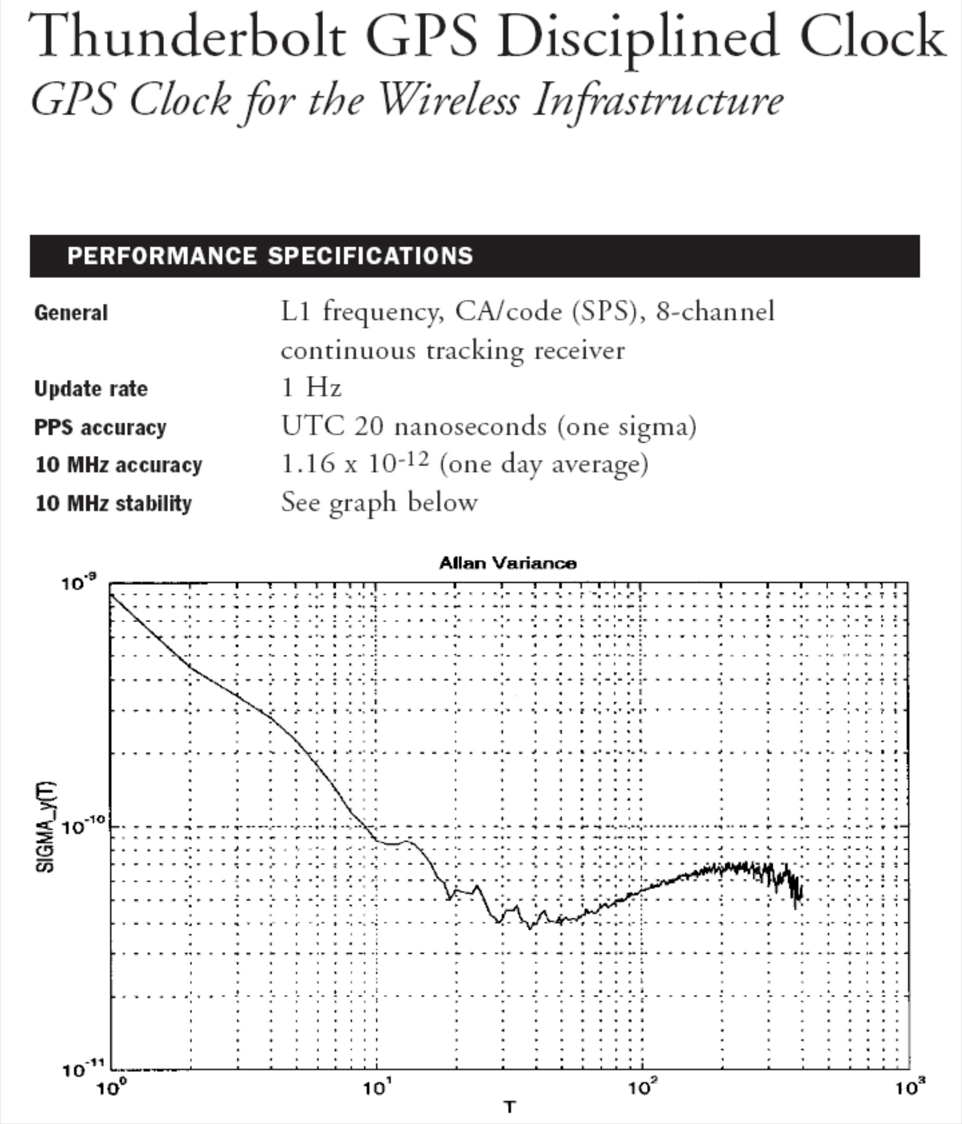
Clock and Data sent by Serendip V to dataservers
starts on the leading edge
of a 1pps signal (pps = pulse per second)

1pps signal and 10MHz reference clock
are provided by a GPS disciplined clock



Thunderbolt GPS disciplined clock,
Trimble Inc.

a precise datation 2/3



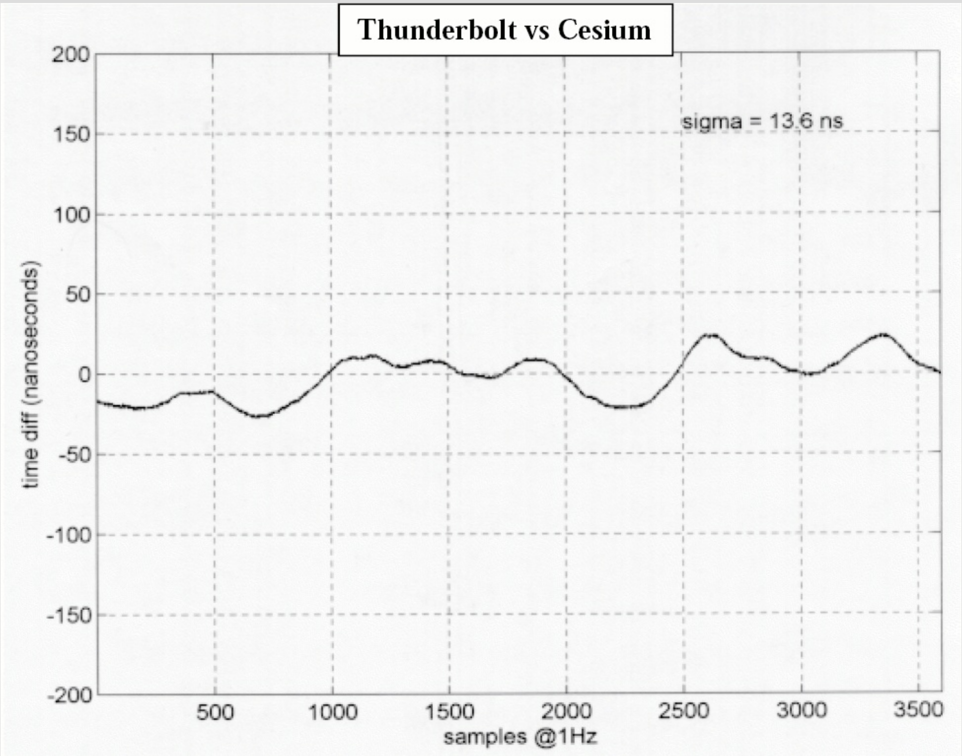
Thunderbolt GPS Disciplined Clock

GPS Clock for the Wireless Infrastructure

PERFORMANCE SPECIFICATIONS

General	L1 frequency, CA/code (SPS), 8-channel continuous tracking receiver
Update rate	1 Hz
PPS accuracy	UTC 20 nanoseconds (one sigma)
10 MHz accuracy	1.16 x 10^{-12} (one day average)
10 MHz stability	See graph below

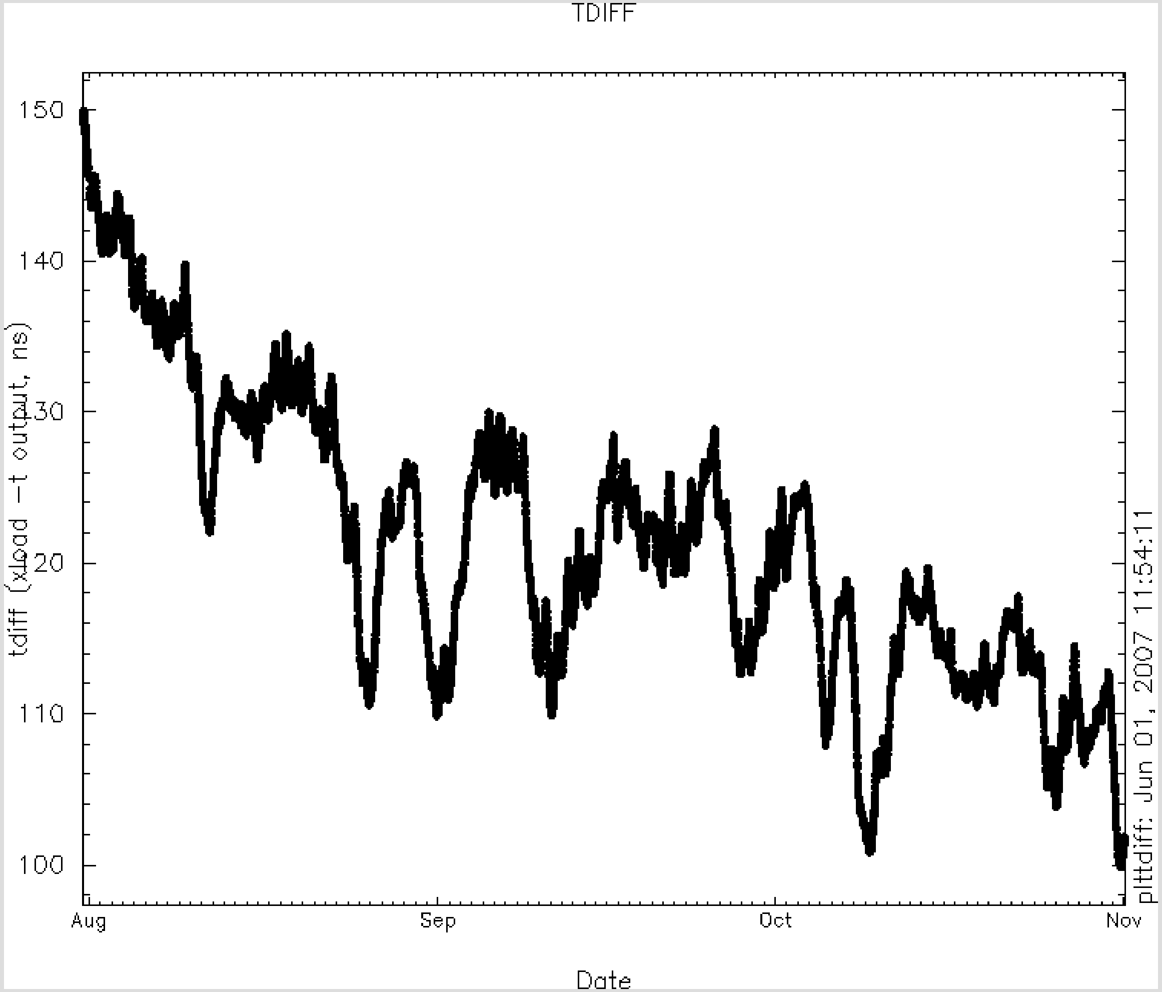
Specifications



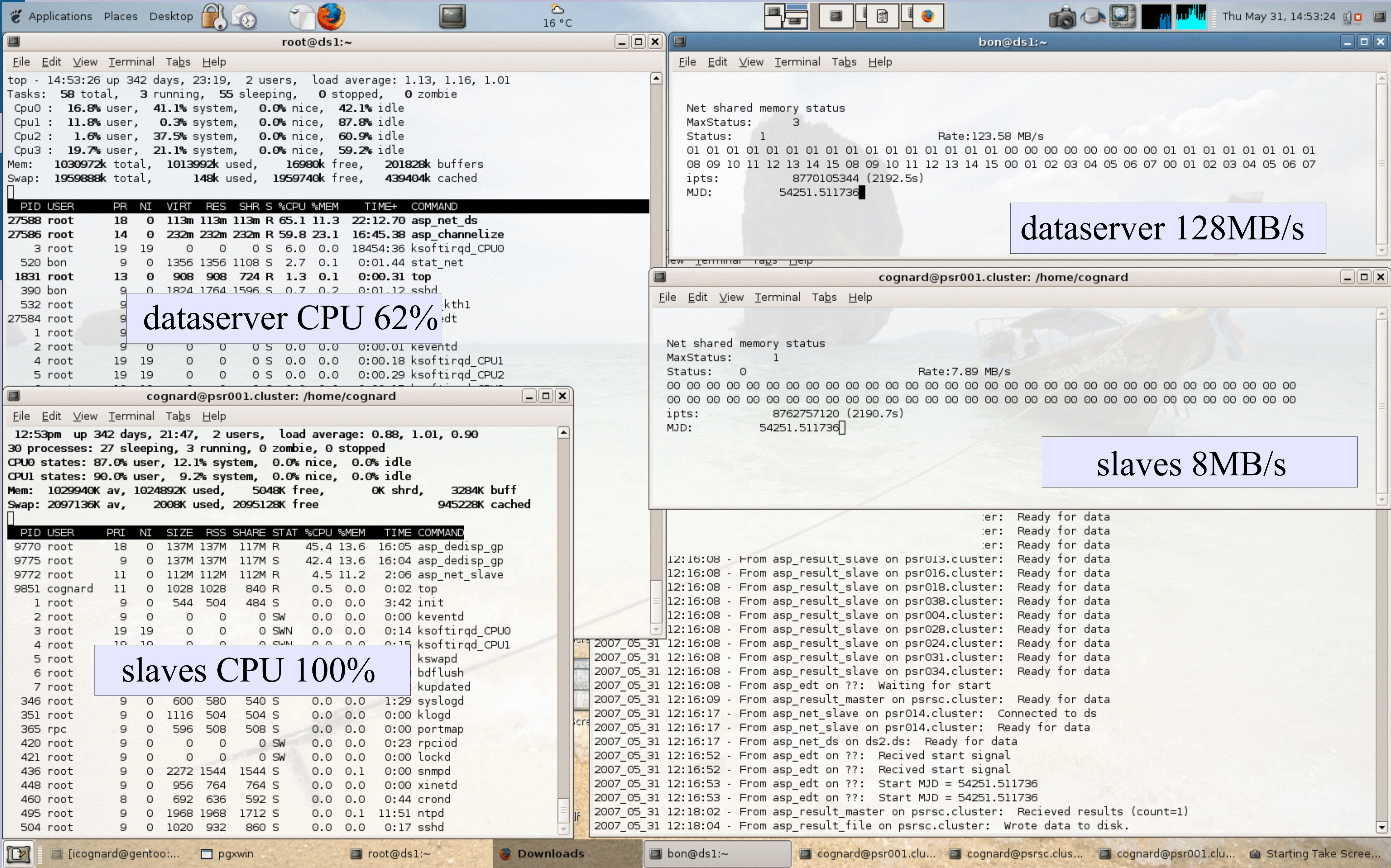
Comparison with a Cesium

a precise datation 3/3

time difference (in ns) between
    1pps signal and
    the leading edge
        of SerendipV internal clock



A running observation...



```
top - 14:53:26 up 342 days, 23:19,  2 users,  load average: 1.13, 1.16, 1.01
Tasks:  58 total,   3 running,  55 sleeping,   0 stopped,   0 zombie
 Cpu0 :  16.8% user,  41.1% system,   0.0% nice,  42.1% idle
 Cpu1 :  11.8% user,   0.3% system,   0.0% nice,  87.8% idle
 Cpu2 :   1.6% user,  37.5% system,   0.0% nice,  60.9% idle
 Cpu3 :  19.7% user,  21.1% system,   0.0% nice,  59.2% idle
Mem:   1030972k total,  1013992k used,    16980k free,   201828k buffers
Swap:  1959888k total,      148k used,  1959740k free,   439404k cached

  PID USER      PR  NI  VIRT  RES  SHR S %CPU %MEM    TIME+  COMMAND
27588 root      18   0  113m 113m 113m R 65.1 11.3  22:12.70 asp_net_ds
27586 root      14   0  232m 232m 232m R 59.8 23.1  16:45.38 asp_channelize
    3 root      19  19     0    0    0 S  6.0  0.0 18454:36 ksoftirqd_CPU0
  520 bon        9   0  1356 1356 1108 S  2.7  0.1   0:01.44 stat_net
 1831 root      13   0   908  908  724 R  1.3  0.1   0:00.31 top
  390 bon        9   0  1824 1764 1596 S  0.7  0.2   0:01.12 sshd
  532 root       9                                           kth1
27584 root       9                                           dt
    1 root       9
    2 root       9   0     0    0    0 S  0.0  0.0   0:00.01 keventd
    4 root      19  19     0    0    0 S  0.0  0.0   0:00.18 ksoftirqd_CPU1
    5 root      19  19     0    0    0 S  0.0  0.0   0:00.29 ksoftirqd_CPU2
```

dataserver CPU 62%

```
Net shared memory status
MaxStatus:       3
Status:     1                        Rate:123.58 MB/s
01 01 01 01 01 01 01 01 01 01 01 01 01 01 01 01 00 00 00 00 00 00 00 00 01 01 01 01 01 01 01 01
08 09 10 11 12 13 14 15 08 09 10 11 12 13 14 15 00 01 02 03 04 05 06 07 00 01 02 03 04 05 06 07
ipts:            8770105344 (2192.5s)
MJD:           54251.511736
```

dataserver 128MB/s

```
Net shared memory status
MaxStatus:       1
Status:     0                        Rate:7.89 MB/s
00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
ipts:            8762757120 (2190.7s)
MJD:           54251.511736
```

slaves 8MB/s

```
 12:53pm  up 342 days, 21:47,  2 users,  load average: 0.88, 1.01, 0.90
30 processes: 27 sleeping, 3 running, 0 zombie, 0 stopped
CPU0 states: 87.0% user, 12.1% system,  0.0% nice,  0.0% idle
CPU1 states: 90.0% user,  9.2% system,  0.0% nice,  0.0% idle
Mem:  1029940K av, 1024892K used,    5048K free,       0K shrd,    3284K buff
Swap: 2097136K av,    2008K used, 2095128K free                  945228K cached

  PID USER      PRI  NI  SIZE  RSS SHARE STAT %CPU %MEM   TIME COMMAND
 9770 root       18   0  137M 137M  117M R    45.4 13.6  16:05 asp_dedisp_gp
 9775 root        9   0  137M 137M  117M S    42.4 13.6  16:04 asp_dedisp_gp
 9772 root       11   0  112M 112M  112M R     4.5 11.2   2:06 asp_net_slave
 9851 cognard    11   0  1028 1028   840 R     0.5  0.0   0:02 top
    1 root        9   0   544  504   484 S     0.0  0.0   3:42 init
    2 root        9   0     0    0     0 SW    0.0  0.0   0:00 keventd
    3 root       19  19     0    0     0 SWN   0.0  0.0   0:14 ksoftirqd_CPU0
    4 root       19  19     0    0     0 SWN   0.0  0.0   0:15 ksoftirqd_CPU1
    5 root                                                      kswapd
    6 root                                                      bdflush
    7 root                                                      kupdated
  346 root        9   0   600  580   540 S     0.0  0.0   1:29 syslogd
  351 root        9   0  1116  504   504 S     0.0  0.0   0:00 klogd
  365 rpc         9   0   596  508   508 S     0.0  0.0   0:00 portmap
  420 root        9   0     0    0     0 SW    0.0  0.0   0:23 rpciod
  421 root        9   0     0    0     0 SW    0.0  0.0   0:00 lockd
  436 root        9   0  2272 1544  1544 S     0.0  0.1   0:00 snmpd
  448 root        9   0   956  764   764 S     0.0  0.0   0:00 xinetd
  460 root        8   0   692  636   592 S     0.0  0.0   0:44 crond
  495 root        9   0  1968 1968  1712 S     0.0  0.1  11:51 ntpd
  504 root        9   0  1020  932   860 S     0.0  0.0   0:17 sshd
```

slaves CPU 100%

```
                                              er:  Ready for data
                                              er:  Ready for data
                                              er:  Ready for data
           12:16:08 - From asp_result_slave on psr013.cluster:  Ready for data
           12:16:08 - From asp_result_slave on psr016.cluster:  Ready for data
           12:16:08 - From asp_result_slave on psr018.cluster:  Ready for data
           12:16:08 - From asp_result_slave on psr038.cluster:  Ready for data
           12:16:08 - From asp_result_slave on psr004.cluster:  Ready for data
           12:16:08 - From asp_result_slave on psr028.cluster:  Ready for data
2007_05_31 12:16:08 - From asp_result_slave on psr024.cluster:  Ready for data
2007_05_31 12:16:08 - From asp_result_slave on psr031.cluster:  Ready for data
2007_05_31 12:16:08 - From asp_result_slave on psr034.cluster:  Ready for data
2007_05_31 12:16:08 - From asp_edt on ??:  Waiting for start
2007_05_31 12:16:09 - From asp_result_master on psrsc.cluster:  Ready for data
2007_05_31 12:16:17 - From asp_net_slave on psr014.cluster:  Connected to ds
2007_05_31 12:16:17 - From asp_net_slave on psr014.cluster:  Ready for data
2007_05_31 12:16:17 - From asp_net_ds on ds2.ds:  Ready for data
2007_05_31 12:16:52 - From asp_edt on ??:  Recived start signal
2007_05_31 12:16:52 - From asp_edt on ??:  Recived start signal
2007_05_31 12:16:53 - From asp_edt on ??:  Start MJD = 54251.511736
2007_05_31 12:16:53 - From asp_edt on ??:  Start MJD = 54251.511736
2007_05_31 12:18:02 - From asp_result_master on psrsc.cluster:  Recieved results (count=1)
2007_05_31 12:18:04 - From asp_result_file on psrsc.cluster:  Wrote data to disk.
```

Plan

- Introduction
  - The pulsar phenomenon
  - Stellar evolution
- Interstellar Medium
  - Scattering
  - Dispersion
- Pulsar Instrumentation
  - Baseband mixing
  - Coherent dedispersion
- Observations
  - Nançay Radiotelescope
  - BON coherent dedispersor
- **Pulsars TOAs**
  - **Timing of pulsars**
  - **Examples**
- Conclusion

Timing of pulsars

determine the arrival times
of radio pulses received on Earth

this needs

- a precise reference clock
- a special instrumentation
  to integrate the signal
  in time and frequency

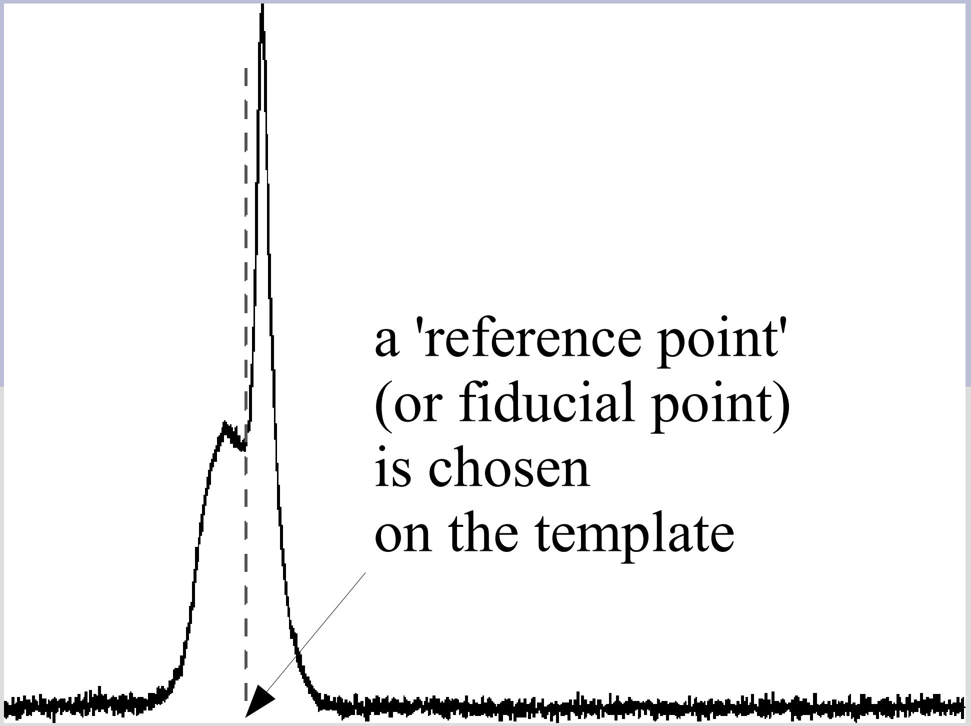
analyze the shape of the time of arrival residuals

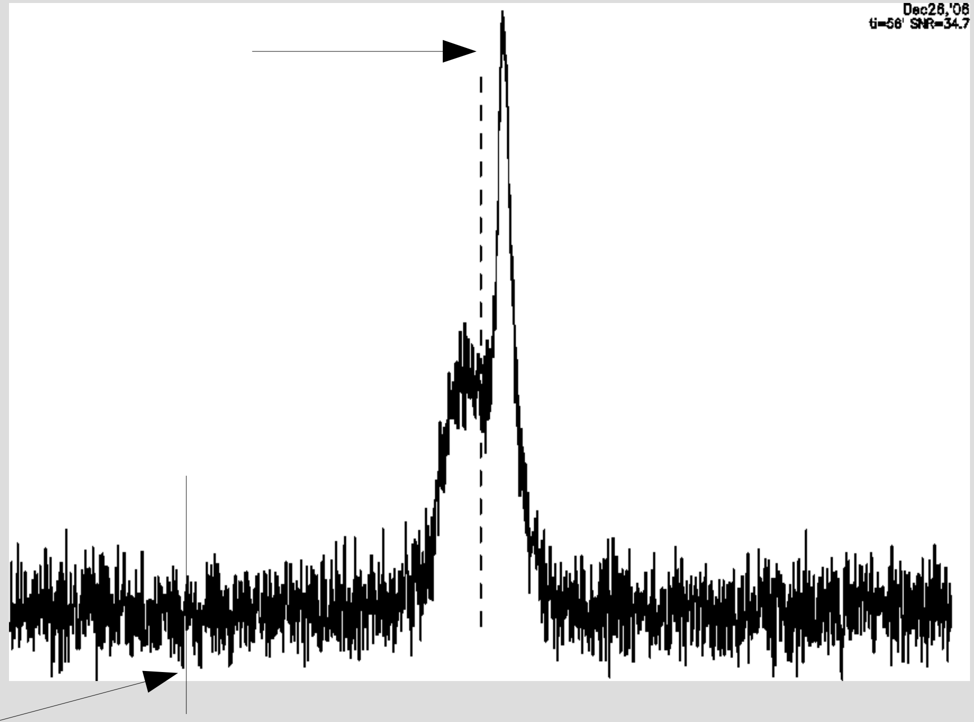
Détermination
of Times of Arrival (TOA)

(example on PSR J1600-3053 P=3.6ms, binary)

build a '**template**', either
- smoothed version
  of a given observation
- sum of sinus/cosinus
- coherent integration
  of many observations

cross-correlation of the 'template' with
the daily observation yields
a shift converted to a time of arrival


a 'reference point'
(or fiducial point)
is chosen
on the template



position of the first data sample
corresponding to the start time
will be taken into account

Times of Arrival for J1600-3053

```
f    1 1600-30  1368.000 54033.5511921591647      0.48
f    1 1600-30  1368.000 54036.5385764225914      0.54
f    1 1600-30  1368.000 54048.5021991052575      0.59
f    1 1600-30  1368.000 54051.5056597667359      0.50
f    1 1600-30  1368.000 54054.4968287444377      0.46
f    1 1600-30  1368.000 54056.4913888998682      0.48
f    1 1600-30  1368.000 54057.4889815273292      0.52
f    1 1600-30  1368.000 54060.4810301095328      0.51
f    1 1600-30  1368.000 54065.4600579101507      0.60
f    1 1600-30  1368.000 54071.4479745723167      0.57
f    1 1600-30  1368.000 54072.4445486474761      0.53
f    1 1600-30  1368.000 54079.4312384526258      0.50
```

observatory_code, '1', pulsar_name, radio_frequency[MHz], TOA[MJD], uncertainty[μs]

Analysis of Times of Arrival

minimize the differences

MEASURED TOAs – CALCULATED TOAs

this can be done with different codes :

- tempo (Princeton, then Parkes)
- antiope (Meudon, then Orléans)
- timapr (O.Doroshenko)

tempo

input files : parameters + TOAs

1600.par :

```
PSRJ          J1600-3053
RAJ           16:00:51.90392          0
DECJ          -30:53:49.325           0
DM            52.333
PEPOCH        52500.0
F0            277.937711457601        1
F1            -7.322E-16              1
PMRA          -0.91
PMDEC         -4.0
POSEPOCH      52500.00
EPHEM         DE405
BINARY        DD
PB            14.348457554            1
E             0.00017371              1
A1            8.8016571               1
T0            52506.3711244           1
OM            181.768043              1
```

tempo

output file is tempo.lis

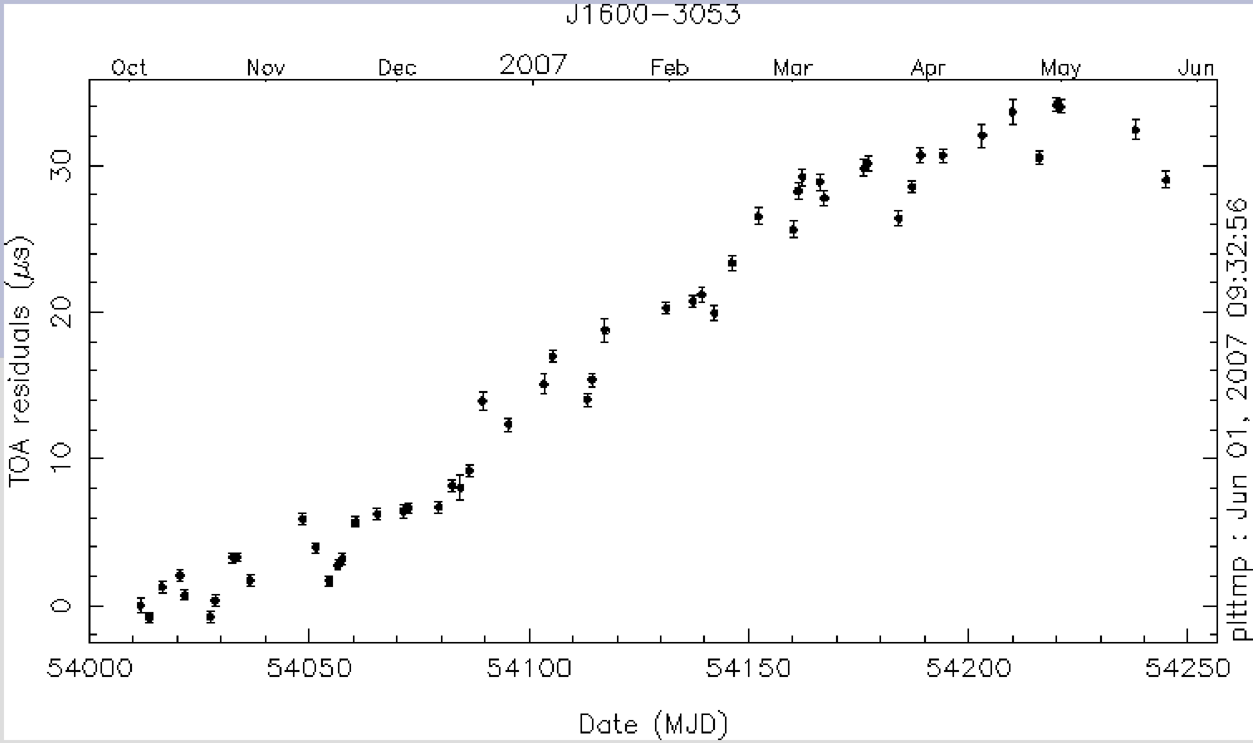
```
PSR J1600-3053 Ephem: DE405 Clk: UNCORR     P Ref: 52500.0000 Pos Ref:   52500.00
      RA                  DEC                PM RA     PM DEC      PM RV   PARALLAX
16 00 51.90392002 -30 53 49.3250000   -0.9100   -4.0000     0.0000    0.0000
       0.00000000          0.0000000   0.0000    0.0000     0.0000    0.0000
       0.00000000          0.0000000   0.0000    0.0000     0.0000    0.0000
16 00 51.90392002 -30 53 49.3250000   -0.9100   -4.0000     0.0000    0.0000

          F0                    F1(D-15)        F2(D-23)      F3(D-00)
 277.93771145760098307   -0.732200000000   0.000000000    0.000000
   0.00000016961066173   -2.442771193969   1.751614040    0.000000
   0.00000001266097278    0.180663222978   0.128783973    0.000000
 277.93771162721162682   -3.174971193969   1.751614040    0.000000

          P0                    P1(D-15)         DM          DM1         PPN GAM
 0.00359792845222264215    0.000009478394   52.333000    0.000000    1.000000
-0.00000000000021956252    0.000031621891    0.000000    0.000000    0.000000
 0.00000000000001638974    0.000002338702    0.000000    0.000000    0.000000
 0.00359792845000307963    0.000041100285   52.333000    0.000000    1.000000

     A1 sin(i)         E            T0(MJD)               PB          OMEGA
   8.801657100  0.0001737100 52506.371124400   14.348457554000 181.768043
  -0.000000265  0.0000000798    -0.000883024   -0.000000022373  -0.022206
   0.000000178  0.0000000448     0.000576593    0.000000010718   0.014472
   8.801656835  0.0001737898 52506.370241376   14.348457531627 181.745837

Mass function:  0.0035560316 +/-  0.0000000002 solar masses
Weighted RMS residual: pre-fit    11.887 us. Predicted post-fit     0.835 us.
```

tempo

pre-fit

TOAs residuals

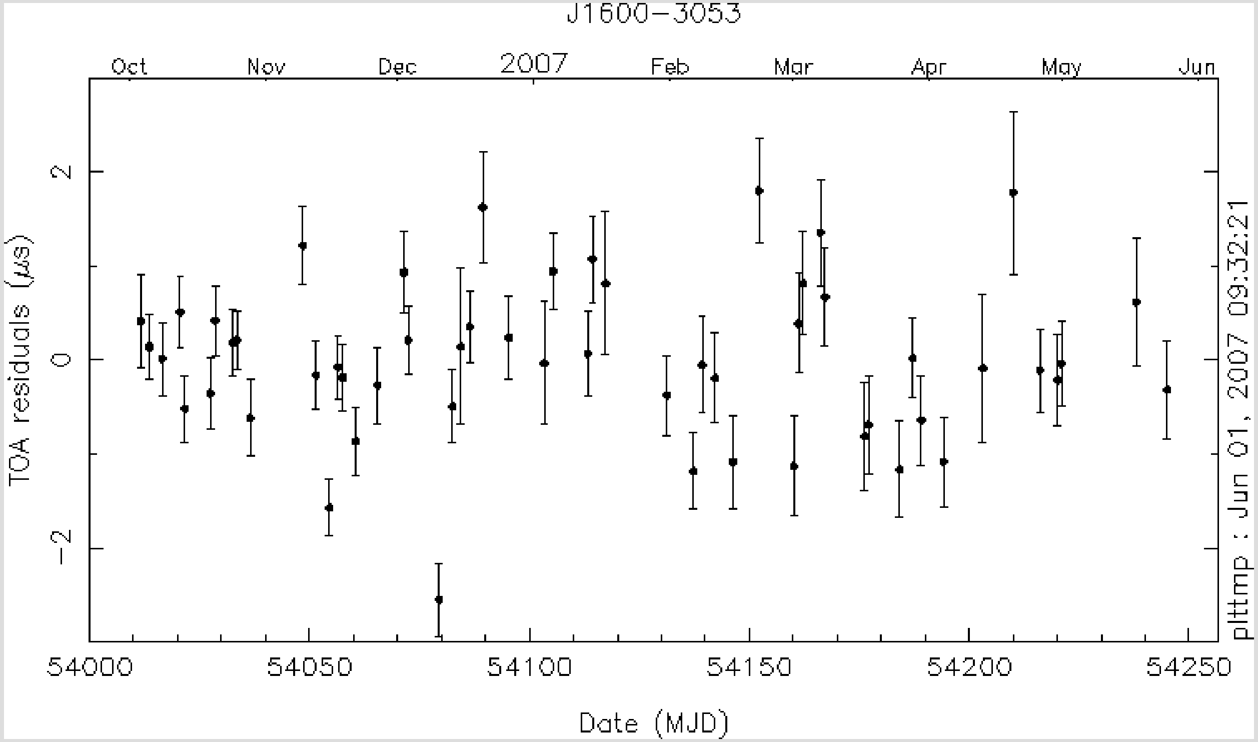
before adjustment of parameters



post-fit

TOAs residuals

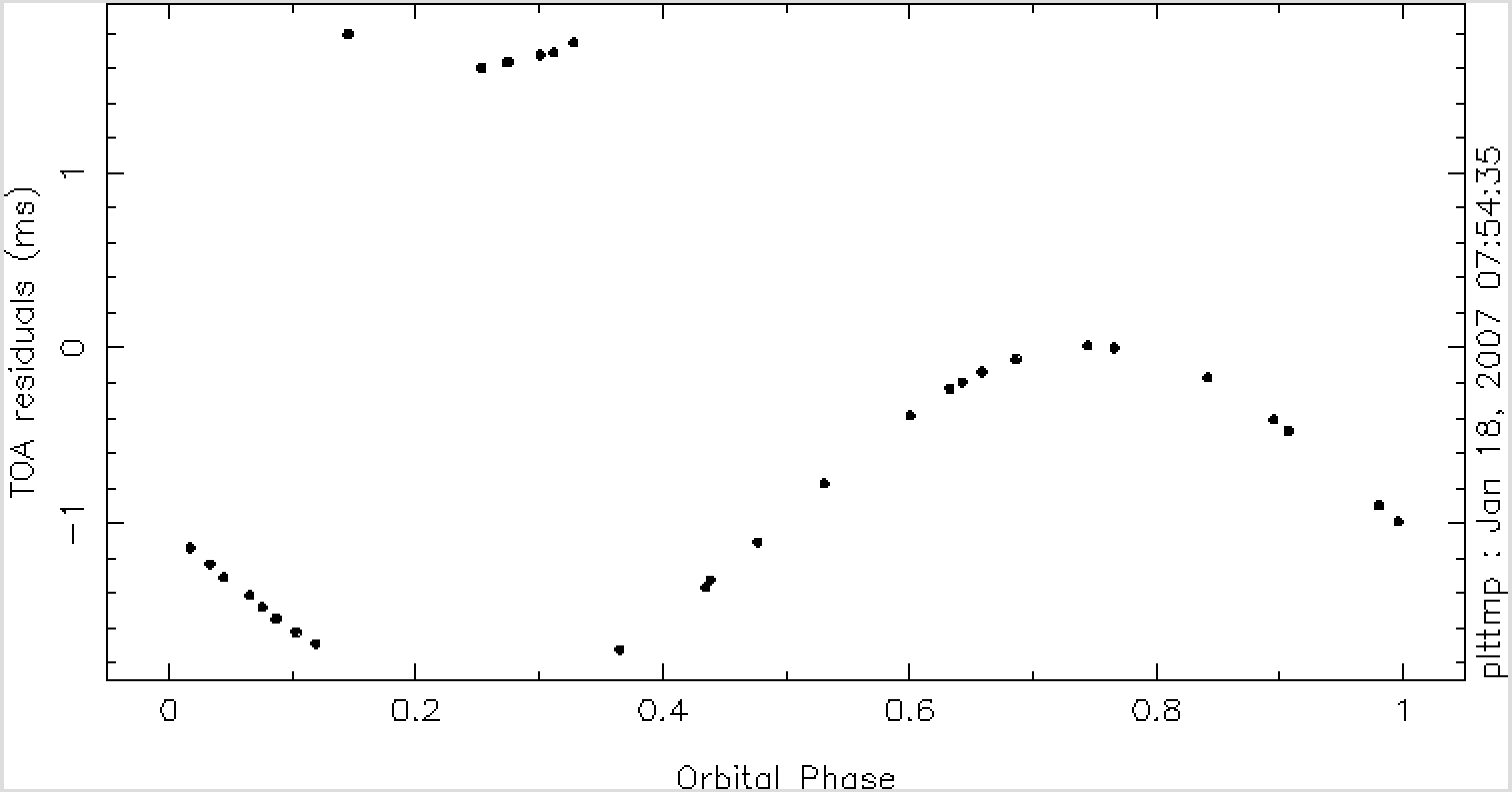
after adjustment of parameters



tempo

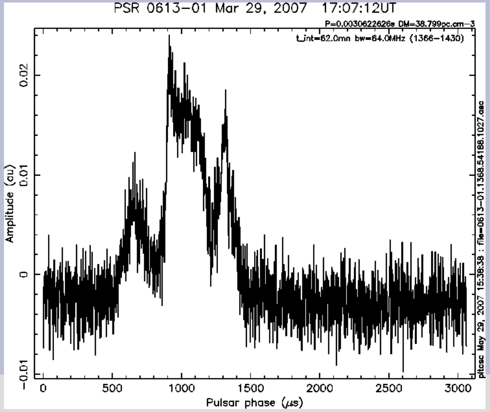
pre-fit

with a 10^{-4} relative offset on A1.sin(i)

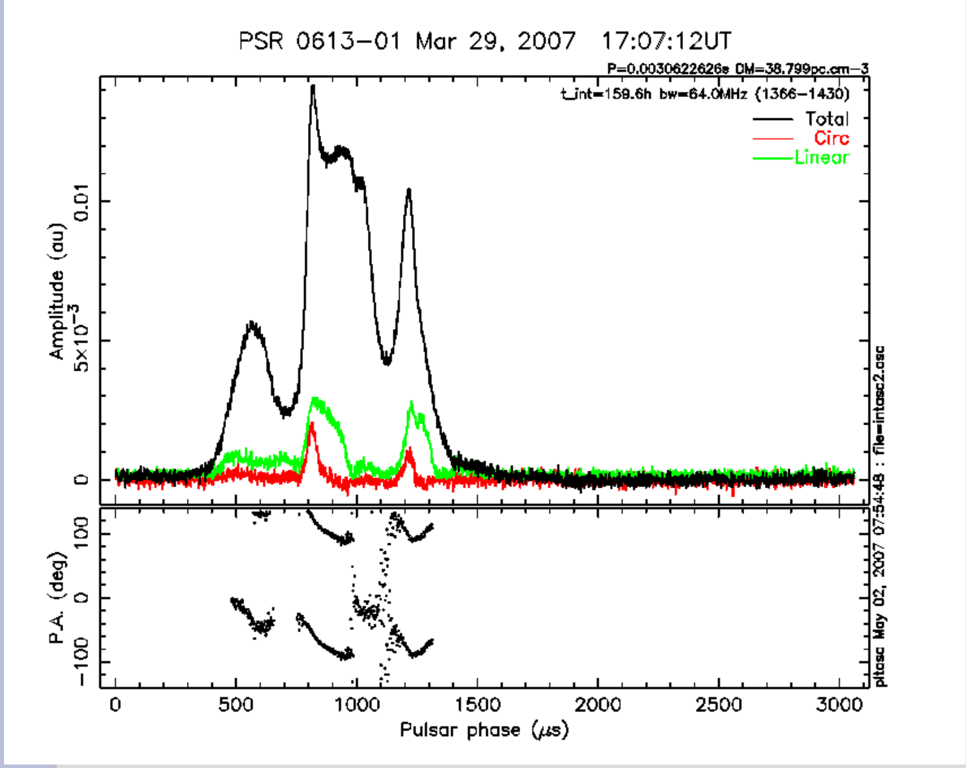


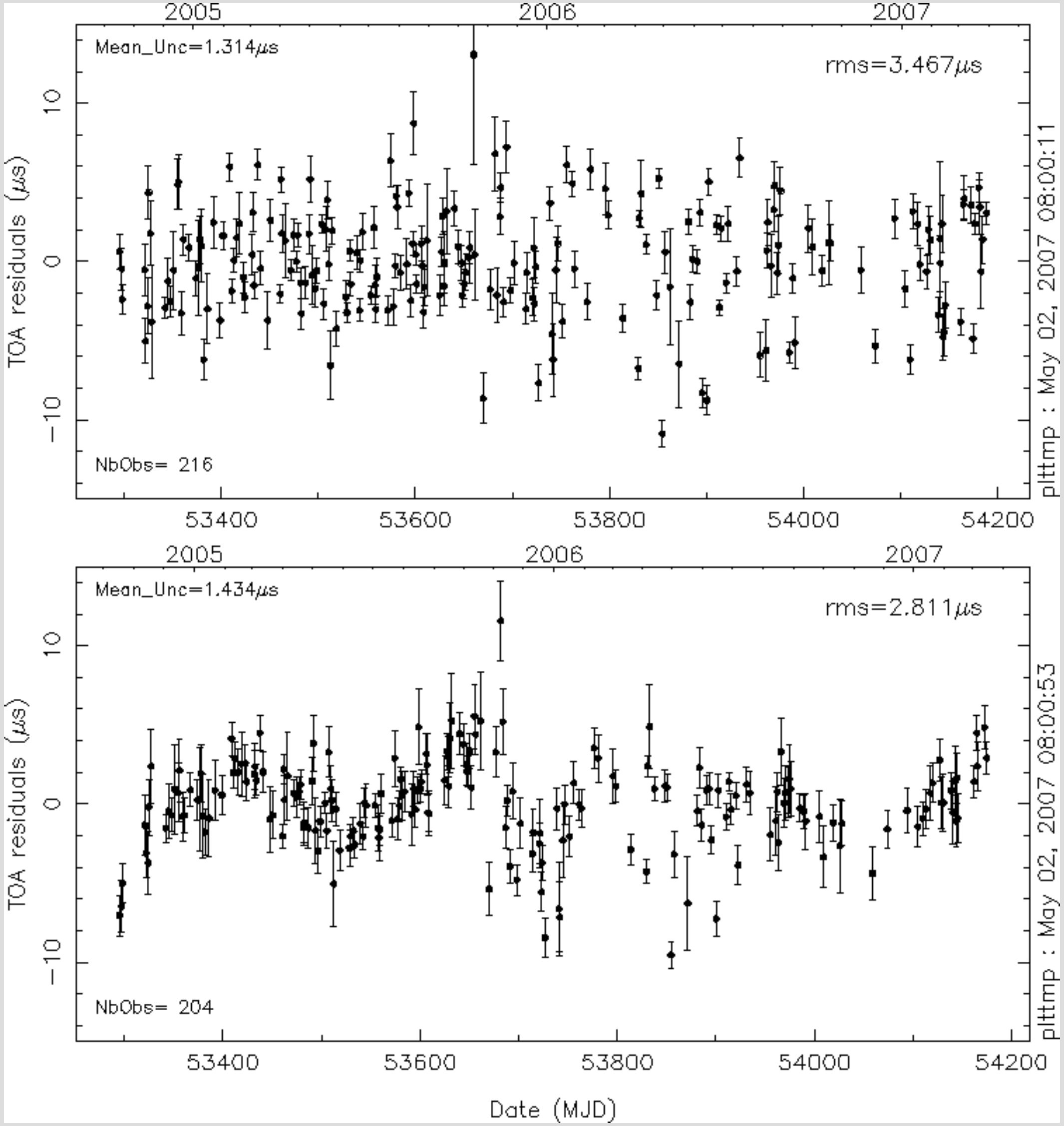
PSR J0613-0200

P=3.062ms P_{Bin}=1.2days



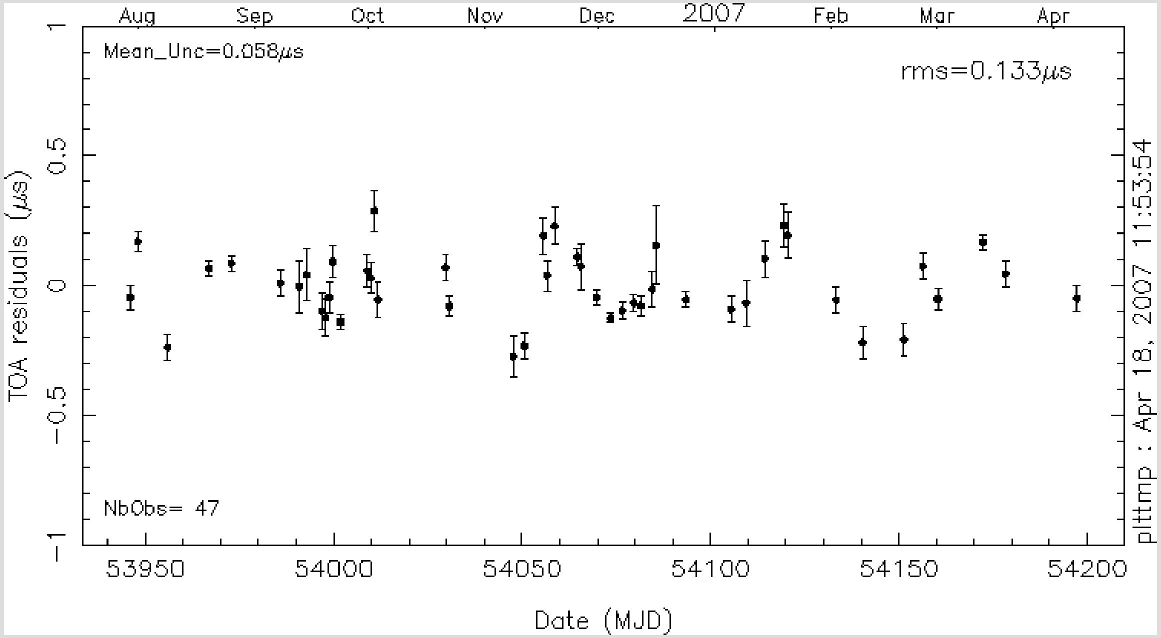
Comparison between integrated
daily profiles for
observational parameters
refined parameters



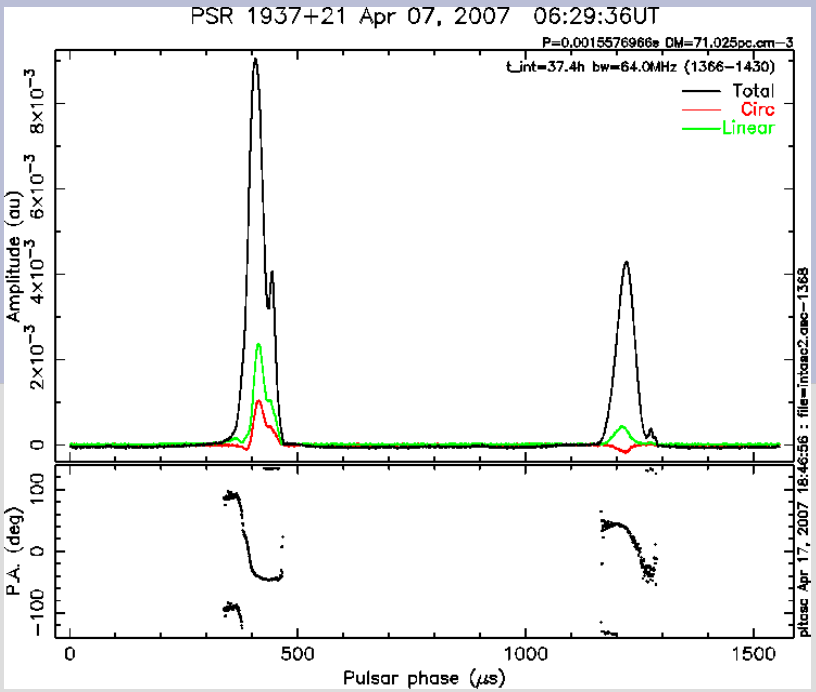


PSR B1937+21

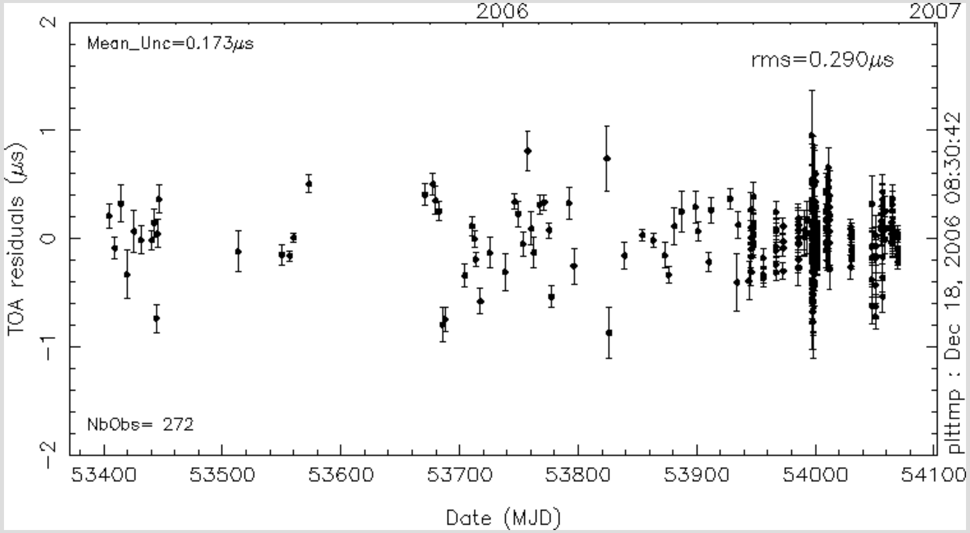
P=1.557ms isolated



uncertainty 60ns over ~20mn
residuals rms 130ns



uncertainty 170ns over 30sec
residuals rms 290ns over ~2ans



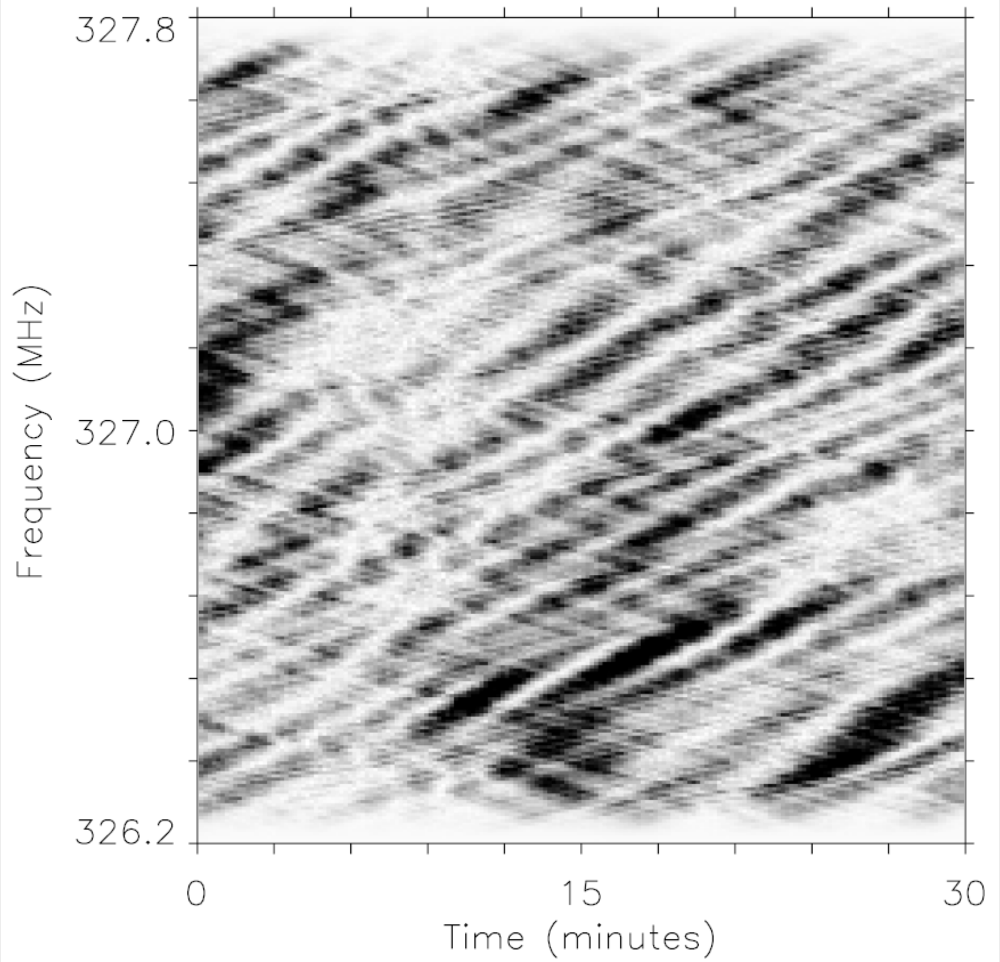
Limiting factors

Multipath produces varying scattering tails, tiny changes in the shape of daily profiles yield to systematics in TOAs

How much is the mean pulse affected by low level contribution of delayed pulses ?

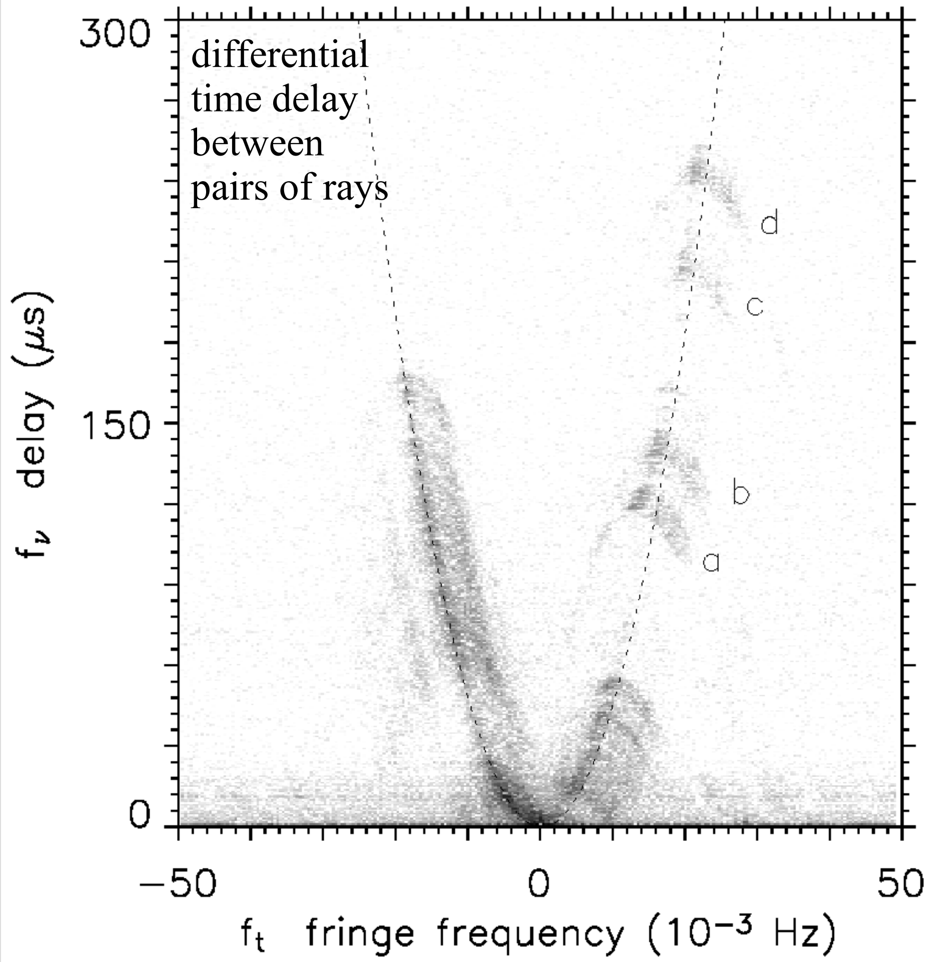
Should we routinely produce a secondary spectrum to be able to correct TOAs ?

dynamic spectra



secondary spectra

squared modulus of the Fourier transform of the dynamic spectrum



differential time delay between pairs of rays

Hill et al., ApJ 619, L171 (2005)

Conclusion

a stable local clock
a baseband dedispersor
a large telescope

and high quality timing measurements of millisecond pulsars
are achieved...
and metrology in radioastronomy becomes a reality !