


Time-domain (Pulsar/FRB) Observing Techniques

Yogesh Maan

Astronomical Techniques II

Main references and sources:

- Low-frequency Radio Astronomy (primarily Chapters 6 and 17),
- Handbook of Pulsar Astronomy,
- J. van Leeuwen's talks available online; and internet.

NCRA • TIFR

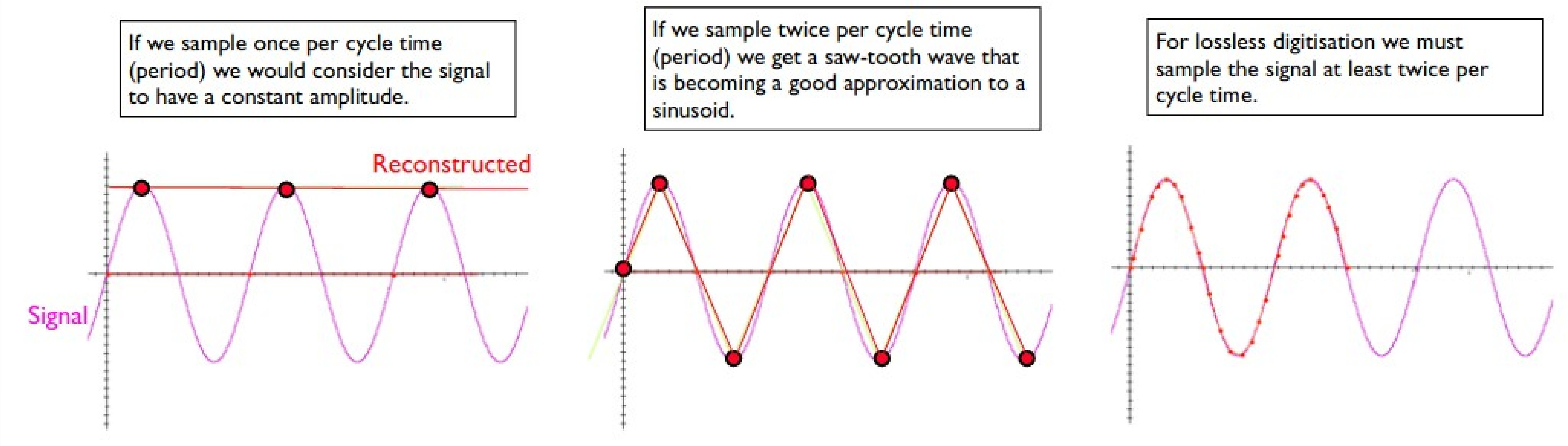
Giant Metrewave Radio Telescope
KHODAD

Sensitivity: The Radiometer Equaiton

- The minimum temperature that a telescope can measure is limited by the noise (root mean square) fluctutions in the receiver system.

$$\Delta T_{\rm sys} = \frac{T_{\rm sys}}{\sqrt{n_{\rm p}\, t\, \Delta f}}.$$

Sensitivity: The Radiometer Equaiton



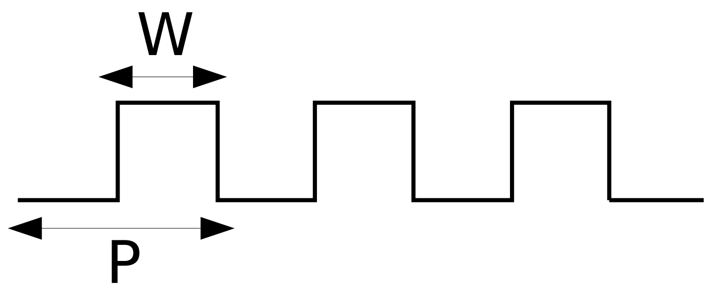
- Nyquist sampling theorem: Number of samples per second > $2xf_{max}$ (2xBandwidth)

Sensitivity: The Radiometer Equaiton

- The minimum detectable "mean" flux density (corresponding to a S/N threshold) depends on receiver noise as well as pulse-width relative to the pulsar's rotation period.

$$S = \frac{2k_{\rm B}T_{\rm A}}{A_{\rm e}} = \frac{T_{\rm A}}{G}$$

$$S_{\rm min} = \beta \frac{({\rm S/N_{min}})T_{\rm sys}}{G\sqrt{n_{\rm p}\, t_{\rm int}\, \Delta f}} \sqrt{\frac{W}{P-W}},$$



(Handbook of Pulsar Astronomy, A1.4)

Sensitivity: The Radiometer Equaiton

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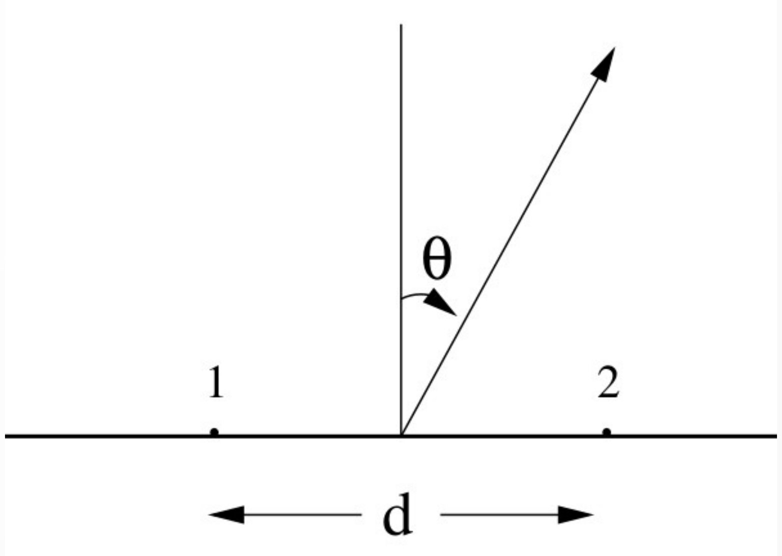
Phased Arrays

- A two-elements phased array



- Reciprocity theorem: Performance of an antenna when collecting radiation form a point source at infinity may be studied by considering its properties as a *transmitter*:

$$E(\theta) = E_1\, e^{j\psi/2} + E_2\, e^{-j\psi/2} \quad , \quad \psi = k\, d\, \sin\theta + \delta$$

$$E(\theta) = 2\, E_0\, \cos(\psi/2)$$

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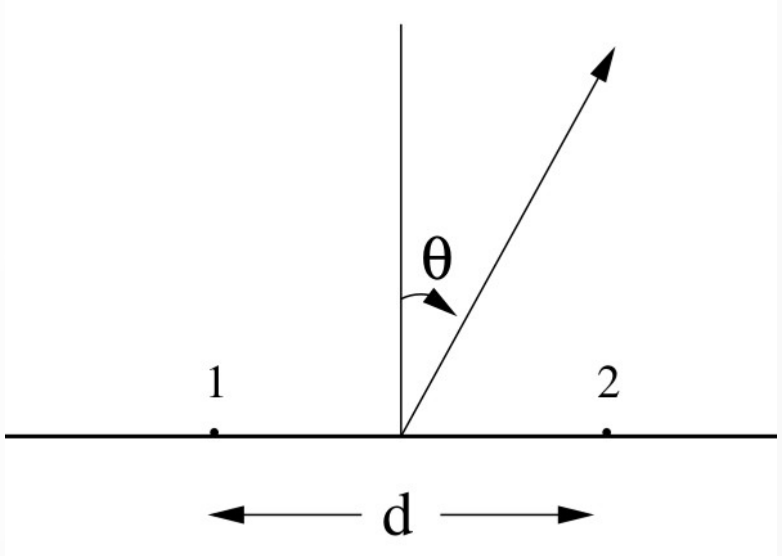

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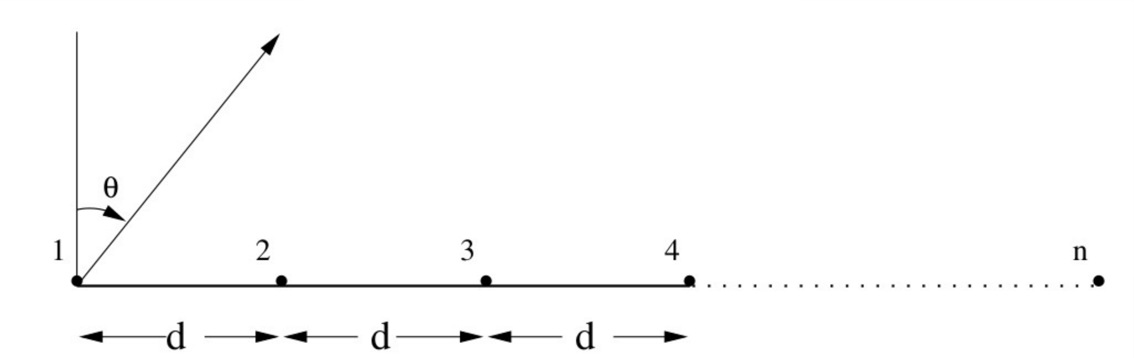
- For d>>λ, the field pattern is a sinusoidal function of Θ, with a period of 2λ/d.
- $\boldsymbol{\delta} \neq 0$ shifts the phase of the above pattern.
- The field pattern is weighted by the directional pattern of individual elements.

Phased Arrays

- n-elements (equally spaced) phased array



$$E(\theta) = E_0 \left[1 + e^{j\psi} + e^{j2\psi} + \ldots + e^{j(n-1)\psi}\right]$$

$$\psi = k\, d\, \sin\theta + \delta$$

$$E(\theta) = E_0 \frac{\sin(n\psi/2)}{\sin(\psi/2)} e^{j(n-1)\psi/2}$$

Phased Arrays

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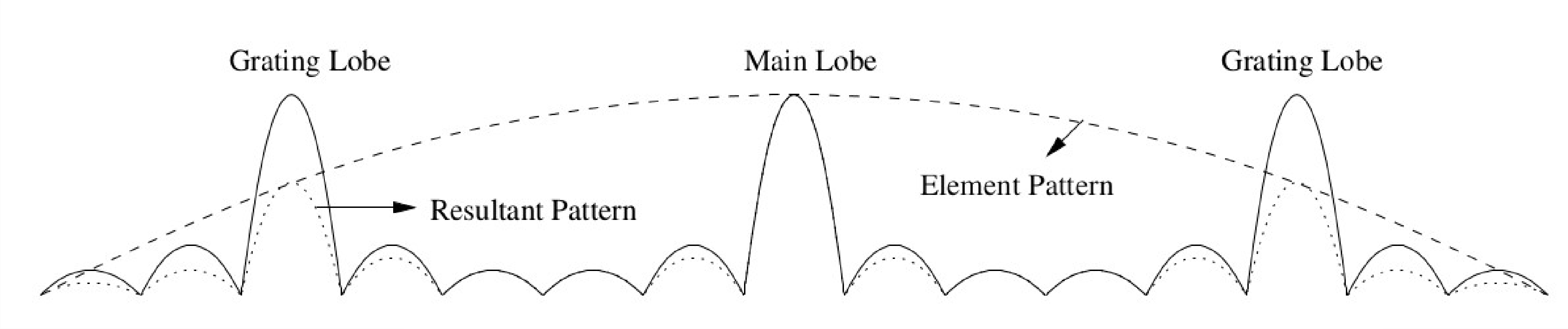
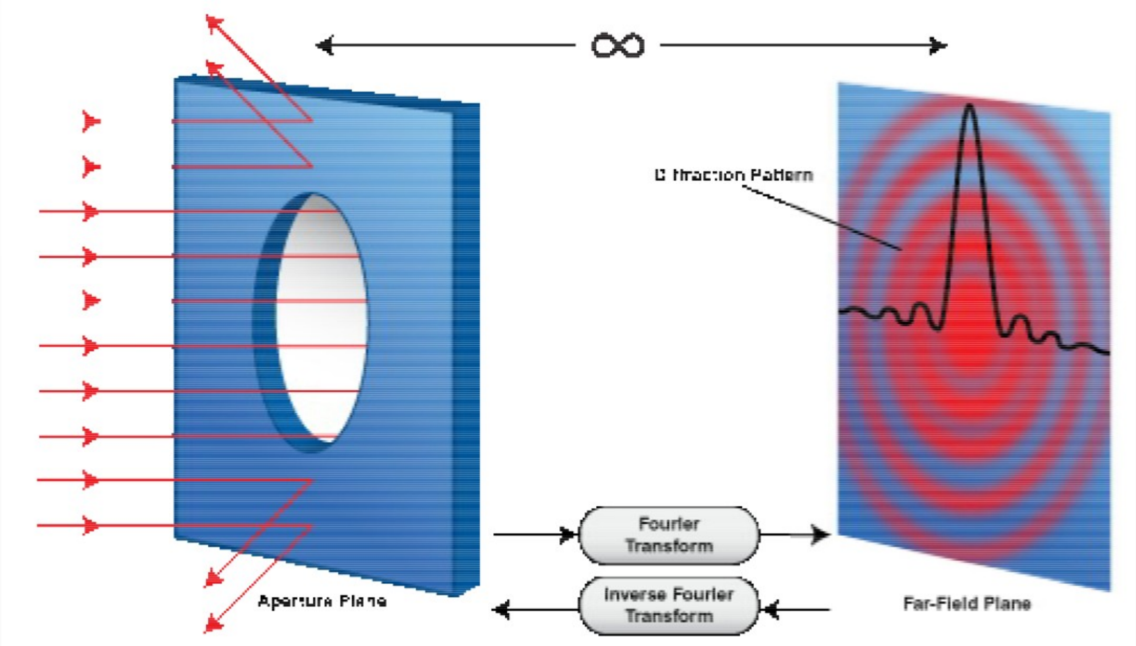


$$E(\theta) = E_0 \frac{\sin(n\psi/2)}{\sin(\psi/2)} e^{j(n-1)\psi/2} \qquad \psi = k\,d\,\sin\theta + \delta$$

- For $d>\lambda$ and $\boldsymbol{\delta}=0$, the field pattern is a periodic function of Θ, with maxima at $\boldsymbol{\Psi}=0$, $2\boldsymbol{\Pi}$, $4\boldsymbol{\Pi}$,...
- $\boldsymbol{\delta}\neq 0$ shifts the phase of the above pattern.
- The field pattern is weighted by the directional pattern of individual elements.
- HPBW ≈ λ/nd.

Phased Arrays

- Two dimensional phased arrays
  - Far-field radiation pattern (the antenna’s “beam”) is the Fourier transform of the aperture plane electric field distribution. True for “phased-array” radiation pattern as well.
  - Radiation pattern of the 1-D n-element phased-array?



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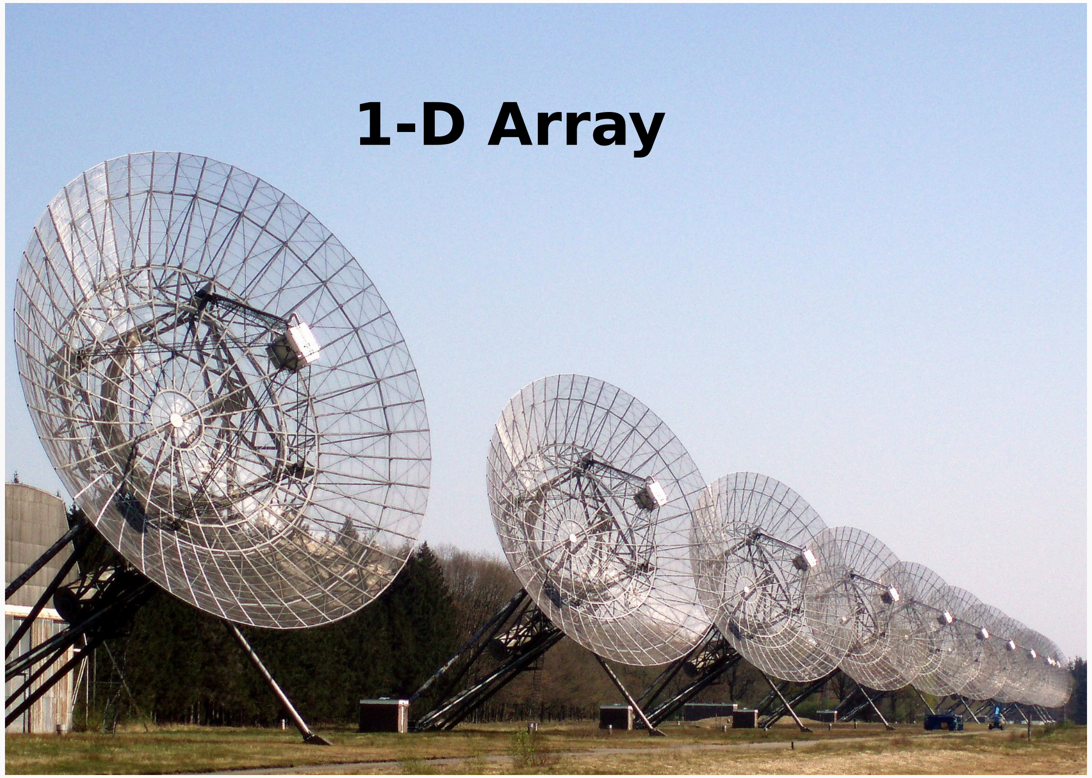
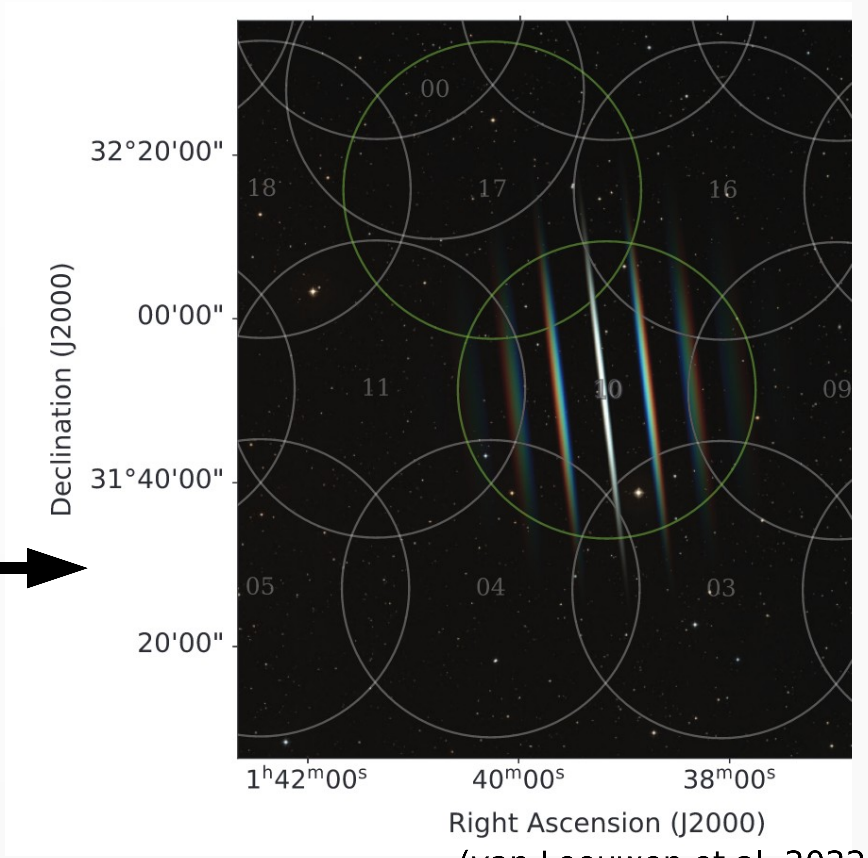




(van Leeuwen et al. 2022)

Coherently Phased Arrays

- Combine the **voltage** signals from the phased-array after all the delay corrections.

- $G \approx n \times G_0$
- Narrow beam

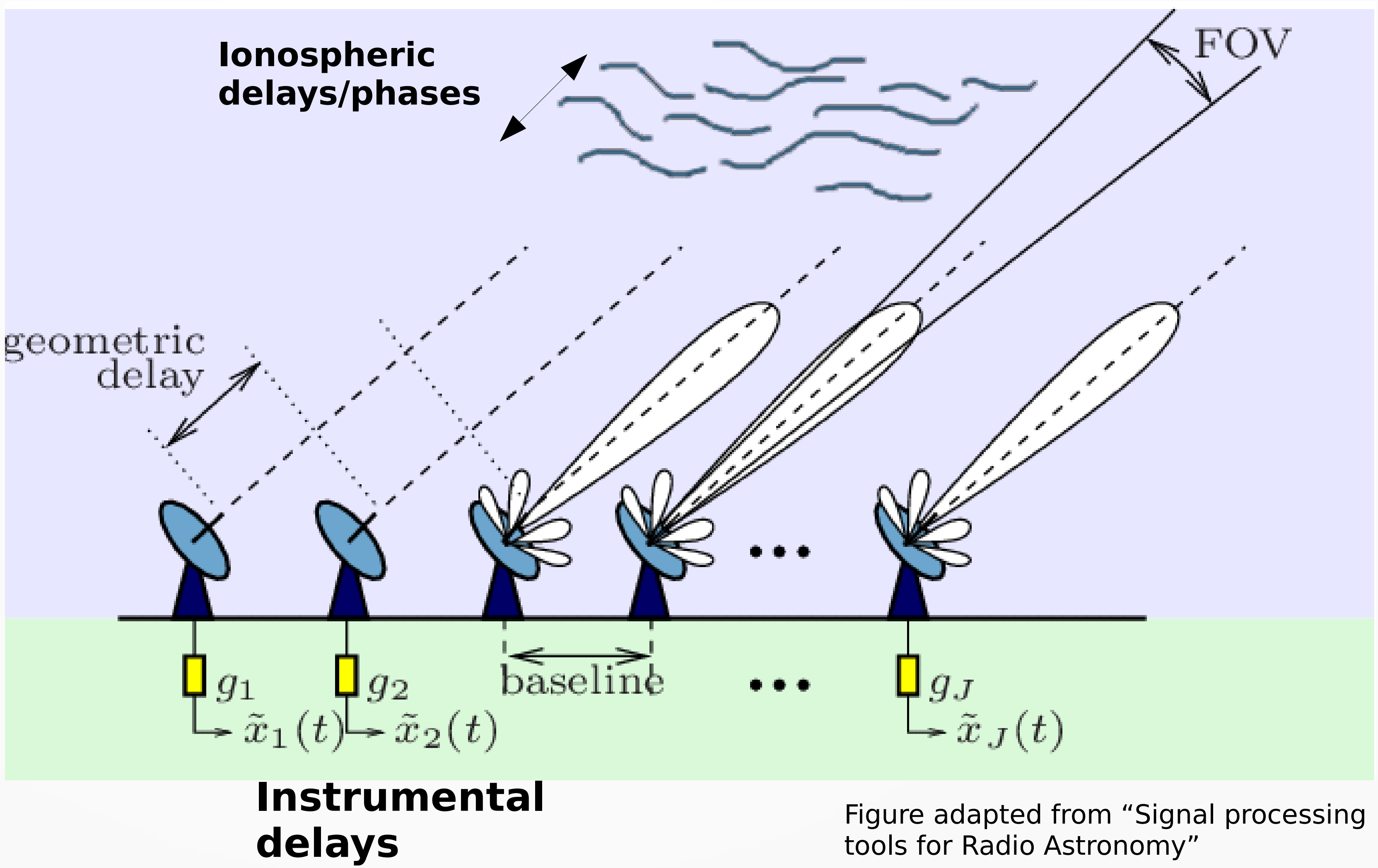
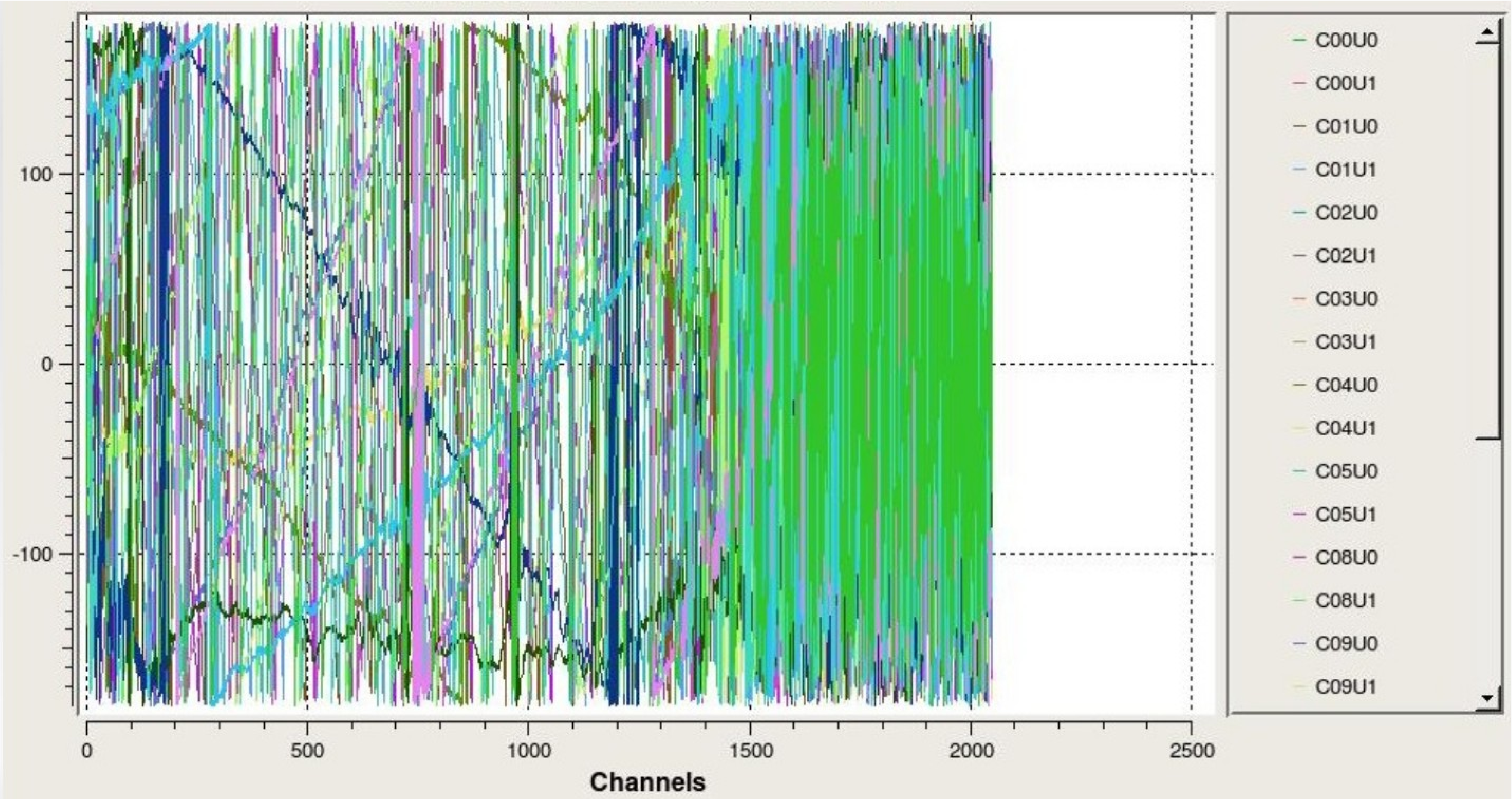
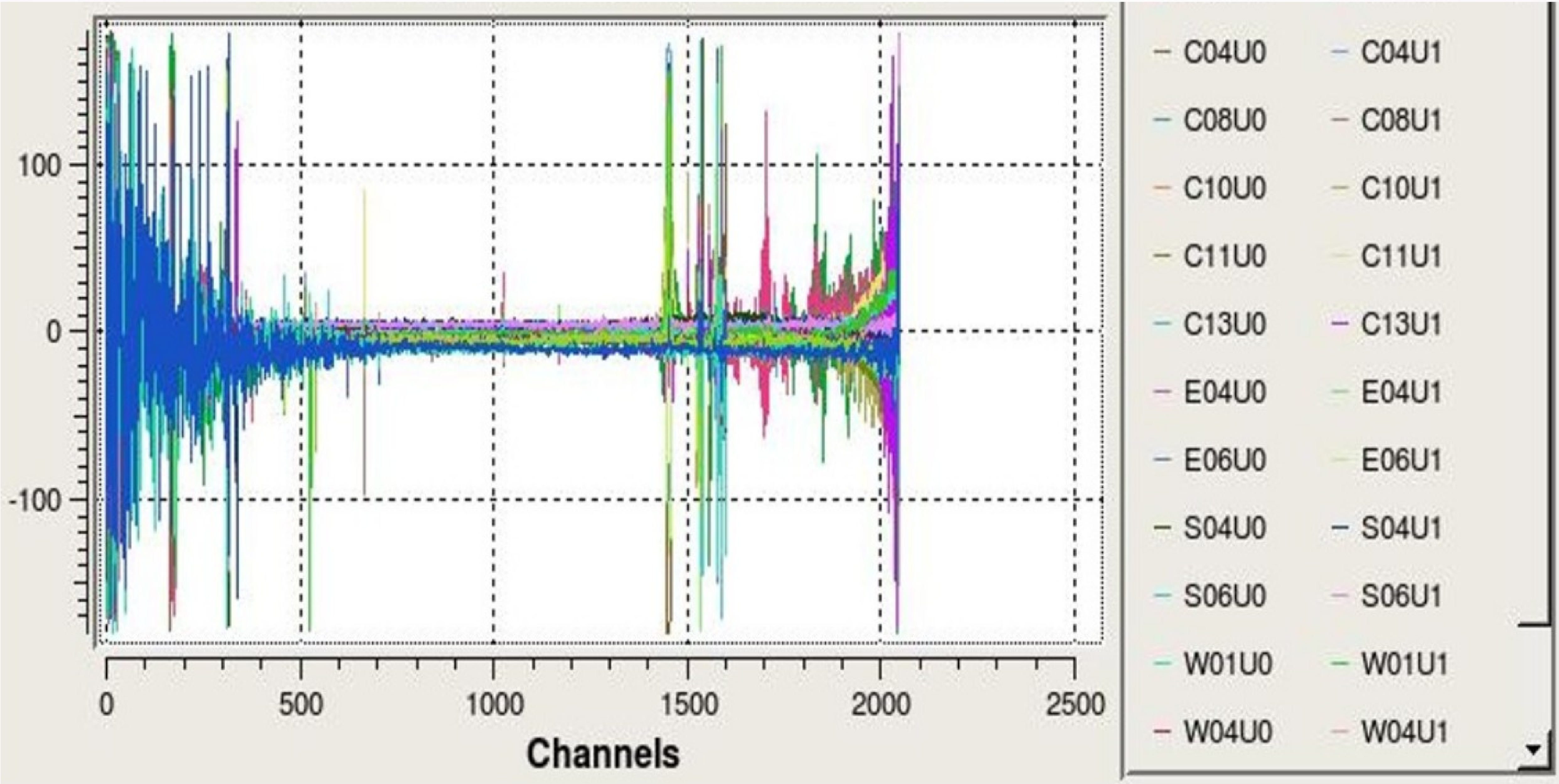


Figure adapted from "Signal processing tools for Radio Astronomy"

Coherently Phased Arrays



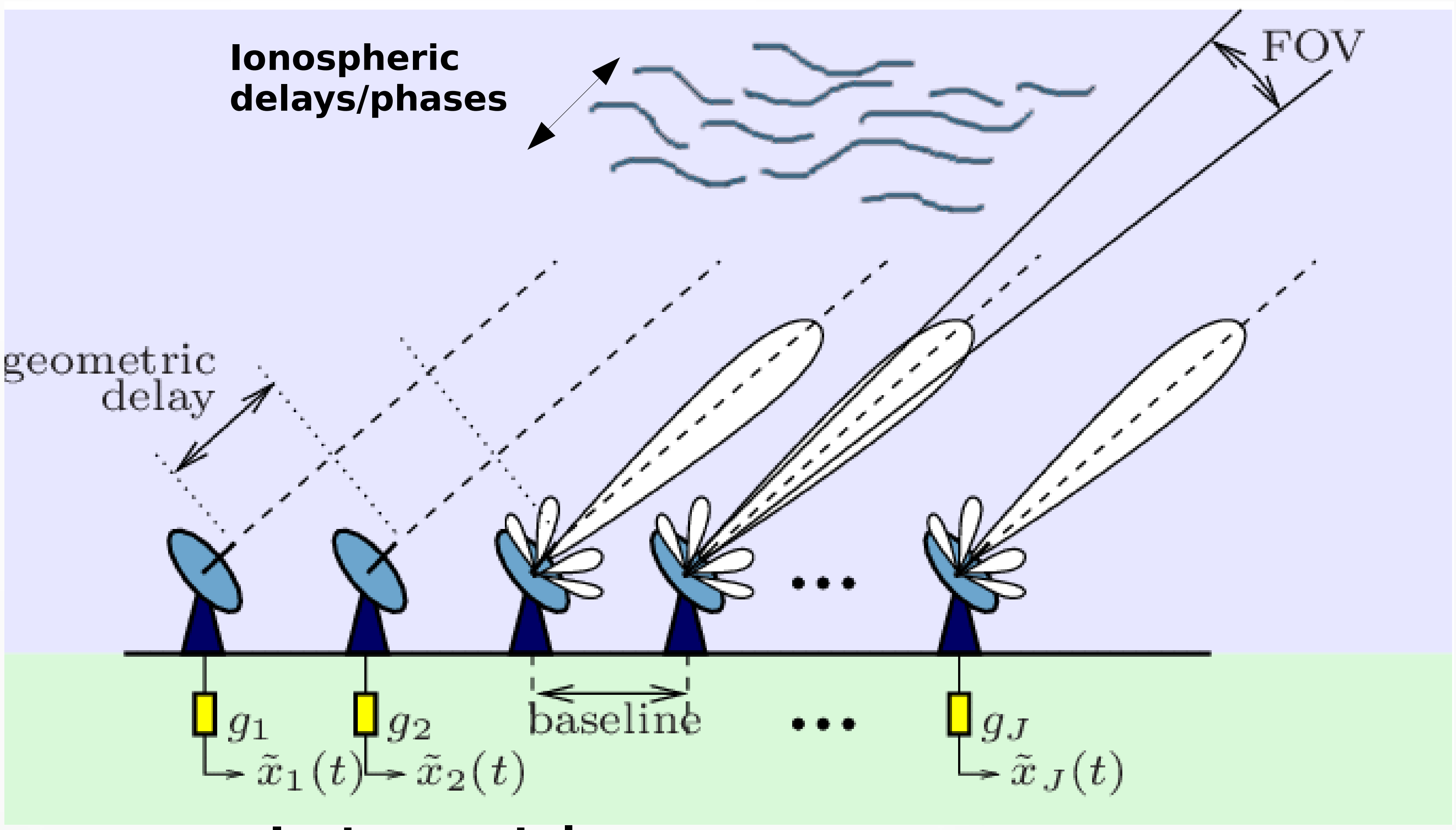
Coherently Phased Arrays



Incoherently Phased Arrays

- Combine the **power** signals from the phased-array after all the delay corrections.

- $G \approx \sqrt{n} \times G_0$
- Beam same as that of the primary element.



Instrumental delays

Figure adapted from "Signal processing tools for Radio Astronomy"

Pulsar observations: Dedispersion

Interstellar medium is (mostly) cold, ionized plasma

Refractive index: $\mu = \left[1 - (\nu_p/\nu)^2\right]^{1/2}$

Plasma frequency: $\nu_p = \left(\frac{e^2 n_e}{\pi m_e}\right)^{1/2}$

Group velocity: $v_g = \mu c$

Delay: $\Delta t = \int_0^d \frac{\mathrm{d}l}{v_g} = \frac{e^2}{2\pi m_e c} \frac{\int_0^d n_e \mathrm{d}l}{\nu^2}$

Dispersion Measure: $\mathrm{DM} = \int_0^d n_e \mathrm{d}l$

=> Frequency-dependent index of refraction implies different frequency signals propagate with different velocities.

=> Arrival time varies as a function of frequency

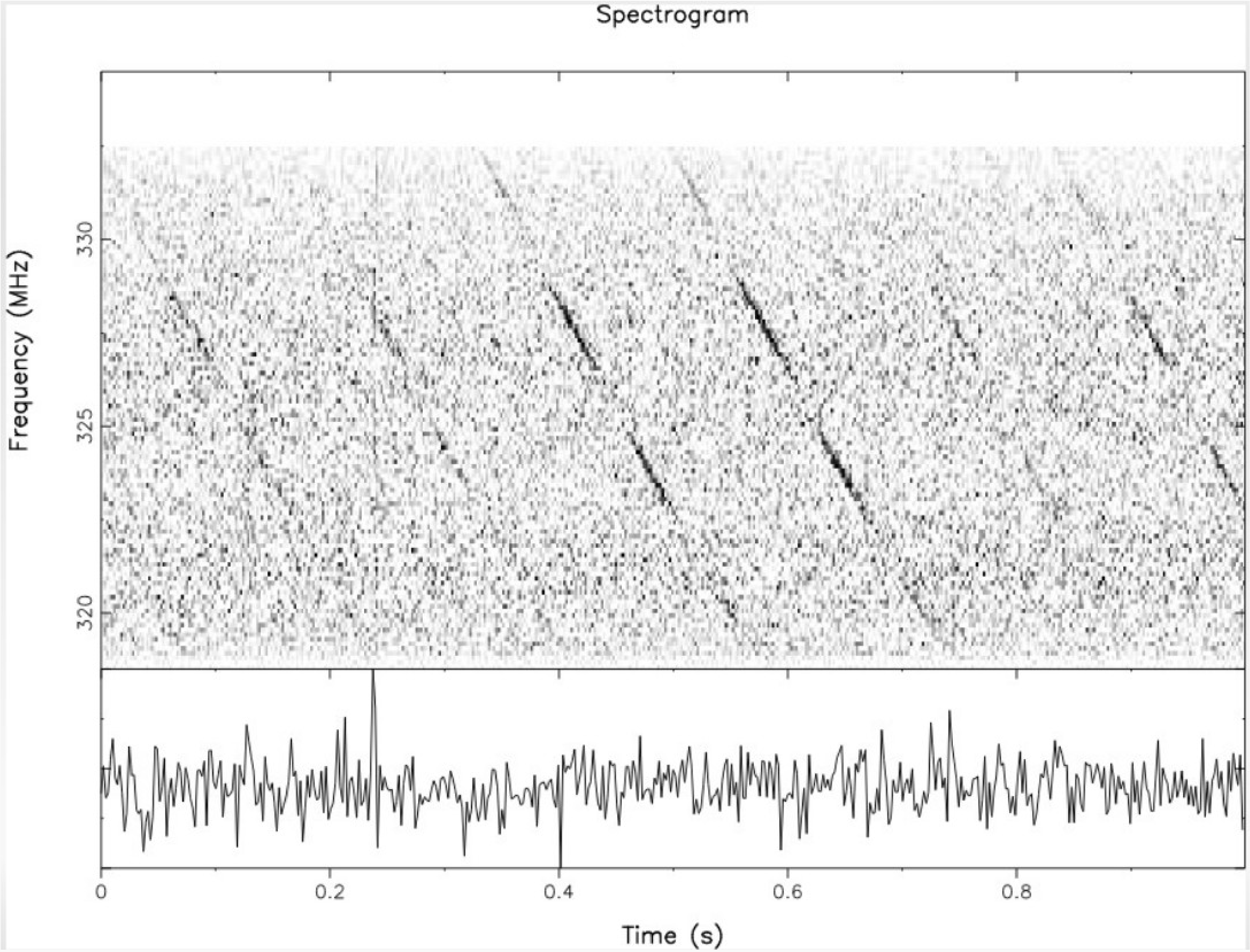
Pulsar observations: Dedispersion

$\Delta t(ms) = 4.15 \times 10^6 \times \int n_e \, d\ell \times (\nu_1^{-2} - \nu_2^{-2})$;   *ν is in MHz*

$\int n_e \, d\ell$ → **Dispersion Measure (DM)**

(*Electron density integrated over the distance from the source to the observer*)

Pulsar observations: Dedispersion



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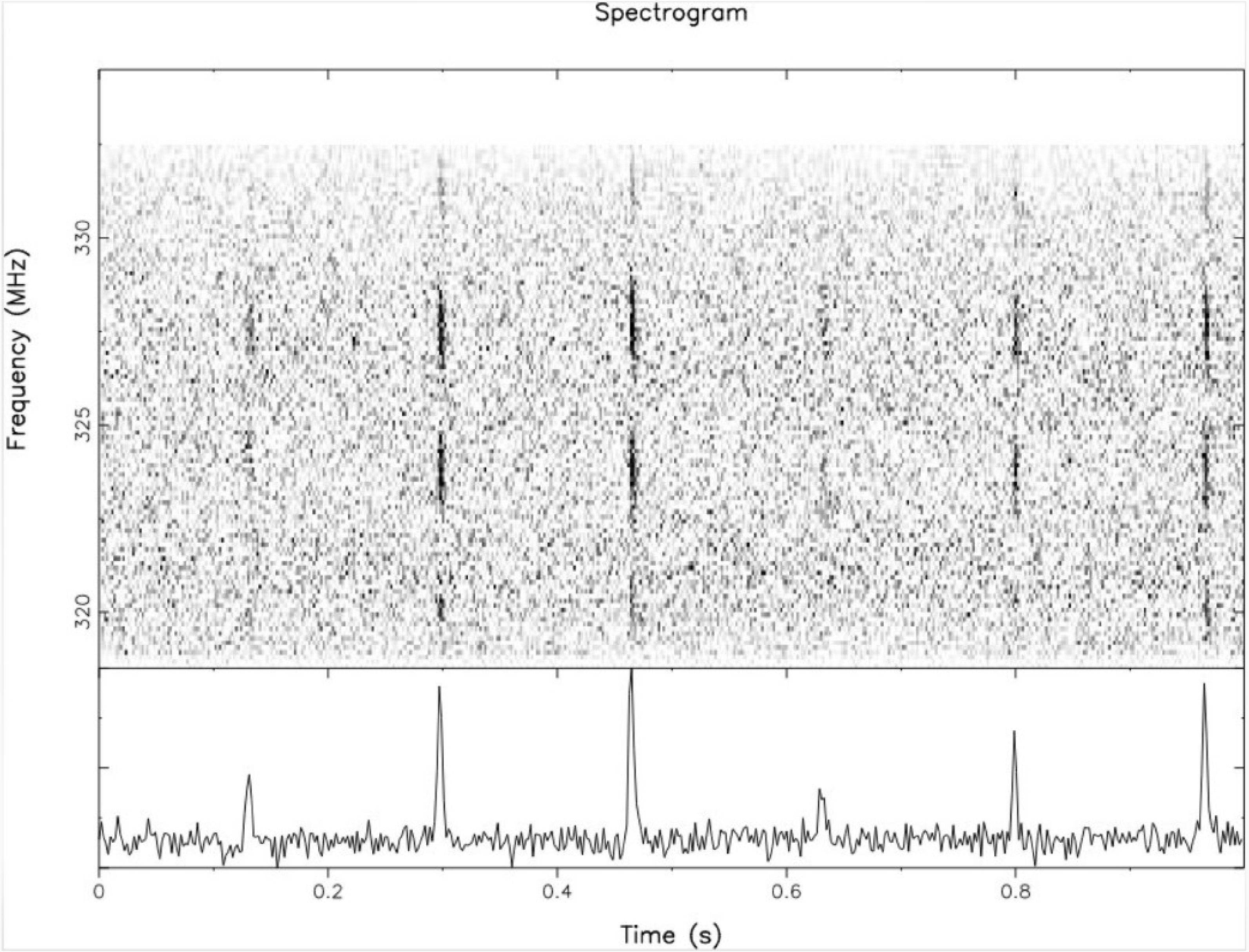

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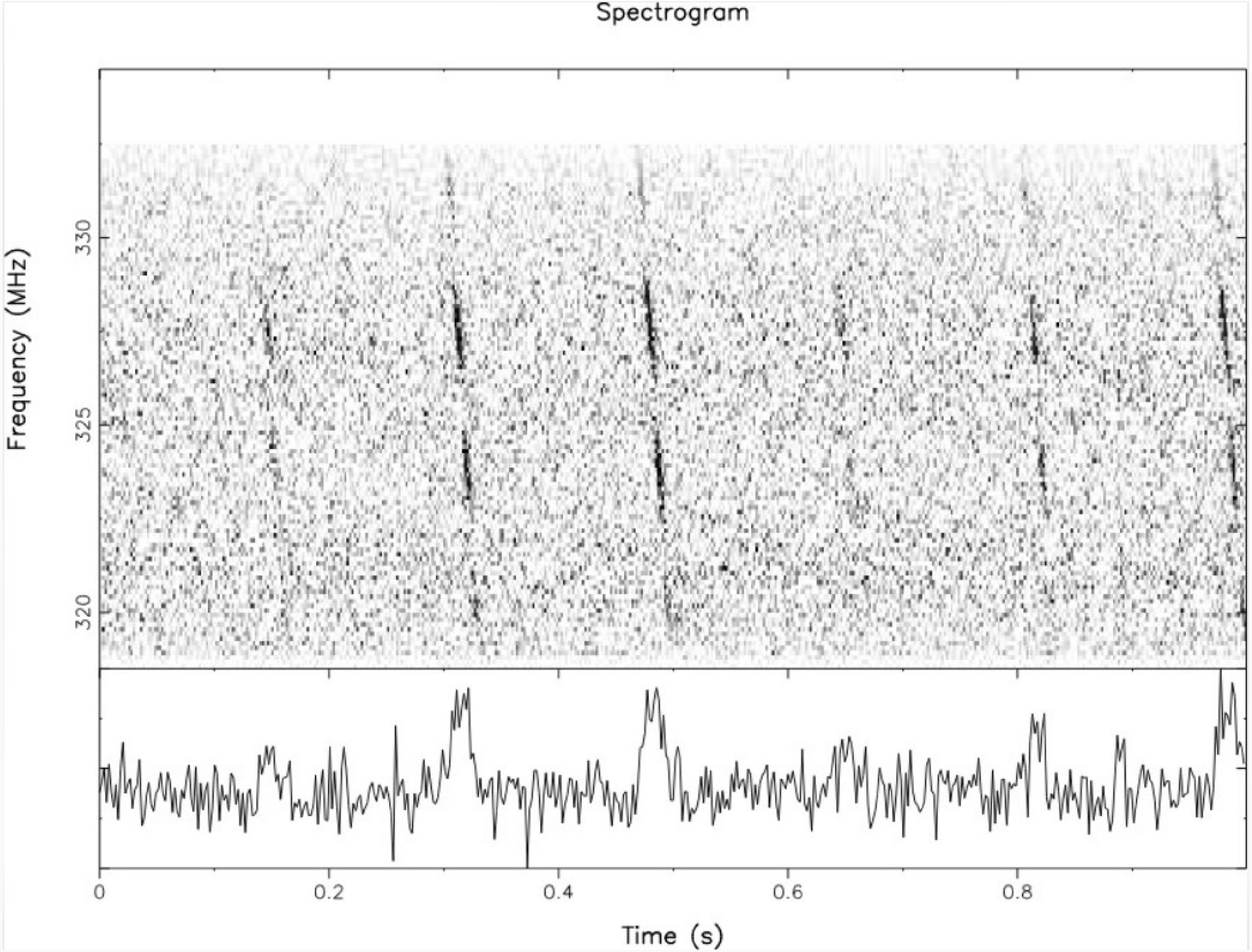
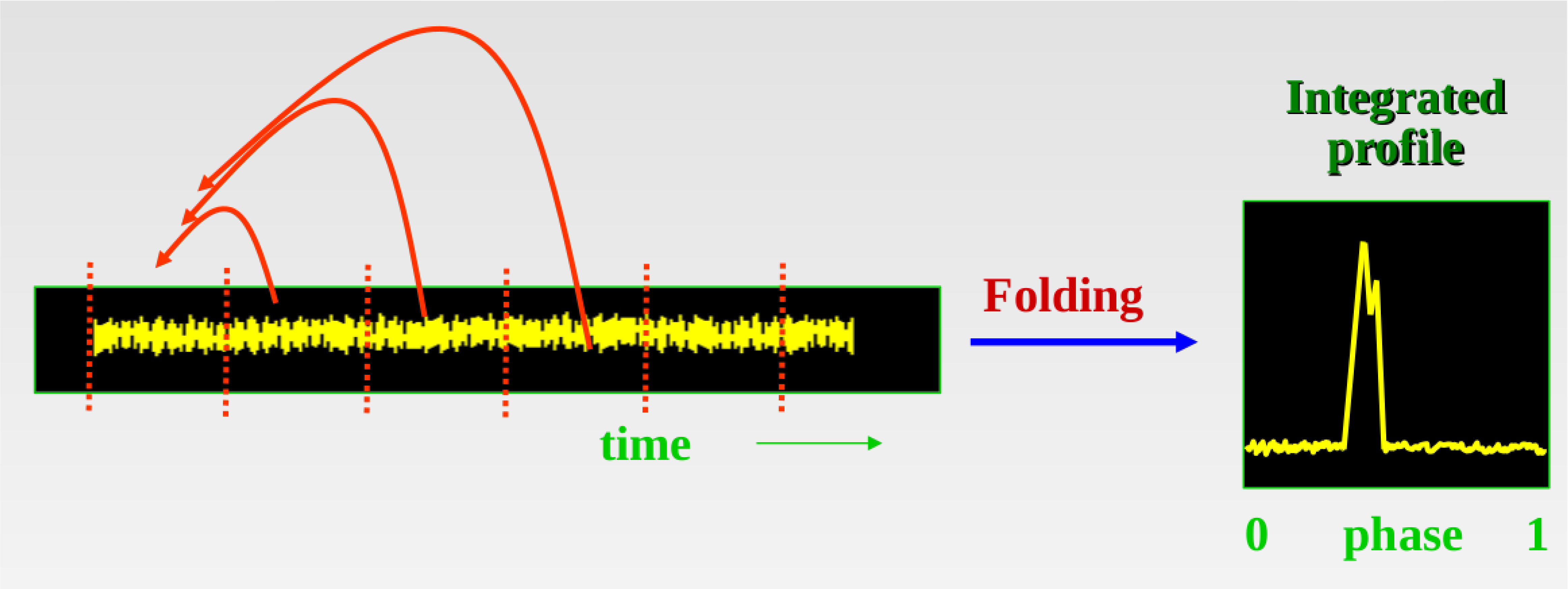


Pulsar Observations: Folding



Pulsar Observations: Folding