

TÄHT7039: Radio astronomy and interferometry

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Some of the figures are from Wilson, Rohlfs, Hüttemeister: 'Tools of Radio astronomy'

Recap from lecture 4

Switched radiometers

Pseudocorrelation

Backends

Receiver noise temperature?

Minimum detectable noise temperature difference:

$$\Delta T_{min} = \frac{T_{sys}}{\sqrt{\Delta\nu\tau}}, \quad (1)$$

where $\Delta\nu$ is bandwidth, τ is integration time and T_{sys} is total receiver system noise:

$$T_{sys} = T_a + T_r + T_{sky} \quad (2)$$

T_a is **antenna temperature** due to target source, T_r is receiver temperature and T_{sky} is noise from the atmosphere.

The first low noise amplifier (LNA) is most important to the total receiver noise temperature because

$$T_{sys} = T_a + T_{sky} + T_1 + T_2/G_1 + T_3/(G_1 G_2) \dots \quad (3)$$

Therefore the first components before and including the first amplifier are decisive and they are *usually cooled* down to 4 - 15 K.

Mixing (or down/upconverting in frequency) is accomplished using a nonlinear device that acts as a voltage multiplier. Schottky diodes and superconducting devices (SIS) are most common in radio astronomy.

Multiplying two sinusoids results

$$\sin(2\pi\nu_1 t) \sin(2\pi\nu_2 t) = \frac{1}{2} \cos[2\pi(\nu_1 - \nu_2)t] - \frac{1}{2} \cos[2\pi(\nu_1 + \nu_2)t], \quad (4)$$

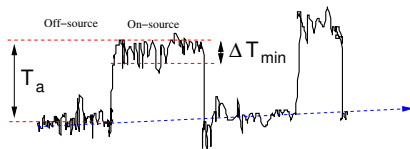
i.e. we get *sum and difference* frequencies. Usually in radio astronomy we need the difference, so the higher sum frequency is filtered out.

The first mm-mixers were based on *Schottky diode* junction. Schottky diodes are fast but otherwise quite normal diodes. *SIS (Superconductor Insulator Superconductor)* tunneling junction is commonly used in mm- and submm-receivers without a preamplifier.

Simple total power radiometer and drift

Radiometer typically contains a LNA, mixer(s), intermediate frequency (IF) amplifier and a detector (total power radiometer == power meter), i.e signal is amplified, mixed to a lower, more comfortable frequency and transformed from AC to DC.

Problem of a simple total power radiometer is $1/f$ drift.

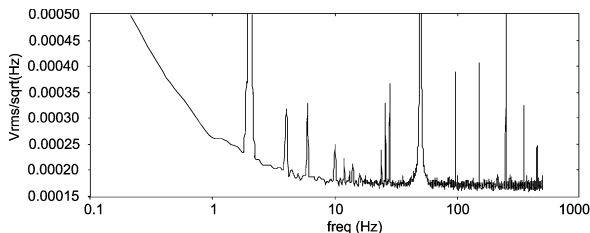


When taking the drift into account, the minimum detectable signal becomes:

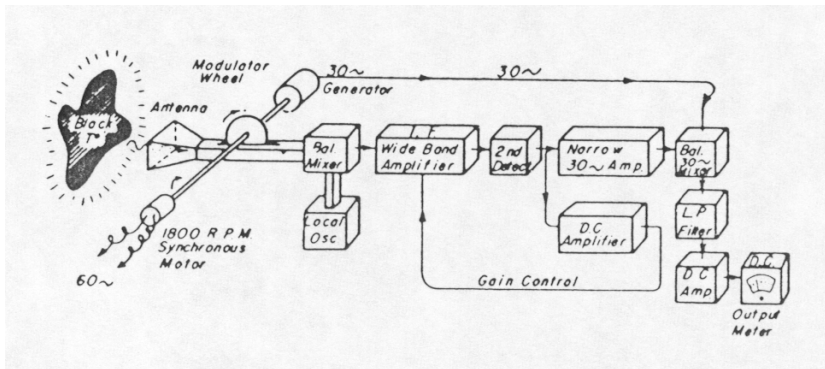
$$\Delta T_{min} = T_{sys} \sqrt{\frac{1}{\Delta\nu\tau} + \left(\frac{\Delta G}{G}\right)^2}, \quad (5)$$

where ΔG and G are the gain variability and total gain respectively. It can be seen that e.g for typical values $\Delta\nu = 1$ GHz and $\tau = 1000$ s, the gain instability starts to dominate when it exceeds 0.003 %. It is impossible to design receivers at this level of stability because quantum-level noise phenomena in transistors start to show up.

Moreover, the spectrum shape of the instabilities is of the form $1/\nu^\alpha$, i.e. the noise gets higher the longer the integration time is.



To tackle the $1/\nu^\alpha$ noise, Robert Dicke proposed (1946) a radiometer that takes a difference between a known and unknown antenna noise sources thus cancelling the gain variations.



Robert Dicke's chopping radiometer. The receiver is connected alternately to the antenna and a thermal load. The receiver detects the average of the difference between the sky and the reference load.

(Rev.Sci.Instruments, vol.17, p268, 1946)



Plate 1.7 Preparing to make measurements with the Dicke radiometer in 1945. Left to right: R. L. Kyhl, E. R. Beringer, A. B. Vane, R. H. Dicke
(by courtesy of R. H. Dicke, Princeton University)

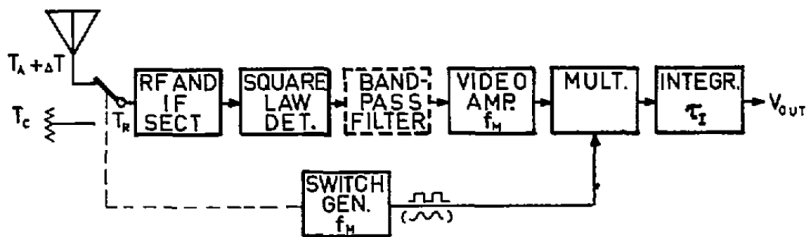


Fig. 4—Dicke receiver (band-pass filter optional).

From Kraus: Radio astronomy

The minimum detectable signal becomes:

$$\Delta T_{min} = 2T_{sys} \sqrt{\frac{1}{\Delta \nu \tau} + \left(\frac{T_{sky} - T_{ref}}{T_{sys}} \cdot \frac{\Delta G}{G} \right)^2}, \quad (6)$$

Therefore the gain variations are cancelled **totally** if

- ▶ the reference and antenna noise temperatures are equal and
- ▶ the switching frequency is sufficiently high so that the gain can be considered nearly constant in the sky-reference cycle.

Graham's receiver

The ultimate sensitivity is halved because only half of the observing time is used to observe the source and two noise-like signals are differenced.

Better performance (by $\sqrt{2}$) is achieved using two receivers:

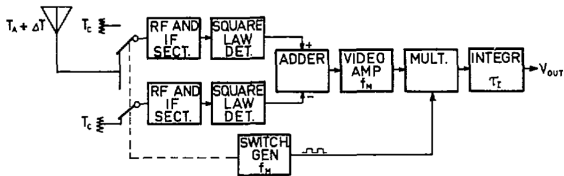


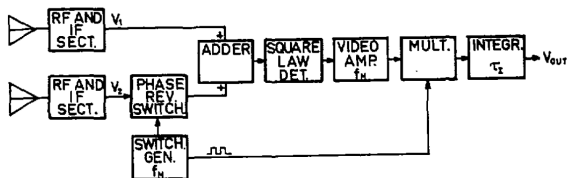
Fig. 8—Graham's receiver.

(From Kraus: Radio astronomy)

However, the loss and finite chopping frequency of the switch lead to reduced sensitivity and eventual drifts.

Interferometer

The switch can be avoided by using an interferometer:



(From Kraus: Radio astronomy)

However, it requires two separate antennas and receiving systems.

Correlation radiometer

Correlation principle can be used also in a single receiver:

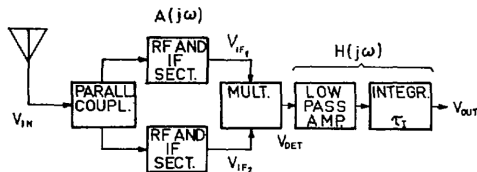
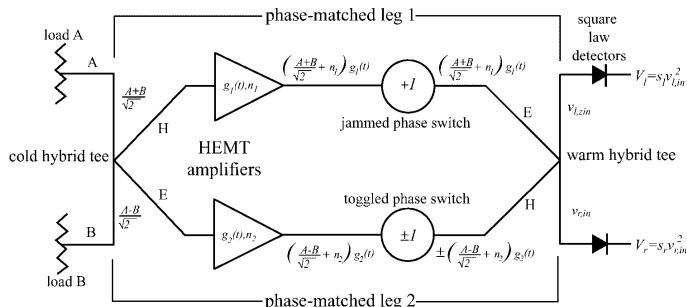


Fig. 9—Correlation receiver.

(From Kraus: Radio astronomy)

Here the comparison is instantaneous (more accurately of the order of $1/\Delta\nu$) but it does not cancel changing sky noise as when switching type receivers when reference load is replaced by a second feedhorn.

Pseudocorrelation receiver



A pseudocorrelation radiometer in its simplest form. It allows a differential measurement without requiring an active switch before the first RF gain stage. (From Jarosik et al. 2003, 145:413 - 436)

If we assume that

$$\overline{AA} \propto kT_{sky} \Delta\nu, \quad \overline{BB} \propto kT_{ref} \Delta\nu \quad (7)$$

$$\overline{AB} = 0, \quad \overline{A} = \overline{B} = 0 \quad (8)$$

Signals at the amplifier inputs after the 'magic tee' coupler are

$$\frac{A+B}{\sqrt{2}} \text{ and } \frac{A-B}{\sqrt{2}} \quad (9)$$

Voltages at the amplifier outputs are

$$v_1 = \left(\frac{A+B}{\sqrt{2}} + n_1 \right) g_1(t) \text{ and } v_2 = \left(\frac{A-B}{\sqrt{2}} + n_2 \right) g_2(t) \quad (10)$$

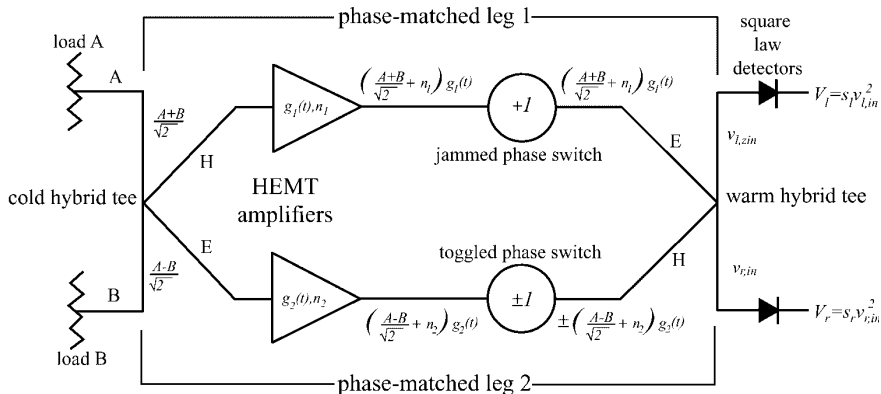
Voltages after the second magic tee:

$$v_{l,in} = \frac{1}{\sqrt{2}} \left(\frac{A+B}{\sqrt{2}} + n_1 \right) g_1(t) \pm \frac{1}{\sqrt{2}} \left(\frac{A-B}{\sqrt{2}} + n_2 \right) g_2(t) \quad (11)$$

and

$$v_{r,in} = \frac{1}{\sqrt{2}} \left(\frac{A+B}{\sqrt{2}} + n_1 \right) g_1(t) \mp \frac{1}{\sqrt{2}} \left(\frac{A-B}{\sqrt{2}} + n_2 \right) g_2(t) \quad (12)$$

The sign before the second term refers to the state of the phase switch in one of the legs.



After detectors the voltages are

$$V_l = s_l v_{l,in}^2 \text{ and } V_r = s_r v_{r,in}^2, \quad (13)$$

where s_l and s_r are responsivities of the detectors and assumed equal (s).

And further

$$V_l = \frac{s}{2} \left\{ \left(\frac{A^2 + B^2}{2} + n_1^2 \right) g_1^2(t) + \left(\frac{A^2 + B^2}{2} + n_2^2 \right) g_2^2(t) \mp (A^2 - B^2) g_1(t) g_2(t) \right\} \quad (14)$$

$$V_r = \frac{s}{2} \left\{ \left(\frac{A^2 + B^2}{2} + n_1^2 \right) g_1^2(t) + \left(\frac{A^2 + B^2}{2} + n_2^2 \right) g_2^2(t) \pm (A^2 - B^2) g_1(t) g_2(t) \right\} \quad (15)$$

and finally

$$V_l - V_r = \mp s (A^2 - B^2) g_1(t) g_2(t) \quad (16)$$

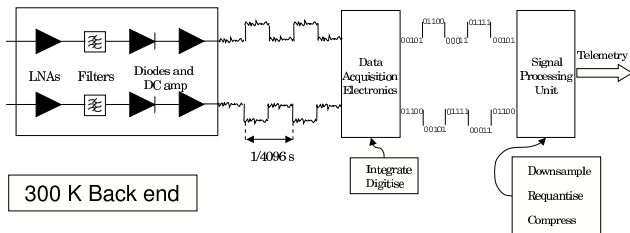
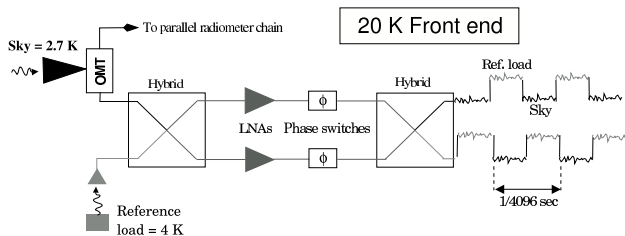
$$V_l - V_r = \mp s(A^2 - B^2)g_1(t)g_2(t) \quad (17)$$

So what's the big deal?

$$V_l - V_r = \mp s(A^2 - B^2)g_1(t)g_2(t) \quad (17)$$

So what's the big deal?

$(A^2 - B^2)$ is much smaller than the sum of the first terms, so the effect of gain variations is smaller.



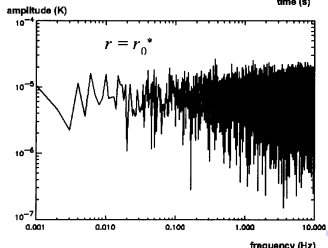
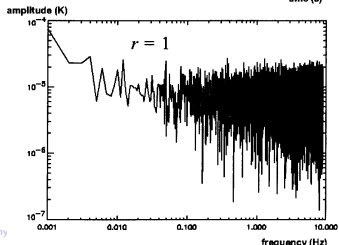
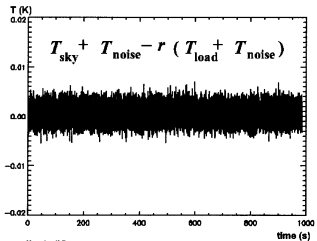
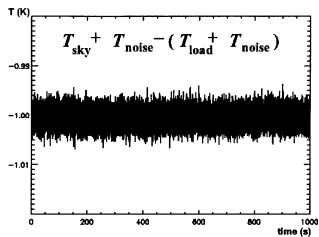
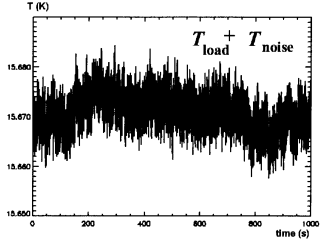
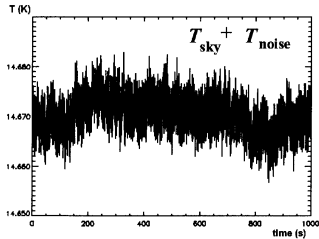
Baseline Planck LFI pseudo-correlation radiometer. (From Mennella et al. 2003, A&A, 410, 1089)

The effect of gain variations are further reduced if the signals are balanced.

Balancing can be done in software simply by fulfilling the following condition:

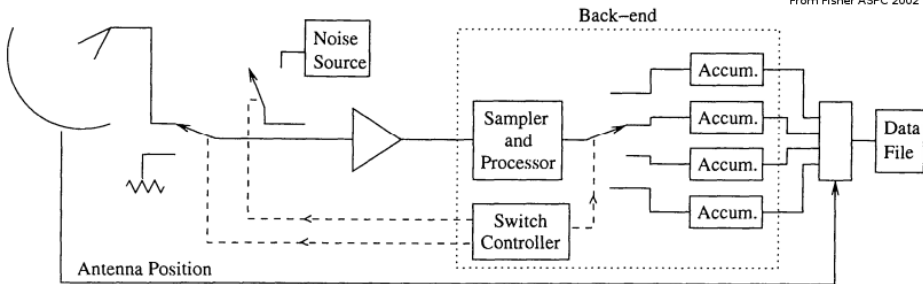
$$r = \frac{T_{\text{sky}} + T_{\text{noise}}}{T_{\text{ref}} + T_{\text{noise}}}, \quad (18)$$

where r is the gain ratio between channels.

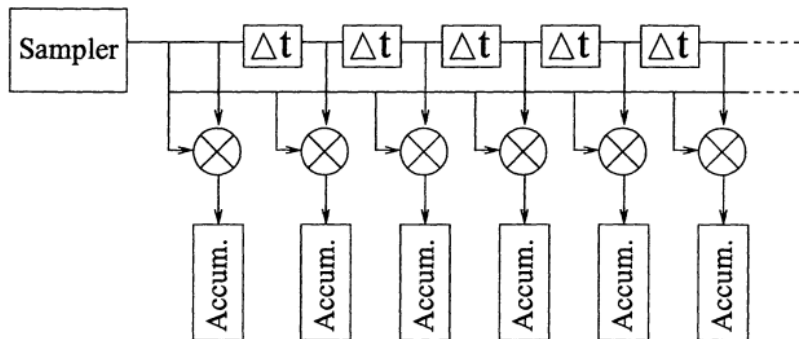


Typical continuum backend

From Fisher ASPC 2002



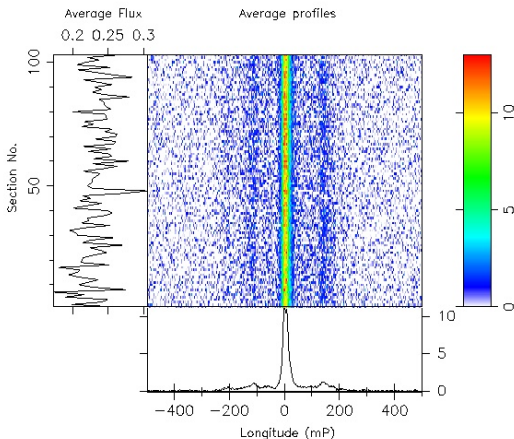
Spectrometry by autocorrelator: after integration, the lags are Fourier transformed



From Fisher ASPC 2002

Figure 4. Hardware block diagram of an autocorrelator. The Δt boxes represent time delays and the crosses represent multiplications.

Pulsar backends: pulse stacking and averaging



The data set
used in making
a new template
profile (bottom)

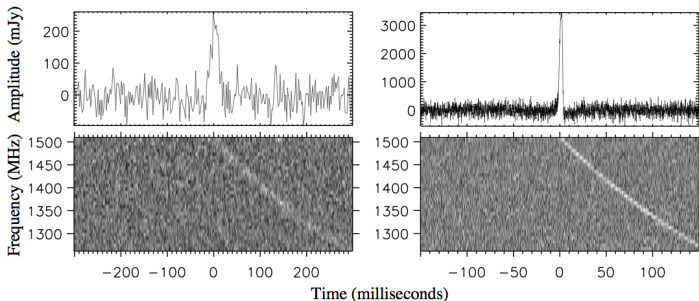
J0437-4715
->ATCA
Sky_f 1410.25 MHz
to 1410.25 MHz
Bins: 512
Program Version
red_px_M_1.0
Parent data_file:
J0437-4715_51833_1
MJD_0:51833.8141778
data/J0437_51833_1S

#journin 24-Oct-2000 16:52

To lower noise and increase sensitivity, the pulses are stacked and averaged in the backend.

Pulsar backends: interstellar dispersion compensation

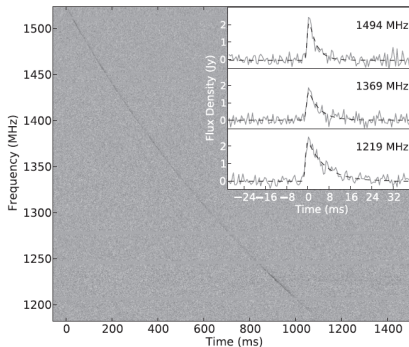
Interstellar plasma causes different delay at different frequencies (dispersion). Backend compensates this and the pulses can be integrated also over frequency



PSR J1443-60 and PSR J1819-1458 ($P = 4.26$ s) are neutron stars in our galaxy and they belong to class of rotating radio transients (RRATs) first discovered in 2006. Image credit: M. McLaughlin.

Fast Radio Bursts (FRB)

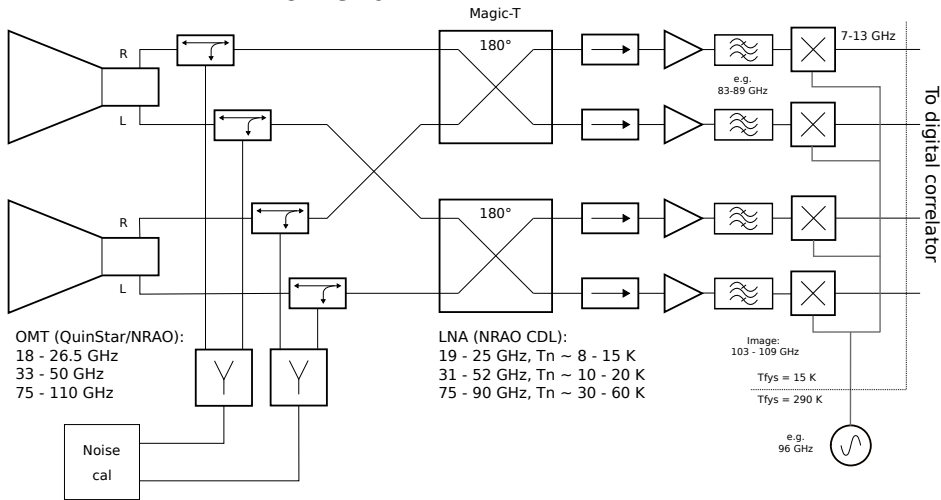
Fig. 2. A dynamic spectrum showing the frequency-dependent delay of FRB 110220. Time is measured relative to the time of arrival in the highest frequency channel. For clarity we have integrated 30 time samples, corresponding to the dispersion smearing in the lowest frequency channel. (**Inset**) The top, middle, and bottom 25-MHz-wide dedispersed subband used in the pulse-fitting analysis (2); the peaks of the pulses are aligned to time = 0. The data are shown as solid gray lines and the best-fit profiles by dashed black lines.



First FRB was detected in 2007, origin is still unknown. Size of emission region is no larger than a few hundred kilometers. If the origin is at cosmological distances, it is difficult to explain the extreme brightness. Could be colliding black holes, magnetars. . . ?

Metsähovi continuous comparison polarimeter

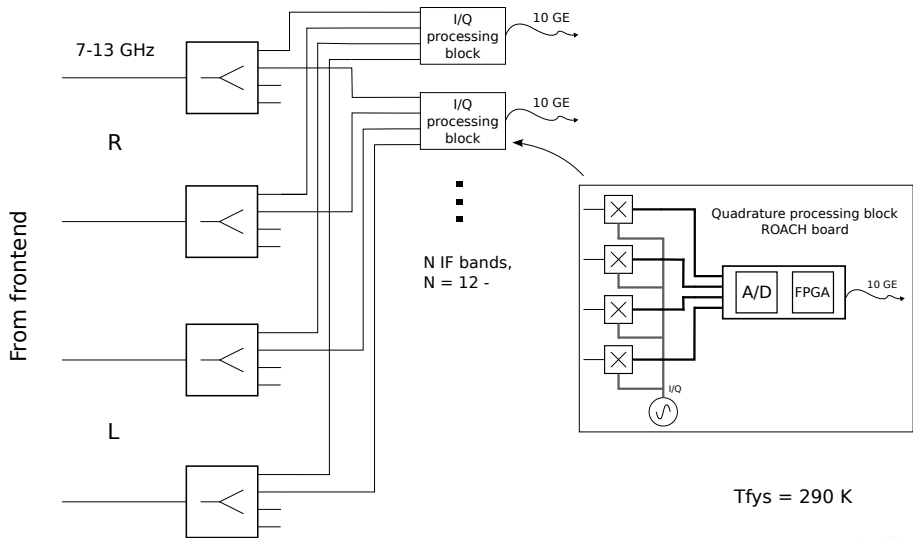
Frontend



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Metsähovi continuous comparison polarimeter

Digital polarization correlator



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More information on backends

More about backends:

<http://cdsads.u-strasbg.fr/abs/2002ASPC..278..123H>

Spectrometers:

<http://cdsads.u-strasbg.fr/abs/2002ASPC..278..113F>