Max-Planck-Institut für Radioastronomie

MAX-PLANCK-GESELLSCHAFT

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Pulsar Back-ends

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"Pulsar Tutorials" Workshop

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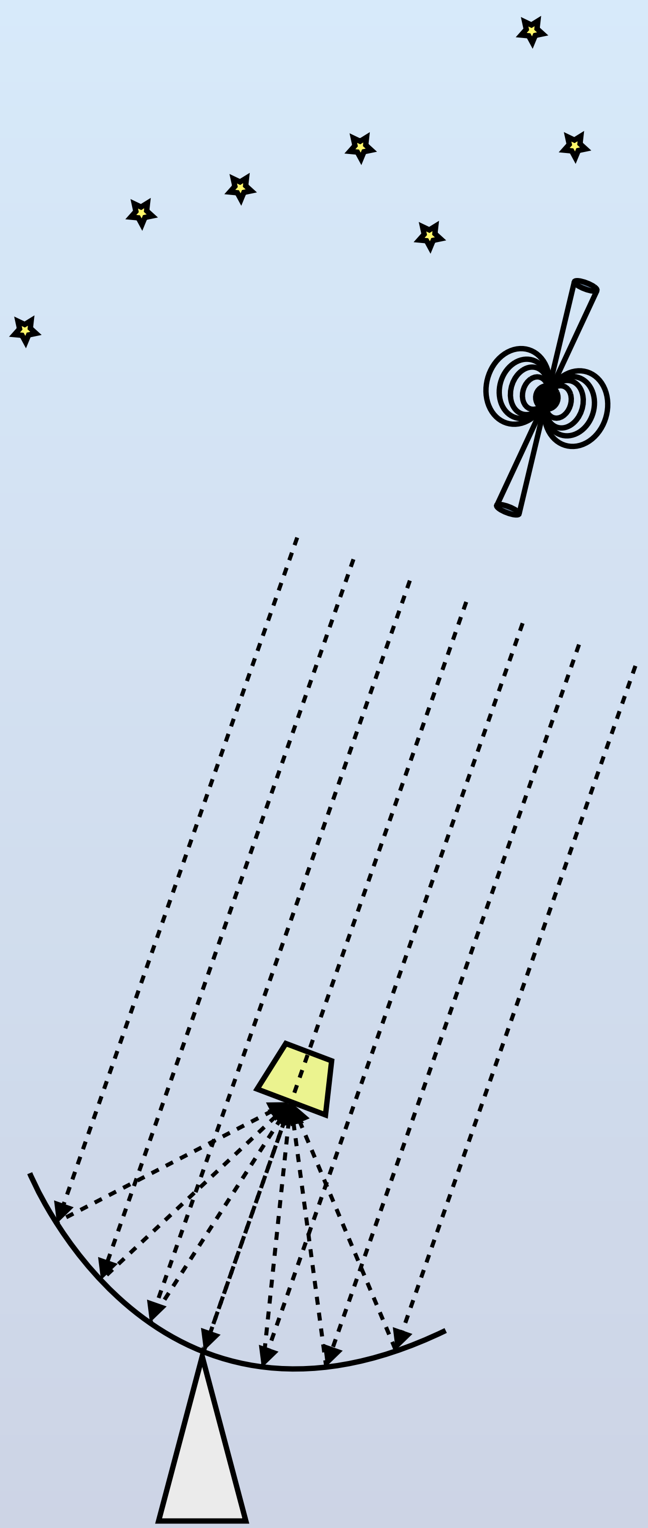
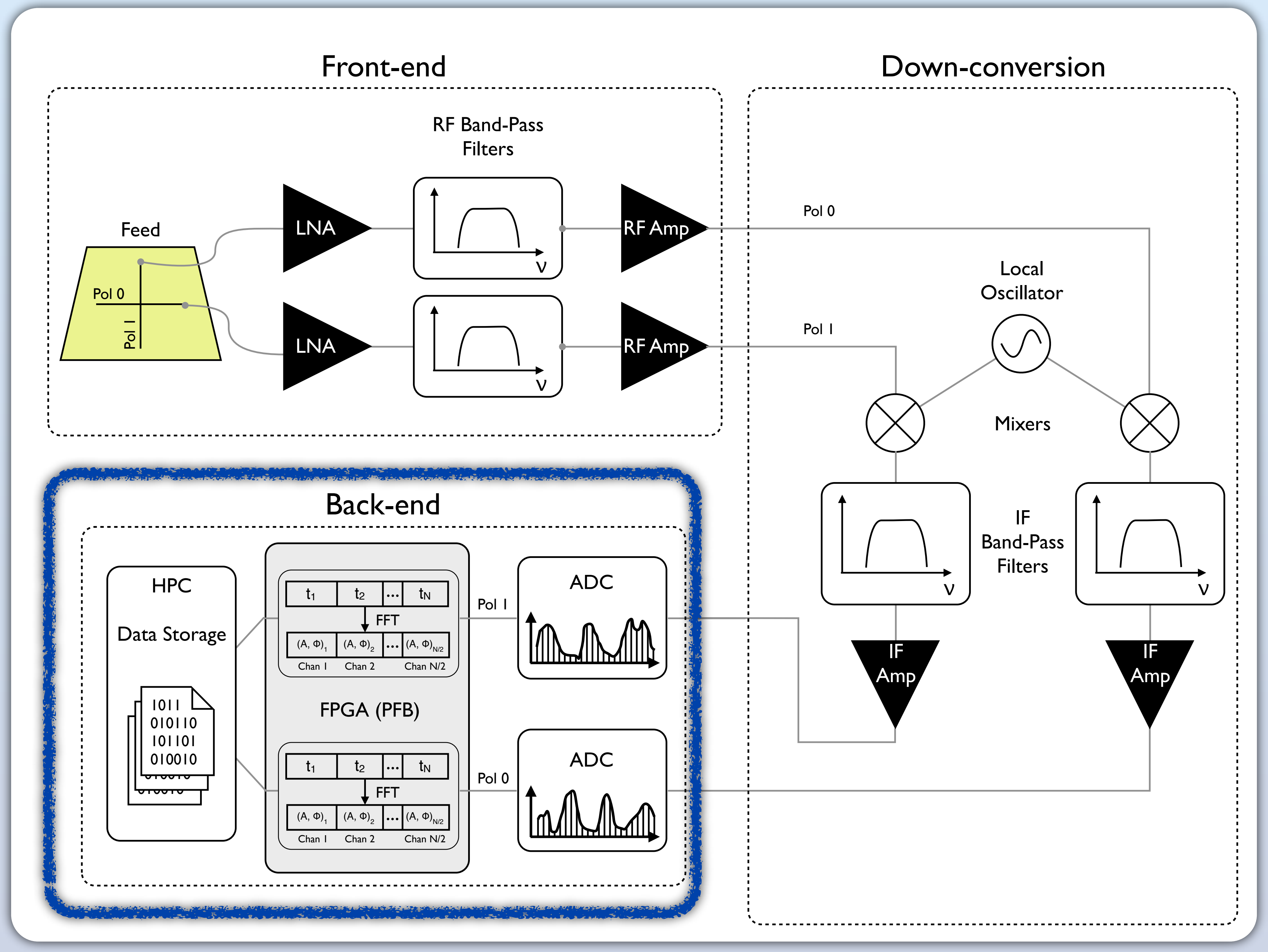
A simple scheme of a single-dish radio telescope





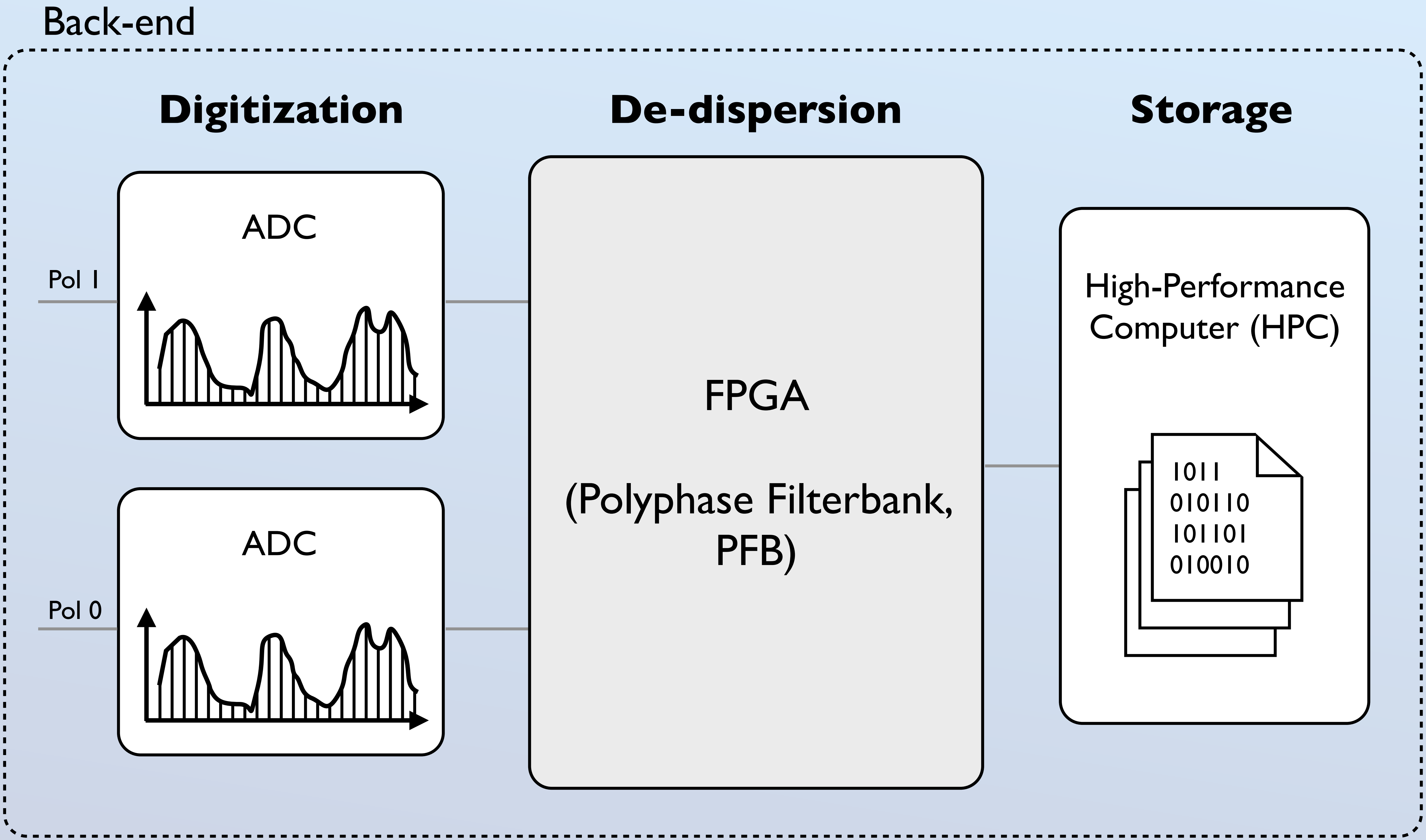
What is a back-end?

A back-end can be regarded as the data “recorder”.

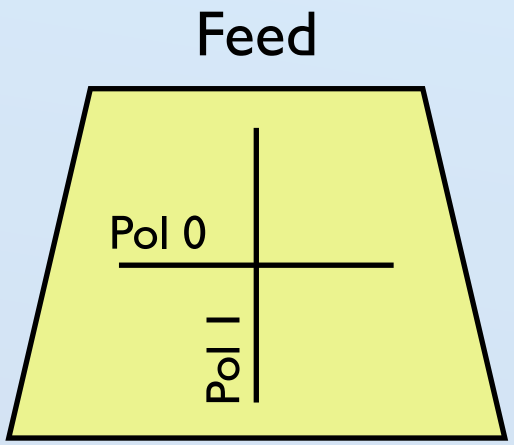
It is a piece of hardware and/or software responsible for:

- the **digitization** of the pulsar signal
- further processing of the pulsar signal (e.g. **de-dispersion**)
- final **storage** of the data (in a convenient file format)

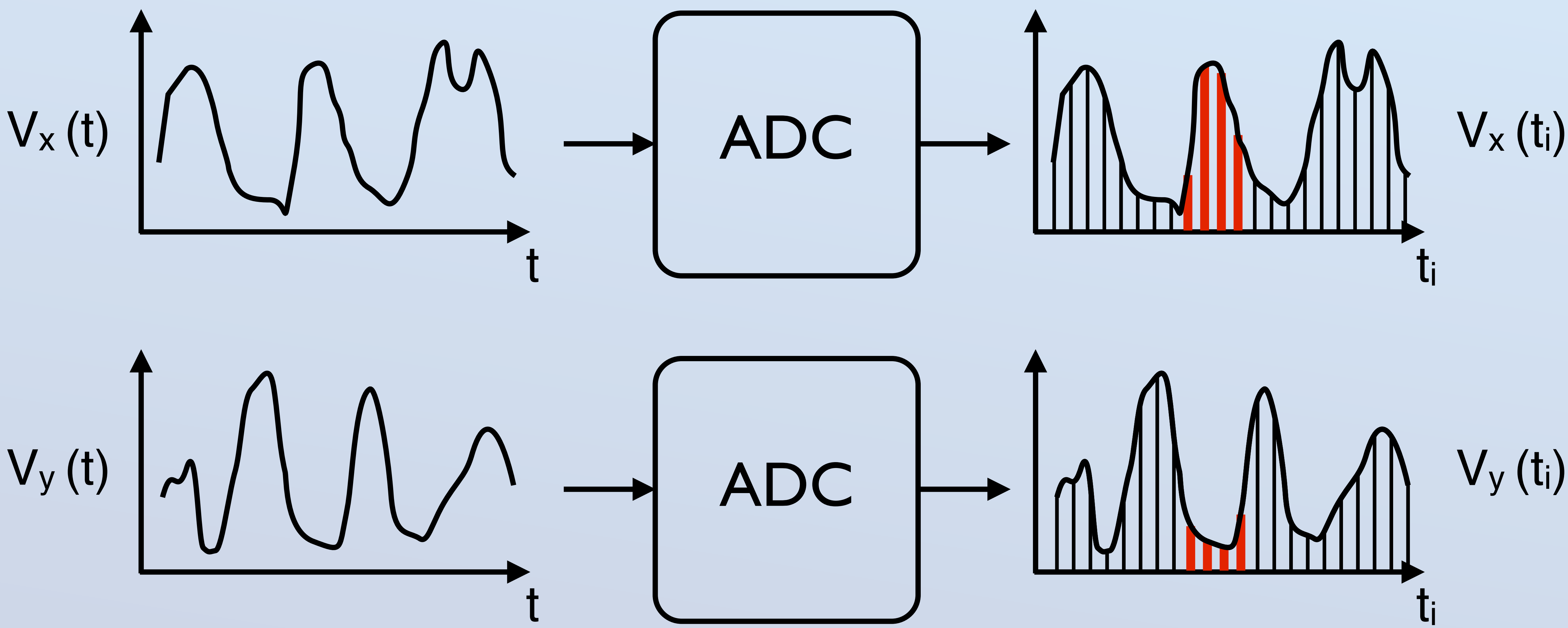
Main parts of a typical back-end



1) Digitization



When we observe a pulsar with our radio telescope, the electromagnetic wave coming from the source will induce a time-varying voltage in the two orthogonal feeds (X and Y) of the receiver.



1) Digitization

Fourier theorem: Any signal, periodic or non-periodic, *s(t)*, can always be represented as the sum of a (possibly infinite) number of sinusoids

Nyquist theorem: Given a signal *s(t)* whose Fourier spectrum has no frequencies higher than f_{max}, the signal can be fully reconstructed if sampled at a frequency $\boldsymbol{f > 2f_{max}}$

Hence, if I observe a pulsar, e.g.:

at L-band (e.g 1.2 – **1.7 GHz**) ⟶ need to sample at minimum **3.4 GHz**

at S-band (e.g 3.0 – **4.0 GHz**) ⟶ need to sample at minimum **8.0 GHz**

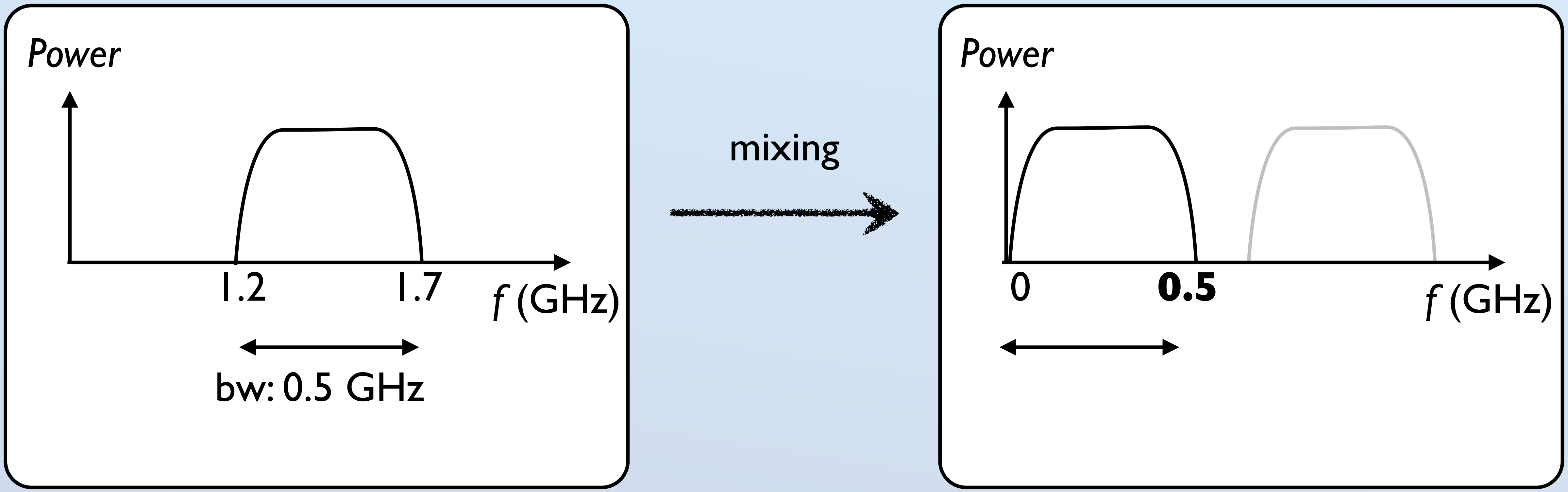
at X-band (e.g. 8.0 – **10 GHz**) ⟶ need to sample at minimum **20 GHz**

However, the fastest ADCs are able to generate about **2 Gsample/s (2 GHz)**

How can we then perform high-frequency observations?

1) Digitization - Baseband

The spectral content of the signal is shifted in the Fourier domain via the down-conversion system.



L-band	Base-band
1.2 – 1.7 GHz	0.0 – 0.5 GHz
f_{max} = 1.7 GHz	f_{max} = 0.5 GHz (= bw)
↓	↓
f_{sample} = 3.4 GHz	f_{sample} = 1.0 GHz = **2 * bw**

1) Digitization - Baseband

The ADC sampling speed determines how large our observing bandwidth can be.

$$BW_{max} = f_{sample} / 2$$

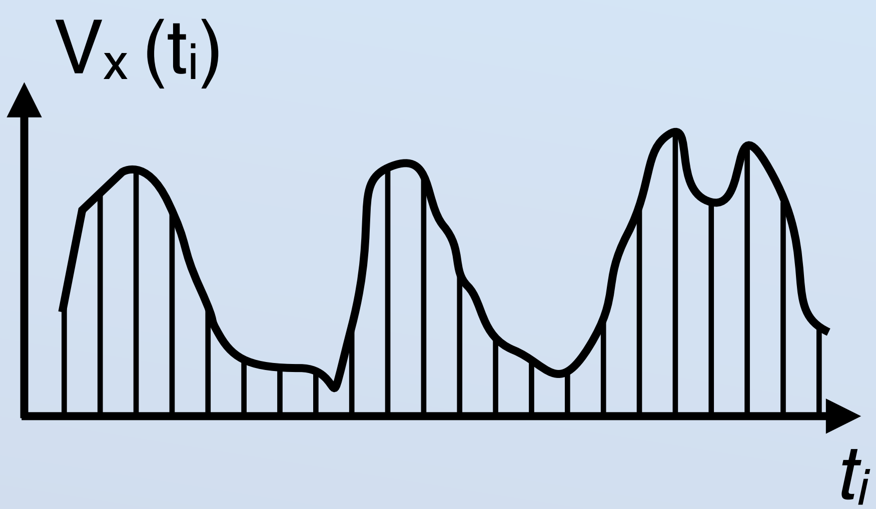
1 Gsample/s $\rightarrow$ BW_{max} = 500 MHz

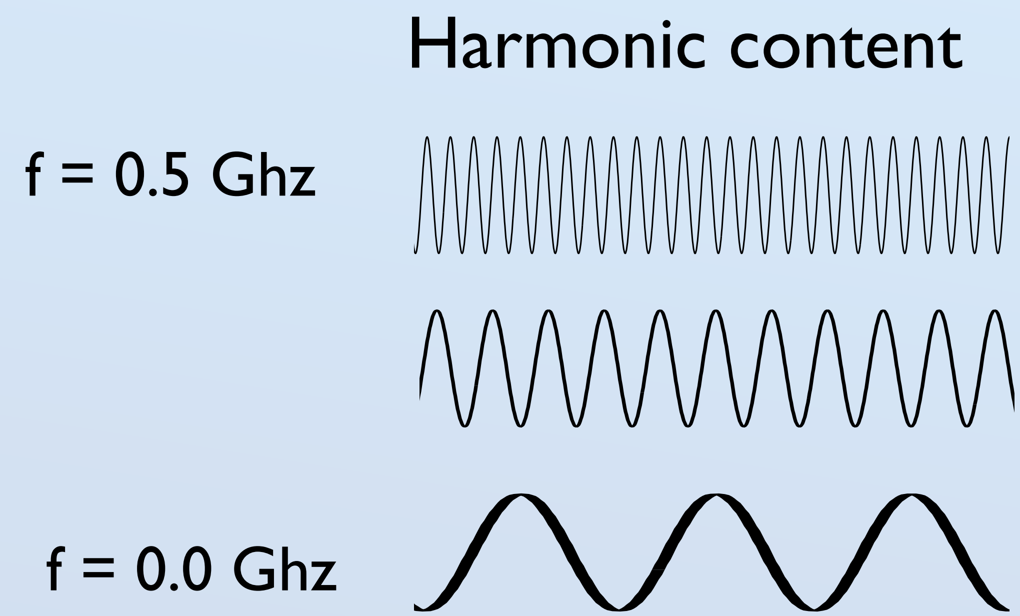
2 Gsample/s $\rightarrow$ BW_{max} = 1 GHz

4 Gsample/s $\rightarrow$ BW_{max} = 2 GHz

2) De-dispersion

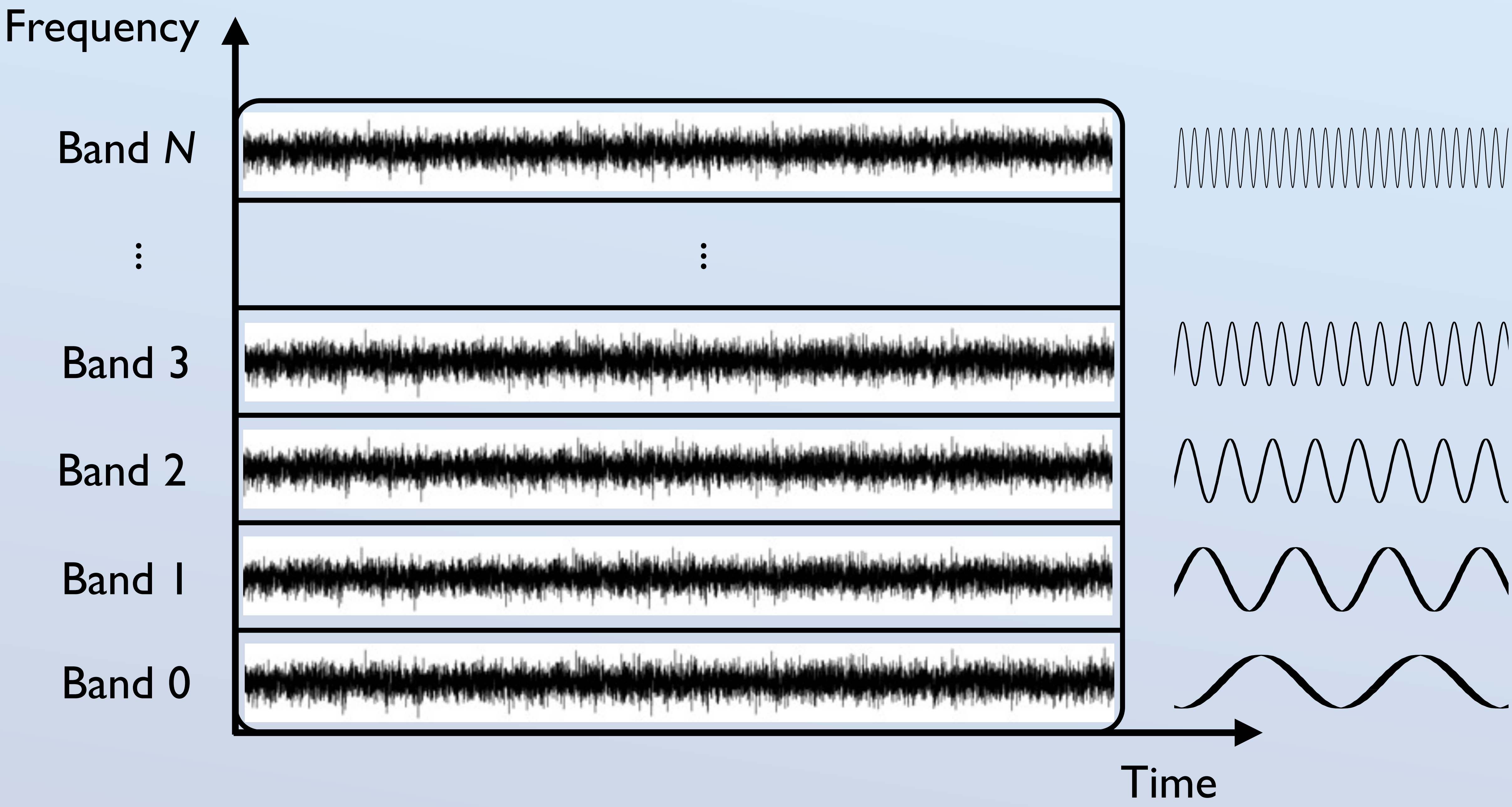
The digitized signal (for each polarization) is essentially a time series that embodies all the harmonic content of the observing bandwith.





However, it is convenient to split the signal into sub-bands.

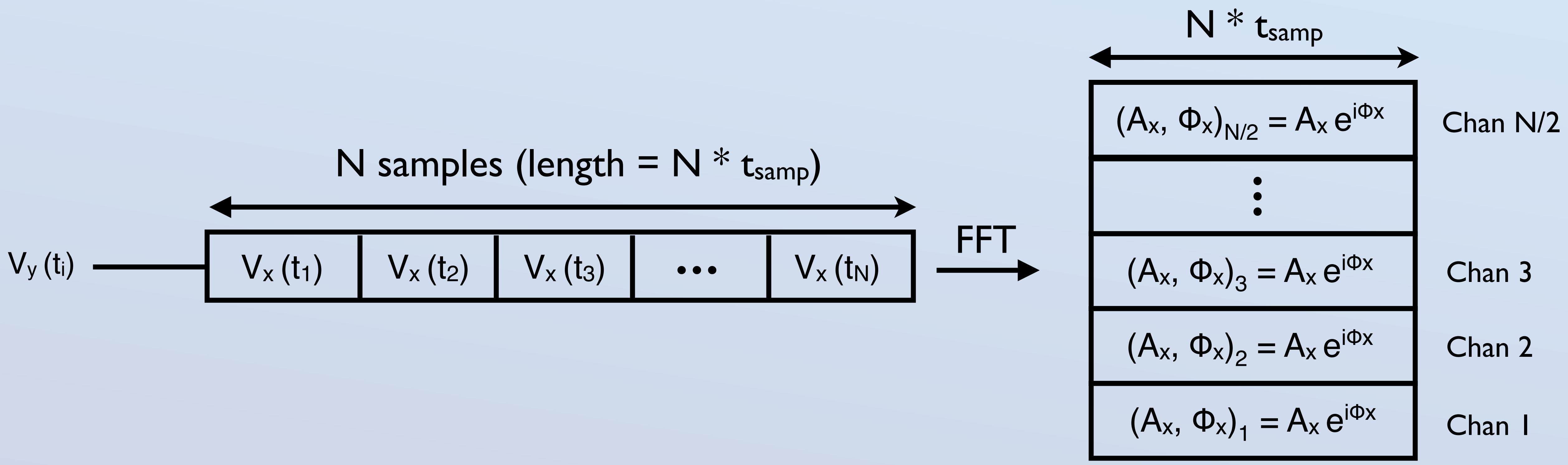
2) De-dispersion



2) De-dispersion

The device responsible for this is the Polyphase Filterbank, implemented on an FPGA.

It takes *N* samples and, by performing an FFT, it transforms them into N/2 complex numbers, which represent the amplitudes+phases of the harmonic content.



2) De-dispersion

Example:

ADC speed: 1 GHz → t_{samp}: 1 / 1GHz = 10^{-9} s → BW: 500 MHz

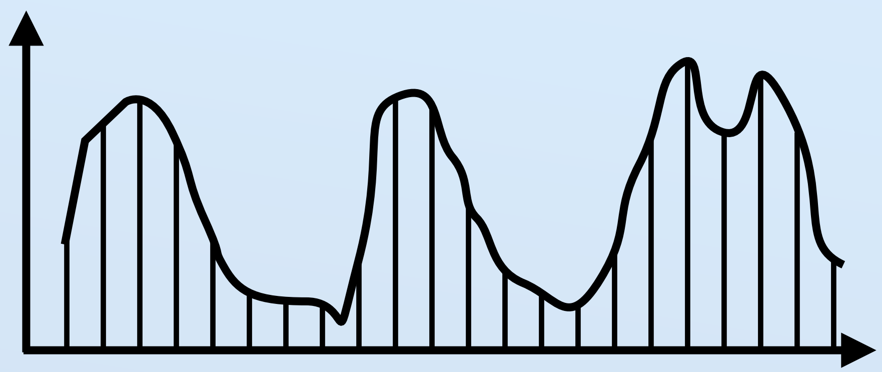
I want 32 subbands → FPGA takes 64 samples (64 ns of data)

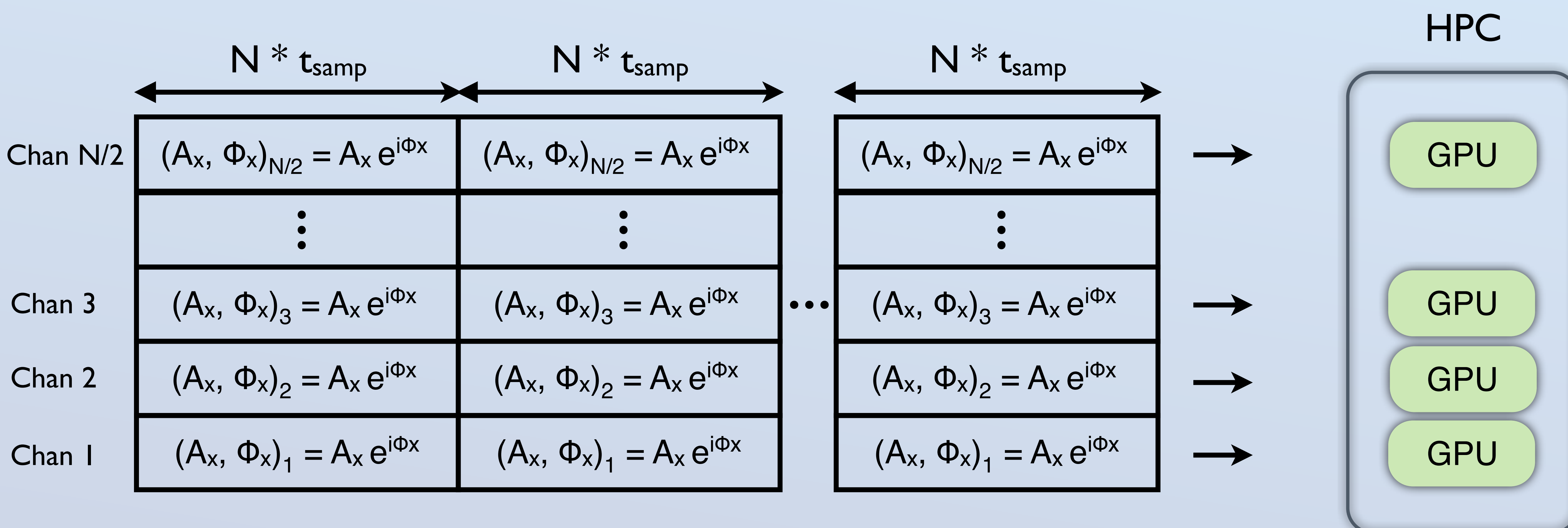
→ FFT → 32 channels, each with 1 sample (64 ns) of data

$$V_x(t) \overset{\text{Sampling}}{\Rightarrow} 64\text{–point } V_x(t_i) \overset{\text{FFT}}{\Rightarrow} \begin{cases} 32 \text{ amplitudes } A_k^x \\ 32 \text{ phases } \phi_k^x \end{cases} \Leftrightarrow 32 \text{ complex numbers } A_k^x \cdot e^{j\phi_k^x}$$

$$V_y(t) \overset{\text{Sampling}}{\Rightarrow} 64\text{–point } V_y(t_i) \overset{\text{FFT}}{\Rightarrow} \begin{cases} 32 \text{ amplitudes } A_k^y \\ 32 \text{ phases } \phi_k^y \end{cases} \Leftrightarrow 32 \text{ complex numbers } A_k^y \cdot e^{j\phi_k^y}$$

2) De-dispersion





3) Data storage

There are three main observing modes:

- **Baseband mode**

  The (digitized) raw voltages are stored in full time/freq resolution. All information is retained. One time series per subband. Maximum post-processing flexibility. Data stored as *.dada* files (~Many TB / h)

- **Search mode**

  The bandwidth is divided into a few hundreds or thousands of channels. Groups of samples are added together to retain a time resolution of typically a few tens of μs. Coherent de-dispersion and/or full-Stokes are also usually possible. Data stored as *filterbank* or *PSRFITS* files (~10–100 GB/h)

- **Folding (Timing) mode**

  Need to know the pulsar parameters. Dispersion effect is removed (coherently or incoherently) according to pulsar's DM. The data in then *folded* according to the pulsar's ephemeris. Full-Stokes is possible. Data stored as *folded archives* (~10–500 MB/h)