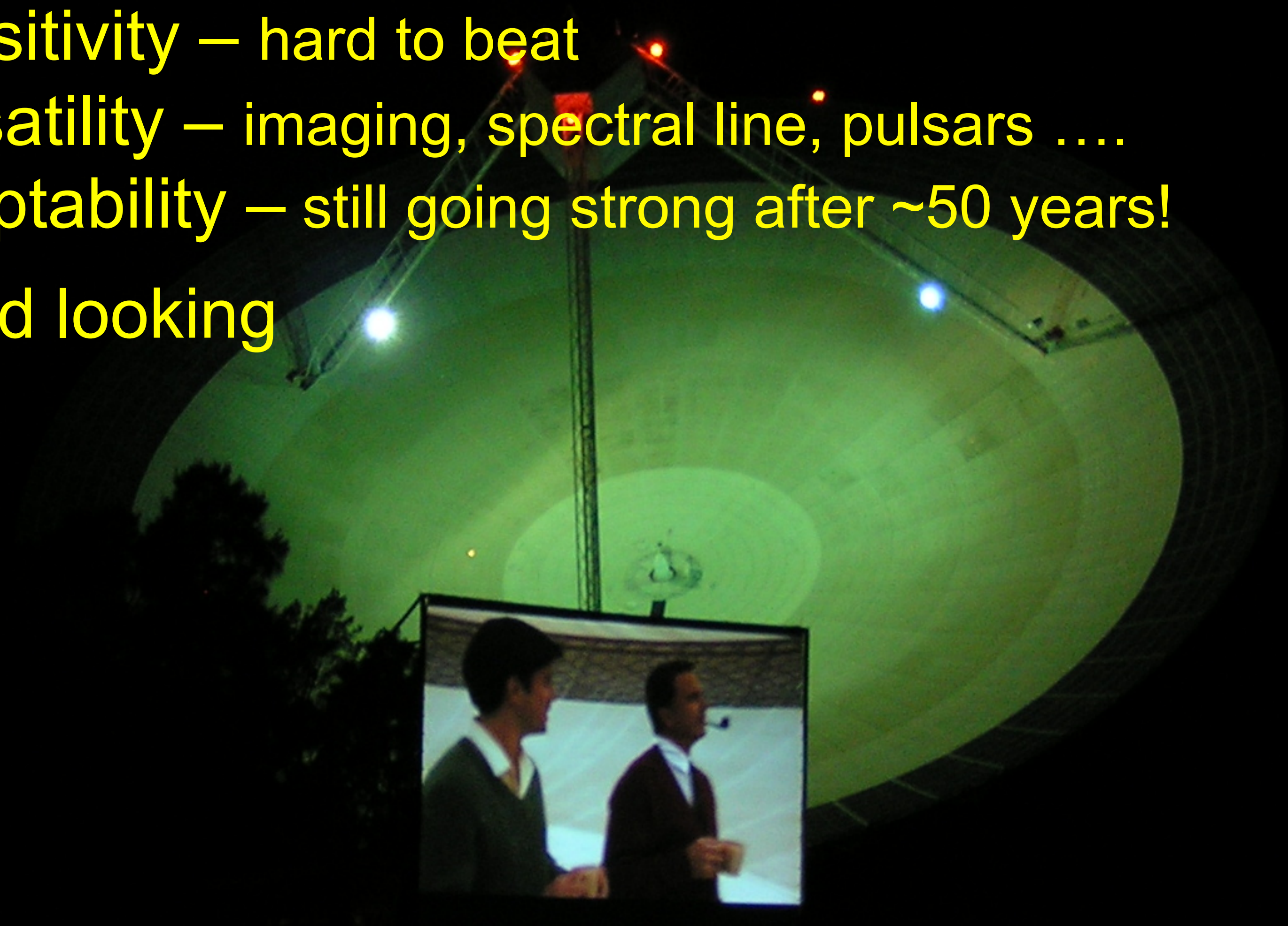
The Signal Path

John Reynolds

Picture © Paul Varley

The “Dish” Advantage



Simplicity – cost effective for collecting area

Sensitivity – hard to beat

Versatility – imaging, spectral line, pulsars ….

Adaptability – still going strong after ~50 years!

Good looking

And not done yet

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Overview

- Signal Path: the basics
  - Conversion systems
  - Sampling theorem (re)visited
  - Samplers (aka digitizers, ADCs)

- Calibration
  - Noise cal injection
  - Single-dish strategies

How complicated can it be?

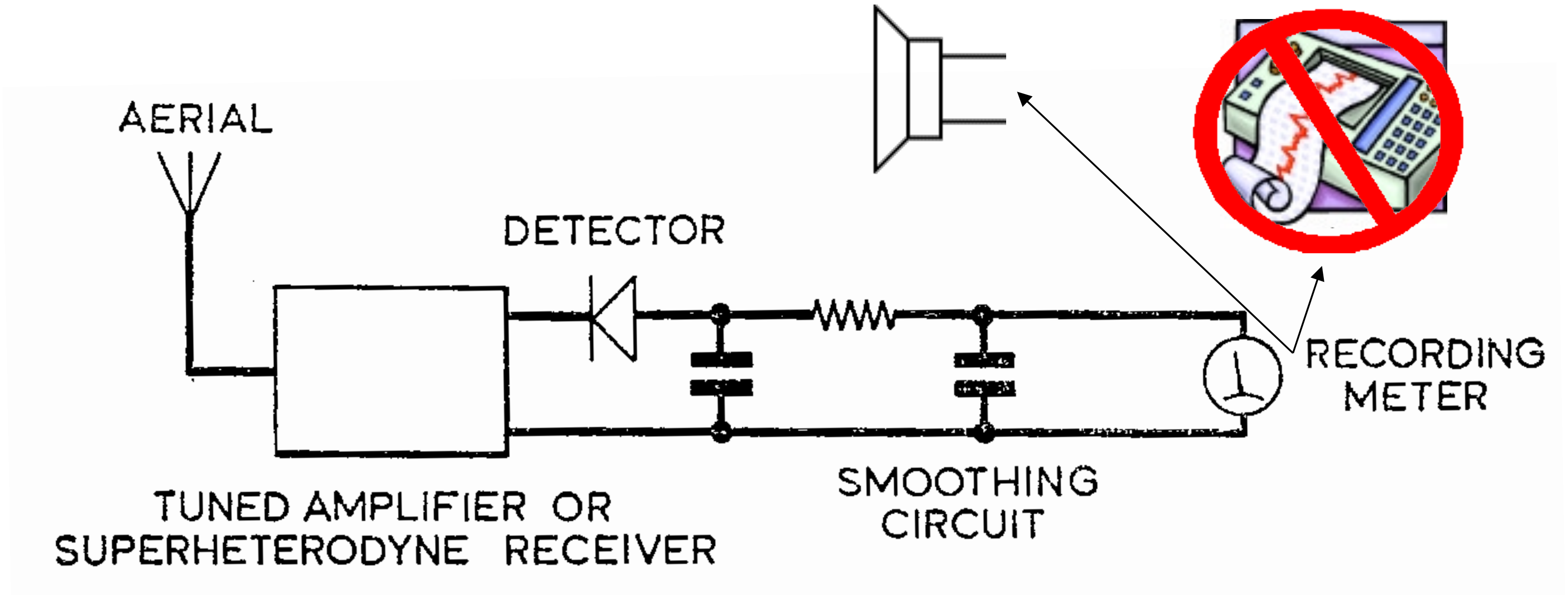
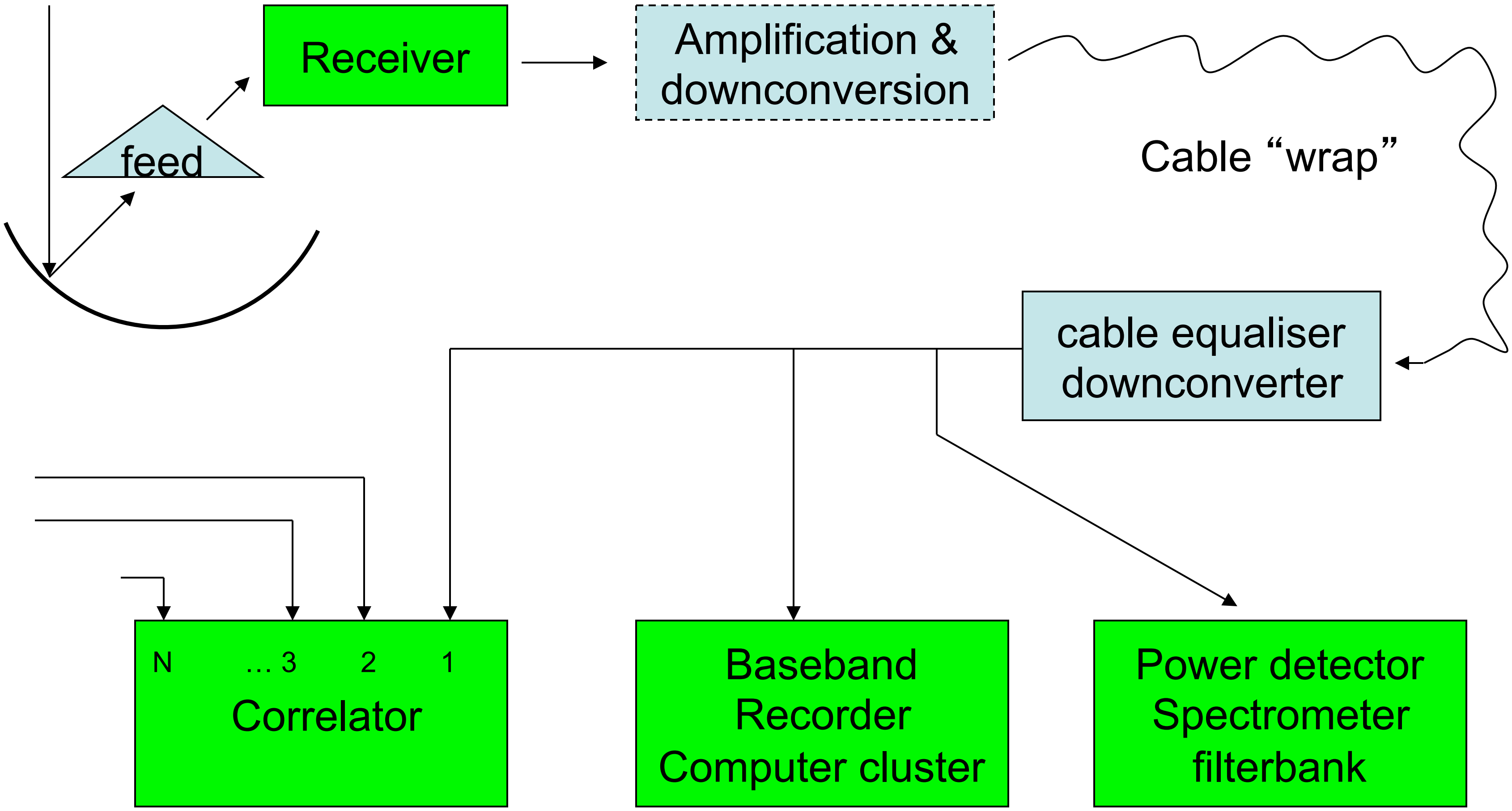


Fig. 2. A simple radio astronomy receiver

From “Radio Astronomy”, R.C.Jennison (1966)


CAL CONTROL UNIT

Signal path – the basics



feed

Receiver

Amplification & downconversion

Cable “wrap”

cable equaliser downconverter

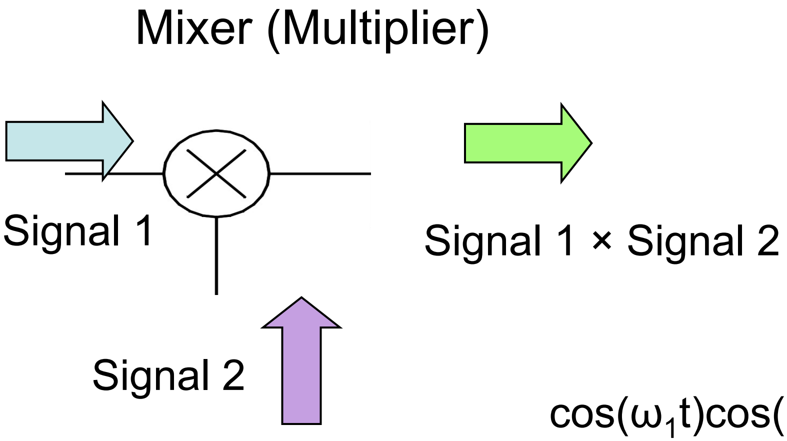
N … 3 2 1

Correlator

Baseband Recorder Computer cluster

Power detector Spectrometer filterbank

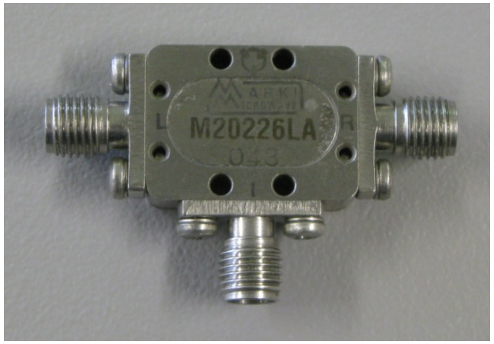
Mixing it down – Frequency Conversion


Mixer (Multiplier)

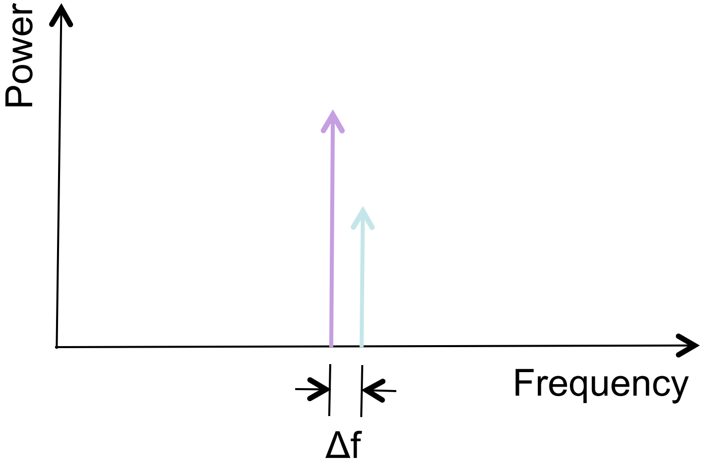
Signal 1

Signal 2

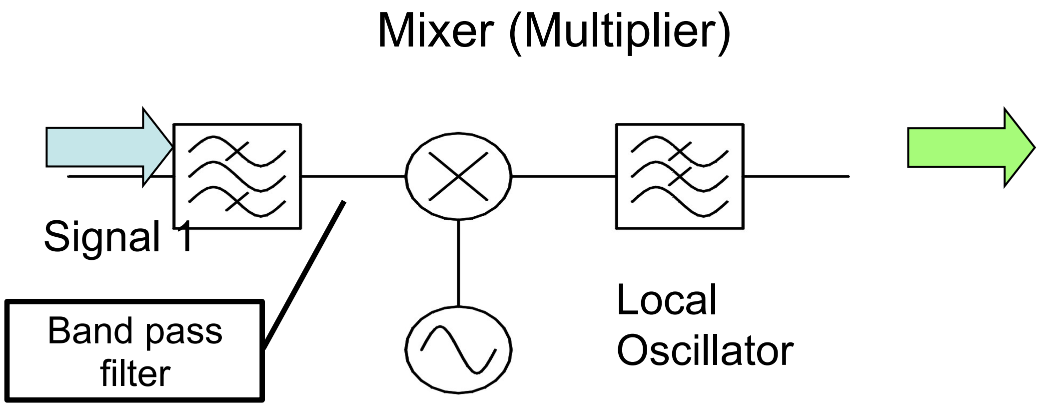
Signal 1 × Signal 2



$$\cos(\omega_1 t)\cos(\omega_2 t)=½[\cos((\omega_1+\omega_2)t)+\cos((\omega_1-\omega_2)t)]$$



Mixing it down II– Frequency Conversion (aka superheterodyne principle)

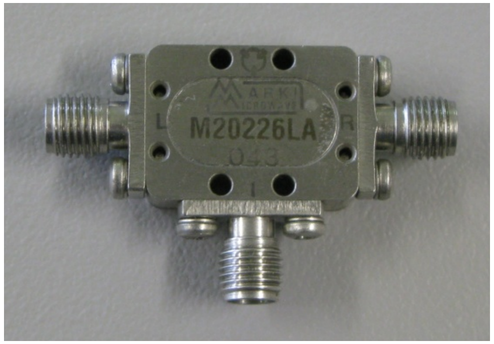


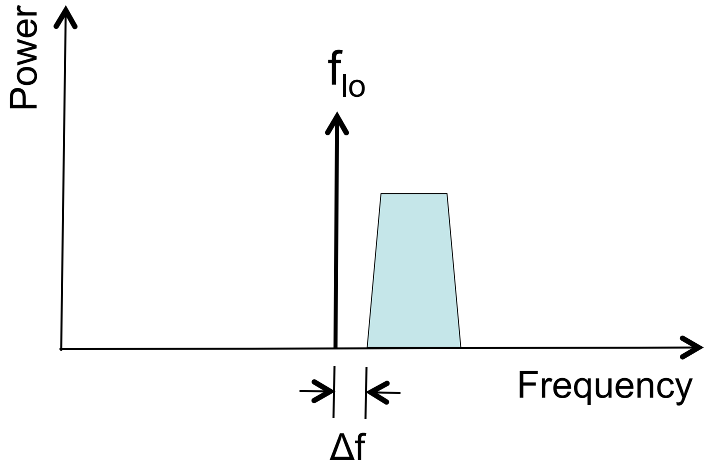
Mixer (Multiplier)

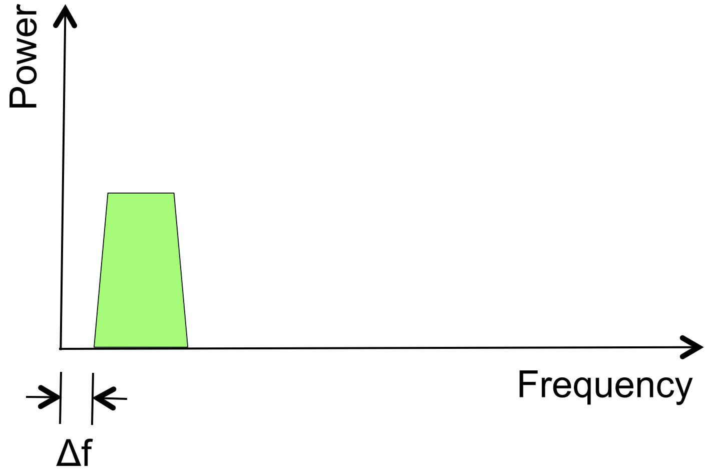
Signal 1

Band pass filter

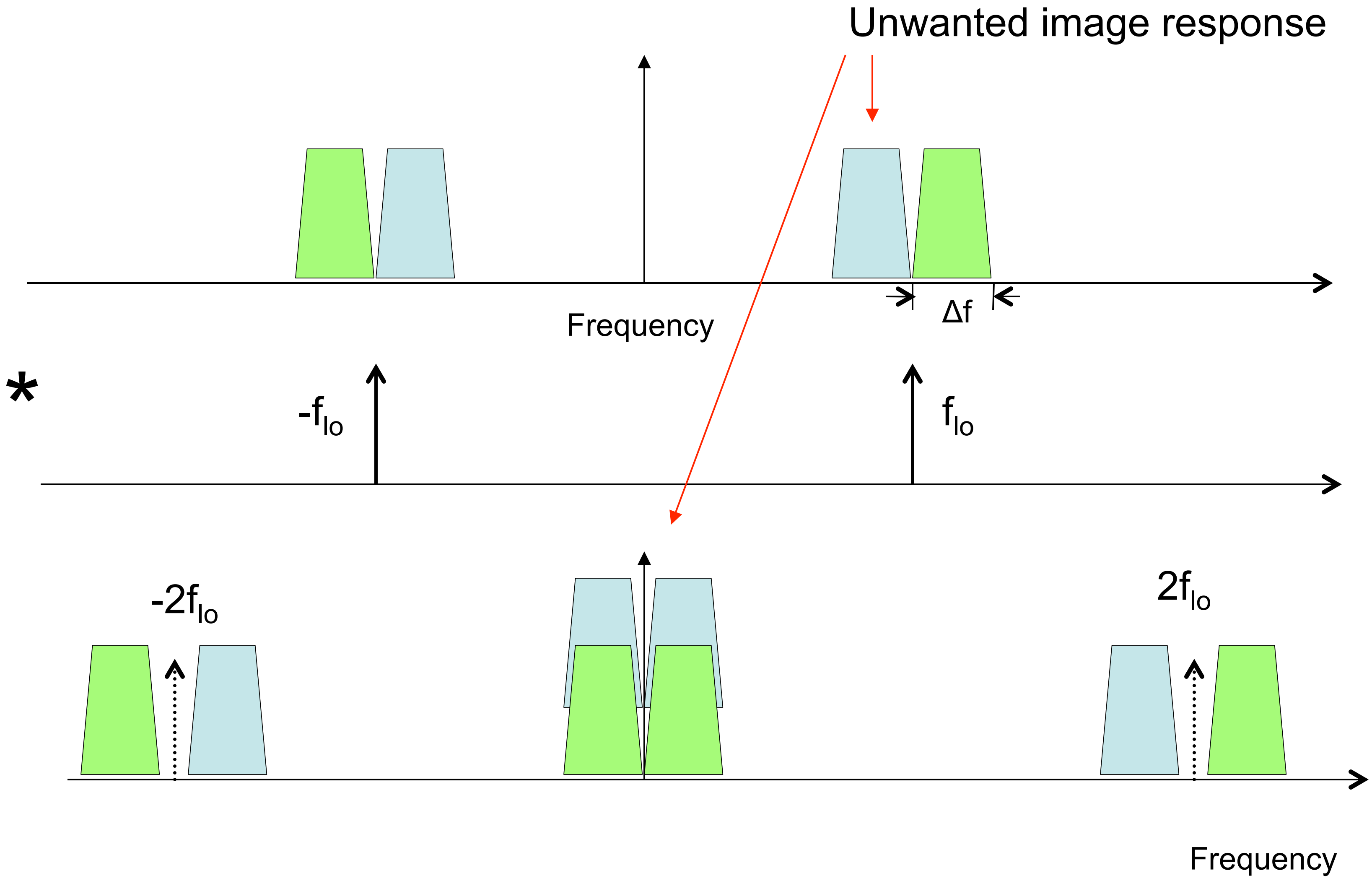
Local Oscillator



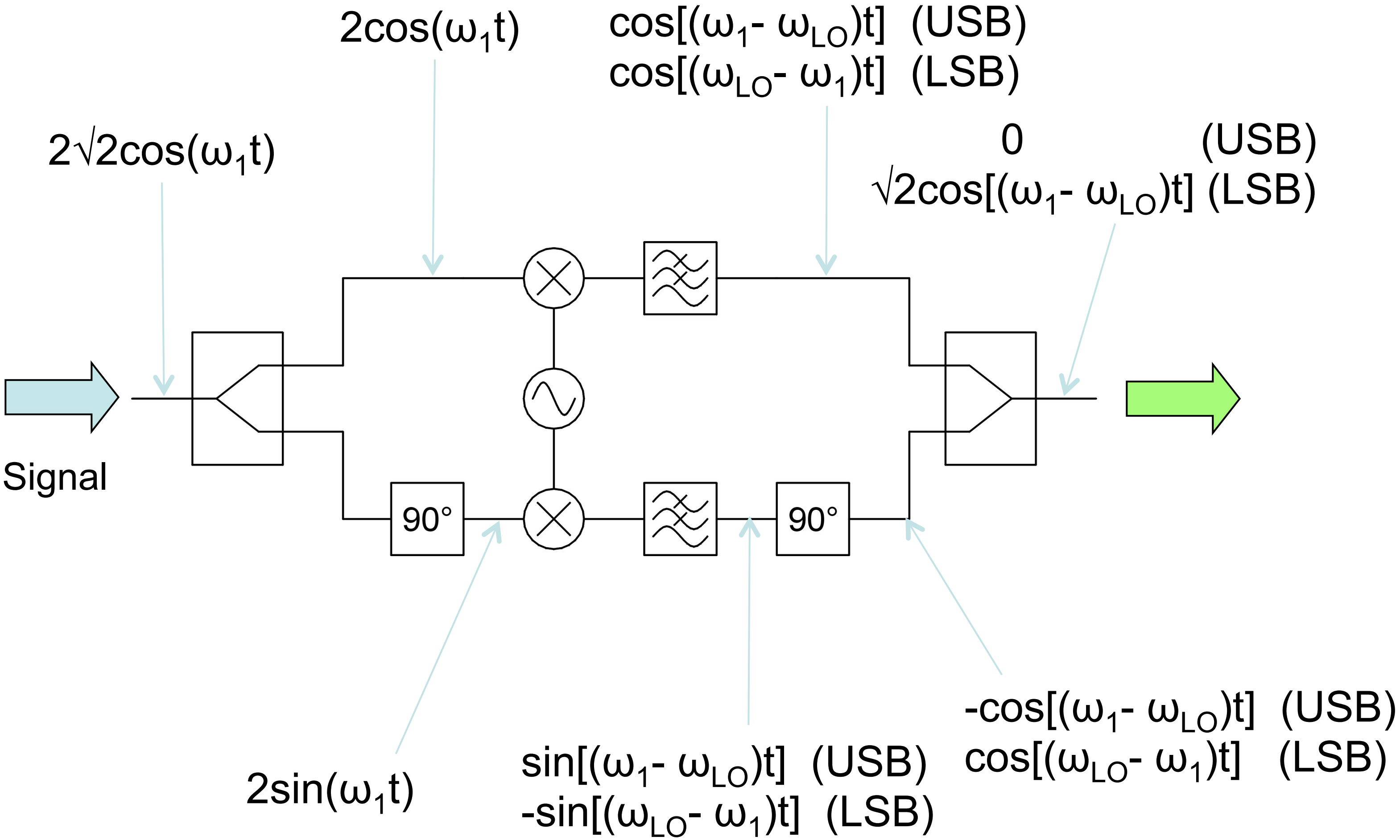




Real-world problems



Single Sideband Mixers



$2\cos(\omega_1 t)$

$\cos[(\omega_1 - \omega_{LO})t]$ (USB)
$\cos[(\omega_{LO} - \omega_1)t]$ (LSB)

$2\sqrt{2}\cos(\omega_1 t)$

0 (USB)
$\sqrt{2}\cos[(\omega_1 - \omega_{LO})t]$ (LSB)

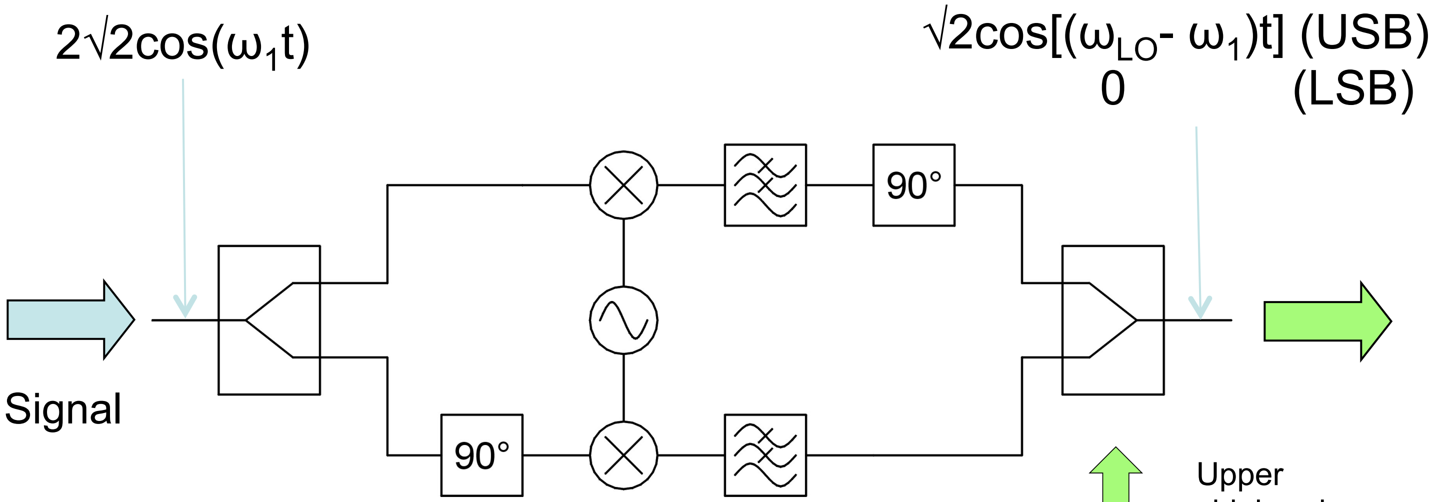
Signal

$-\cos[(\omega_1 - \omega_{LO})t]$ (USB)
$\cos[(\omega_{LO} - \omega_1)t]$ (LSB)

$2\sin(\omega_1 t)$

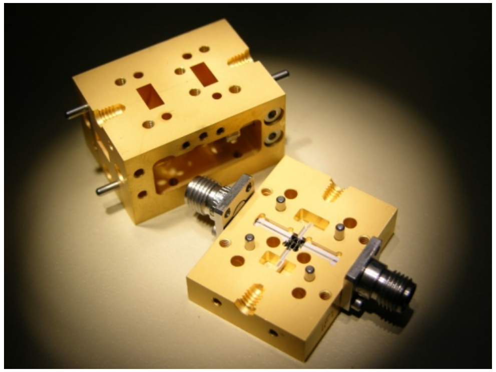
$\sin[(\omega_1 - \omega_{LO})t]$ (USB)
$-\sin[(\omega_{LO} - \omega_1)t]$ (LSB)

Single Sideband Mixers


$2\sqrt{2}\cos(\omega_1 t)$

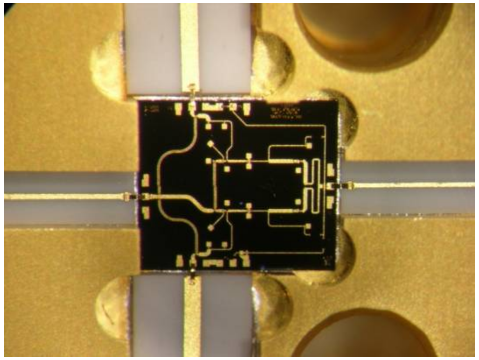
$\sqrt{2}\cos[(\omega_{LO} - \omega_1)t]$ (USB)

0 (LSB)



Upper sideband

Signal



Local Oscillator

Lower sideband

Filterbanks, vs spectrometers vs correlators

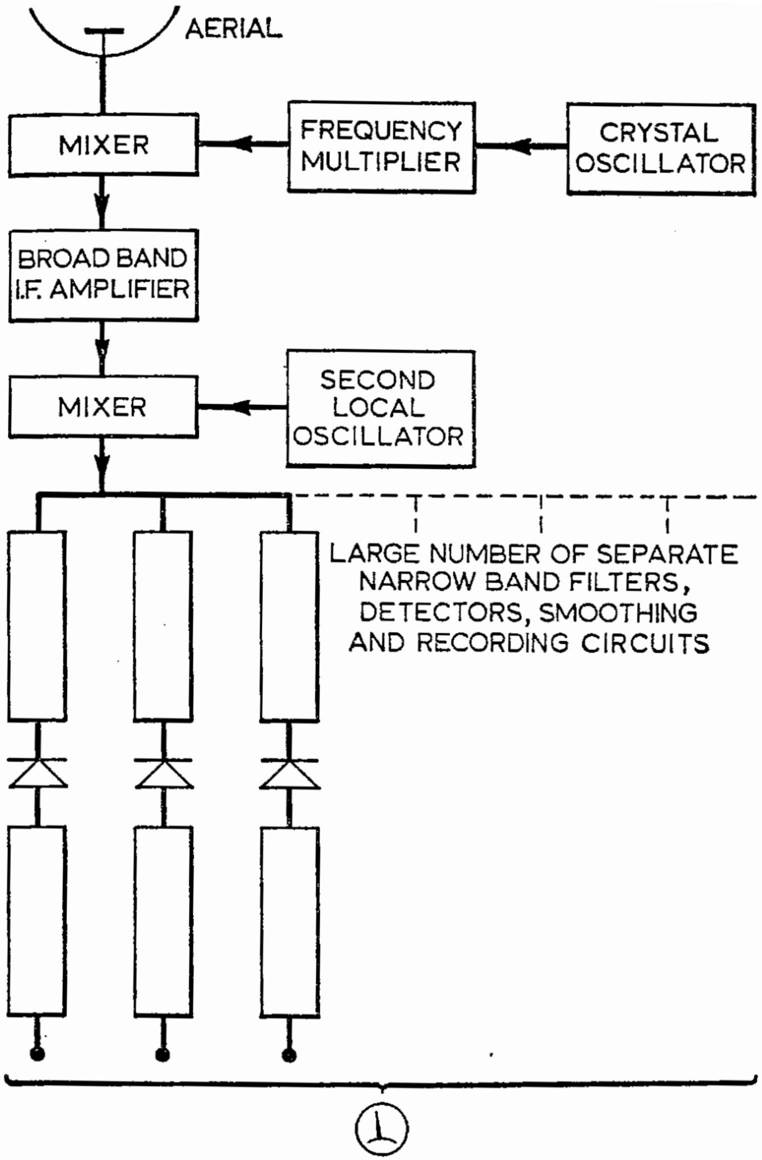
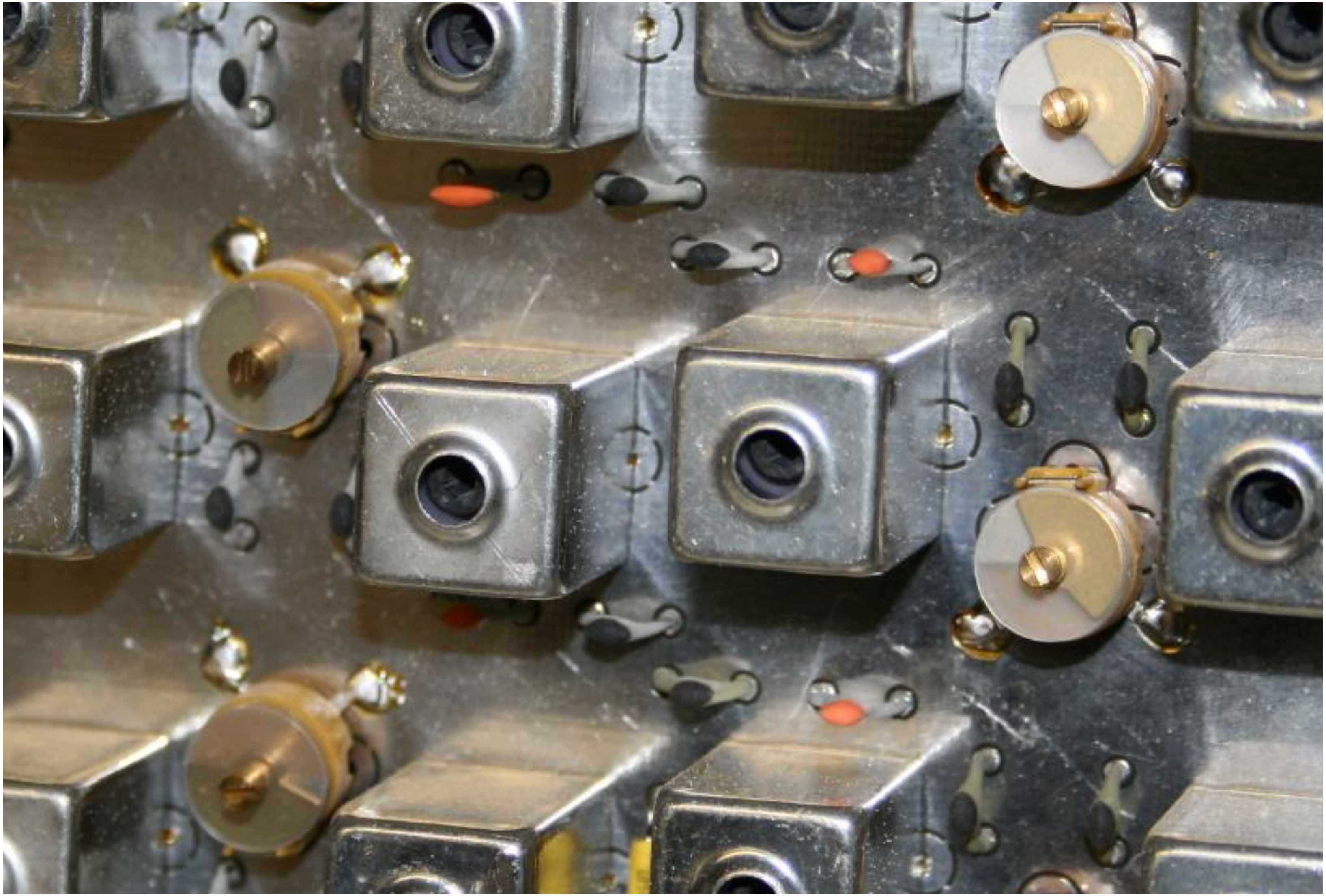


Fig. 7. Simple multi-channel hydrogen line spectrometer receiver

The last great analogue filterbank?



Sampling Theorem – History

The theorem is commonly called the **Nyquist sampling theorem**; since it was also discovered independently by E. T. Whittaker, by Vladimir Kotelnikov, and by others, it is also known as **Nyquist Shannon–Kotelnikov**, **Whittaker–Shannon–Kotelnikov**, **Whittaker–Nyquist–Kotelnikov–Shannon**, **WKS**, etc., sampling theorem, as well as the **Cardinal Theorem of Interpolation Theory**.

It is often referred to simply as ***the sampling theorem*****.**

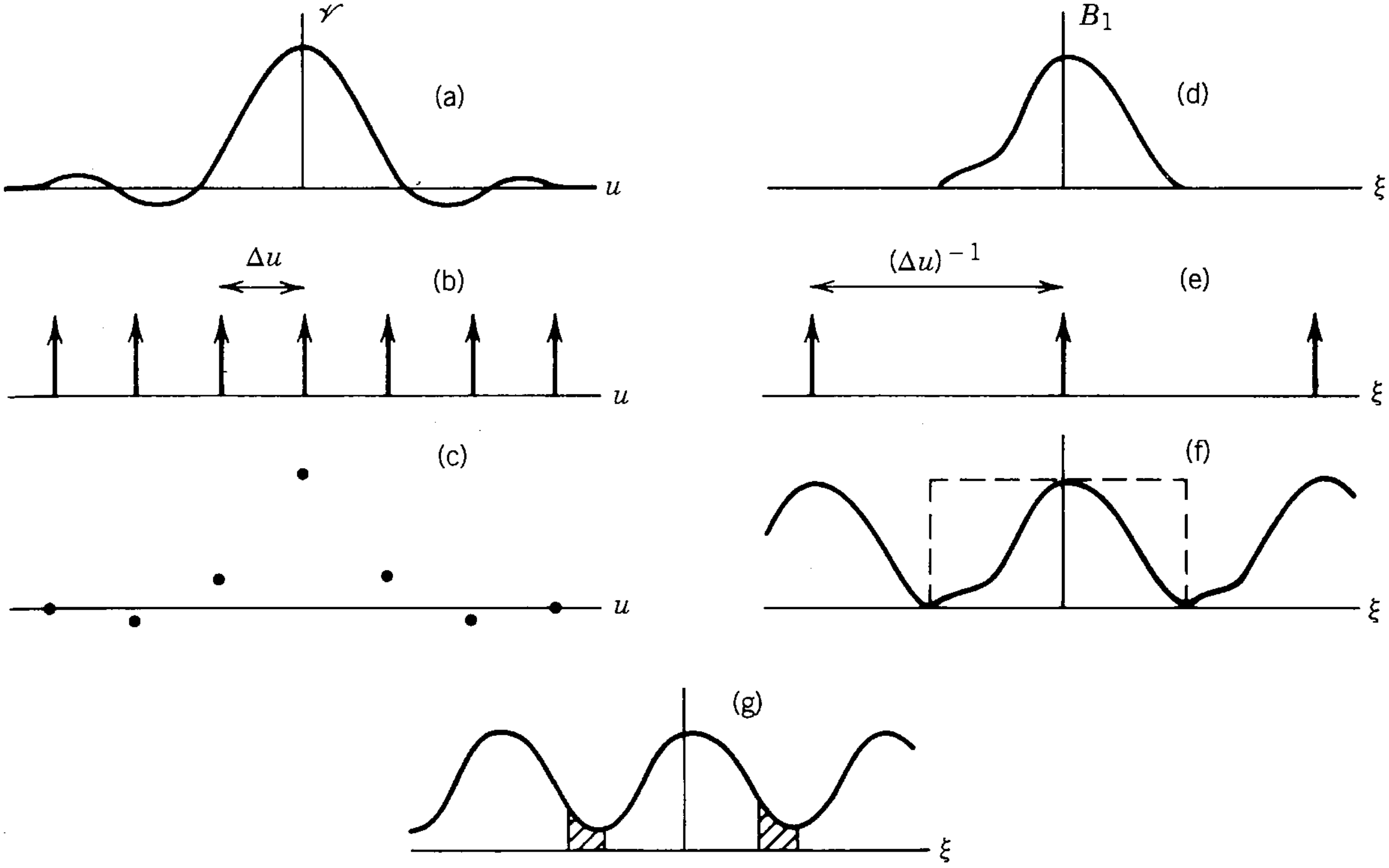
(From Wikipedia)

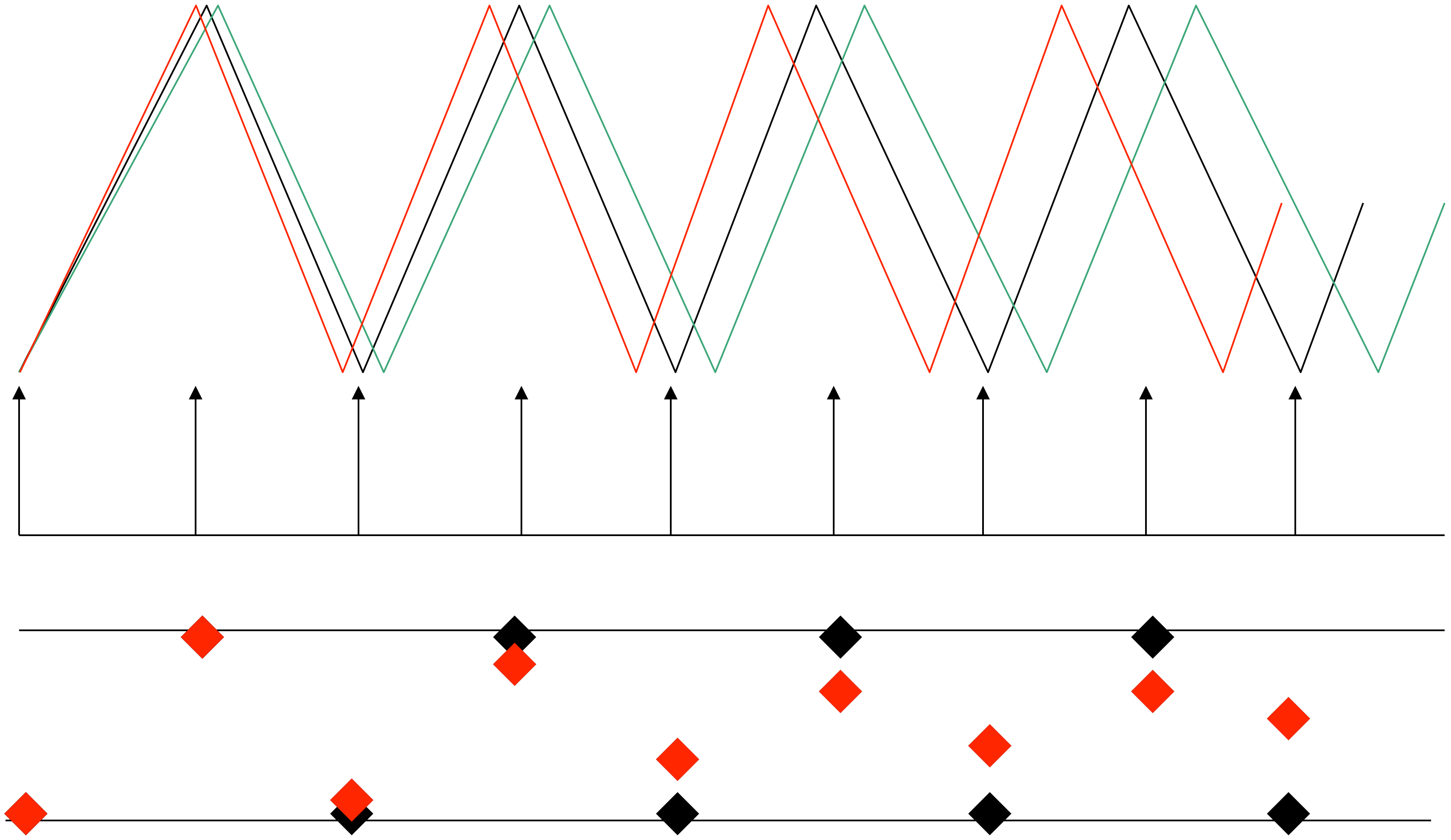
Sampling Theorem (Shannon)

If a function $x(t)$ contains no frequencies higher than B hertz, it is completely determined by giving its ordinates at a series of points spaced $1/(2B)$ seconds apart.

$$t_{samp} < 1 / 2B$$

Sampling Theorem

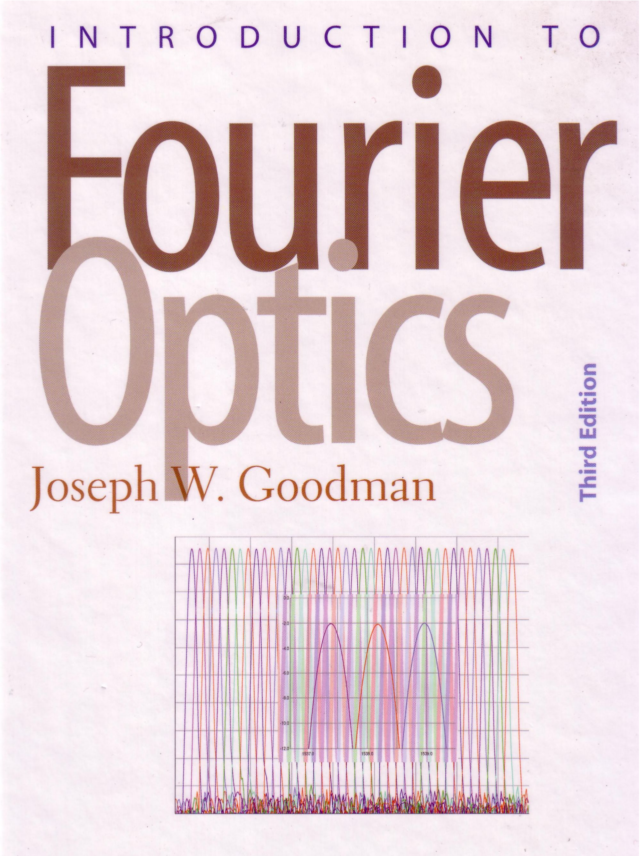




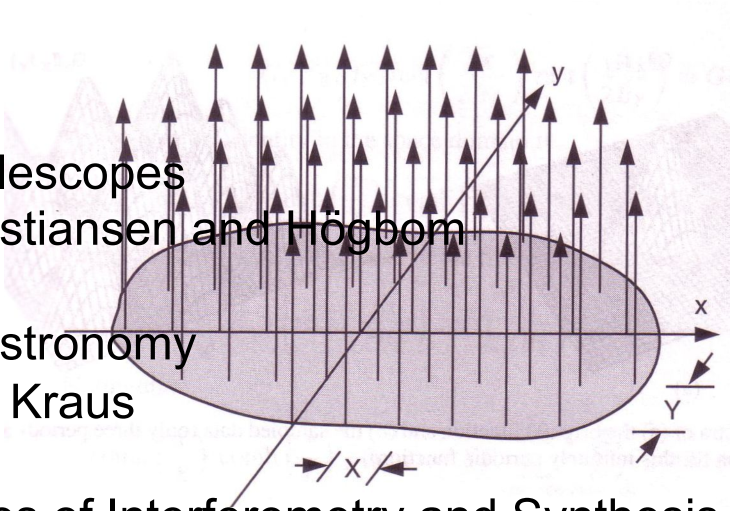
t_s=1/2B (Nyquist)

t_s=1/B (x2 undersampled)

Sampling Theorem continued



INTRODUCTION TO
Fourier Optics
Joseph W. Goodman
Third Edition

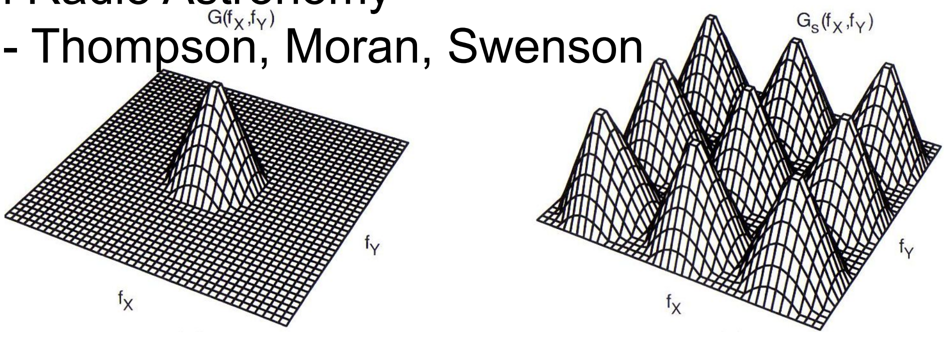


Also;

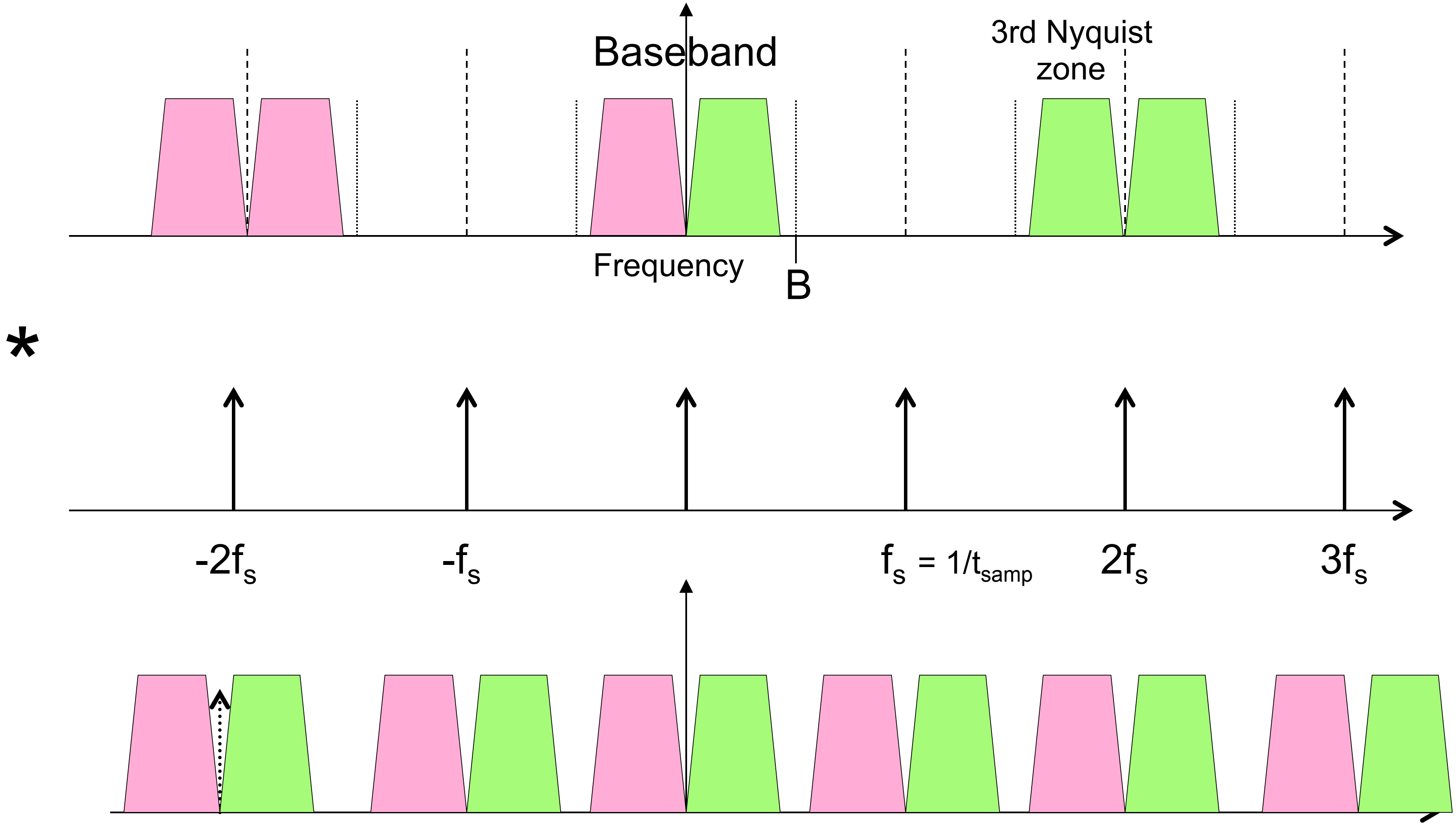
Radiotelescopes
- Christiansen and Högbom

Radio Astronomy
- J.D. Kraus

Principles of Interferometry and Synthesis in Radio Astronomy
- Thompson, Moran, Swenson

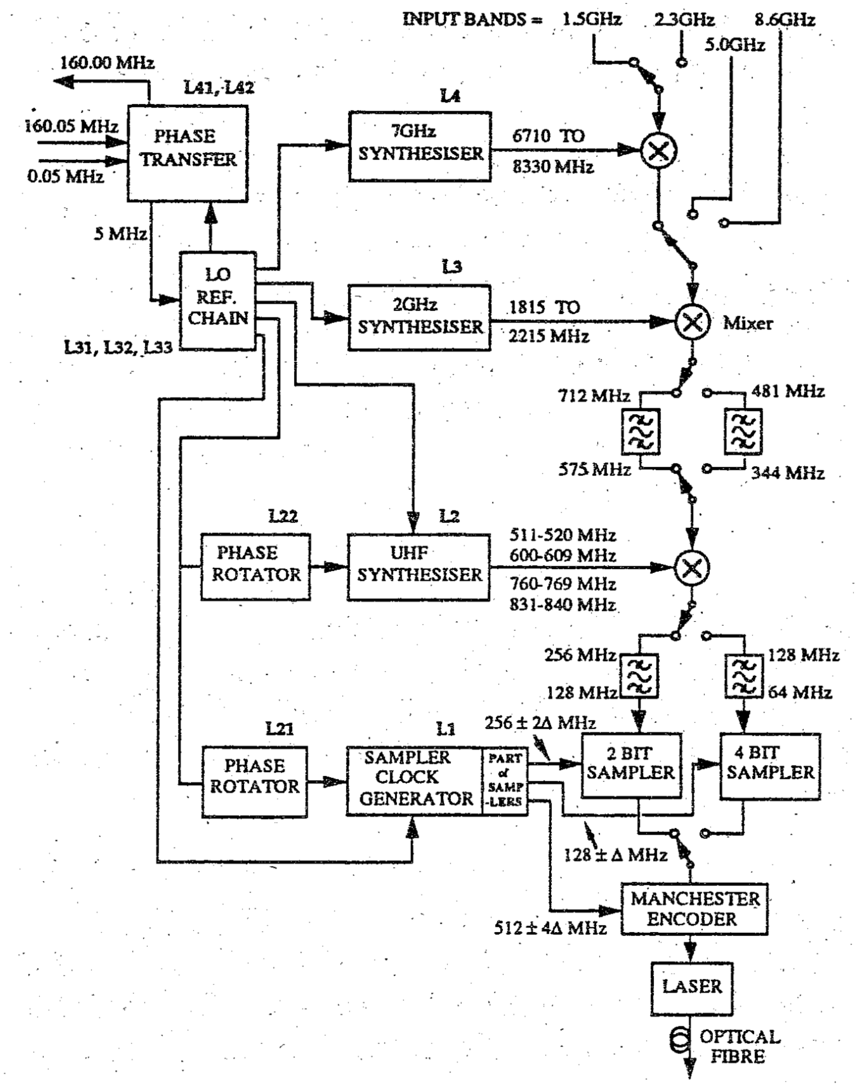


Aliased sampling



Sampling theorem: $f_s = 1/t_{samp} > 2B$

The old ATCA conversion chain



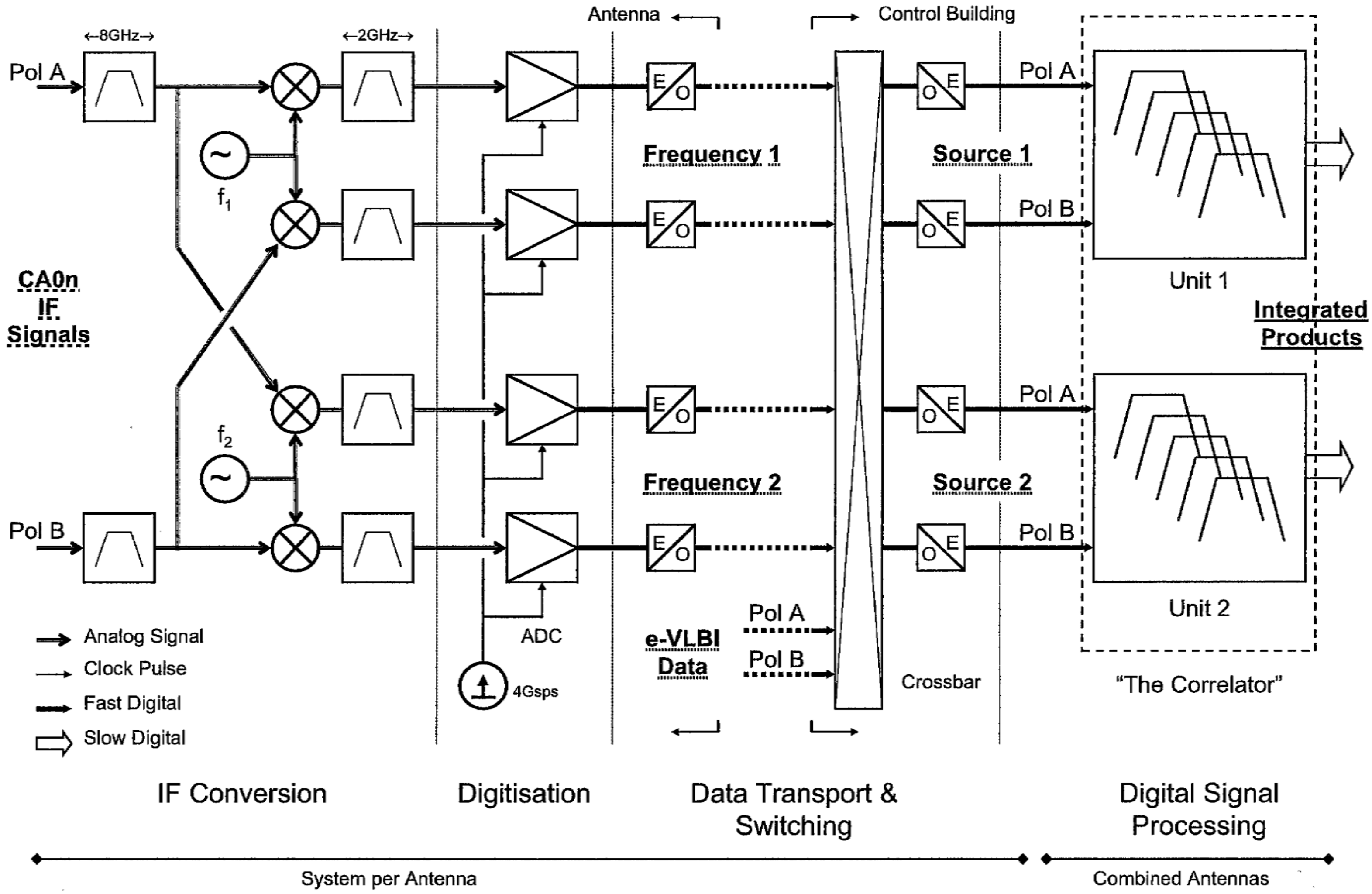
Recent Trends

- Faster, cheaper, samplers
- Faster, cheaper processing, data storage

→Wider sampled bandwidths
→Fewer downconversion

→“direct conversion” (no downconversion)
e.g. DRAO receiver at Parkes)

CABB signal path



Out of scope

- Limits;
  - Distortion: harmonic, intermodulation
  - Finite precision sampling (1-bit, 2-bit …)

  - The joys of cabling
  - “RFoF” – RF over fibre

- Complexities
  - Complex sampling

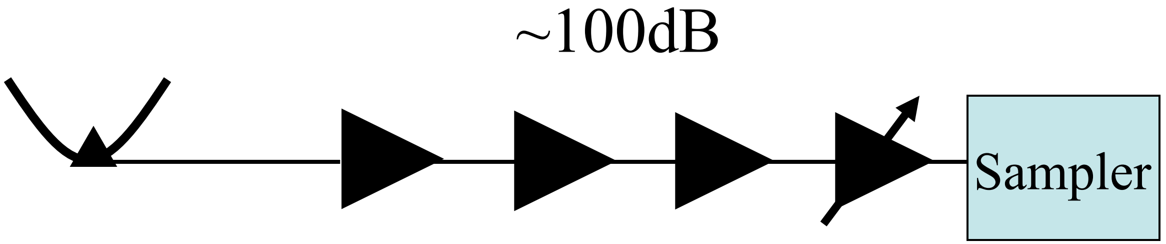
Calibration

You never know – it might be important.

What are we measuring?

- Typical receiver systems have large gain which varies with time.

  Abandon detected power for calibration: use only equivalent noise temperatures.



Dicke Switch

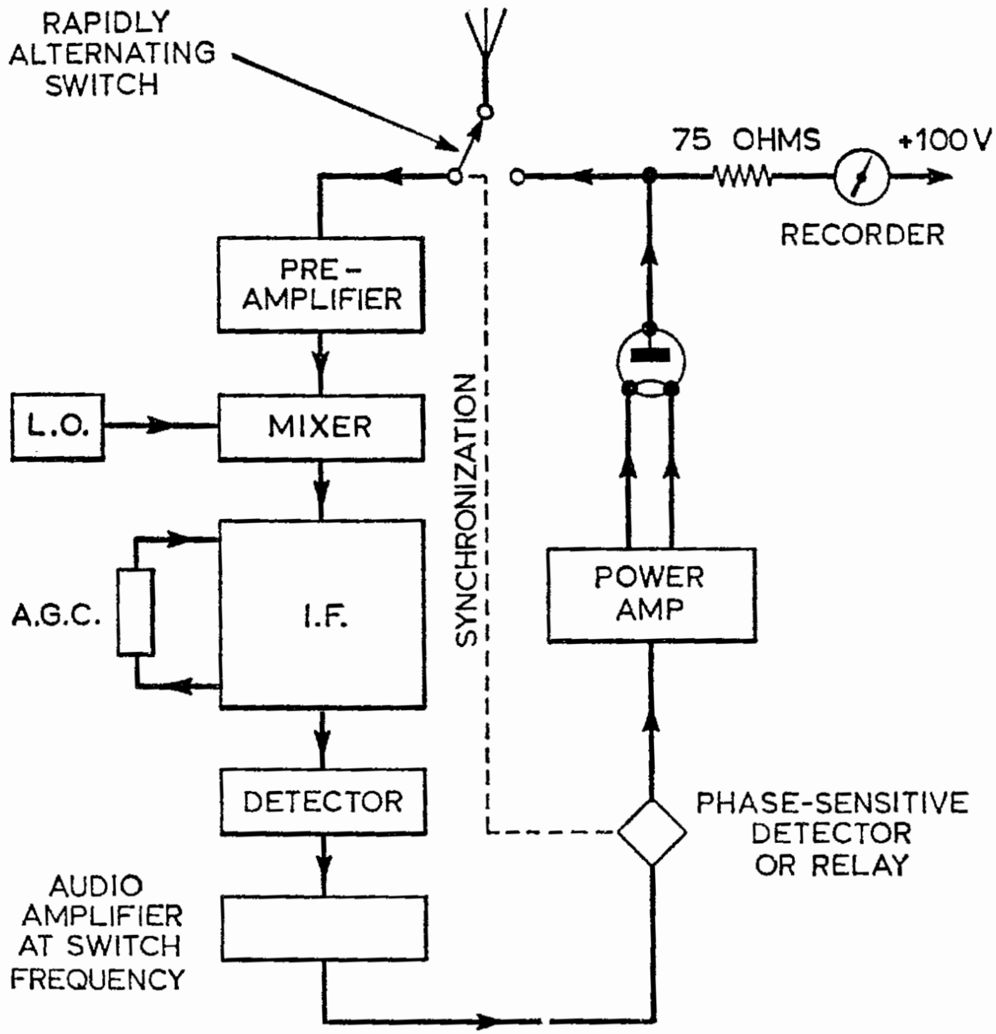


Fig. 3. A servo controlled receiver in which the signal is rapidly compared with that from a noise diode
(Ryle and Vonberg, following a principle first used by R. H. Dicke)

NAR – noise-adding radiometer

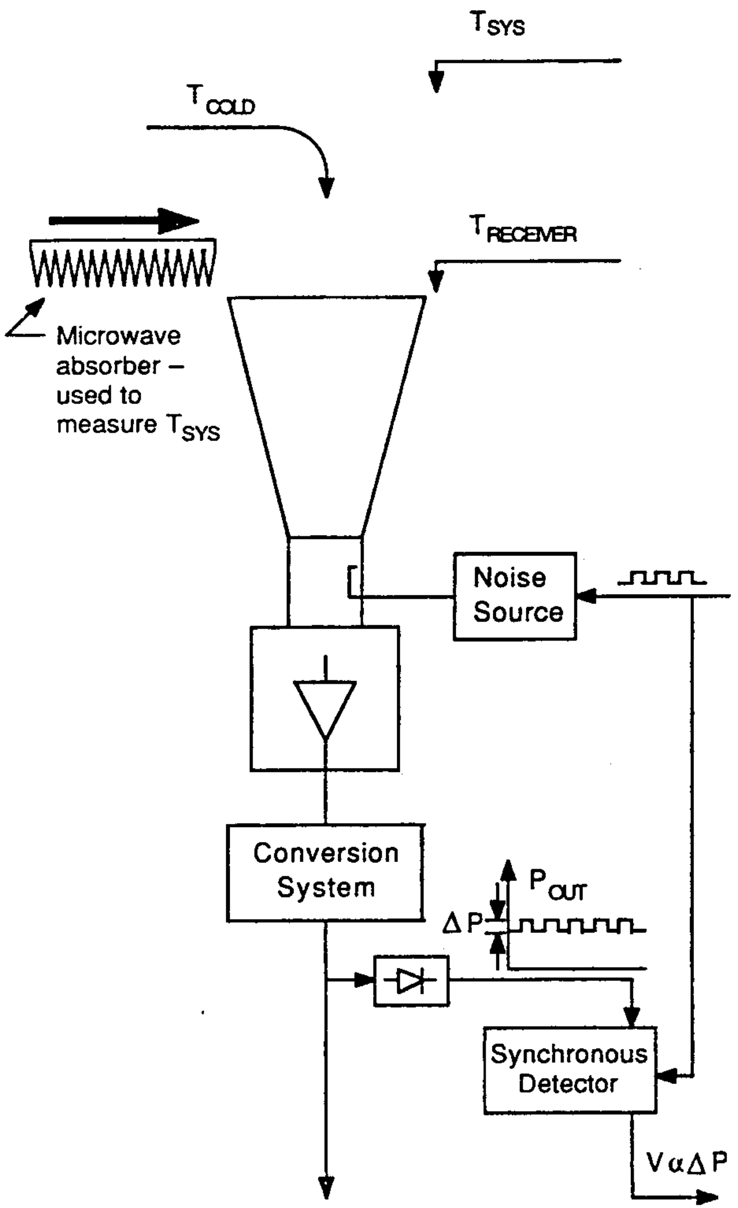
Jargon:

“noise tube”

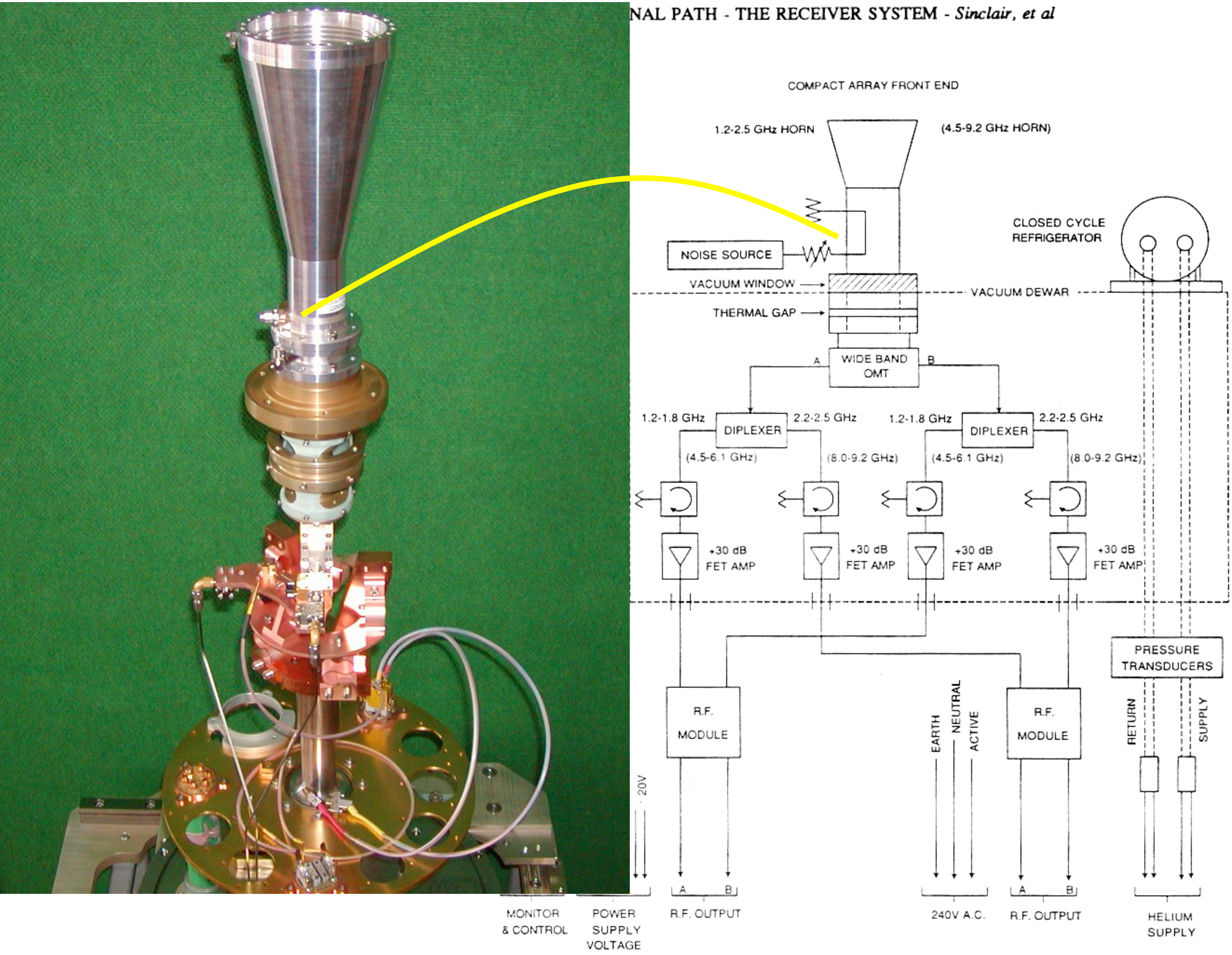
=“noise diode”

=“noise source”

=“cal”

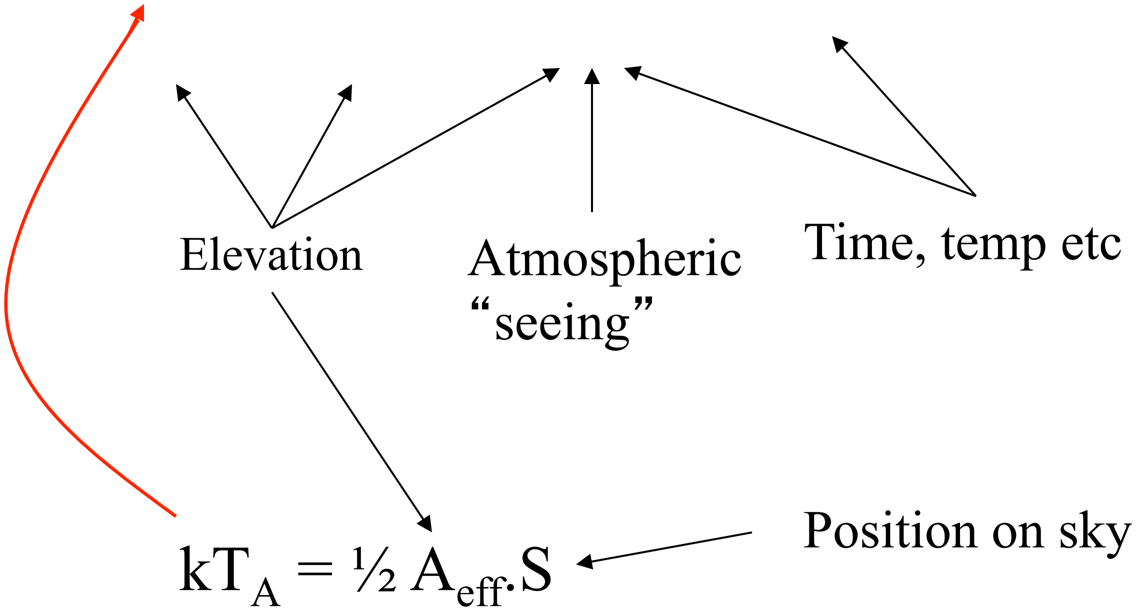


NAL PATH - THE RECEIVER SYSTEM - *Sinclair, et al*



The noise equation

$$T_{sys} = T_A + T_{spill} + T_{sky} + T_{rx} + T_{2.7K}$$



Elevation

Atmospheric
“seeing”

Time, temp etc

$$kT_A = \tfrac{1}{2} A_{eff} . S$$

Position on sky

Radiometer Equation

$$\mathrm{SE}(\mathrm{T_{sys}}) = \alpha\,.\mathrm{T_{sys}}/\ \sqrt{\mathrm{t}\,.\,\Delta f}$$

where;

t = integration time (seconds)

Δf = detector bandwidth (Hz)

α = factor of order unity (system dependent)

1 sigma (SE) not usually enough → 3 or 5 sigma

There's noise and there's noise:

above does not include "flicker" noise

Single-dish calibration

Pointing (at higher frequencies)

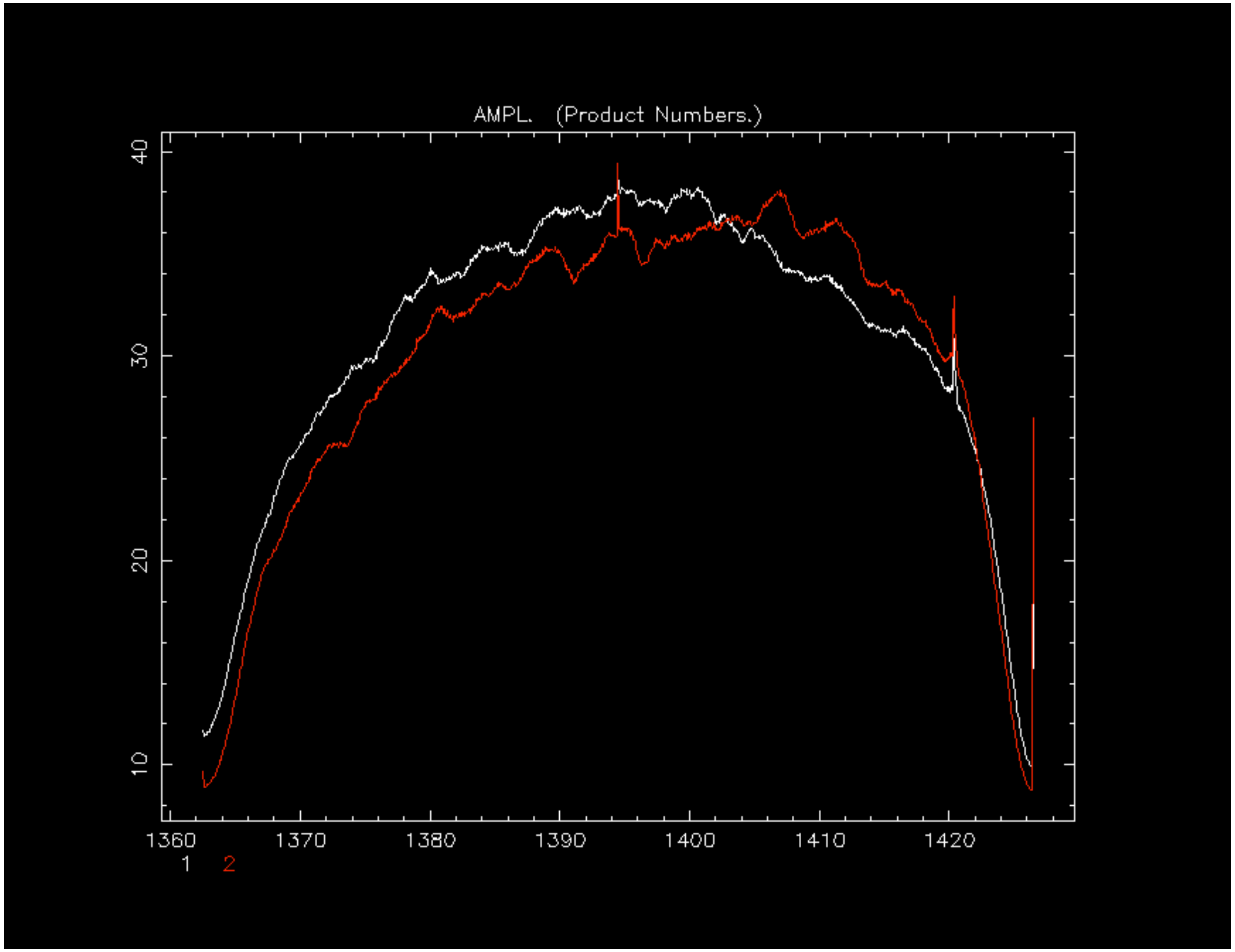
Gain vs Elevation

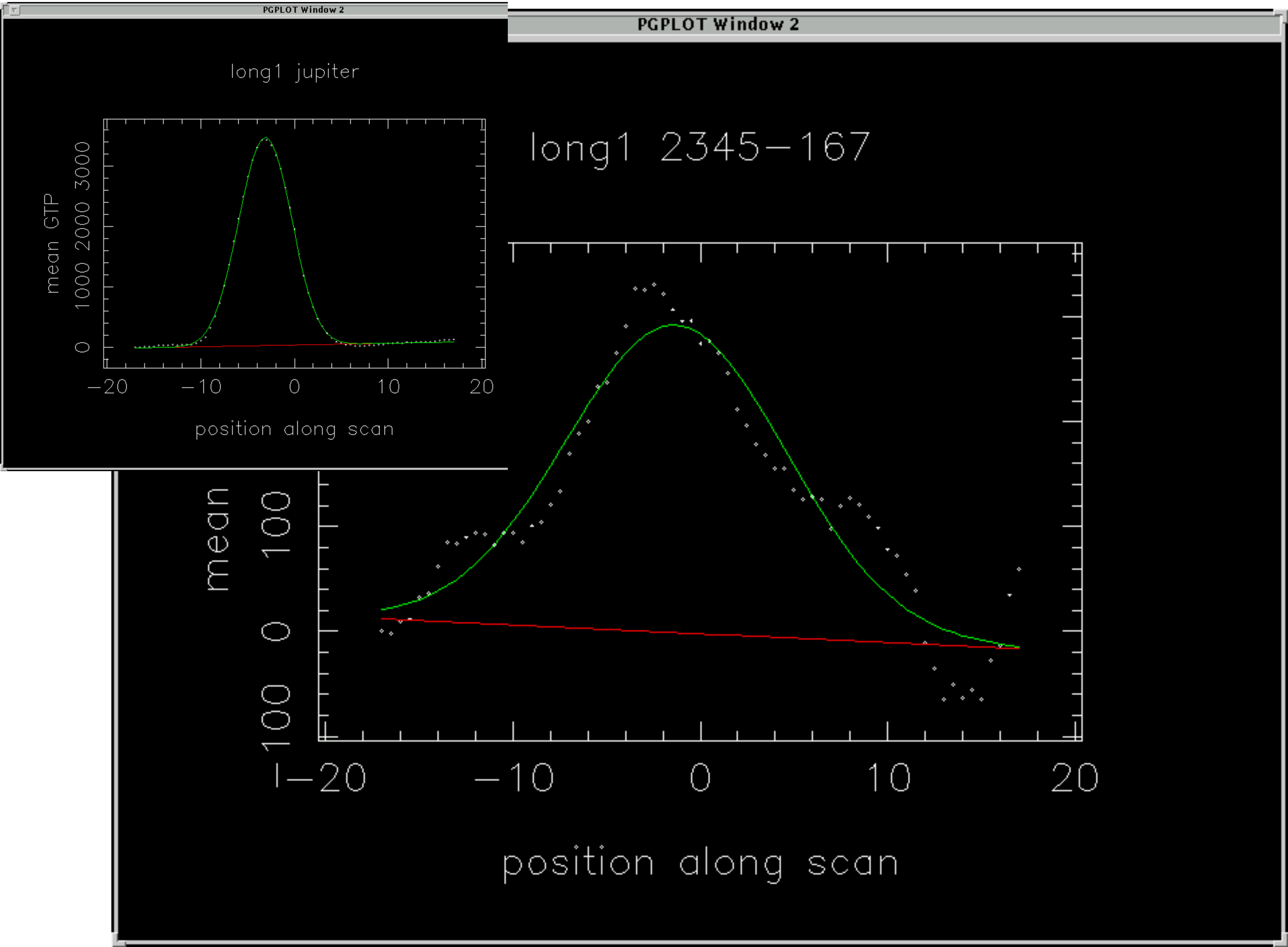
Tsys vs time

Remove the noise pedestal!

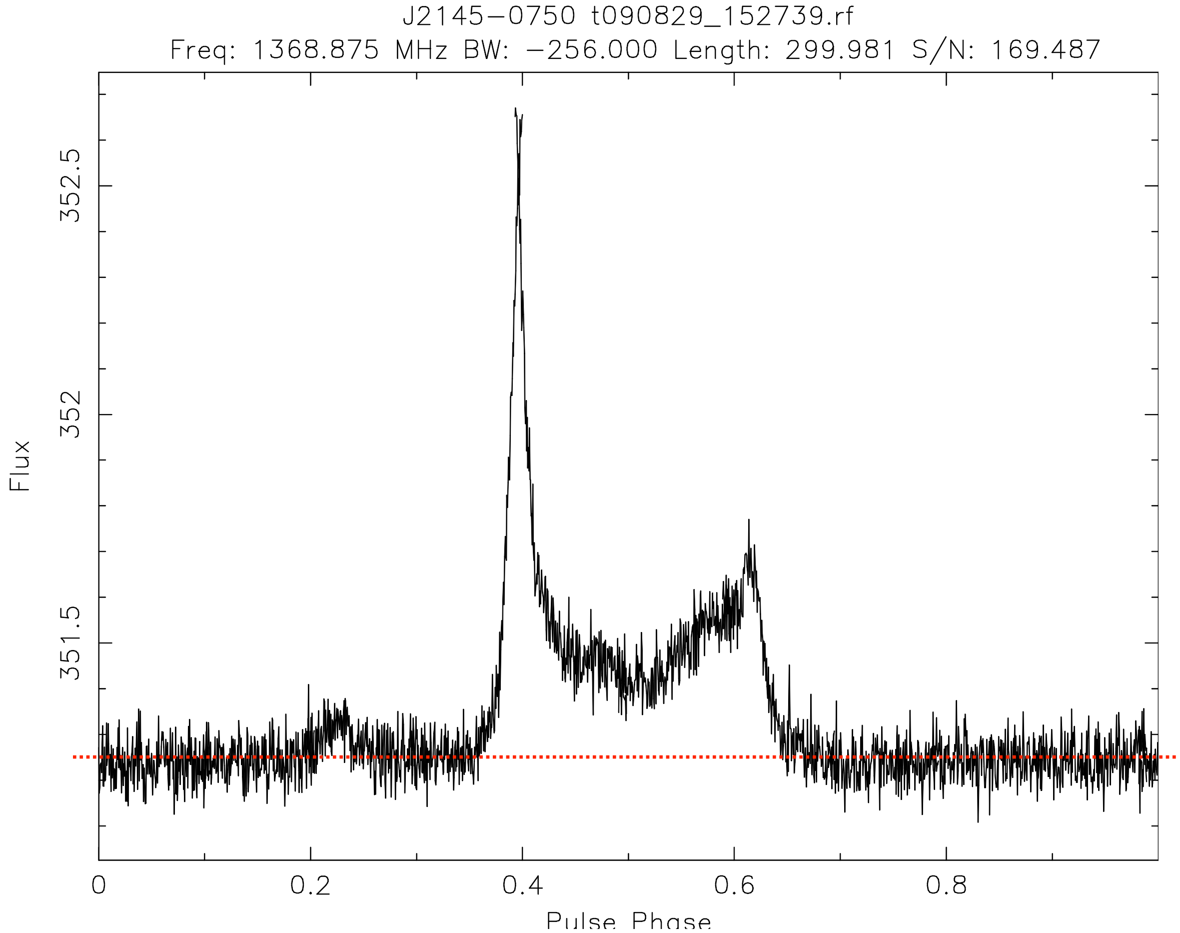
The single-dish millstone

Large and quasi~constant “DC” noise pedestal floor –
Small fluctuations with time/frequency are important!

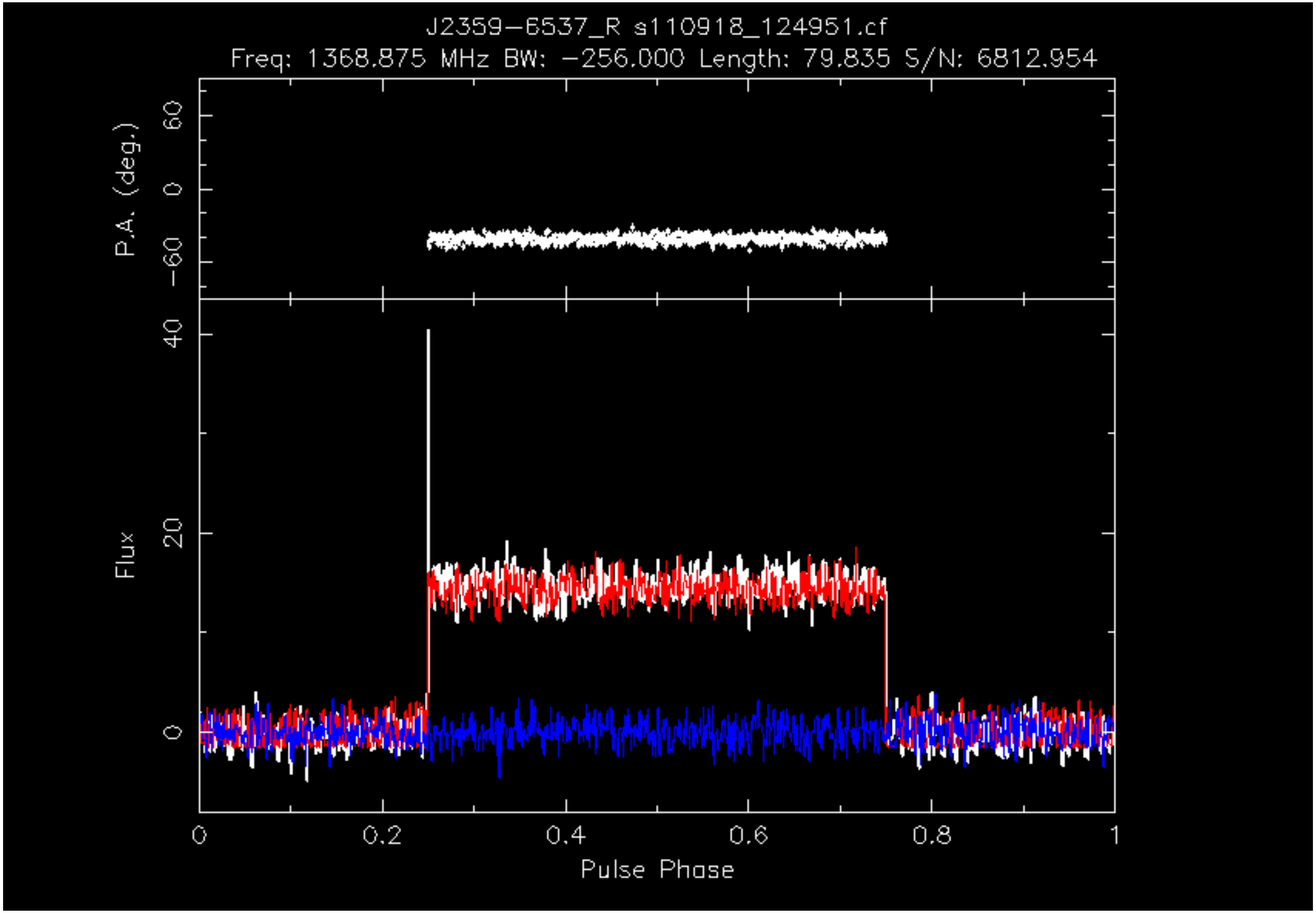



PGPLOT Window 2
long1 jupiter
mean GTP
0
1000
2000
3000
−20
−10
0
10
20
position along scan
PGPLOT Window 2
long1 2345−167
mean
100
0
100
−20
−10
0
10
20
position along scan

Pulsars: average “off pulse” noise;



Single dishes use correlators too



Spectral-line / continuum

- On source – Off source

  Switch between on and off-source, subtract/divide

  “MX” mode on Multibeam receivers

- Frequency shift

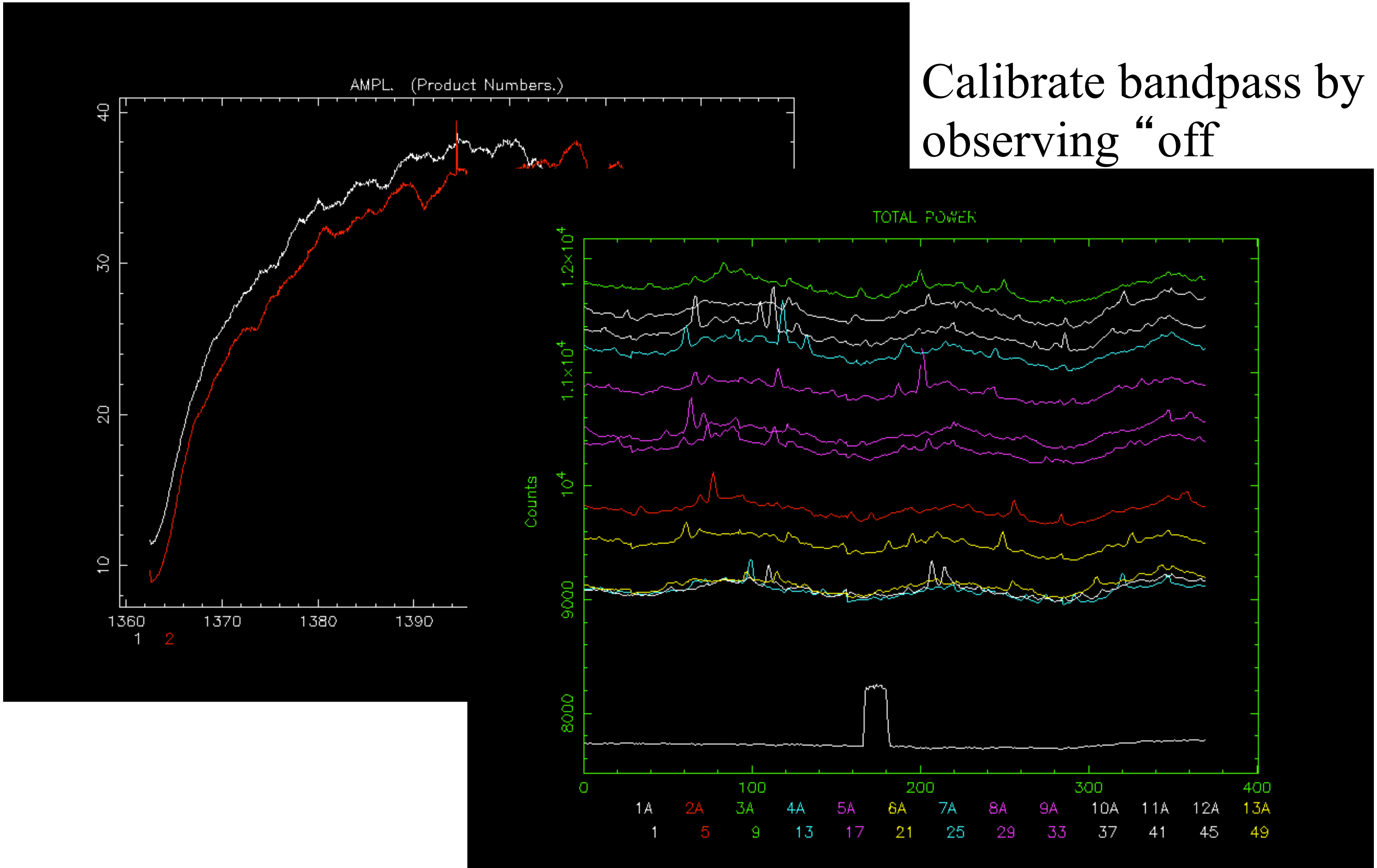
  Switch between two adjacent frequencies, divide

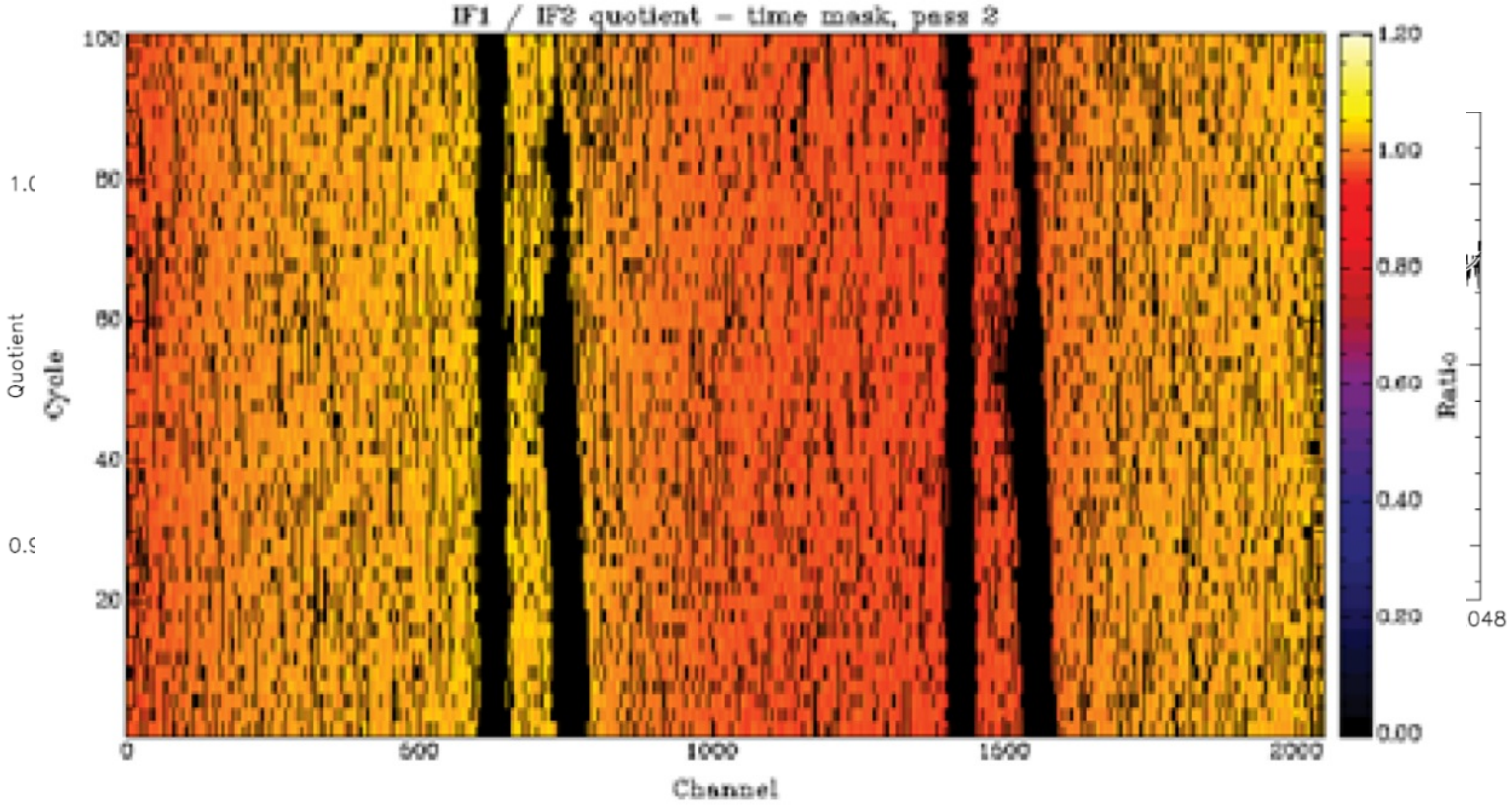
- Scan and average

  Subtract mean (median) of entire scan

Bandpass calibration

Calibrate bandpass by observing “off




IF1 / IF2 quotient – time mask, pass 2
Cycle
100
80
60
40
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Channel
0
500
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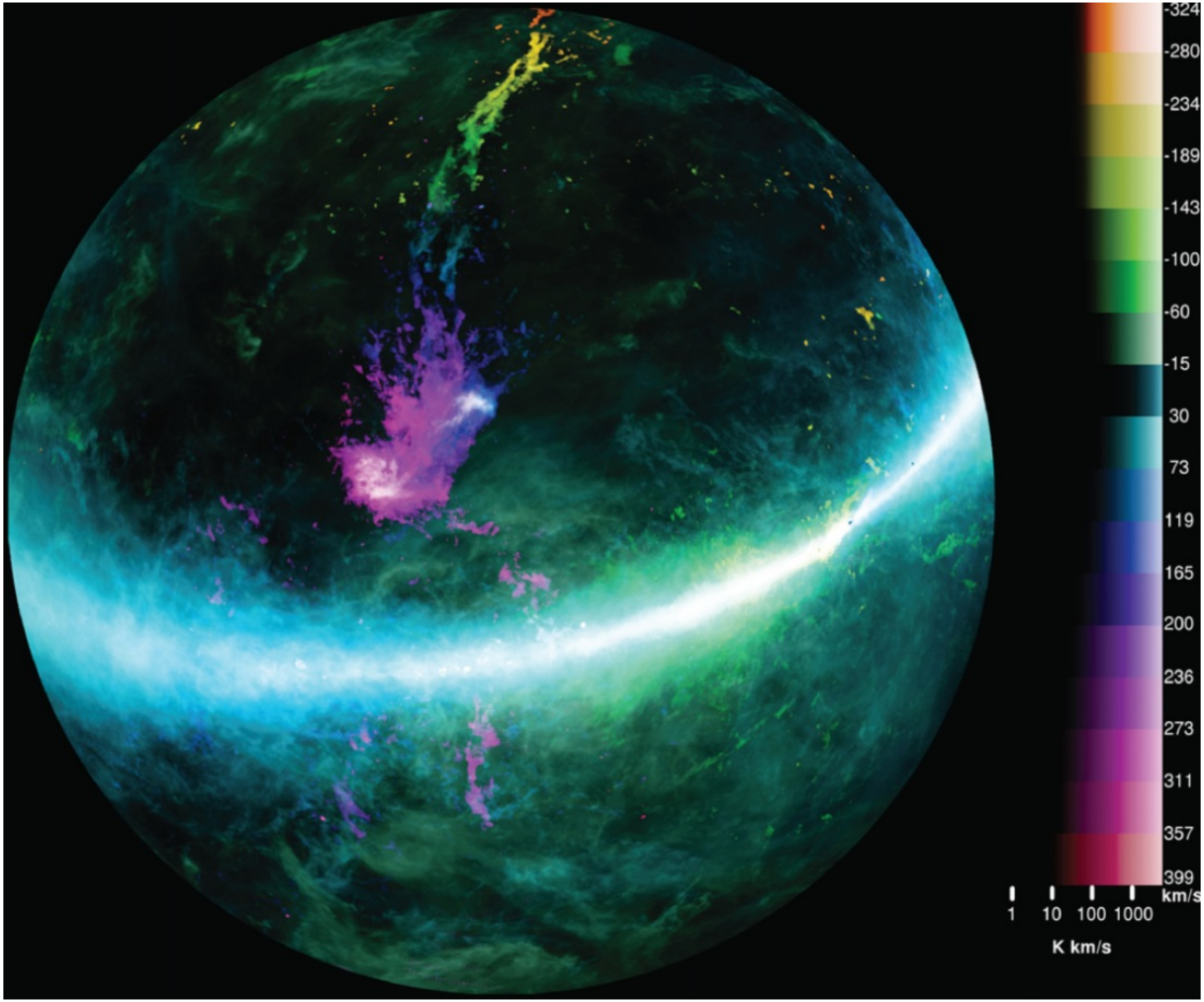
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-280
-234
-189
-143
-100
-60
-15
30
73
119
165
200
236
273
311
357
399
km/s
1
10
100
1000
K km/s

The End