Radio Receivers

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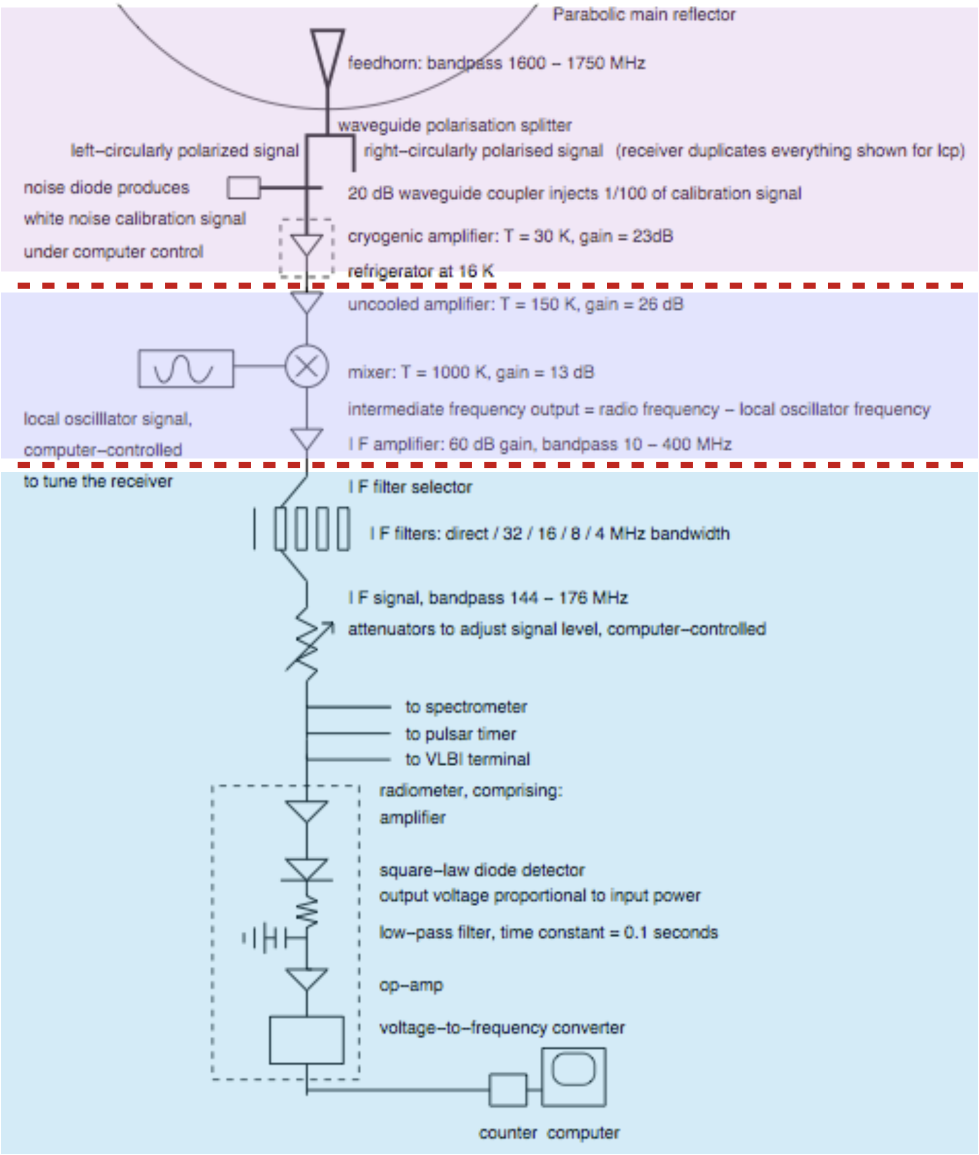
Overview

- Receiver architectures
  - Continuum
  - Spectral line
  - Interferometer
- Typical components:
  - OMT
  - LNA
  - Filters
  - Mixers
- Cryogenic systems
- System Temperature

Receiver system components

- Accepts signal from feed horn/antenna
- Gain…gain, gain , gain.
- Filters to define the frequency band
- Downconversion to more convenient frequency
- Power detection (auto- or cross-correlation)



Receiver architectures

Single-dish continuum: it's all about $1/f$

- Simple radiometer
- Dicke switch
- Noise-adding
- CW-adding
- Pseudo-correlation

Single-dish spectral line: it's all about baseline subtraction

- Autocorrelation
- FFT

Interferometers: it's all about correlation

Dicke-switched radiometer

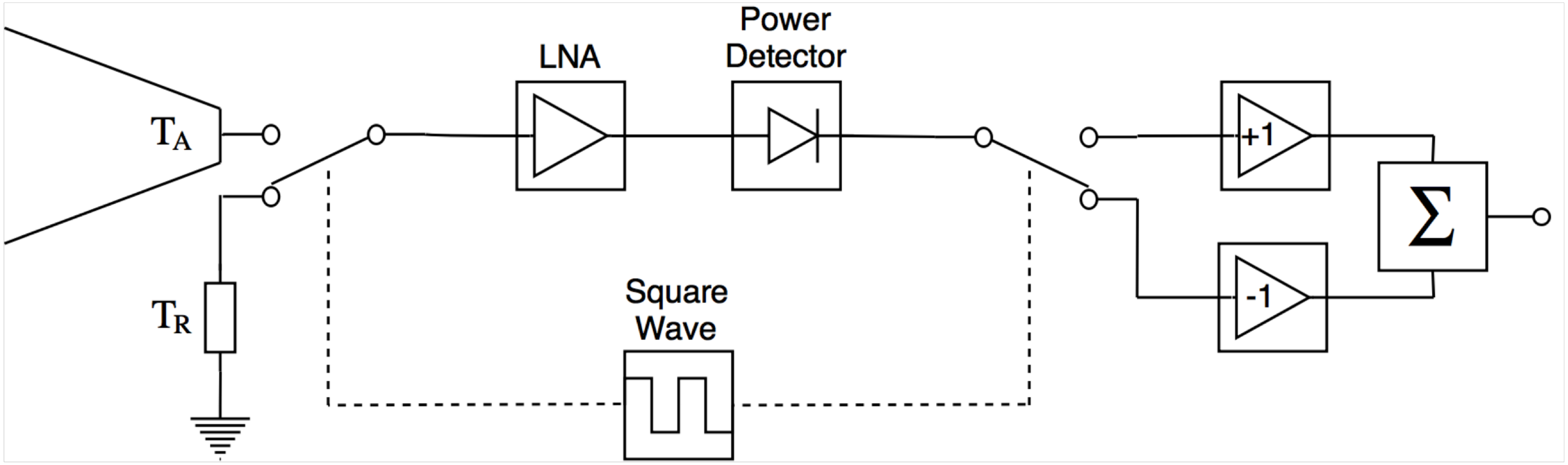


Figure 5.4: Schematic of a Dicke receiver which switches between the antenna signal T_{A} and a reference load T_{R}. The two switches are controlled by a square wave signal with a duty cycle of 50 percent. The reference signal is then subtracted from the antenna signal in the integration block.

$$\Delta T = 2T_{\mathrm{sys}}\sqrt{\frac{1}{\tau\Delta\nu} + \left(\frac{\Delta G_{\mathrm{res}}}{G}\right)^2},$$

Figures from Alex Pollak DPhil thesis, 2018

Pseudo-correlation radiometer

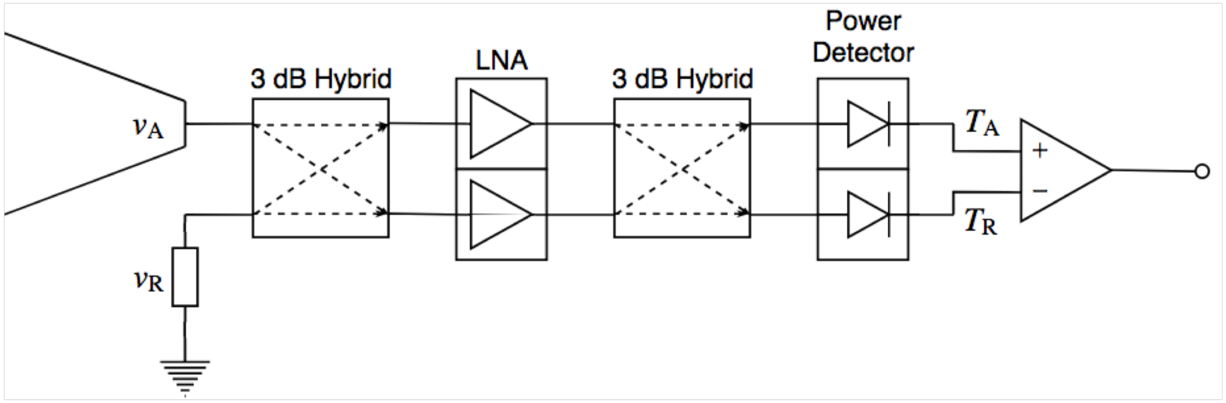


Figure 5.5: Schematic of a pseudo-correlation receiver using a 3 dB hybrid to combine the antenna and reference signal before the amplification. The combined signals go through both amplifiers and are then separated again using a second hybrid. The output signals are the antenna signal and the reference signal, both signals experienced the same gain fluctuations and the reference signal can be used to correct the antenna signal.

$$\Delta T = \sqrt{2} T_{\text{sys}} \sqrt{\frac{1}{\tau \Delta \nu} + \left(\frac{\Delta G_{\text{res}}}{G} \right)^2}.$$

Figures from Alex Pollak DPhil thesis, 2018

Noise-adding radiometer

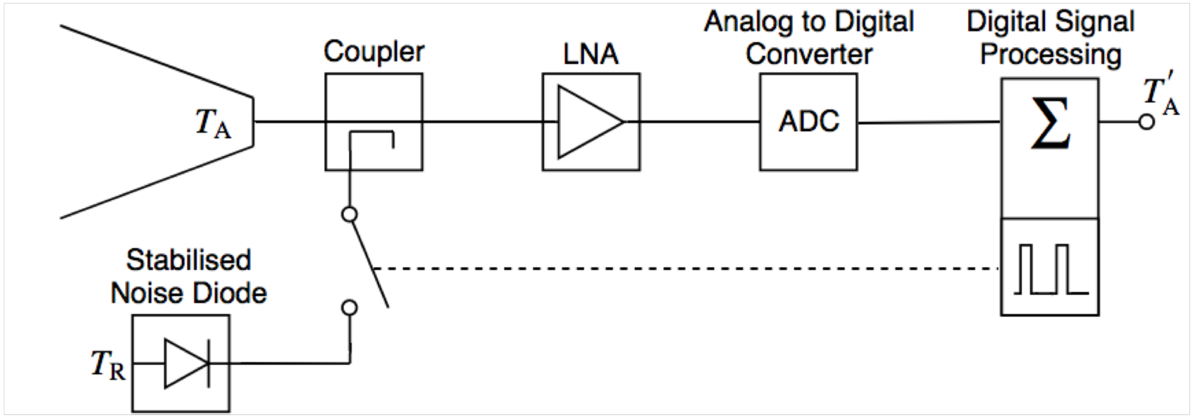


Figure 5.6: Schematic of a noise-adding receiver using a stabilised noise diode signal to track the gain fluctuations. The noise signal is added via a coupler and modulated with a switch. The duty-cycle and the modulation frequency is controlled by the digital backend of the receiver, which applies either an online calibration or writes the measured gain together with the antenna data to disk. Hence, the gain correction can be applied offline.

$$\Delta T = K T_{\mathrm{sys}} \sqrt{\frac{1}{\tau \Delta \nu} + \left(\frac{\Delta G_{\mathrm{res}}}{G}\right)^2}.$$

$1 < K \leq \sqrt{2}$ depending on the applied duty-cycle of the reference signal

Figures from Alex Pollak DPhil thesis, 2018

CW-adding radiometer

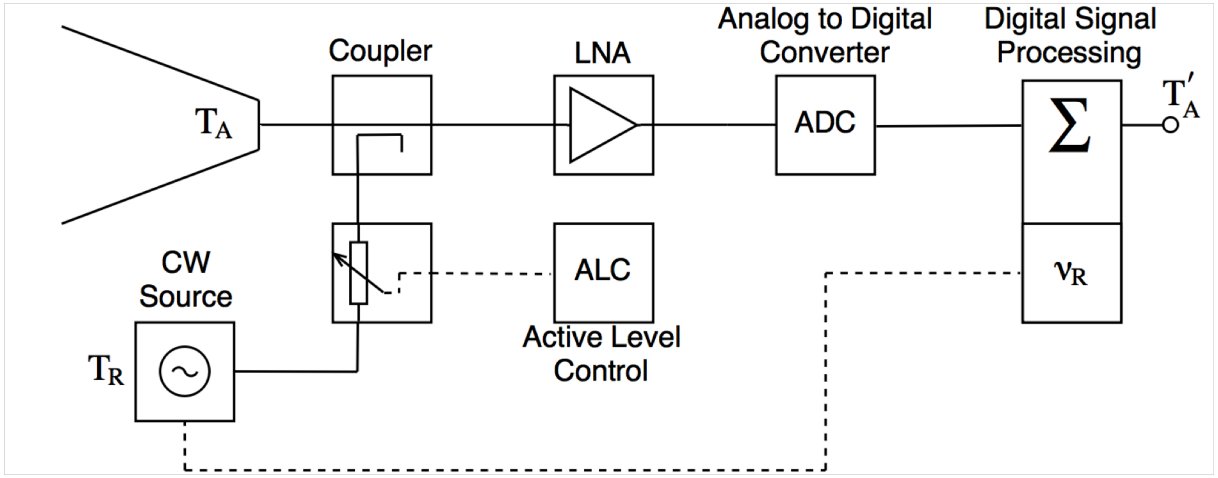


Figure 5.7: Schematic of a continuous-wave stabilised receiver using an amplitude stabilised local oscillator to track gain fluctuations. The reference signal is added via a coupler and stabilised with an analogue active level control loop. The local oscillator frequency can be controlled by the digital backend of the receiver, allowing to map the entire receiver band with the reference signal. The measured gain fluctuation is either corrected in real time or written to disk allowing for an offline correction.

$$\Delta T = T_{\rm sys}\sqrt{\frac{1}{\tau\Delta\nu} + \left(\frac{\Delta G_{\rm res}}{G}\right)^2}.$$

Figures from Alex Pollak DPhil thesis, 2018

Spectral line receivers

Voltage as function of time ←FT→ Voltage as function of frequency

Autocorrelate ↓ ↓ Square

Voltage autocorrelation function ←FT→ Power spectral density

- Two routes to spectral power density:
  - FFT then square
  - autocorrelate then FFT
- Wiener-Kinchin theorem

1532 Rev. Sci. Instrum., Vol. 72, No. 2, February 2001

A. I. Harris and J. Zmuidzinas

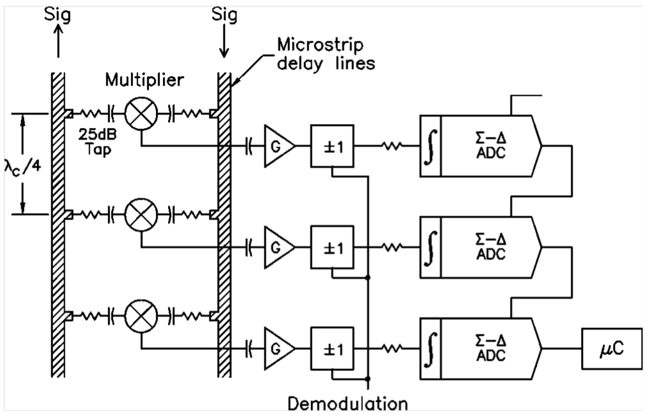


FIG. 1. Schematic view showing a section of the ''ladder'' of multipliers within WASP2 and its low-frequency signal processing electronics. Sections of microwave stripline provide propagation-time delays between fast transistor multipliers.

FFT (PFB) spectrometer

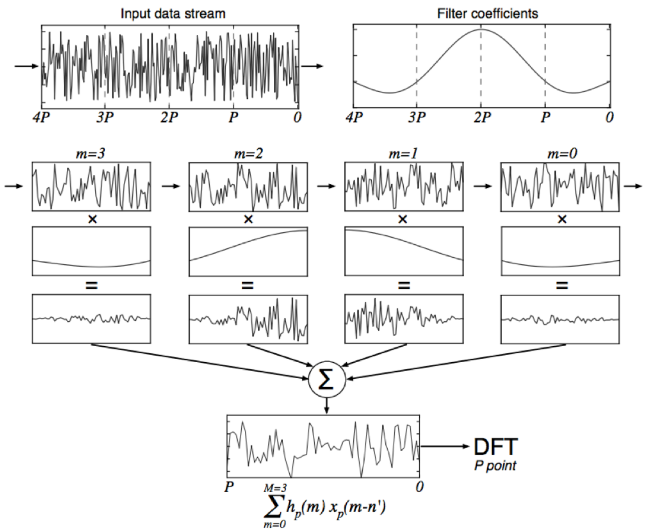
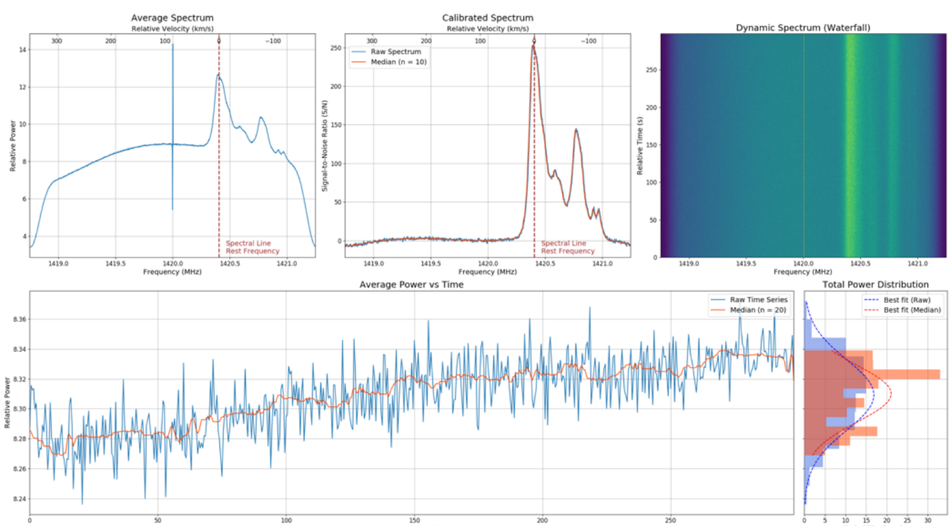


Fig. 9. Graphical representation of a polyphase filterbank, with $P = 64$ and $M = 4$ polyphase taps. Data are read in blocks of length P until $M \times P$ samples are buffered. The data and filter coefficients are then split into M taps, multiplied together, and then summed over taps. After this, a P-point DFT is computed and another P input samples are read.

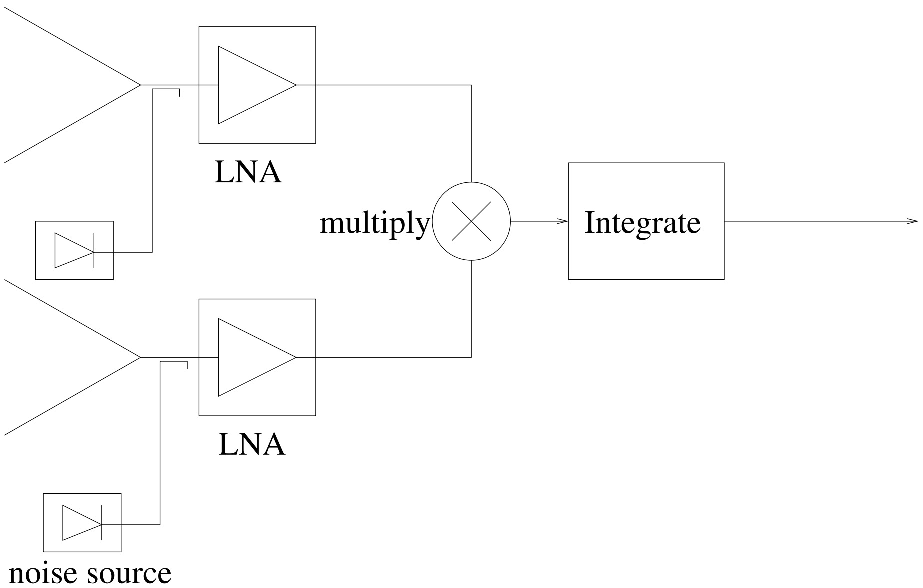


- Modern (digital) instruments use FFTs in FPGA or GPU
- Polyphase filterbank is an efficient long FFT with window to give sharp channels

github.com/0xcoto/VIRGO

Interferometer

- Interferometer multiplies and integrates (correlates) signals from two different antennas
- $1/f$ noise is uncorrelated between two gain chains
- No $1/f$ in output!
- Noise diode used for gain calibration per antenna



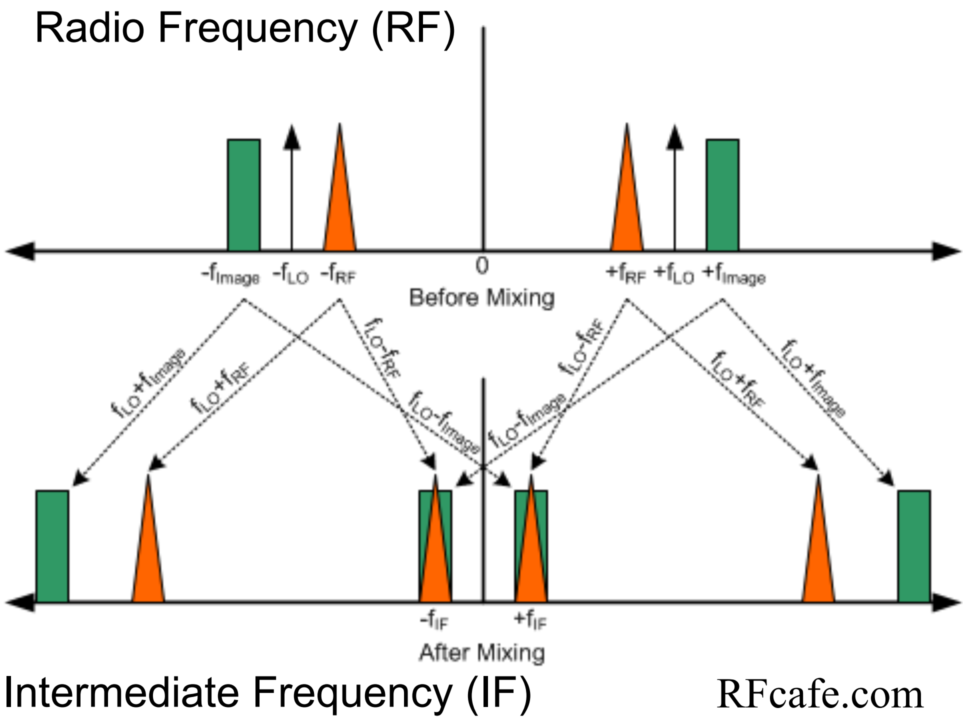
Downconversion

All previous diagrams have ignored frequency conversion…

- Very often need to shift frequency before further processing

  $\cos(A)\cos(B) = (\cos(A-B) + \cos(A+B))/2$

i.e. multiplying by a single frequency gives you the sum and difference frequencies out



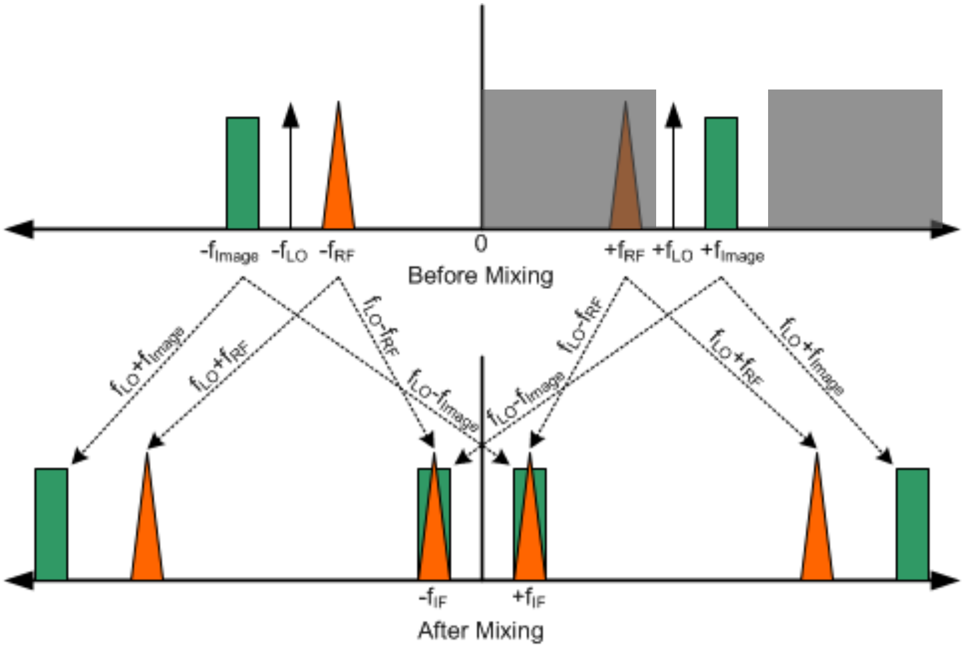
Downconversion

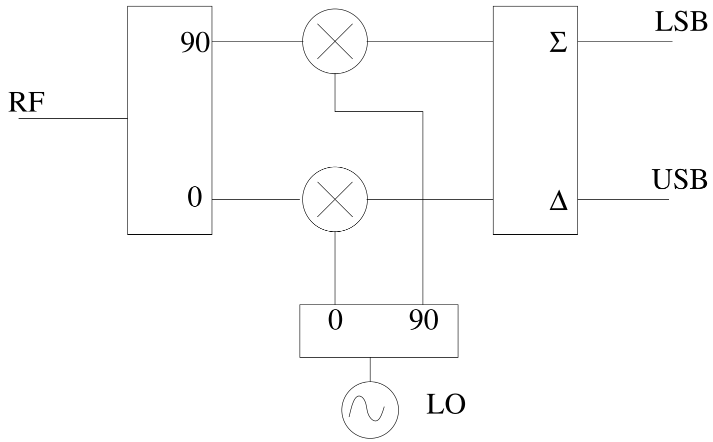
Various solutions to the image band problem:

- Use an RF filter to remove one sideband
- Use a *single-sideband mixer*:

  sin(A)sin(B) = (cos(A-B)-cos(A+B))/2

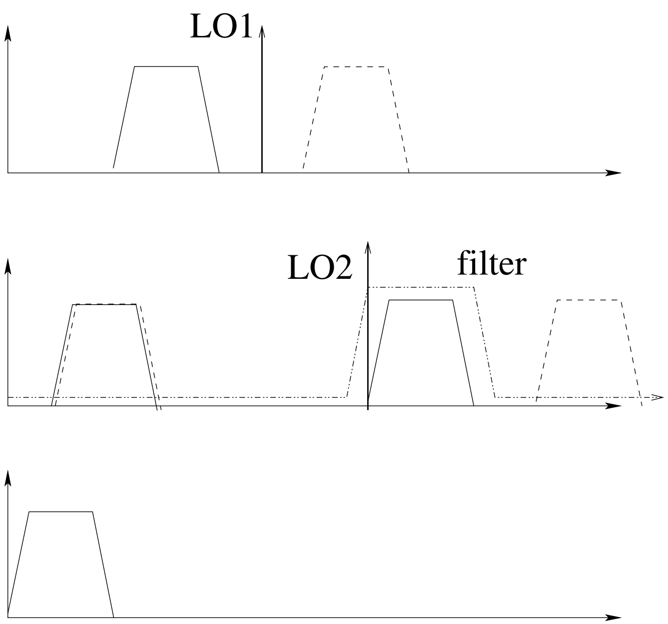
  cos(A)cos(B) = (cos(A-B) + cos(A+B))/2





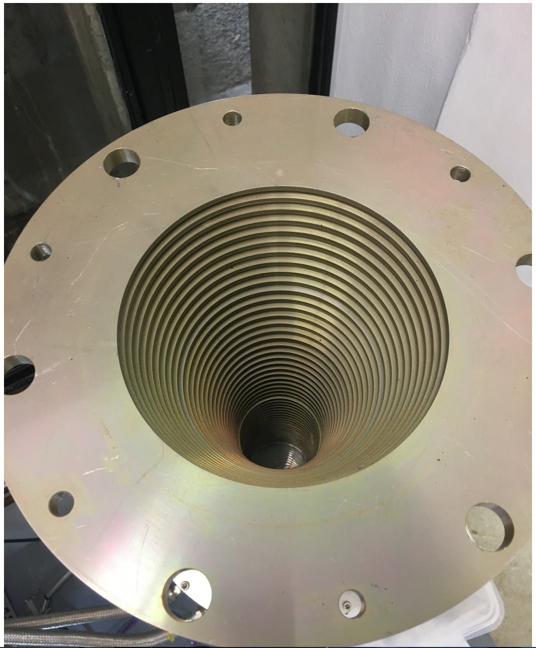
Downconversion

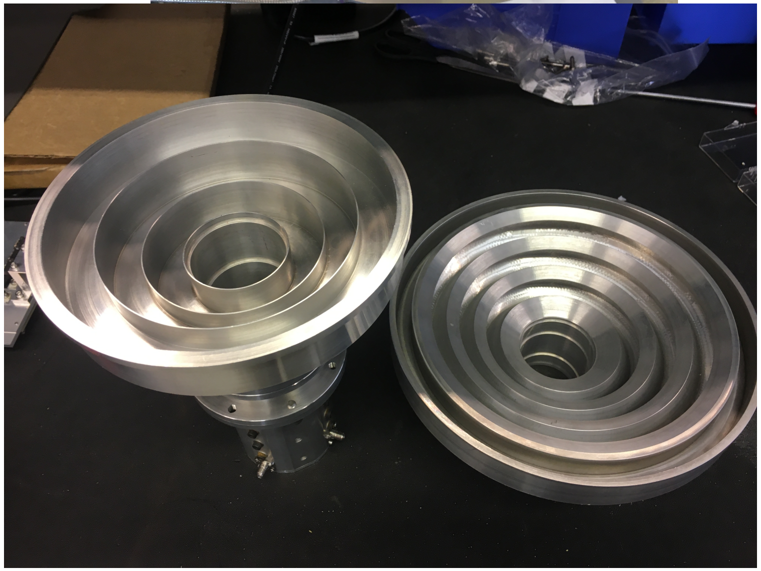
- Even more of a problem if you want to tune receiver – tuning RF filters is difficult.
- Sometimes use up-down-converter:
- Send image band far away with up-conversion, then down-convert isolated band



Feed horns

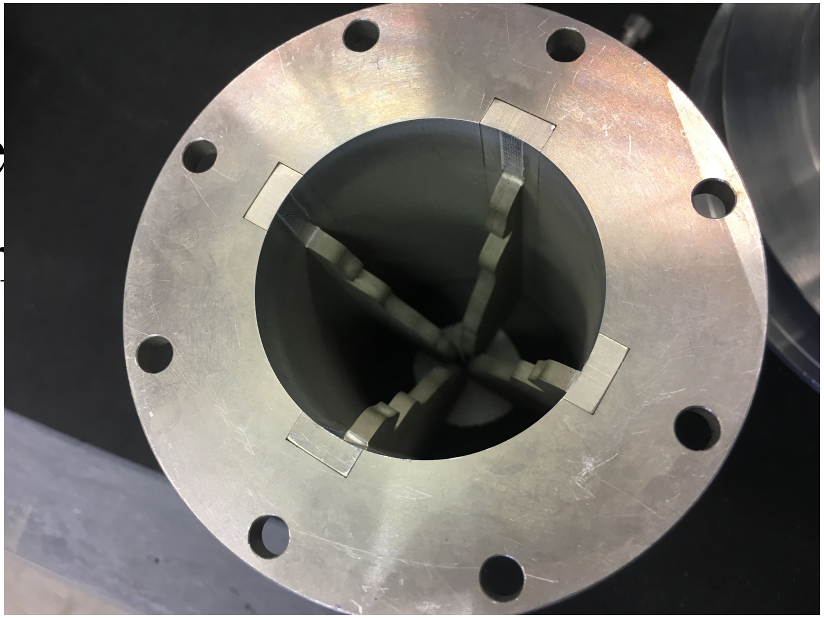
- Conceptually part of the antenna…physically often part of the receiver
- Corrugated horns give beams with very circular pattern and low cross-polarization, but narrow beam
- Wide angle horns use choke rings to control pattern

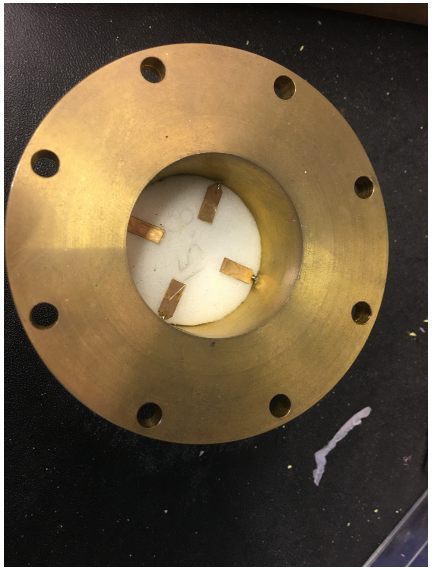




Ortho-mode transducers

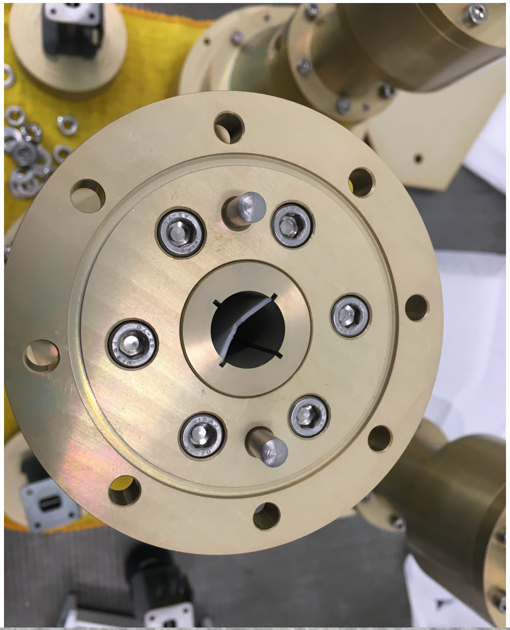
- Extract orthogonal polarizations from waveguide
- Various designs depending on requirements… bandwidth, w/g or coax output.
  - Quad-ridge
  - Turnstile
  - T-junction
  - 4-probe

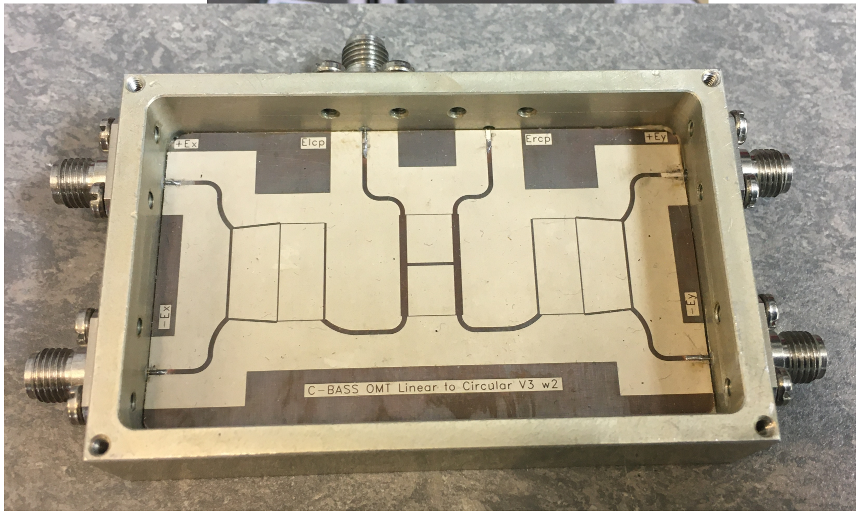




Polarizers

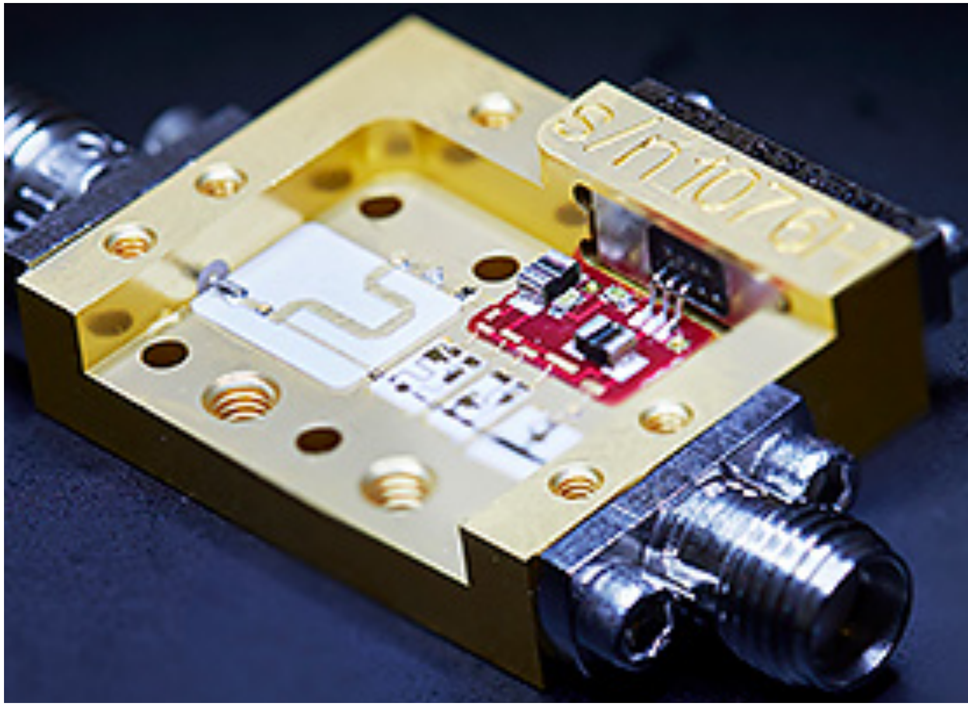
- Most OMTs extract linear polarizations – what if you want circular?
- Polarizers convert linear to circular by delaying one polarization by 90 deg
- Dielectric or waveguide retarder.
- Or, combine polarizations after OMT



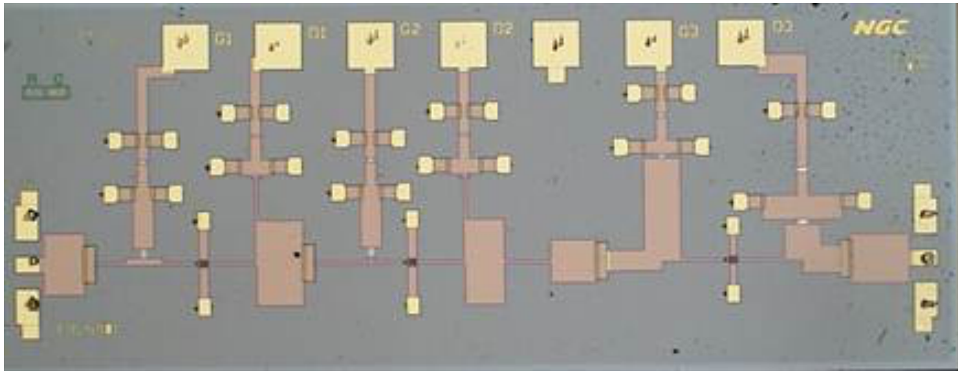


Low Noise Amplifiers

- Dominant technology is the High-Electron Mobility Field-Effect Transistor (HEMT)
- Usually uses a III-V semiconductor (GaAs or InP) – sometimes Si or SiGe
- HEMTs have very low noise when matched to correct impedance
- Narrow bandwidths – not bad at room temperature
- Wide bands – cooled
- Discrete transistors (good, expensive) – MMICs (cheaper)



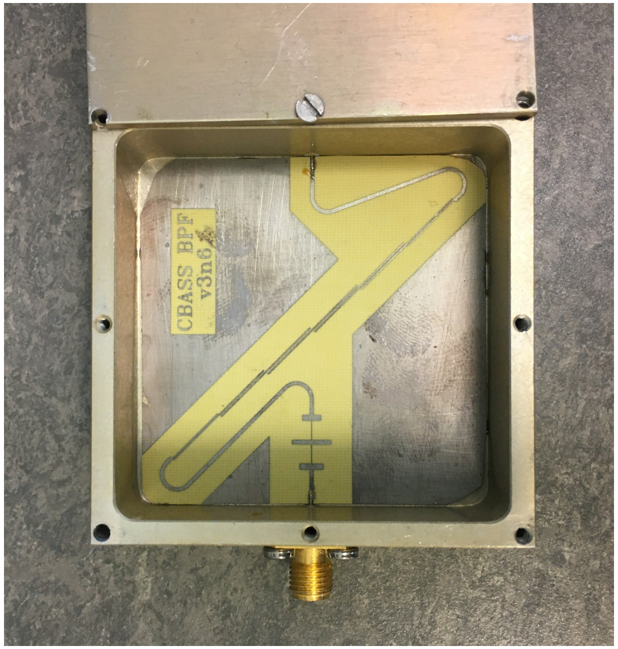
Low Noise Factory

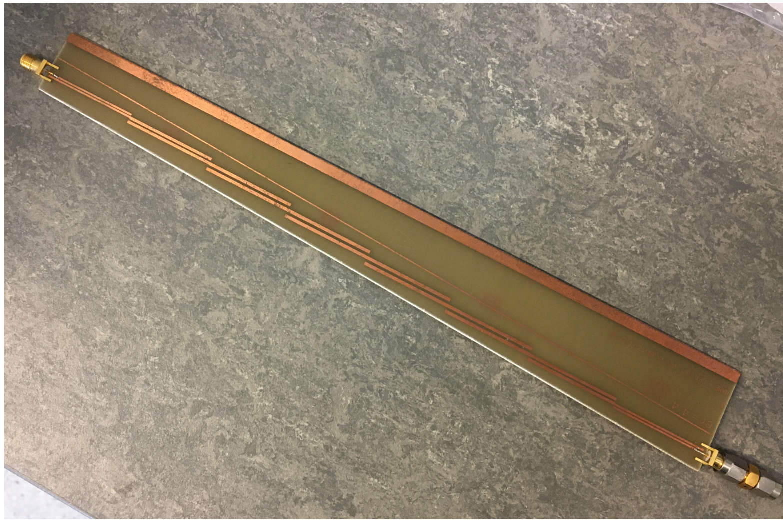


NRAO

Filters

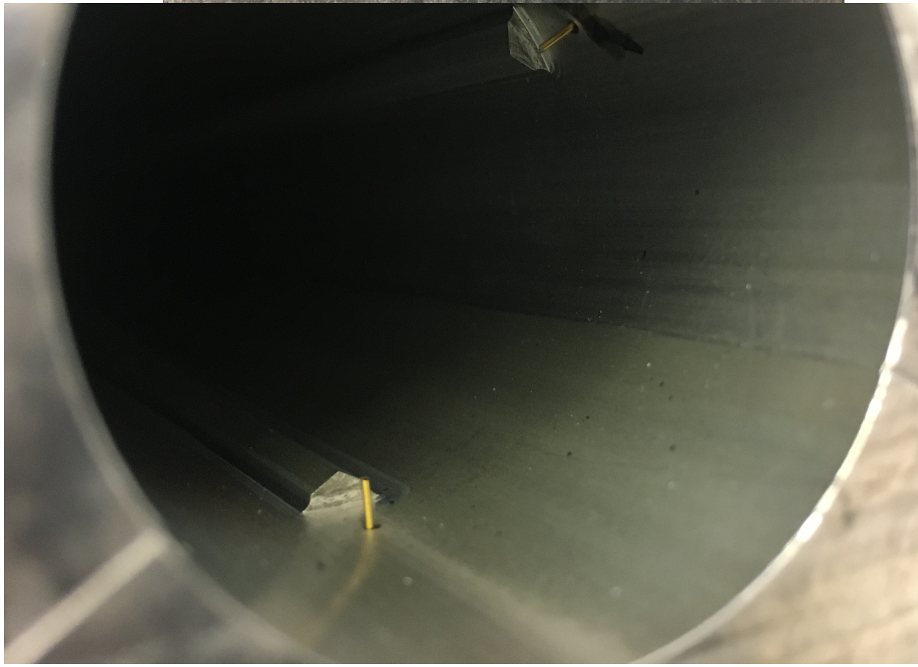
- Need to define frequency band – exclude interference
- Many types, in waveguide and planar circuits, using either transmission or coupling between tuned elements





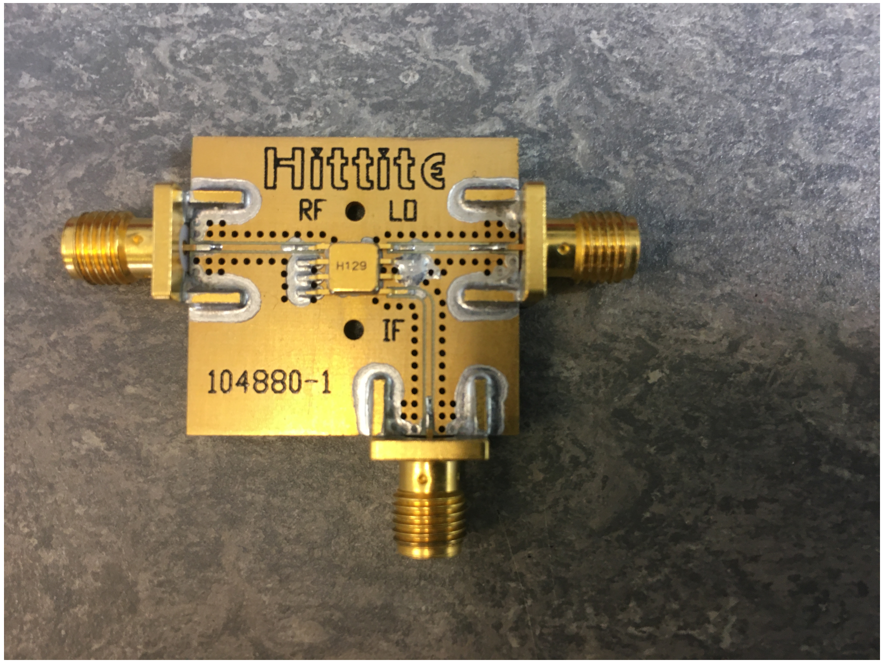
Calibration

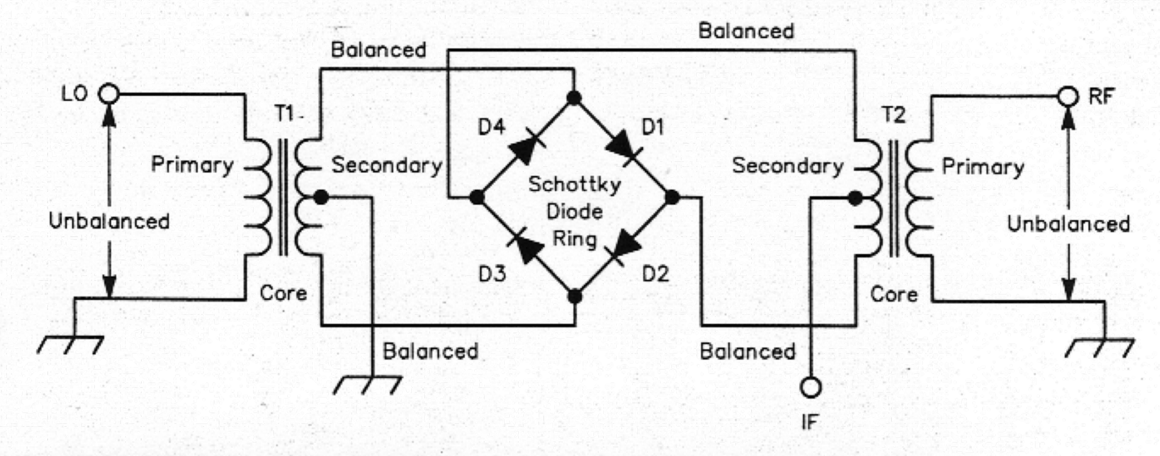
- Calibration hardware usually includes a noise source
- Broadband, stable power – generated by diode reverse breakdown
- Coupled in using coax coupler or waveguide probe



Mixers

- Needed for downconversion
- Use non-linear response of diodes to form product:
- A+B → (A+B) + $(A+B)^2$ + …
- Double-balanced mixer cancels out everything apart from AB

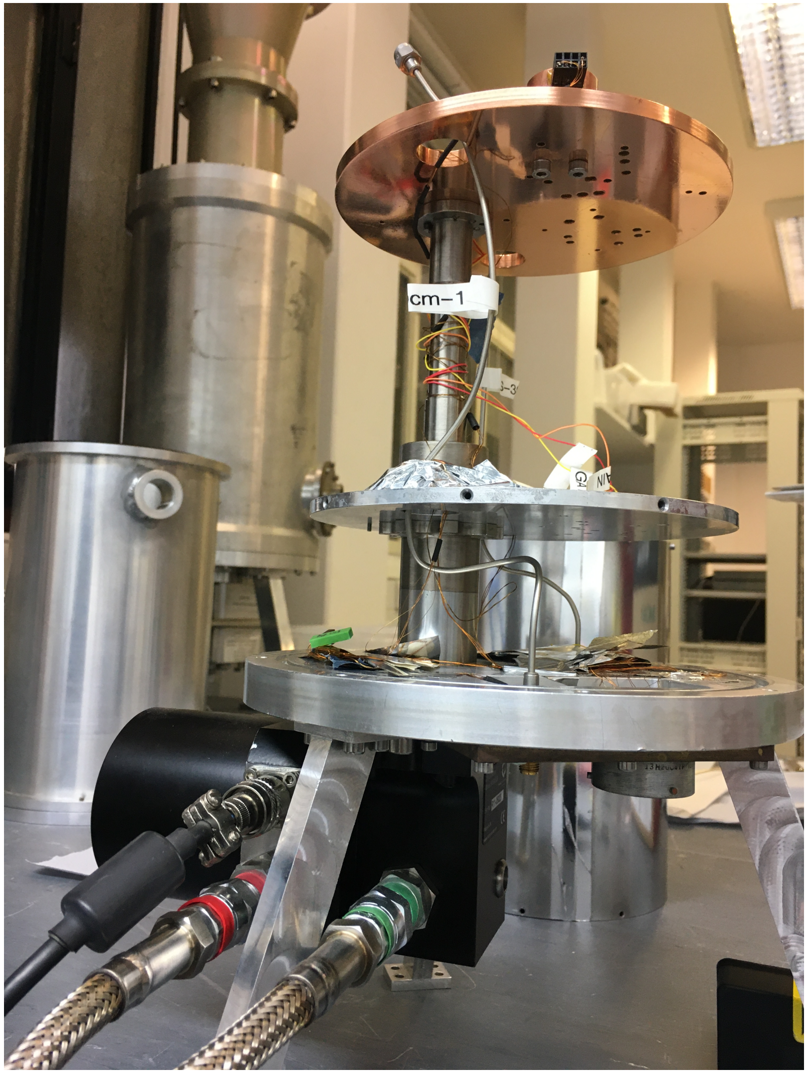




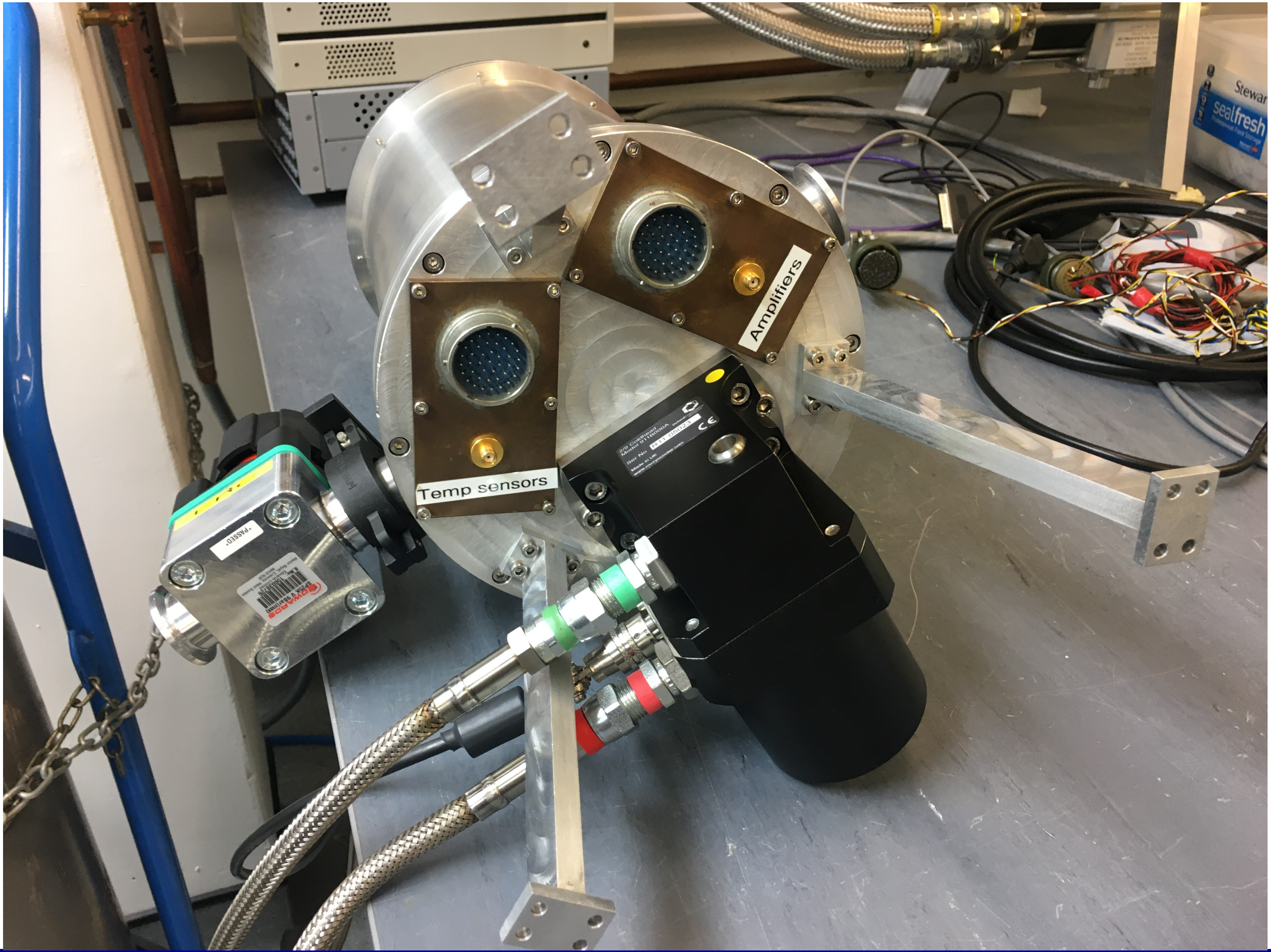
robkaljmeijer.nl

Cryogenics

- Many RA receivers cooled to reduce system temperature
- Gifford-McMahon cooler gets to ~10 K with closed cycle cooler
- Design for high vacuum (clean, low outgassing, hermetic connectors) and thermal management (polished heatshields, multi-layer insulation)



Inside a cryostat…



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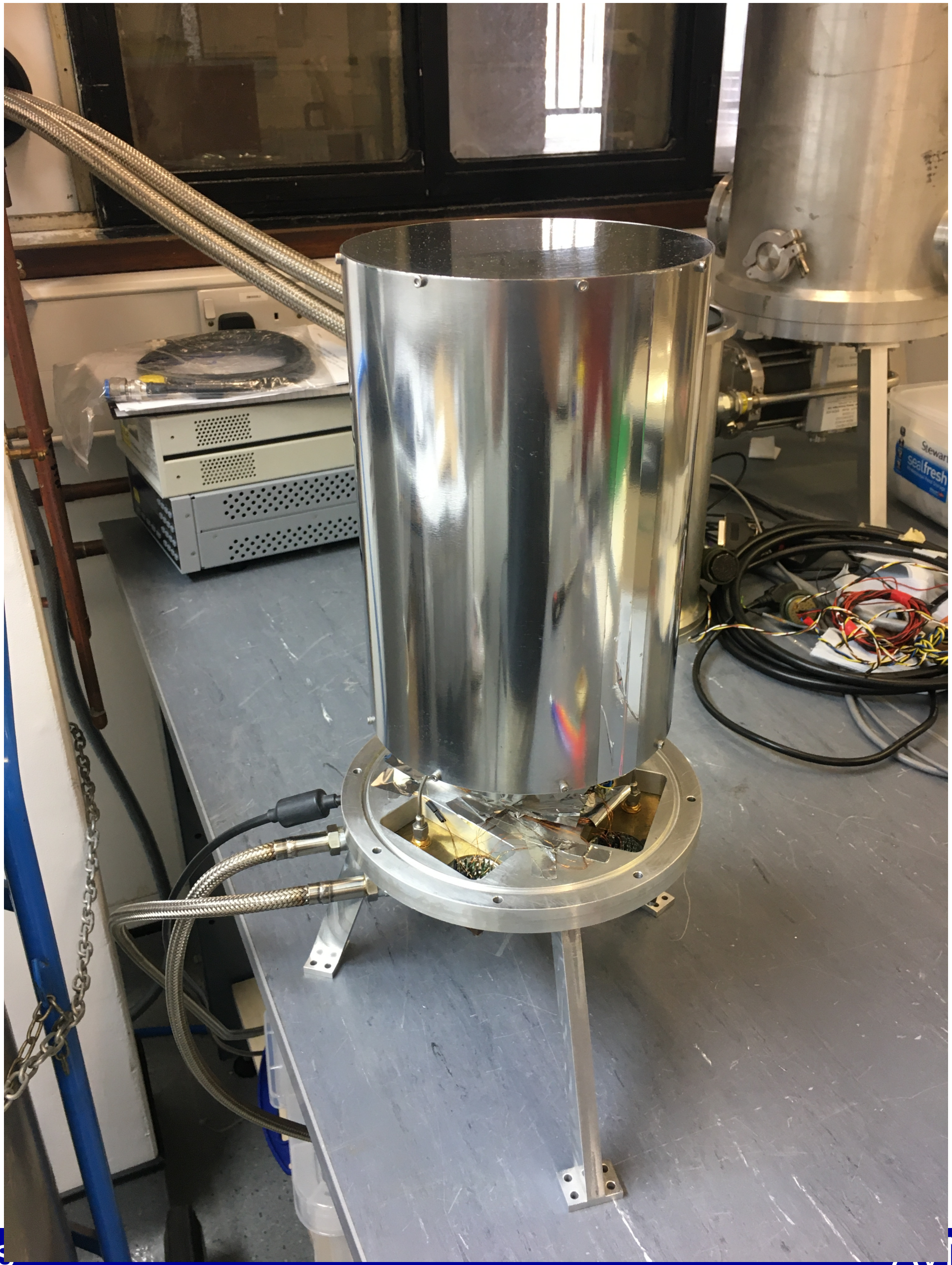

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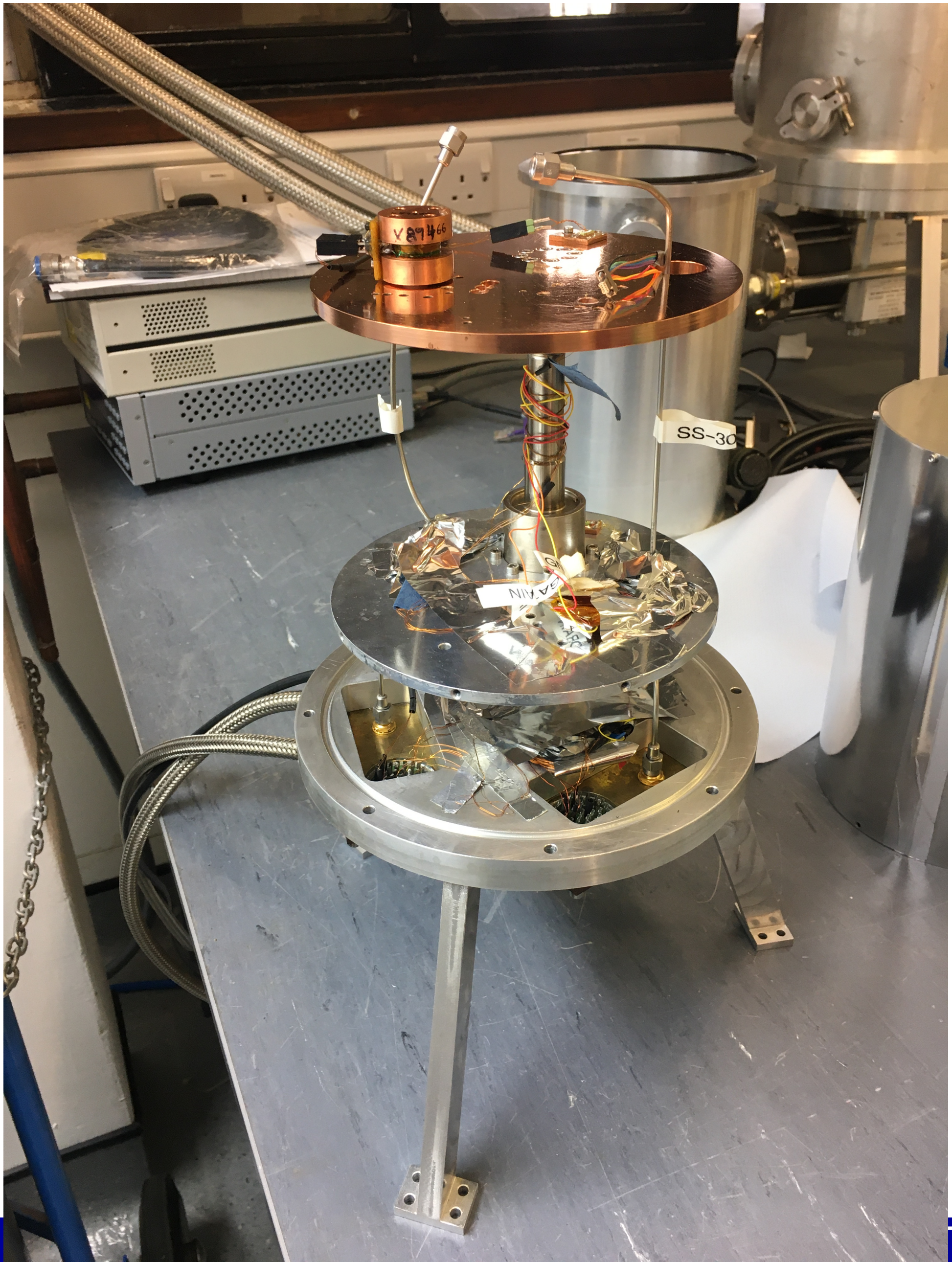

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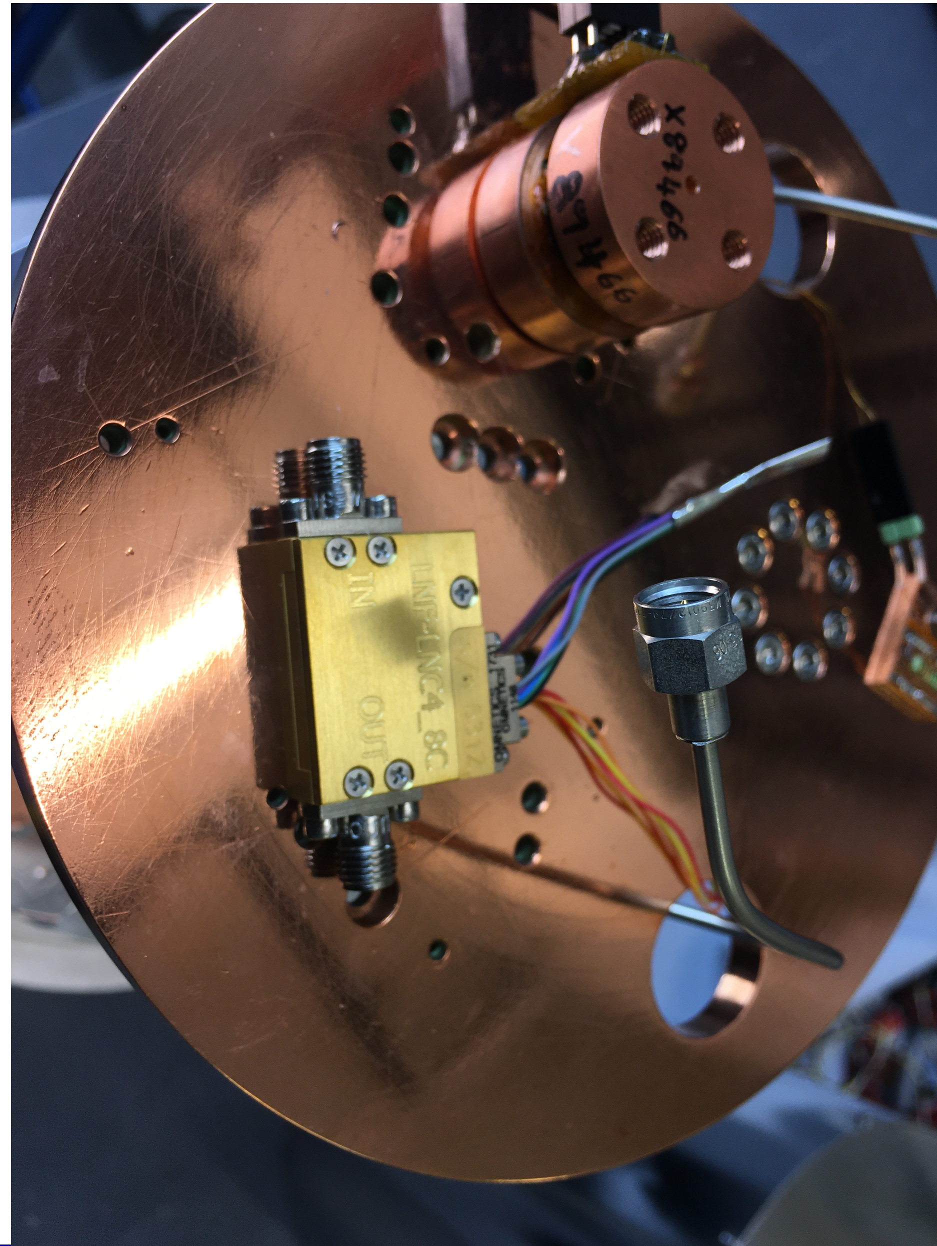

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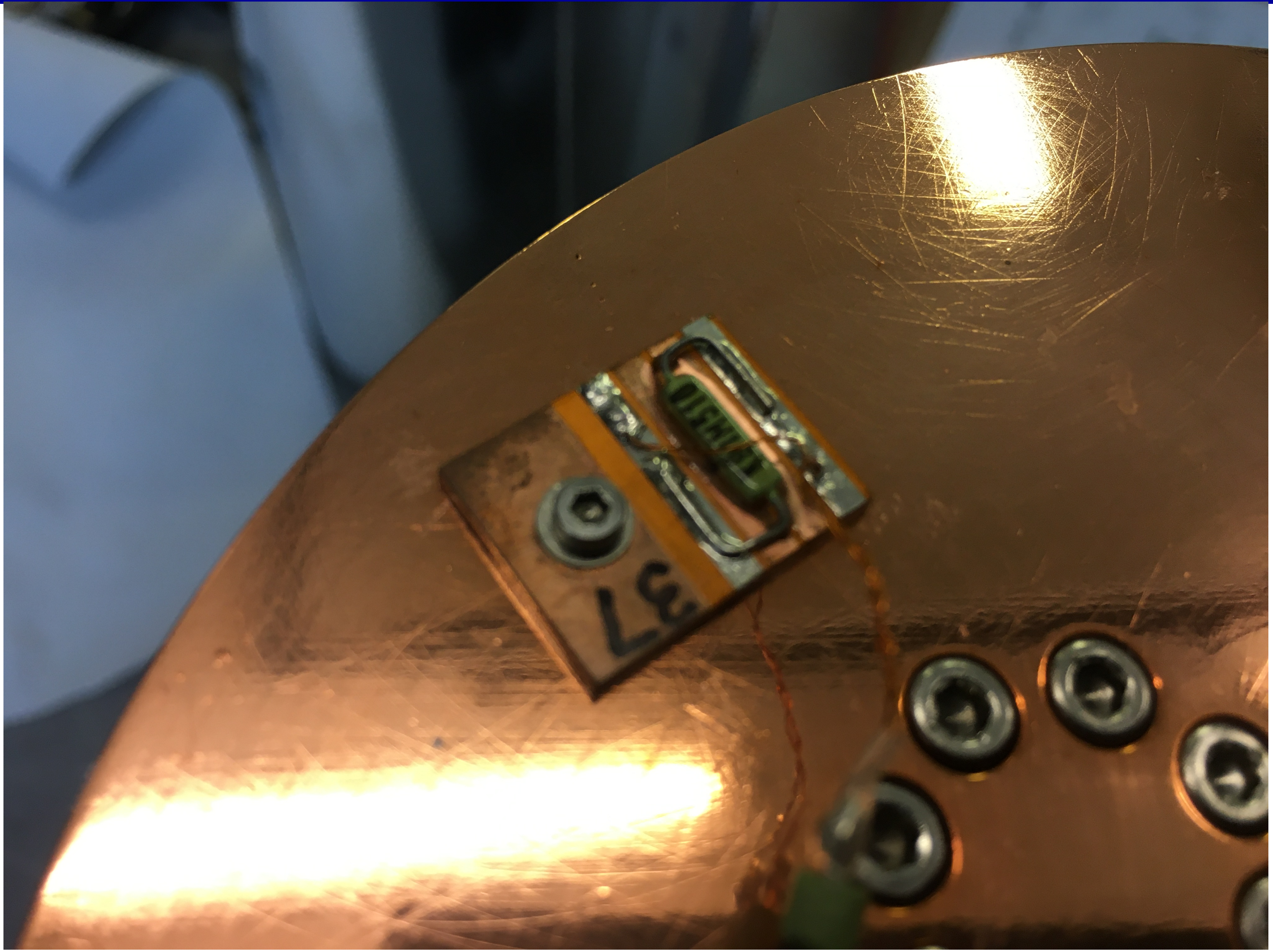
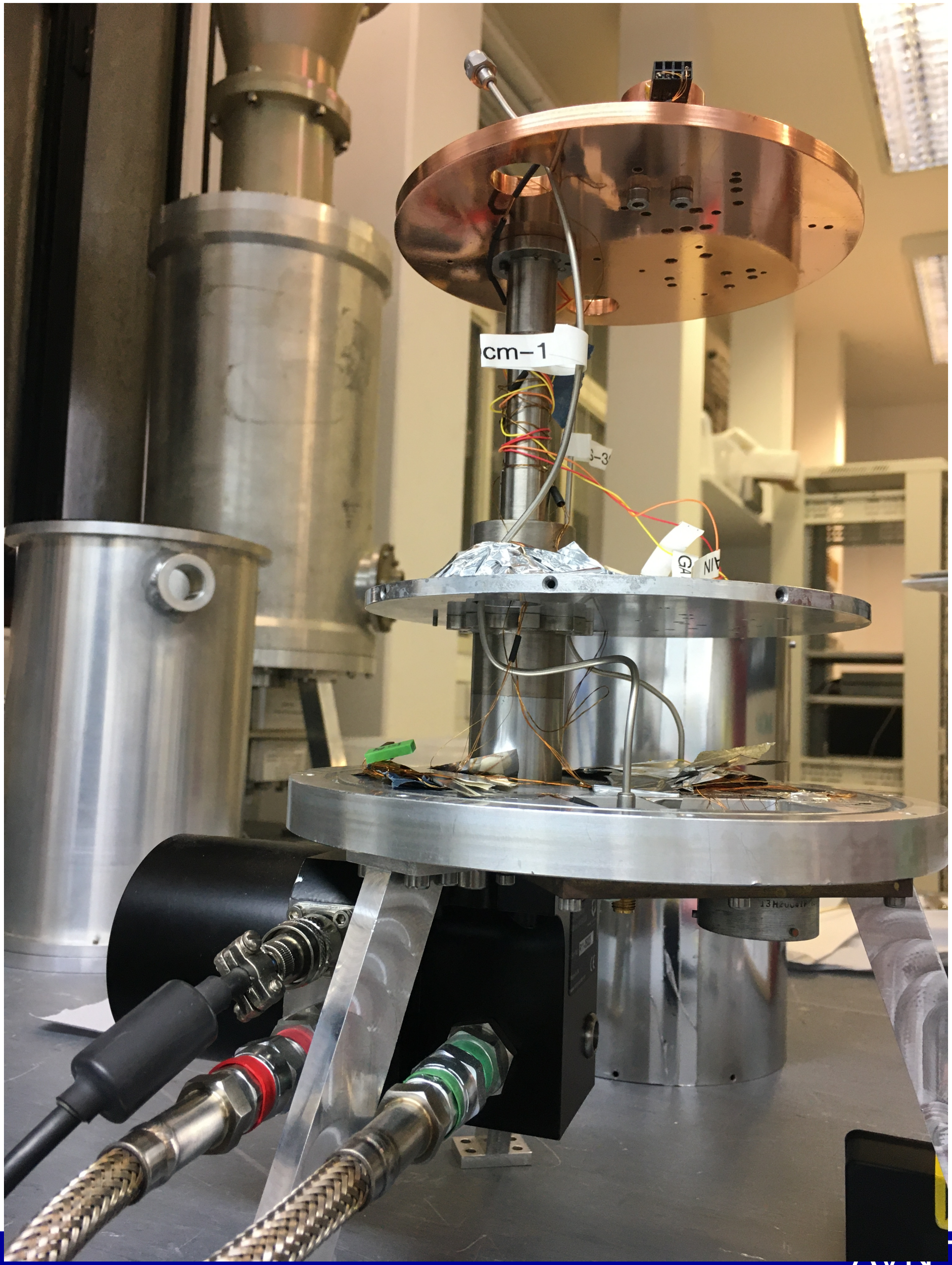
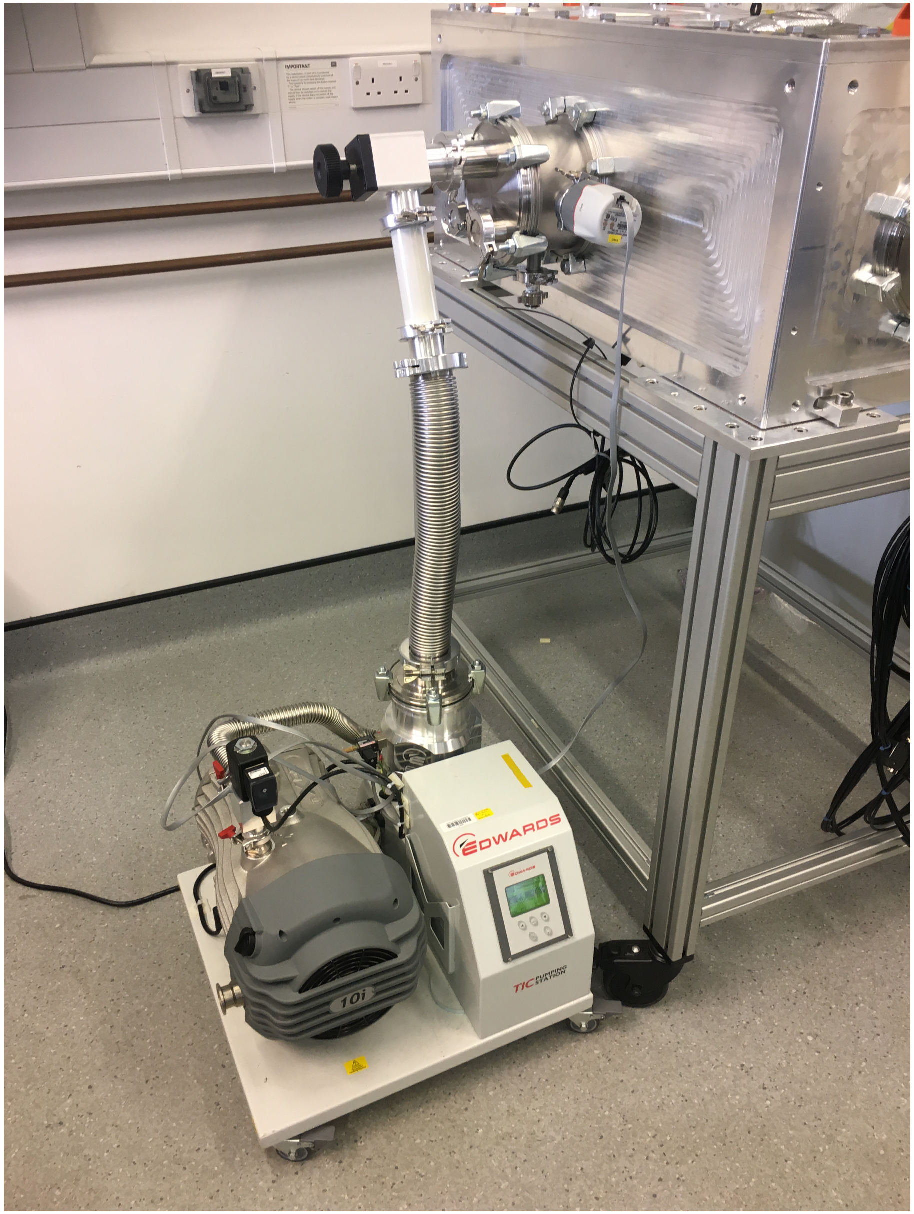


Inside a cryostat…

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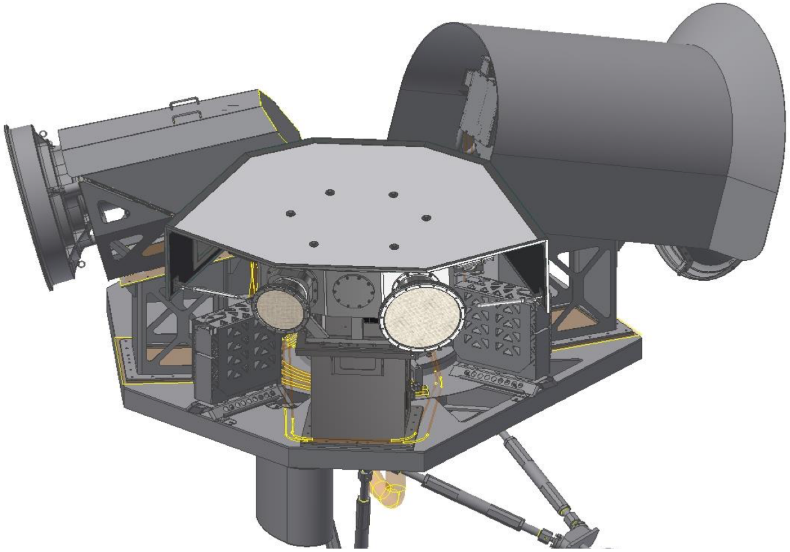
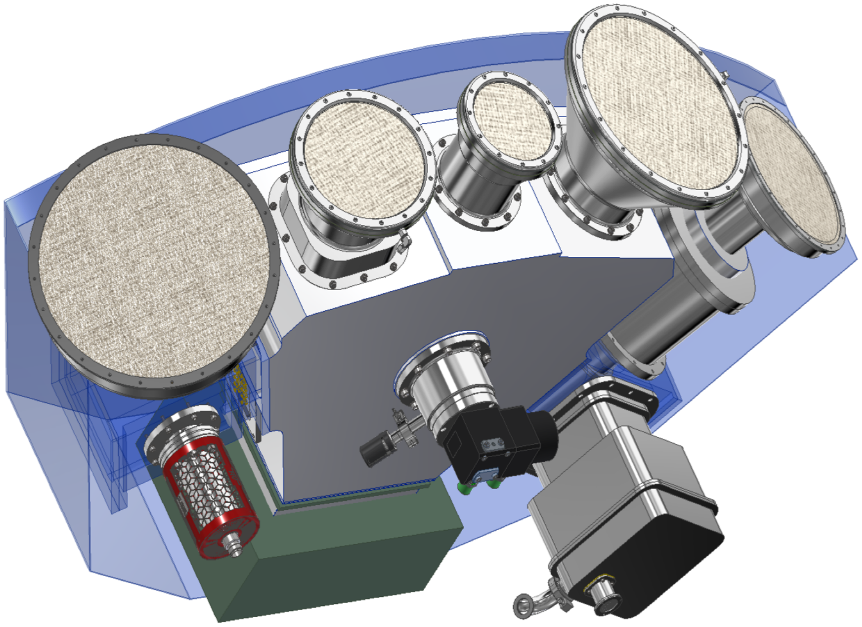
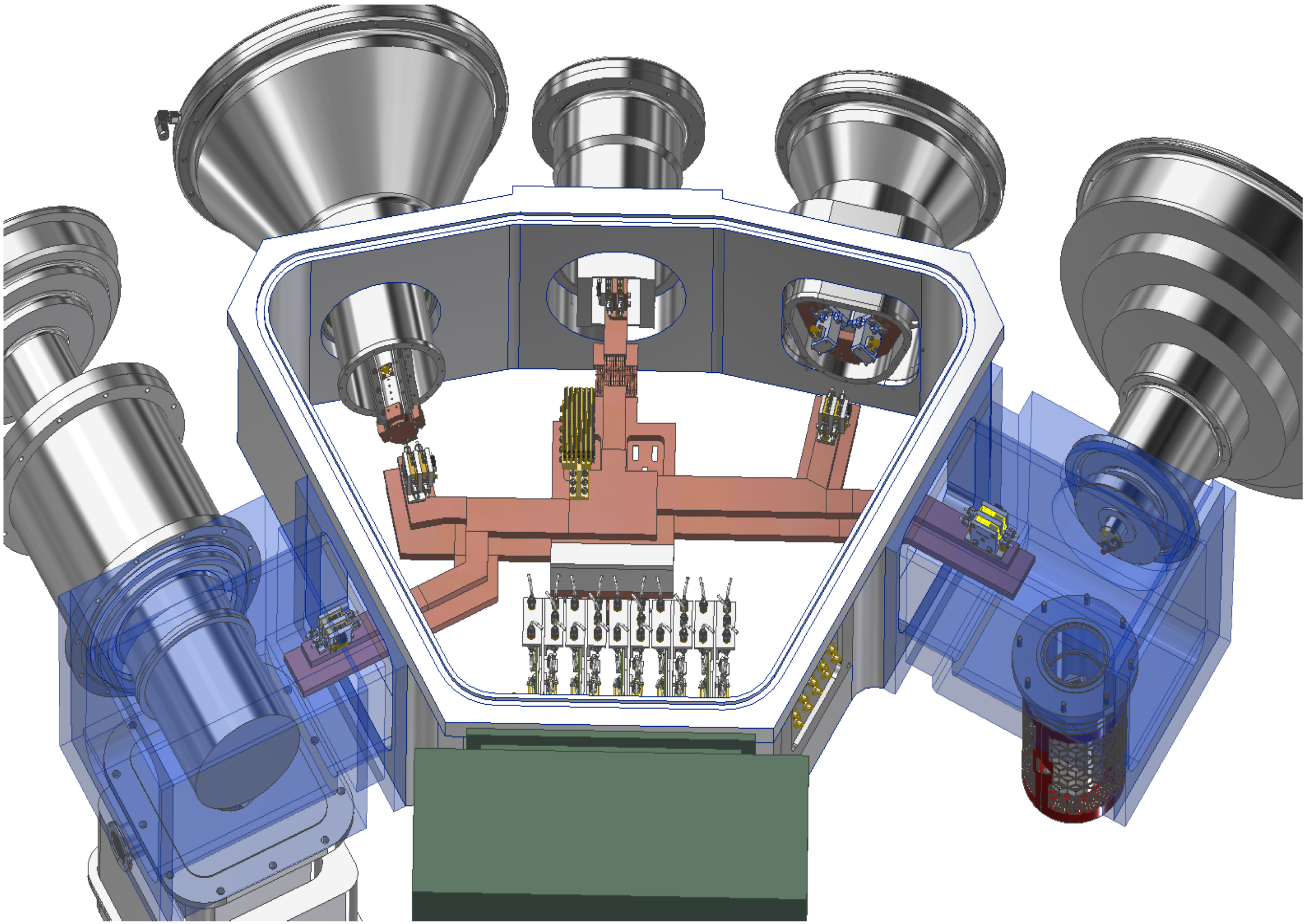
SKA Band 345(6) receiver





SKA Rx design



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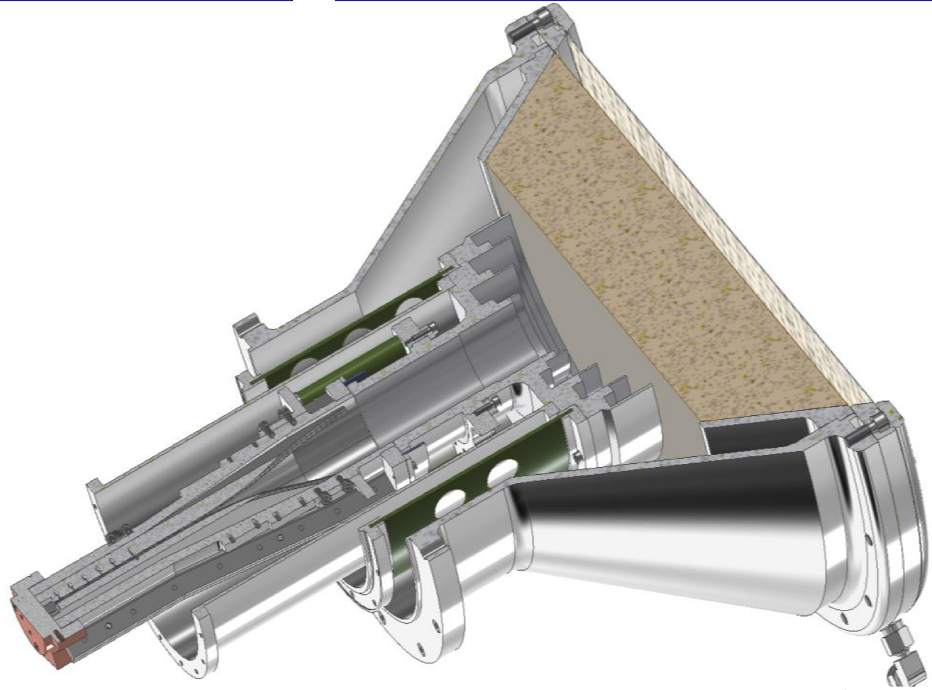
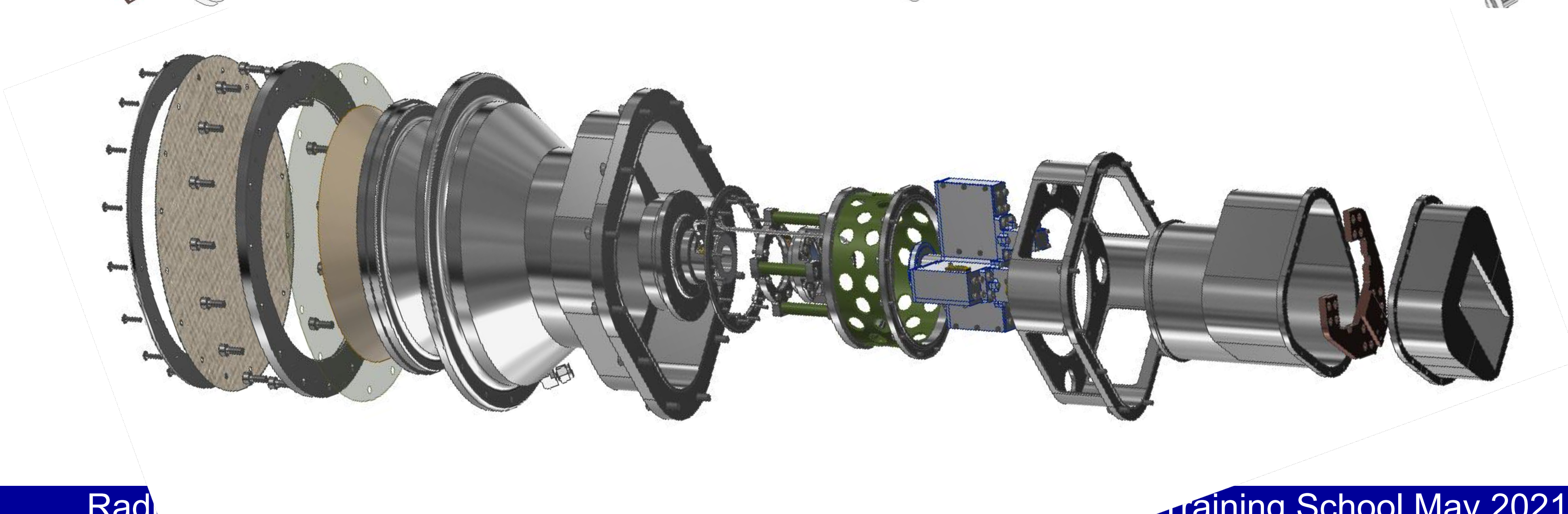
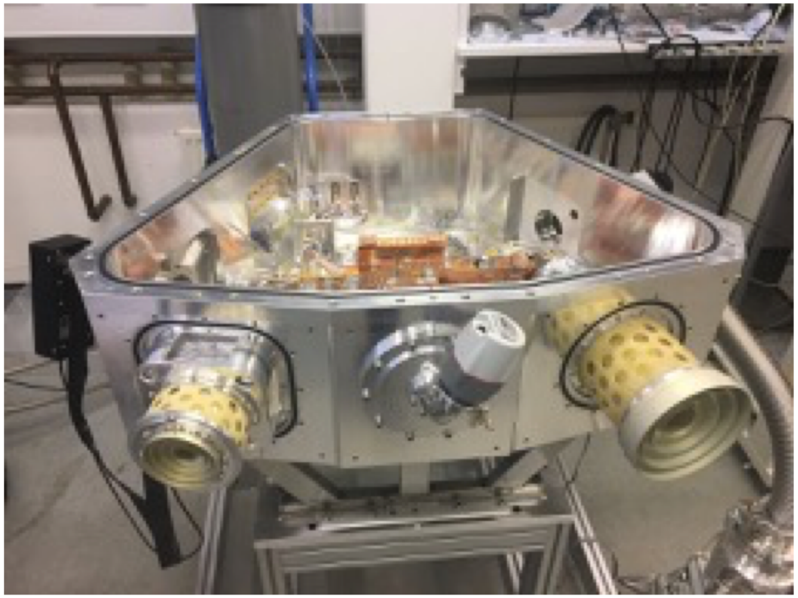
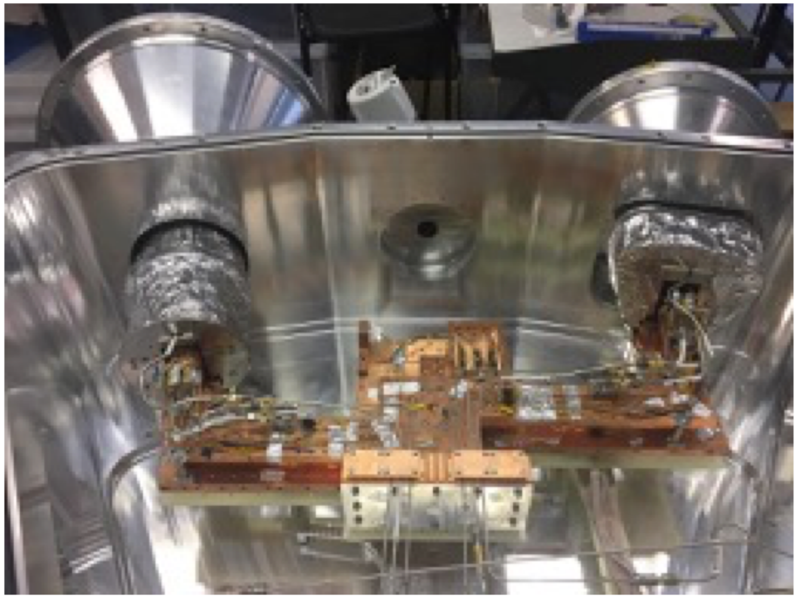
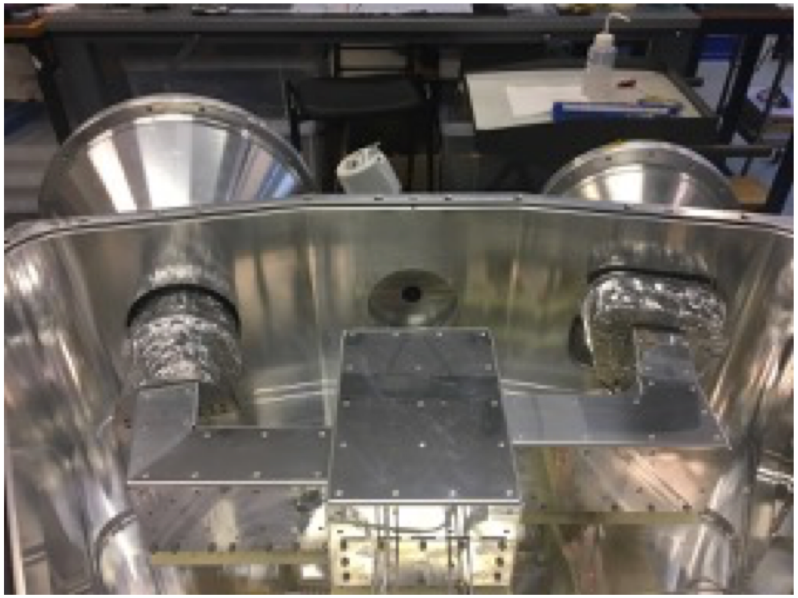


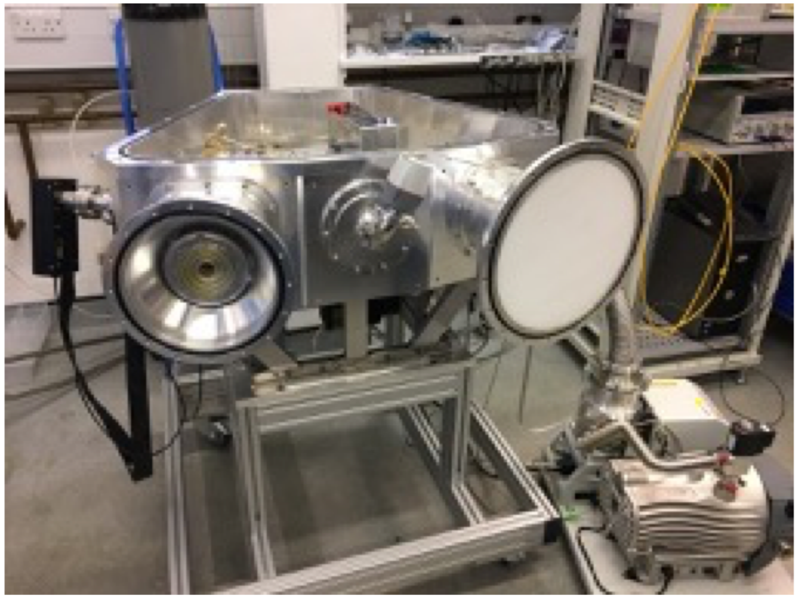


SKA Band 345(6) receiver









System temperature

- Key measure of receiver performance
- Hopefully is very low – can be < 10 K – but this is hard to measure
- Use hot-cold load method:
  - Measure power T_1 with hot (ie ambient) load
  - Measure power T_2 with cold load – liquid N_2 or sky
- $Y = T_{1/}\ T_2$

- $T_1 = G(T_{RX} + T_{hot})$
- $T_2 = G(T_{RX} + T_{cold})$
- $T_{RX} = (T_{hot} - Y\ T_{cold})/(Y-1)$

- Tricky to measure accurately when T_{RX} is small – need T_{cold} to be as small as possible, and accurately known

Tsys measurements in real life…

Thanks!