Space Instrumentation: Microwave Spectroscopy

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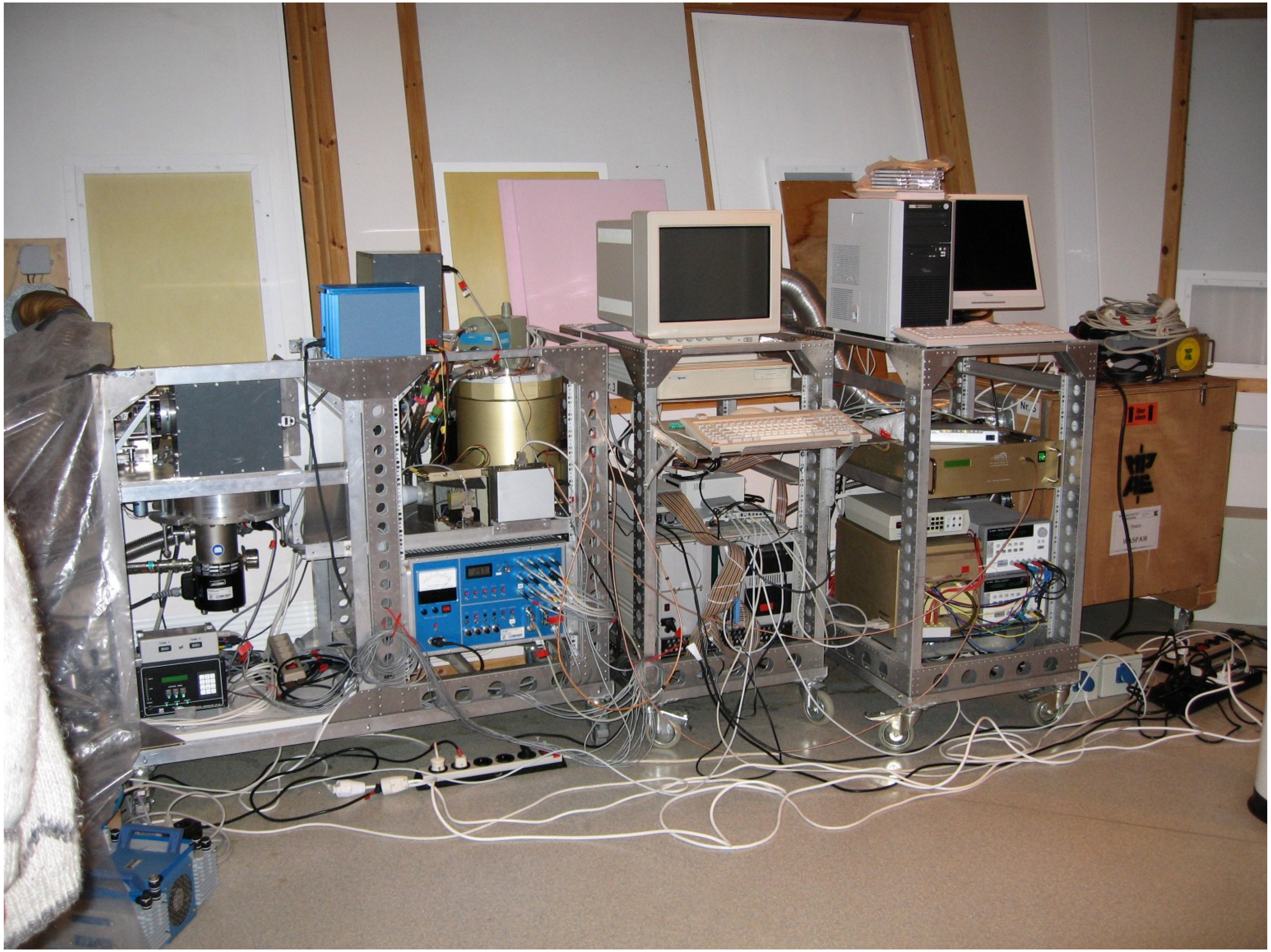
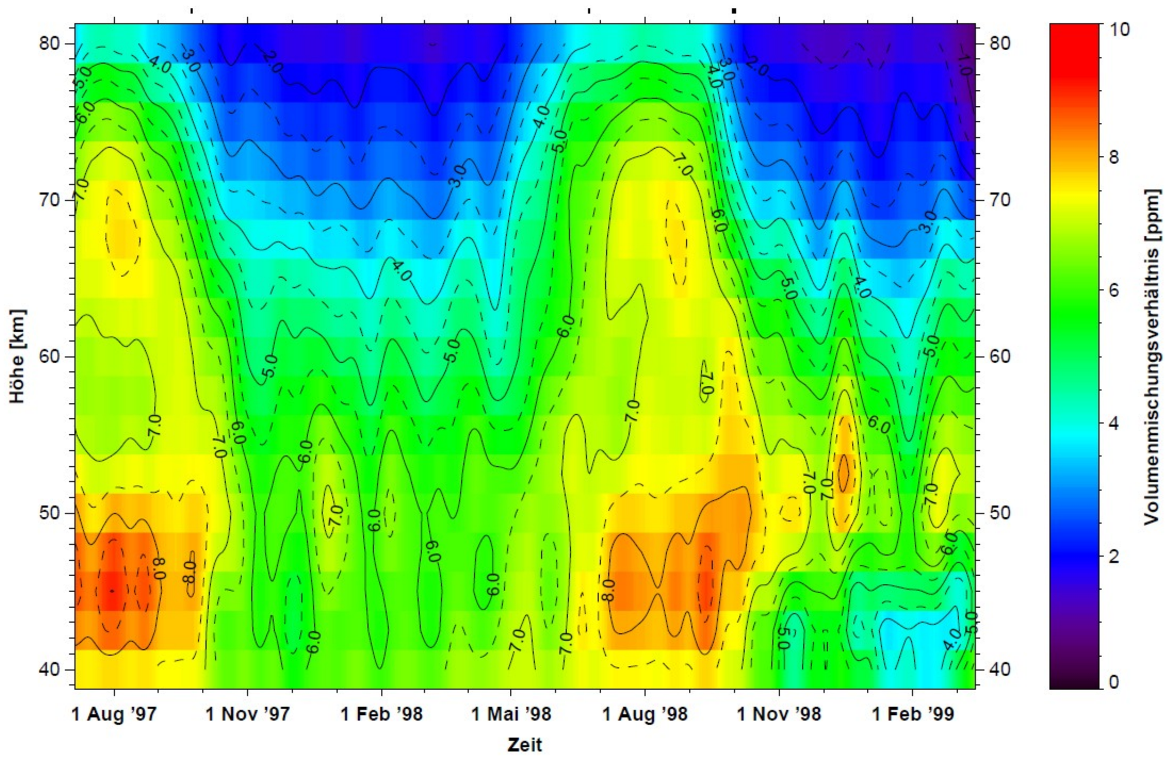


Oops, what's this ?

This is a ground-based microwave radiometer located at Northern Norway to detect the emission of atmospheric water vapour at 22 GHz (wavelength of 1.348 cm).

I hope after these 45 minutes you have an idea how such an instrument works!

By the way: From the data of this instrument we can derive the vertical distribution of H_2O in the Earth's atmosphere and its seasonal variation:



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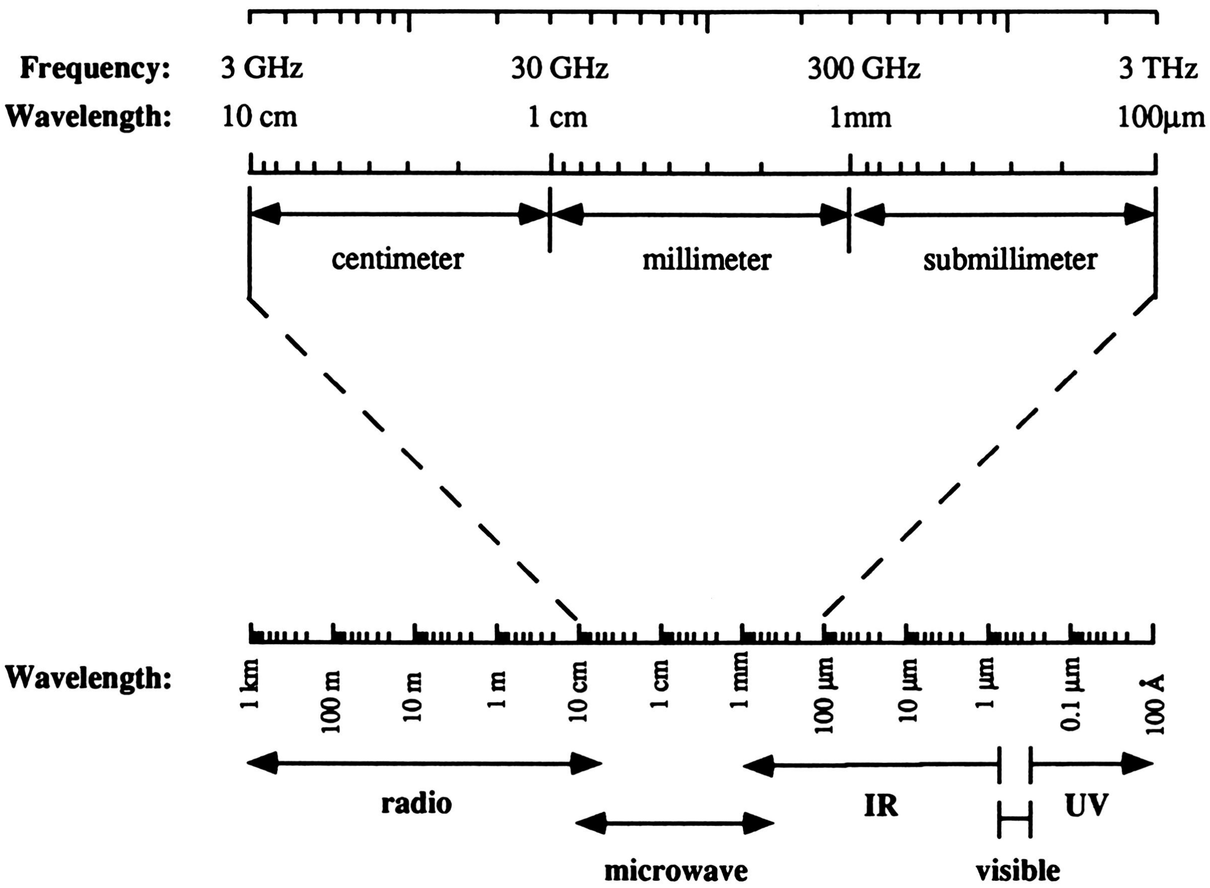
Motivation

Motivation

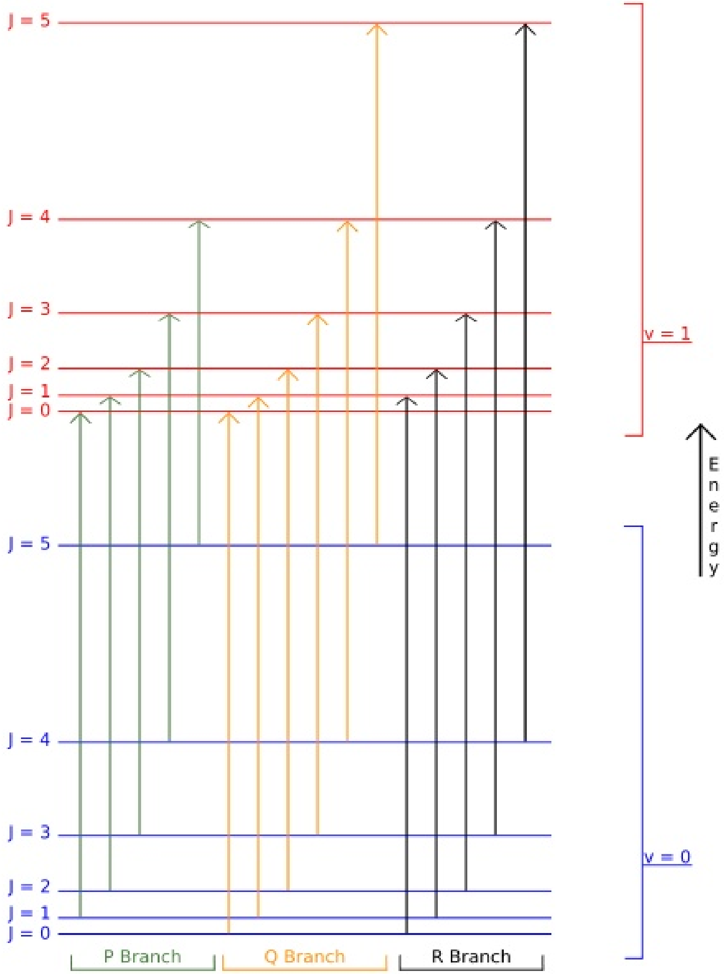


We want to measure electromagnetic radiation intensity I_ν received from a certain solid angle $\Delta\Omega$ around a certain direction by an absorbing area ΔA within a certain frequency range $\Delta\nu$:

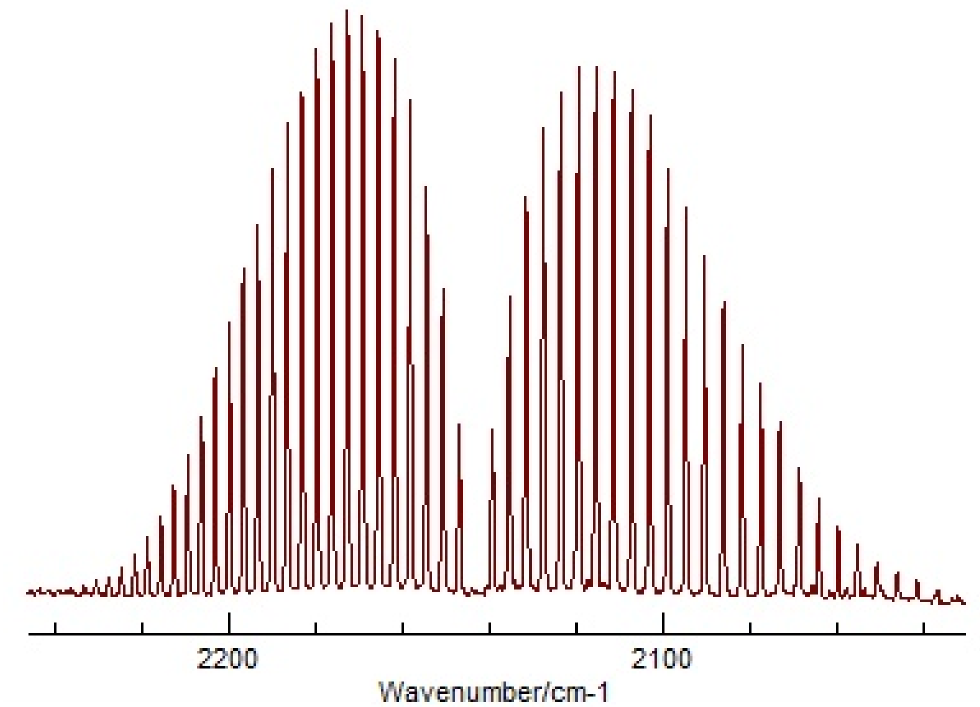
$$I_\nu \stackrel{\text{def}}{=} \frac{P_\nu}{\Delta A \cdot \Delta\nu \cdot \Delta\Omega} \qquad \left[\frac{\mathrm{W}}{\mathrm{m}^2 \cdot \mathrm{Hz} \cdot \mathrm{sr}}\right]$$

Motivation

We are interested in the microwave region (30–3000 GHz frequency, 10–0.1 mm wavelength), because molecules interact with this radiation by changing their rotational quantum state. Each molecule has a characteristic pattern of transition frequencies (spectral lines) and can be uniquely identified.



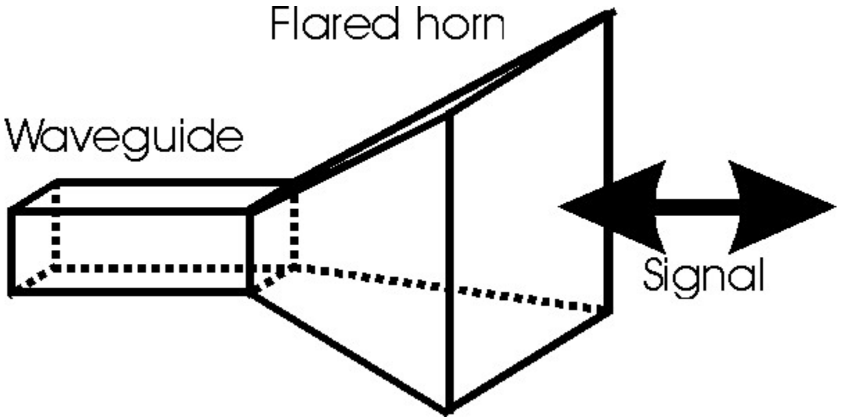
Vibration-rotation energy diagram.



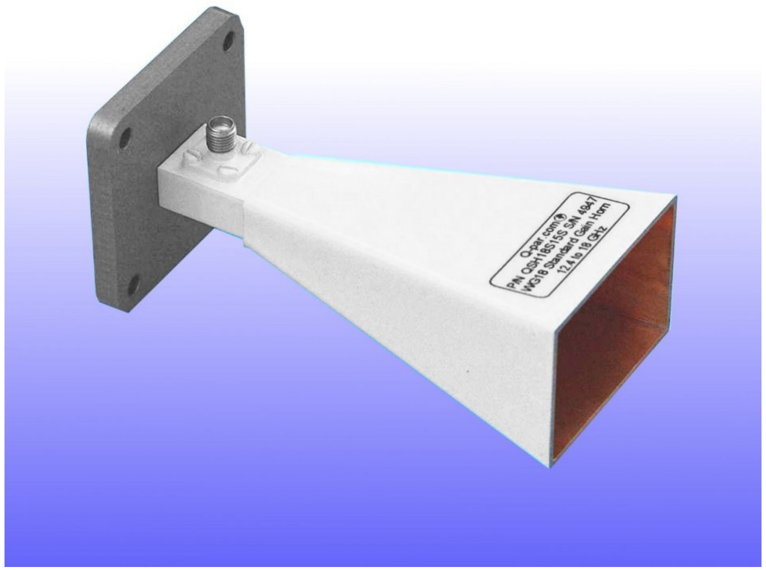
Vibration-rotation spectrum of CO.

Fundamentals of Microwave Radiometers

Microwave receivers work quite similar like an ordinary radio: First we need an antenna to couple the electromagnetic wave from free space into a wire structure, often a coaxial cable. This is most often done using a so-called **horn antenna**.



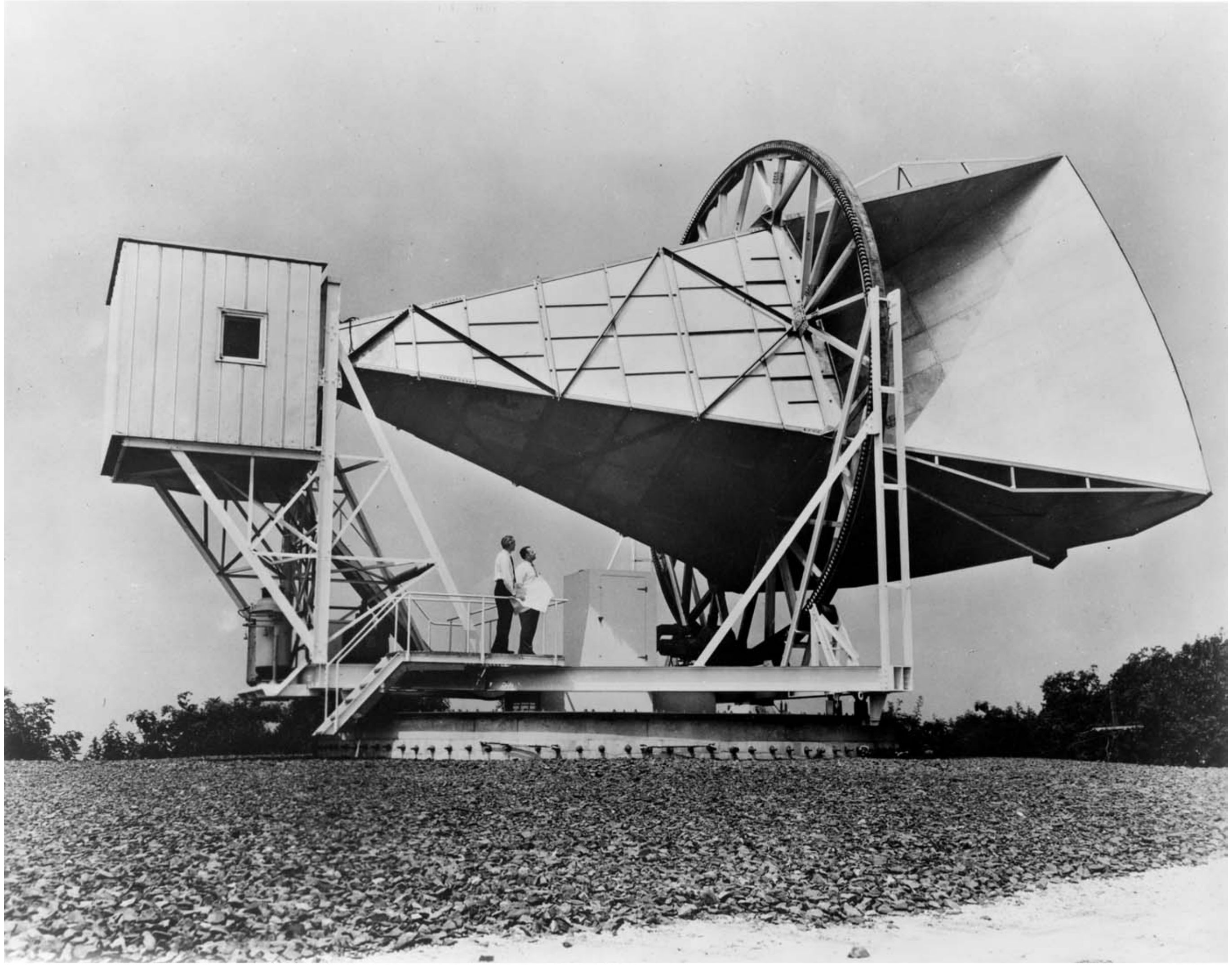
Depending on the wavelength horn antennas can be quite small . . .



Note the small SMA connector for the coax-cable.

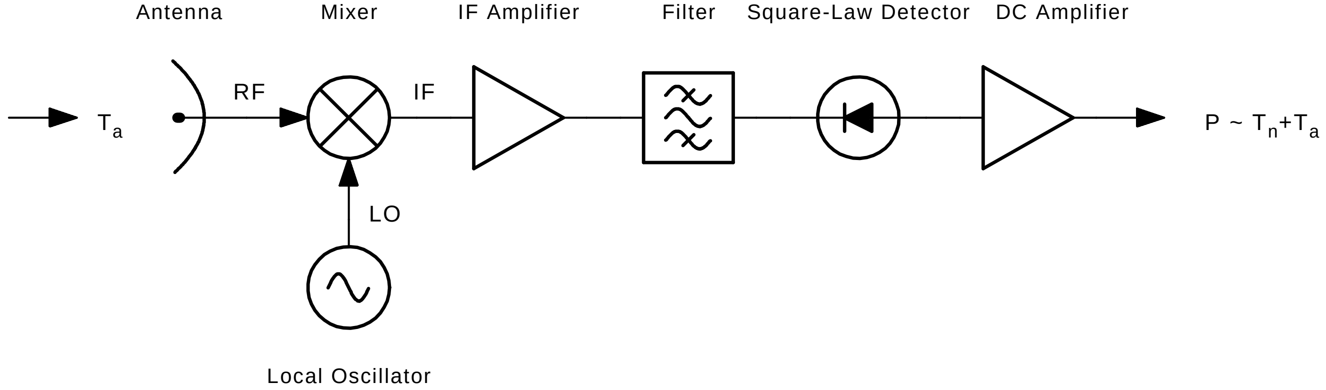
Antenna

. . . or pretty big:



The Horn Antenna at Bell Telephone Laboratories in Holmdel, New Jersey, with which Arno Penzias and Robert Wilson discovered the cosmic microwave background radiation in 1964.

Block diagram of a total power radiometer



The antenna produces a voltage proportional to the incident electric field pattern of the **radio frequency (RF)**:

$$U_{RF}(t) = E \cdot \cos(2\pi\nu t + \Phi)$$

The task of the mixer is to multiply the RF signal with a **local oscillator signal** $U_{LO}(t)$:

$$U_{LO}(t) = Q \cdot \cos(2\pi\nu_{LO} t + \Phi_{LO})$$

The mixer can be any device with a **non-linear** $I(U)$ characteristic, for example a simple diode:

$$\begin{aligned} I(U) &= I_s \cdot (e^{-U/U_0} - 1) \\ &= I_s \cdot \left(\frac{1}{1!}\frac{U}{U_0} + \frac{1}{2!}\left(\frac{U}{U_0}\right)^2 + \frac{1}{3!}\left(\frac{U}{U_0}\right)^3 + \ldots + \frac{1}{n!}\left(\frac{U}{U_0}\right)^n + \ldots \right) \\ &= a_1 U + a_2 U^2 + a_3 U^3 + \ldots + a_n U^n + \ldots \end{aligned}$$

Now insert

$$U(t) = U_{RF}(t) + U_{LO}(t)$$

$$I(U) = a_1(U_{RF}(t) + U_{LO}(t)) + a_2(U_{RF}(t) + U_{LO}(t))^2 + a_3(U_{RF}(t) + U_{LO}(t))^3 + \ldots + a_n(U_{RF}(t) + U_{LO}(t))^n + \ldots$$

Important is the **second order (quadratic)** term:

$$\begin{aligned} I(t) &= \ldots \\ &\quad +a_2\left(E \cdot \cos(2\pi\nu t + \Phi) + Q \cdot \cos(2\pi\nu_{LO} t + \Phi_{LO})\right)^2 \\ &\quad + \ldots \\ &= \ldots \\ &\quad a_2 E^2 \cdot \cos^2(2\pi\nu t + \Phi) \\ &\quad +2a_2 EQ \cos(2\pi\nu t + \Phi) \cdot \cos(2\pi\nu_{LO} t + \Phi_{LO}) \\ &\quad +a_2 Q^2 \cos^2(2\pi\nu_{LO} t + \Phi_{LO}) \\ &\quad + \ldots \\ &= \ldots \\ &\quad +a_2 EQ \left[\cos(2\pi(\nu - \nu_{LO})t + \Phi - \Phi_{LO}) + \cos(2\pi(\nu + \nu_{LO})t - \Phi + \Phi_{LO})\right] \\ &\quad + \ldots \end{aligned}$$

➠ The mixer creates the **sum** and **difference** frequencies of the RF and LO frequency!

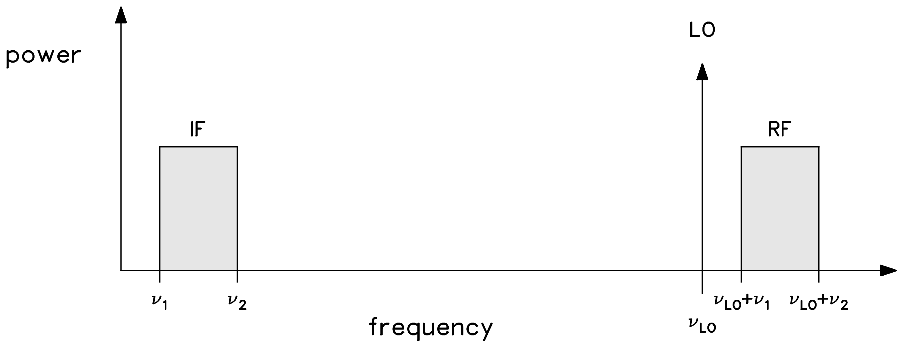
Heterodyne Receiver

By inserting a bandpass filter with bandwidth $\Delta\nu = \nu_2 - \nu_1$ at the output of the mixer we can select only the term with the difference frequency, the so-called **intermediate frequency**:

$$\nu_1 \leq |\nu - \nu_{LO}| \leq \nu_2$$

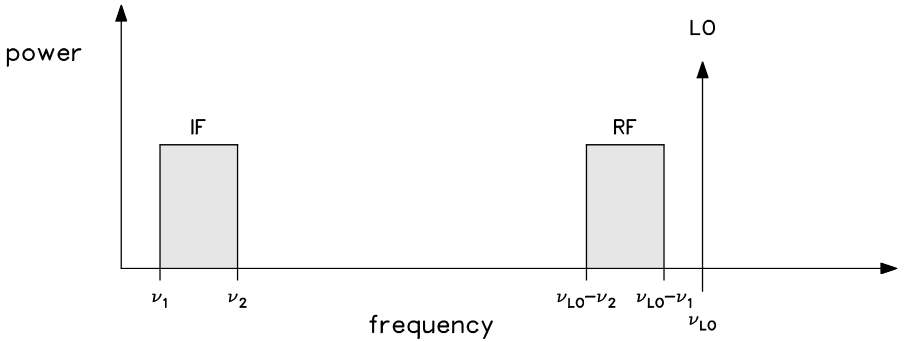
Hence, after mixing and filtering the output signal of the receiver is:

$$I(t) \propto EQ \cos(2\pi(\nu - \nu_{LO})t + \Phi - \Phi_{LO})$$



or:

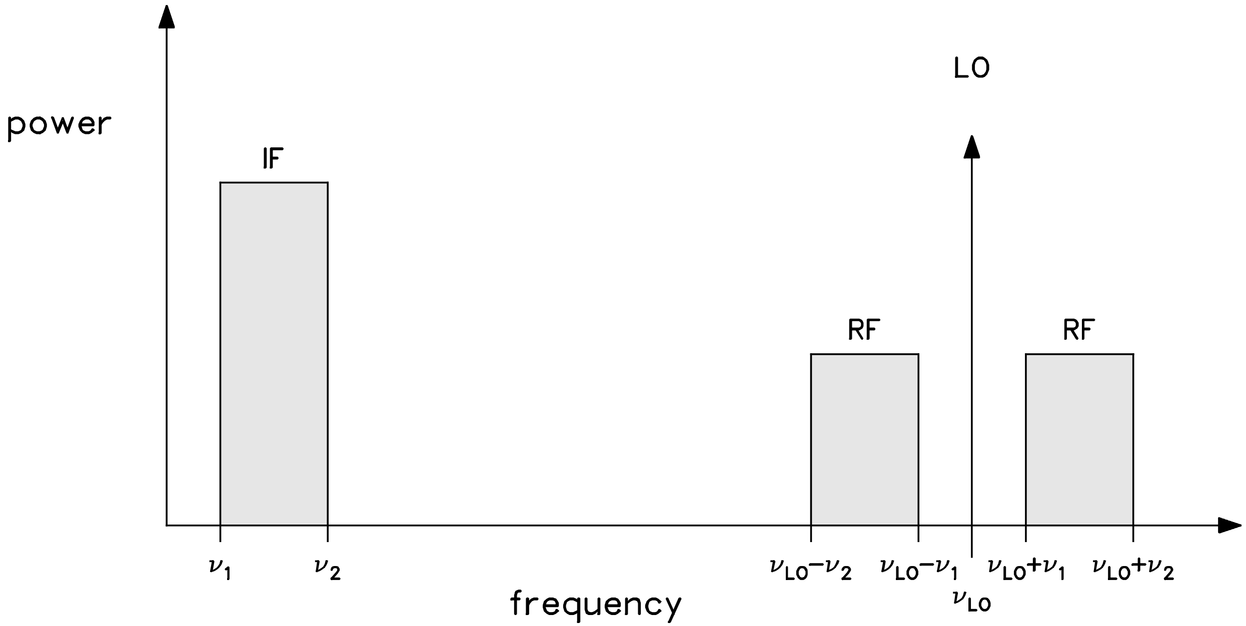
$$I(t) \propto EQ \cos(2\pi(\nu_{LO} - \nu)t - \Phi + \Phi_{LO})$$



Important: The **difference** frequency is low enough (about 1 to 4 GHz) to be amplified and processed by existing electronics!

Bad effect of the mixing process:

The intermediate signal contains always signal from two different frequency ranges, the so-called **upper sideband** and **lower sideband**! Thus a heterodyne receiver is usually always a **double sideband receiver** and assigning the original frequency to a spectral feature is not unique.



Final step: **Square-law detector**

To measure the power of the IF-signal we just need to square it ($P = U^2/R$ or $P = RI^2$) and average the fluctuating signal over some short time Δt (running mean). As seen before this could be done using a diode (hence the symbol of a diode).

The resulting final voltage is proportional to the power of the incident RF-signal at the antenna and can be digitized using standard analog-to-digital converters.

Calibration

So far we have an output signal proportional to the power of the incident RF-signal. But this signal depends on the gain of the amplifiers used, and varies with gain drifts (ie.g. caused by changing room temperature).

➠ We need to calibrate the recorded output signal somehow into physical units!

Idea: Let's look at the **thermal emission of a blackbody** with the heterodyne receiver!

The idea is based on the fact that the power radiated by a blackbody within a **narrow frequency interval** is proportional to its temperature as long as $h\nu \ll kT$ (**Rayleigh-Jeans approximation**) is valid:

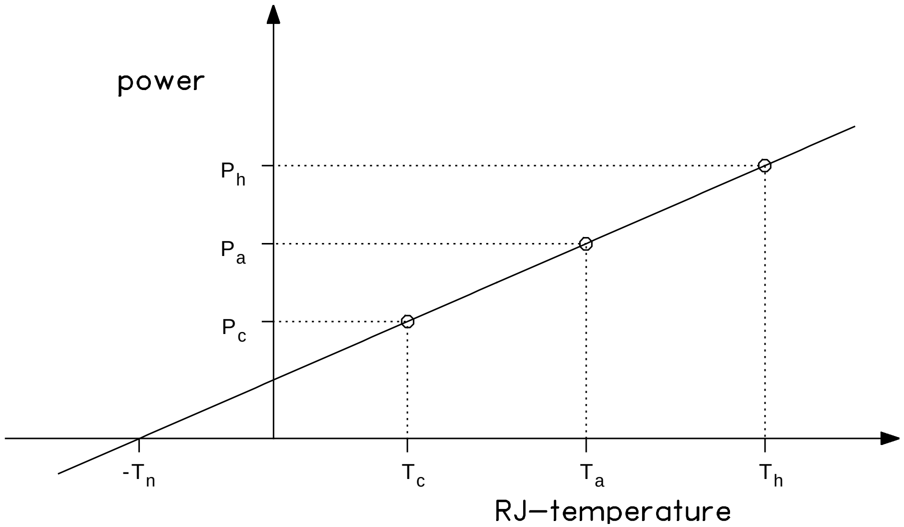
$$
\begin{aligned}
P(T,\nu) &= \frac{2h\nu^3}{c^2} \cdot \frac{1}{e^{h\nu/kT} - 1} \\
&= \frac{2h\nu^3}{c^2} \cdot \frac{1}{(1 + h\nu/kt + \ldots) - 1} \\
&\simeq \frac{2k\nu^2}{c^2} \cdot T
\end{aligned}
$$

Calibration

This means the radiation power indicated by our heterodyne receiver can be written as a linear function of the temperature of the blackbody we are looking at:

$$P = const \cdot (T + T_n)$$

Using two blackbodies at different temperatures – the so-called **hot load** and **cold load** we can assign any indicated power an equivalent blackbody temperature:



$$T_a = \frac{T_h(P_a - P_c) - T_c(P_a - P_h)}{P_h - P_c}$$

In addition we obtain the **receiver noise temperature** T_n (the power which the receiver indicates **without** any input signal) – this is thermal mixer and amplifier noise:

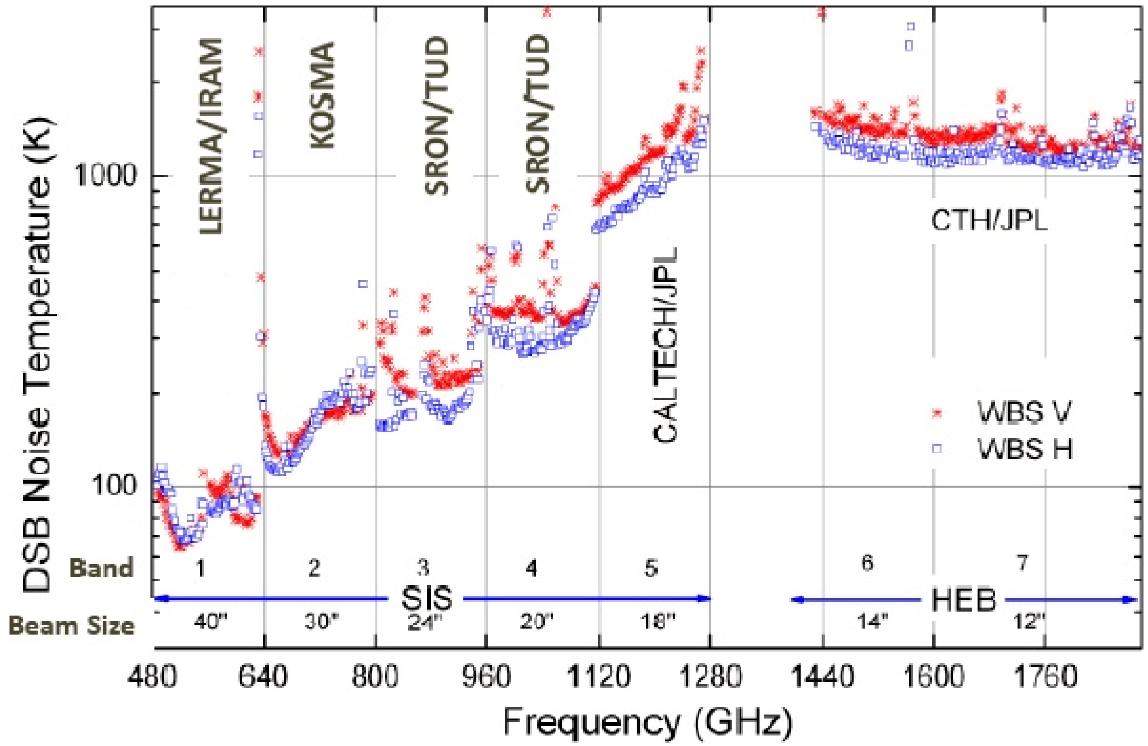
$$T_n = \frac{T_h P_c - T_c P_h}{P_h - P_c}$$

Calibration

This calibration is the reason why in microwave radiometry/spectroscopy the radiation intensity is always stated in terms of **temperature**!

The theoretically lowest (i.e. best) receiver noise temperature is given by the quantum limit $T_n = h\nu/k$.

Example:



Double sideband (DSB) receiver noise temperatures for the HIFI instrument onboard the HERSCHEL space observatory. SIS stands for a superconductor-insulator-superconductor mixer, HEB stands for hot-electron-bolometer mixer. These two mixer technologies provide much lower receiver noise temperatures than a Schottky diode mixer.

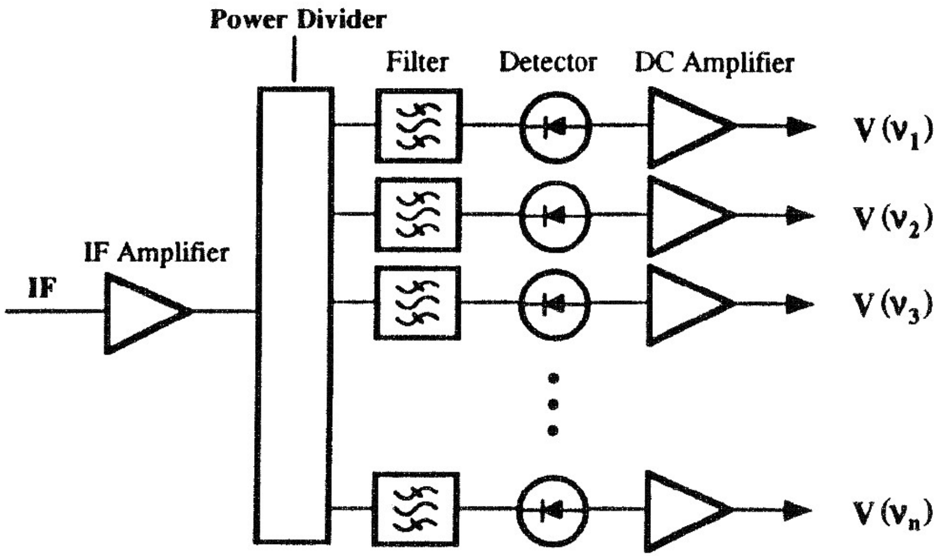
Note: Noise temperatures are several ten to several thousands of Kelvin, but the signal to be detected is usually only several ten milli-Kelvin up to a few Kelvin large! The mixer noise creates most of the observed output power of the receiver!

Spectrometer Technologies

Spectrometer: Filterbank

Sow far we have a receiver with a single output number – a **single channel radiometer**.

To get a spectrum composed of many channels the simplest technical approach is a **filterbank**:

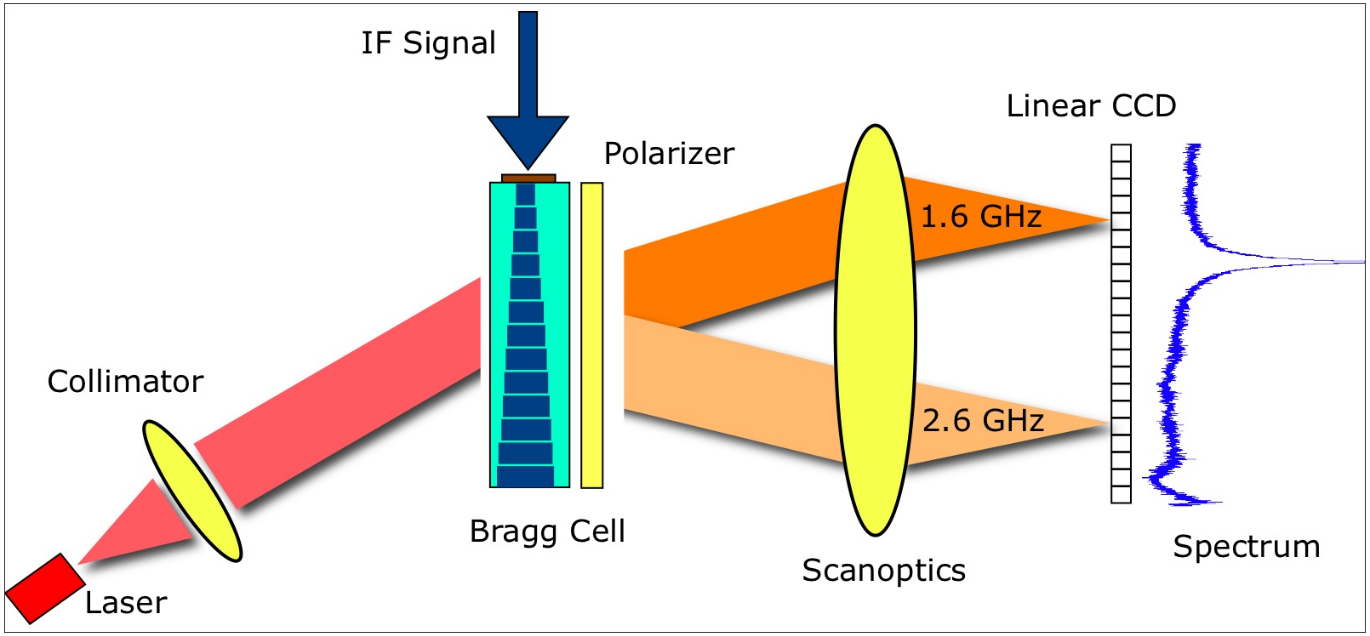


Each filter has a different passband characteristic which determines center frequency and resolution of the corresponding spectral channel.

If we reduce the bandwidth of the passband filter we can increase the **spectral resolving power** $R = \Delta\nu/\nu$ of a heterodyne receiver to nearly arbitrarily high numbers (up to 10^7 is already standard). This is different from e.g. an optical grating!

Useful resolutions for observations of planetary atmospheres and comets are **1 MHz – 50 kHz**!

Spectrometer: Acousto-Optical Spectrometer (AOS)



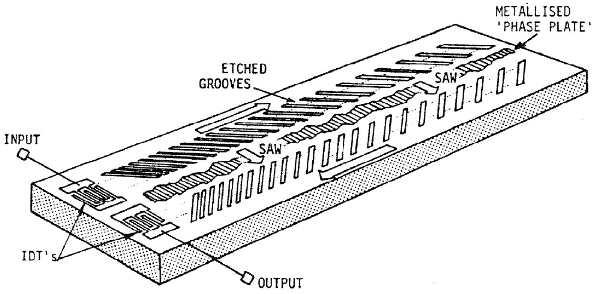
An Acousto Optical Spectrometer (AOS) is based on the diffraction of light at ultrasonic waves. A piezoelectric transducer, driven by the IF signal (from the receiver), generates an acoustic wave in a crystal (the so-called Bragg-cell). This acoustic wave modulates the refractive index and induces a phase grating. The Bragg-cell is illuminated by a collimated laser beam. The angular dispersion of the diffracted light represents a true image of the IF-spectrum according to the amplitude and wavelengths of the acoustic waves in the crystal. The spectrum is detected by using a single linear diode array (CCD), which is placed in the focal plane of an imaging optics.

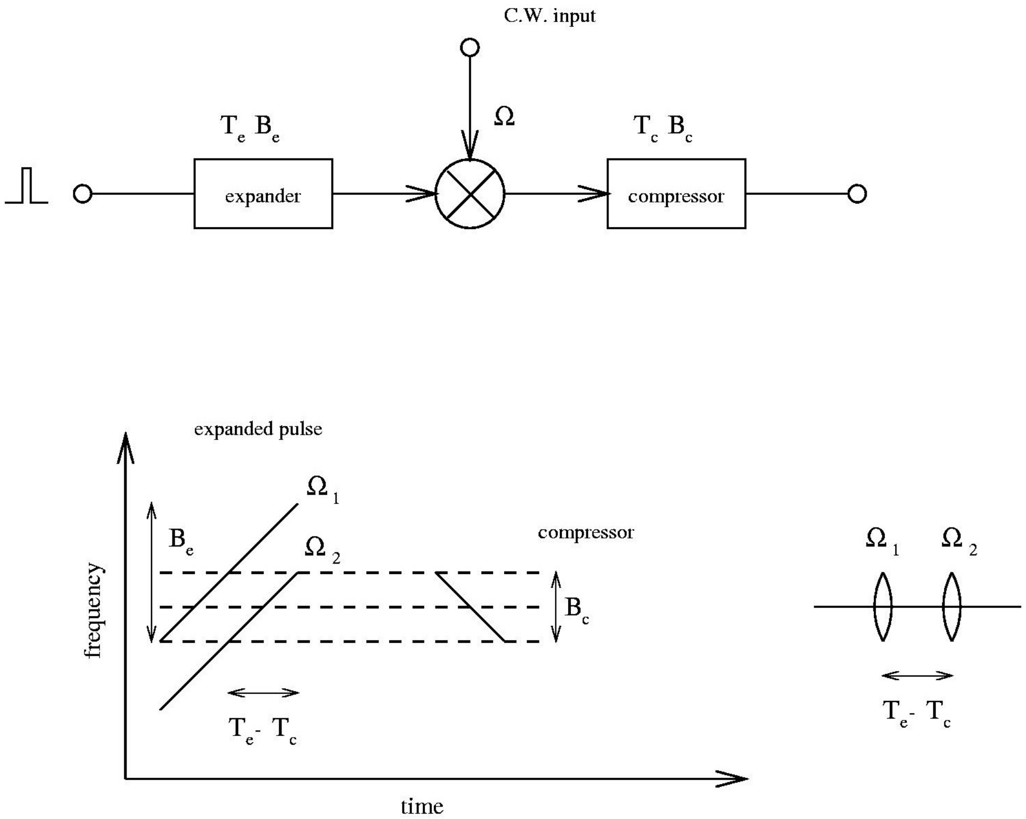
taken from http://en.wikipedia.org/wiki/Acousto_Optical_Spectrometer

Spectrometer: Chirp Transform Spectrometer (CTS)

Chirp Transform Spectrometers are based on Surface Acoustic Wave (SAW) filters.

These filters can be created in such a way, that a delta pulse as input signal shows up as a chirp output signal (linear increasing frequency versus time). If such a signal is put into another so-called matched SAW-filter, which would create a similar, but decreasing chirp signal, then the output would be a delta pulse again.





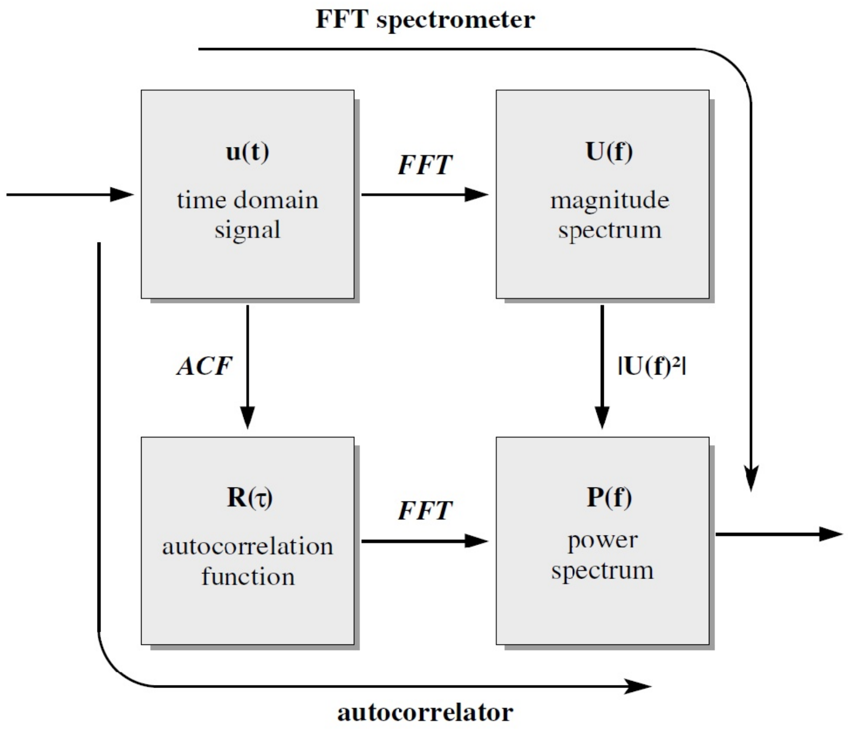
Mixing the increasing chirp signal with a continous wave (CW) signal will shift the chirp signal in frequency and as finally the moment in time when the delta pulse apears as output of the matched filter. This behaviour is used to analyze the frequency of the CW-signal, and finally to use this filter combination as spectrometer.

Spectrometer: Digital Autocorrelator Spectrometer (ACS)

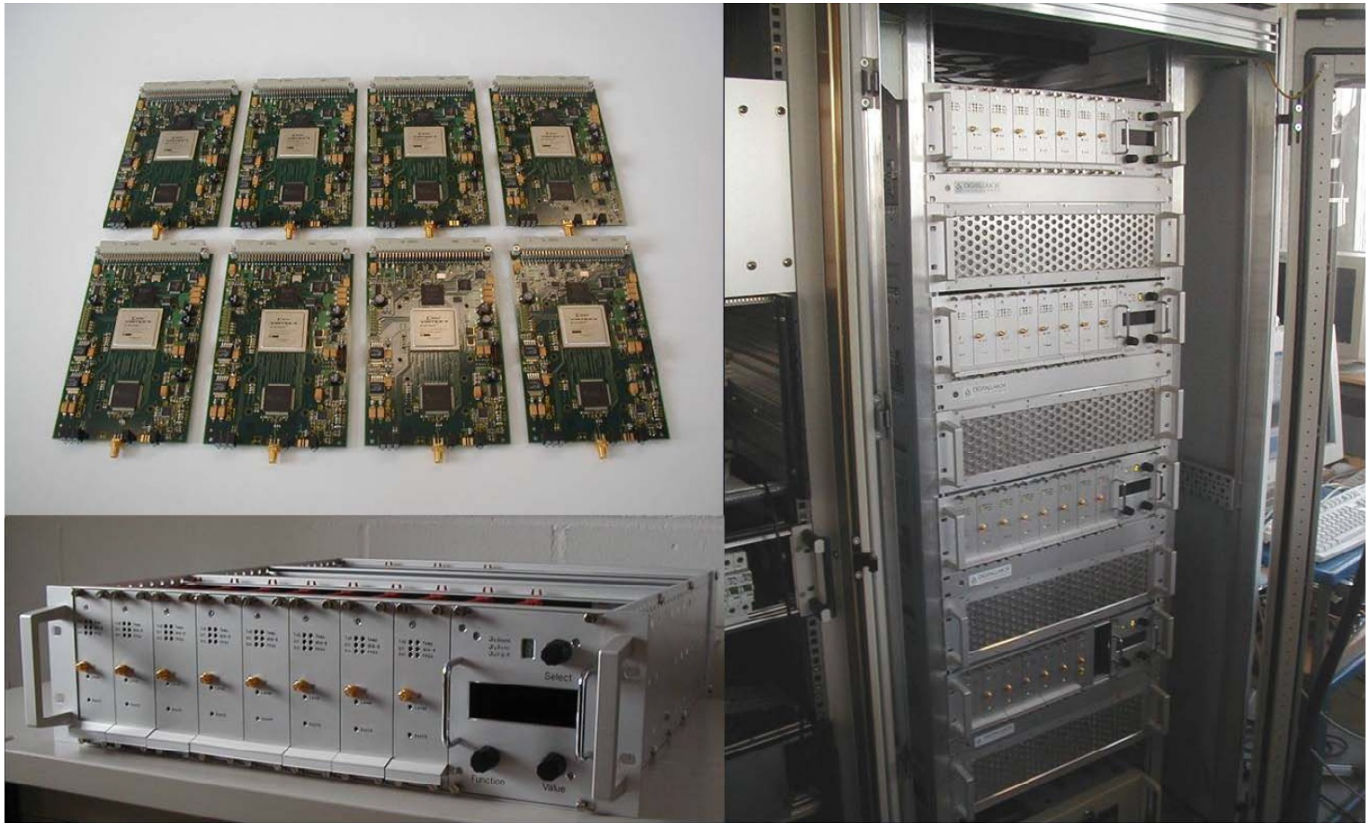
A digital autocorrelator is the digital version of an analog Fourier Transform Spectrometer. Using a fast analog-to-digital converter (only 1 or 2 bit resolution) a short time interval Δt of the IF-signal is sampled with N data points. A highly specilized digital circuit calculates the autocorrelation function (as with an analog Fourier Transform Spectrometer this step creates an interferogram.

These two steps are repeated and all the interferograms are co-added.

Finally the Fourier Transform of the interferogram provides the power spectrum of the IF-signal (Wiener-Khinchin-Theorem).



Visualisation of the “Wiener-Khinchin-Theorem”.



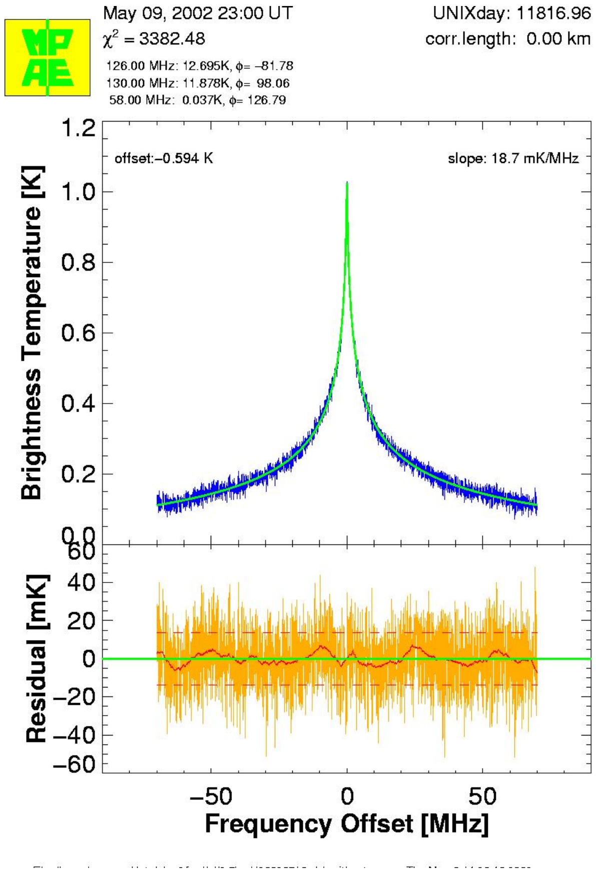
In the last few years the Max-Planck-Institut für Radioastronomie in Bonn developed spectrometers, which perform a **real-time** digital fast fourier transformation of the IF-signal. This technology became possible with the development of extremely fast analog-to-digital converters and field programmable gate arrays (FPGAs).
In general a short time intervall of the IF-signal is digitized and then a highly specilized digital circuit calculates the spectrum using the Fast Fourier Transform algorithm. The trick is to do this transformation as fast as the sampling of the IF, that means transforming a sample of length Δt does not take longer than a duration Δt. No time gaps, no loss of IF-signal!

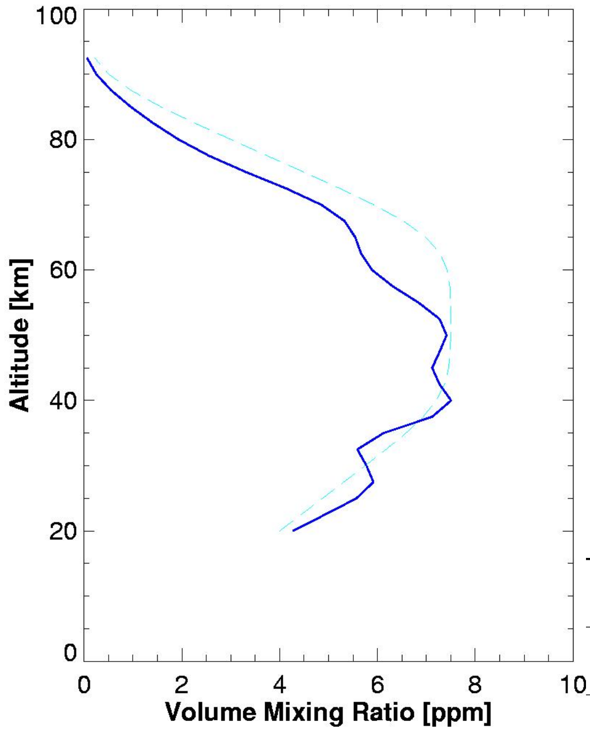
However, this technology needs further developments to survive space environment!

Applications

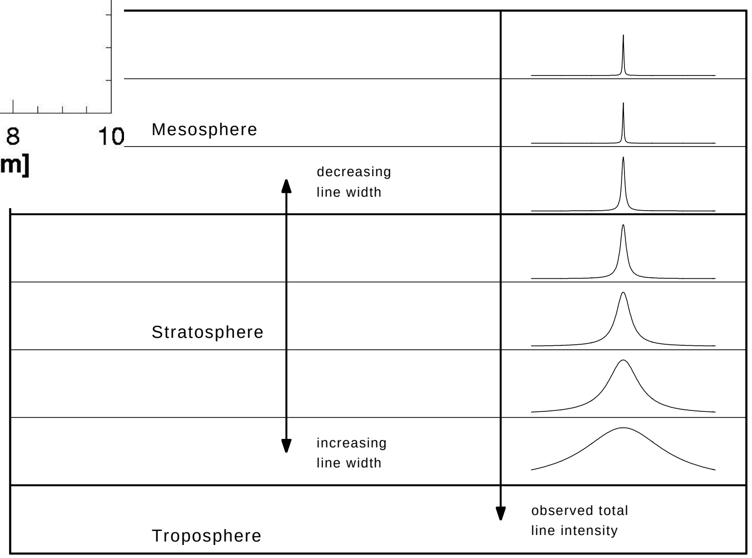
Ground-based Remote Sensing of the Earth's Atmosphere

We observe the thermal emission of atmospheric H_2O when the molecule transits between two rotational quantum states.





Profile information in the spectra: The line width is proportional to the atmospheric pressure (altitude information), the line amplitude is proportional to the molecule's abundance (mixing ratio information).



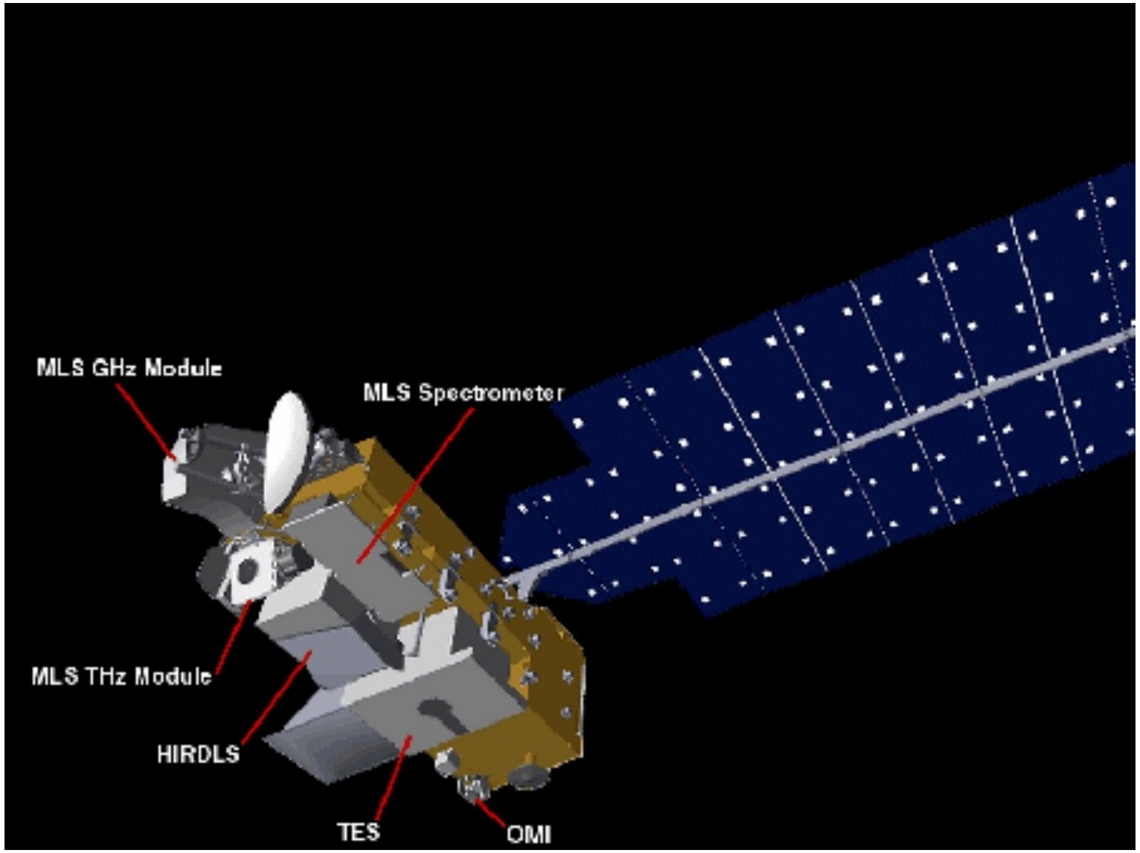
Space-based Remote Sensing of the Earth's Atmosphere

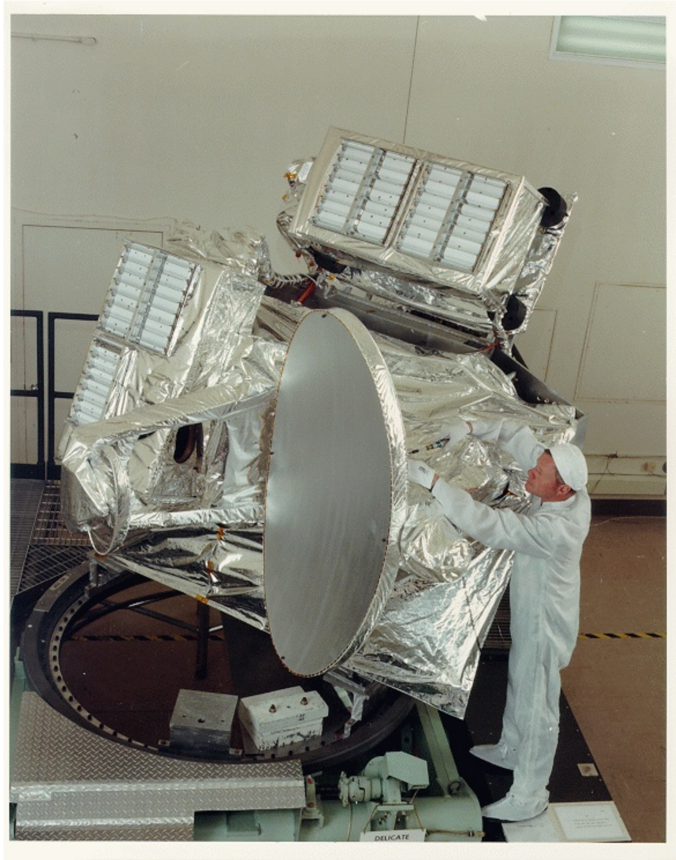
Remote sensing of the Earth's atmosphere has been also done extensively from space!

Advantages:

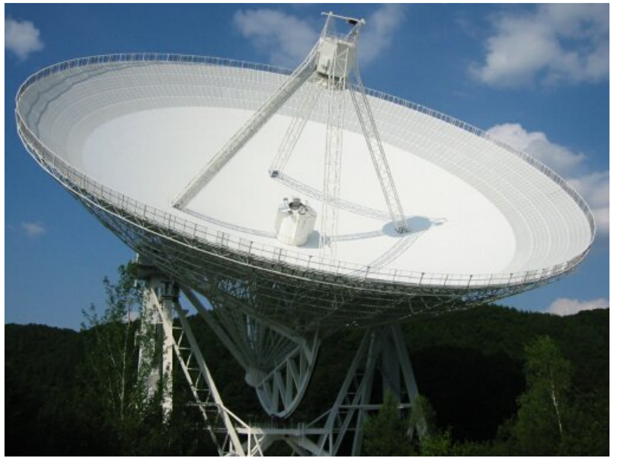
1. Global coverage
2. Scanning the limb of the atmosphere with a narrow antenna beam gives additional altitude information and better altitude resolution of the ob

Here needs to be named the **Microwave Limb Sounder (MLS)** onboard the **Upper Atmosphere Research Satellite (UARS, launched 1991)** and the second generation MLS instrument onboard the AURA satellite (launched 2004).





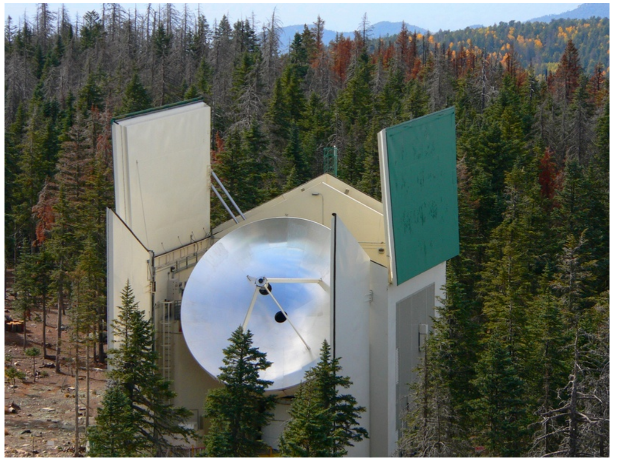
Radio Telescopes



Effelsberg 100m close to Bonn

IRAM 30m close to Granada, Spain

James Clerk Maxwell Telescope, Hawaii

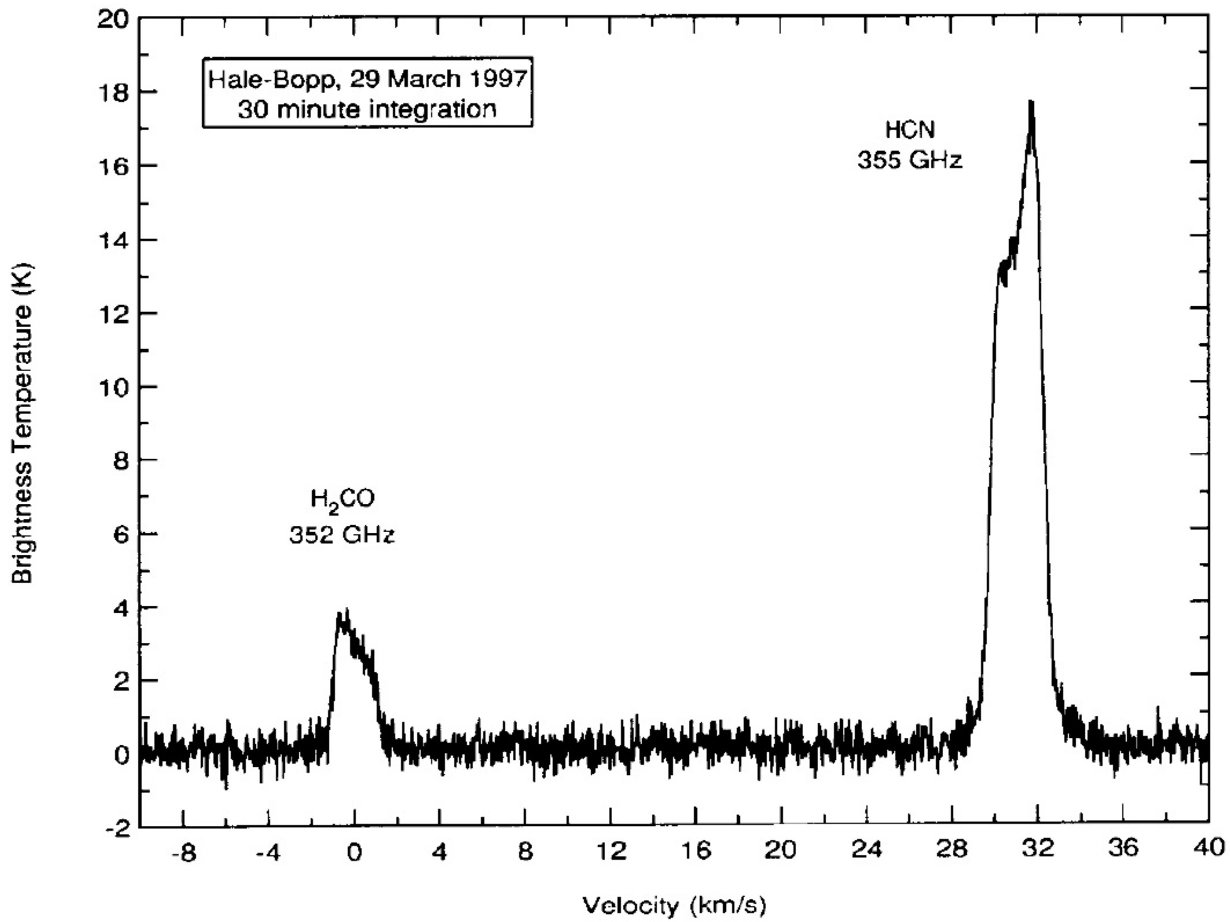


Heinrich Hertz Telescope, Arizona

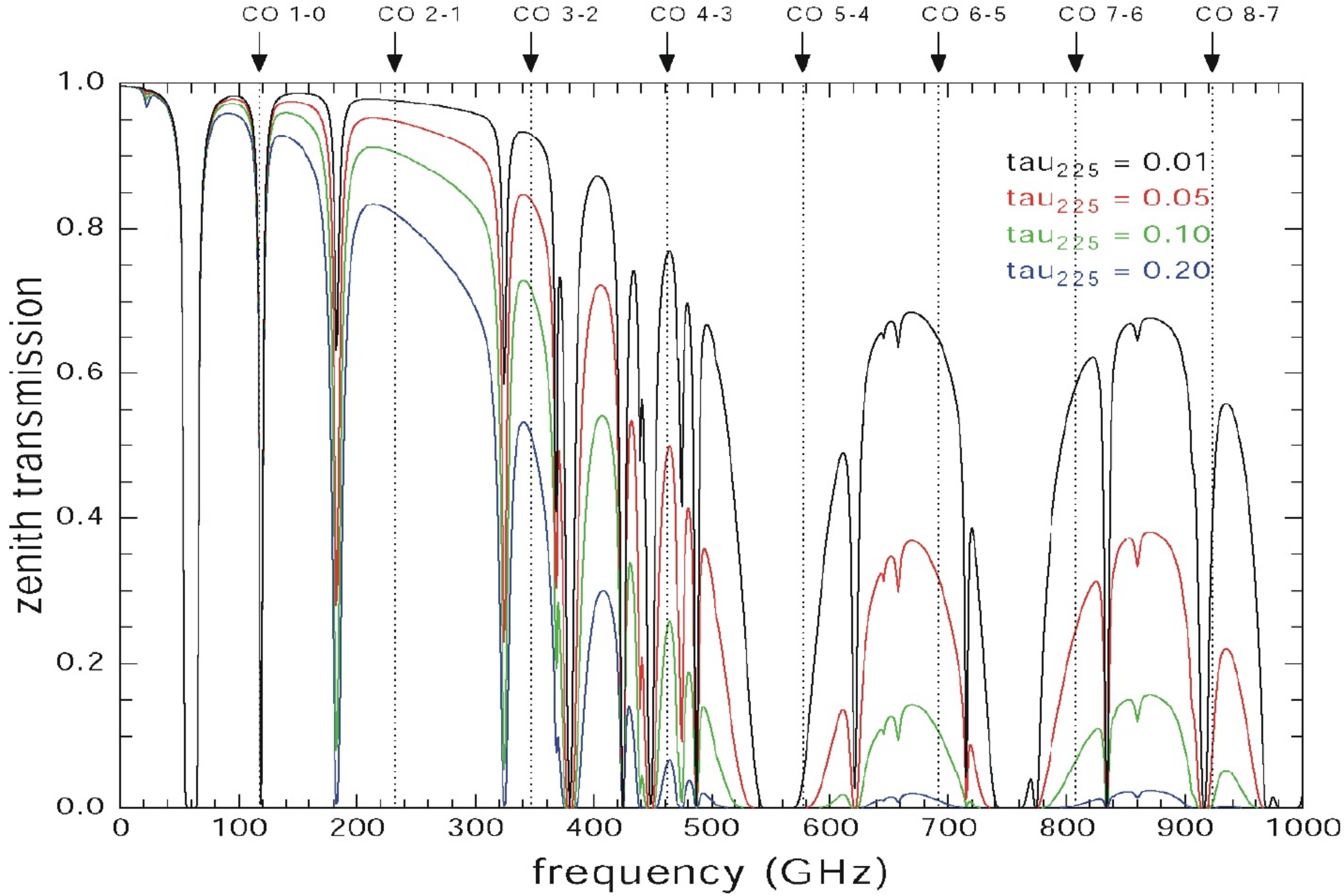
Radio Telescopes

Remember: a radio telescope dos not provide images, but instead the spectrum of a single pixel!

Images can be only obtained by slowly rastering across the sky.

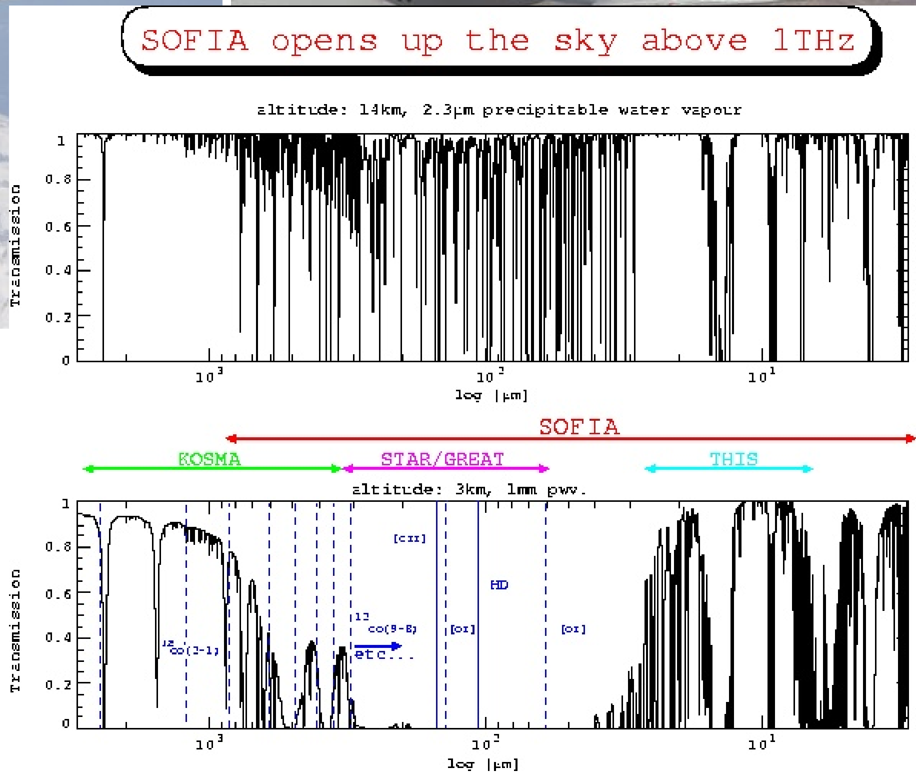


Detection of H_2CO and HCN in the coma of Hale-Bopp, observed 1997 at the Heinrich Hertz Telescope with a CTS as spectrometer.



Water vapour and oxygen in the Earth's atmosphere prohibit clear view of the sky!

SOFIA: an airborne far-infrared (FIR) telescope

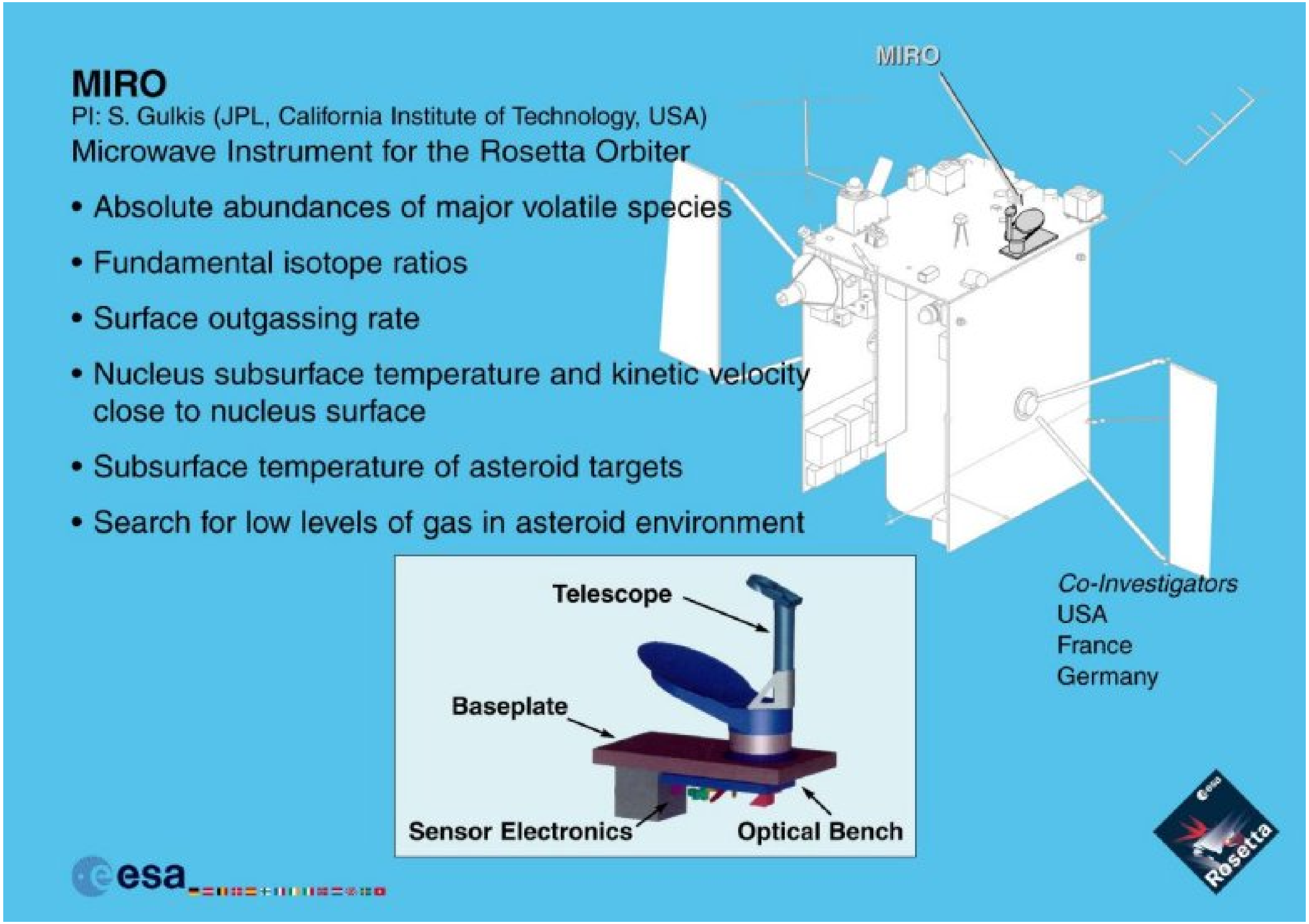


SOFIA

MIRO: a tiny radio telescope onboard ROSETTA

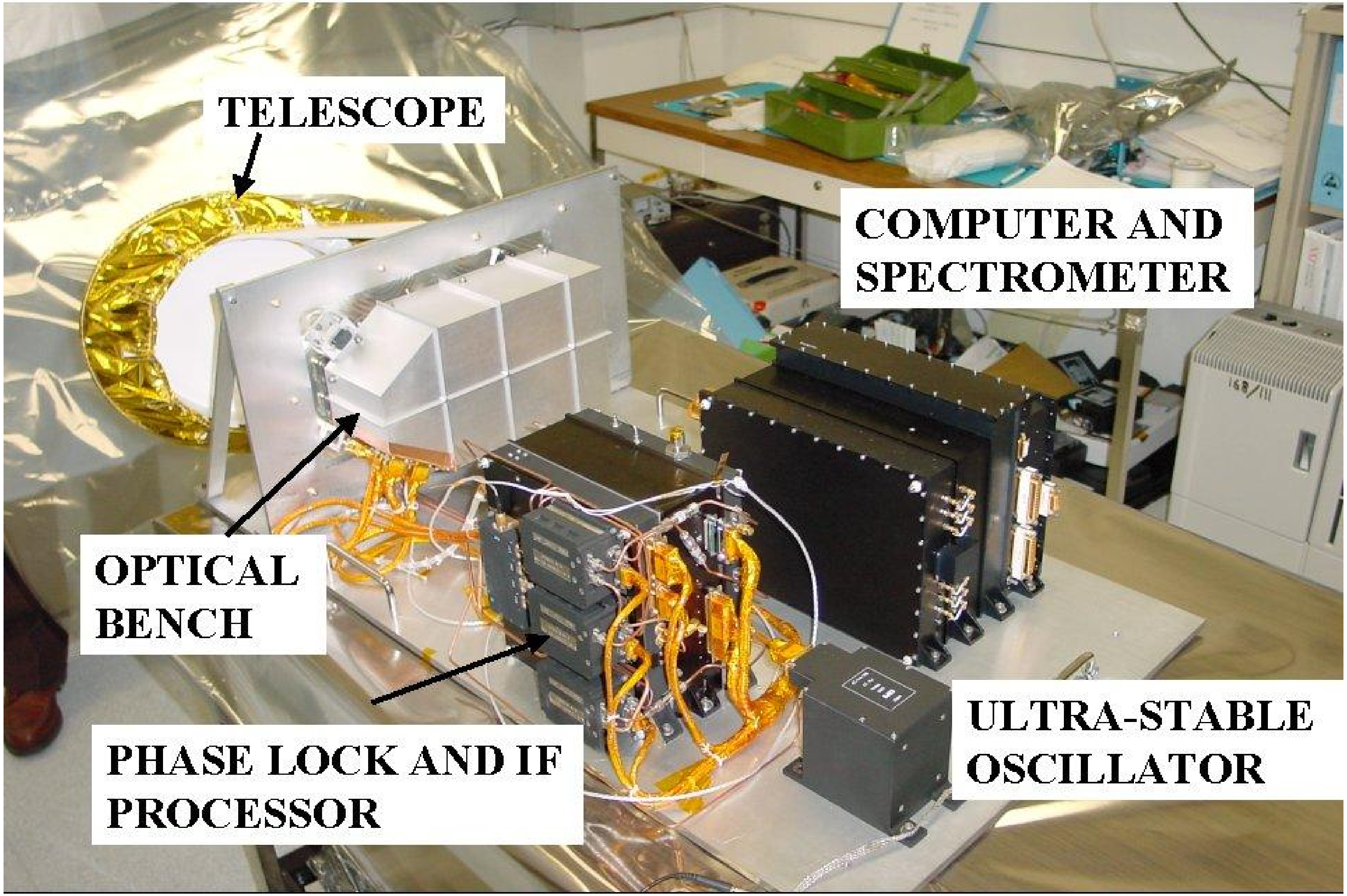
Even the ROSETTA spacecraft towards comet 67P/Churyumov-Gerasimenko carries a tiny radio telescope!

MIRO: a tiny radio telescope onboard ROSETTA

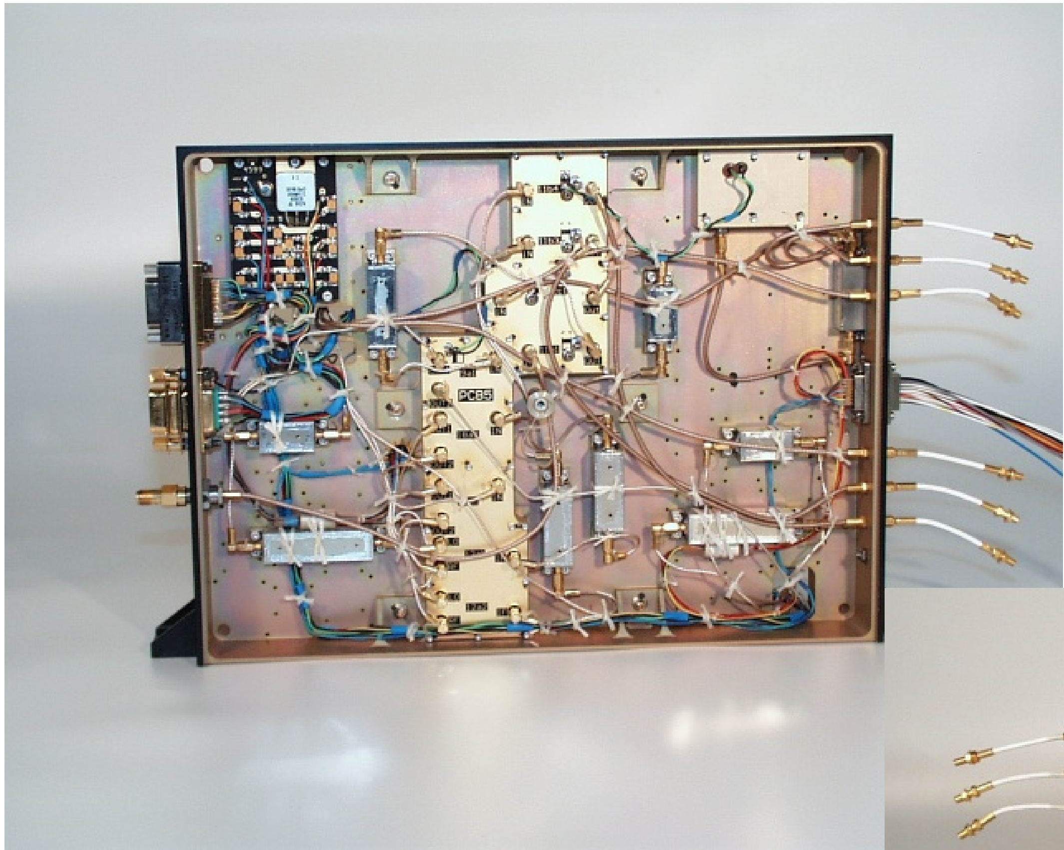


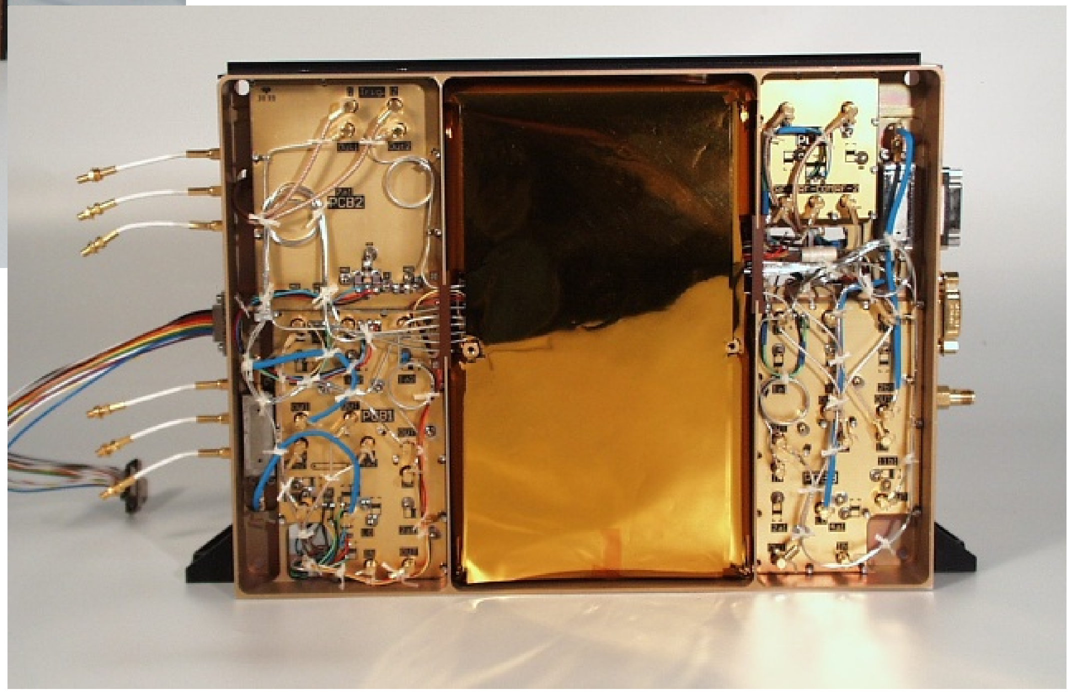
MIRO: a tiny radio telescope onboard ROSETTA

MIRO FLIGHT INSTRUMENT

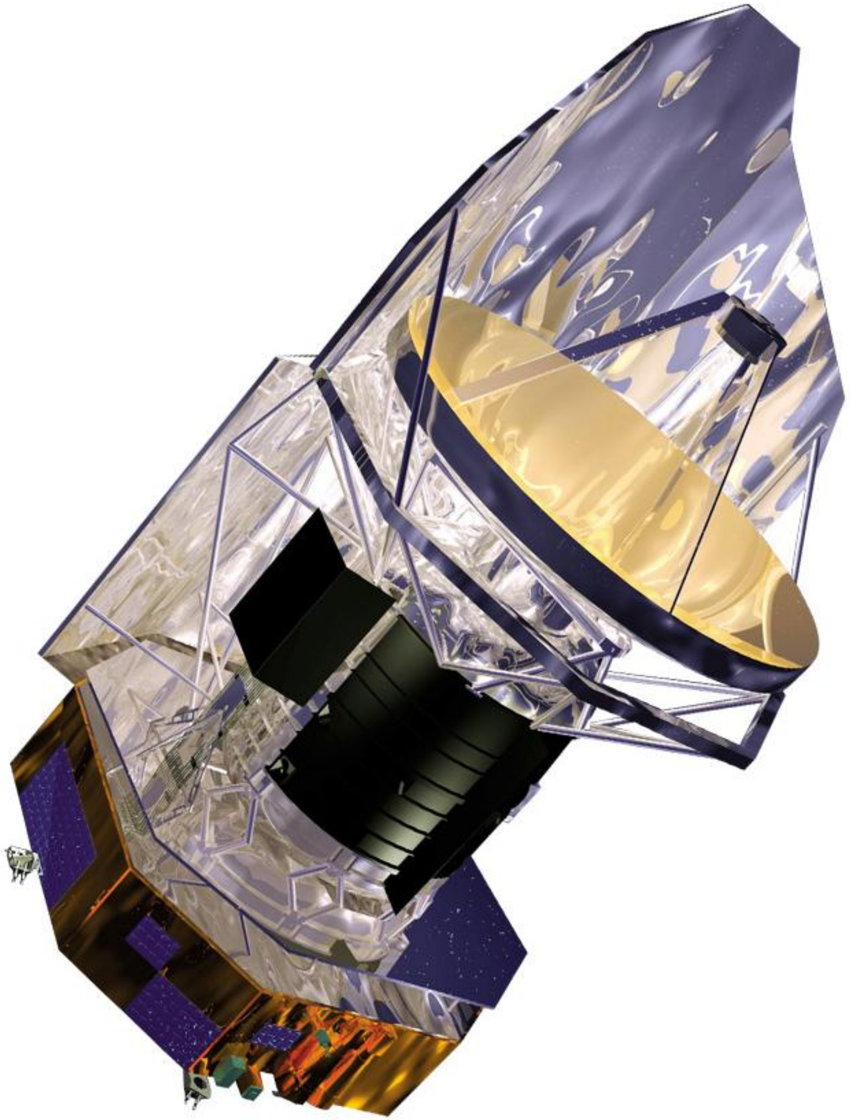


MIRO: CTS developed 1997–2000 at MPS



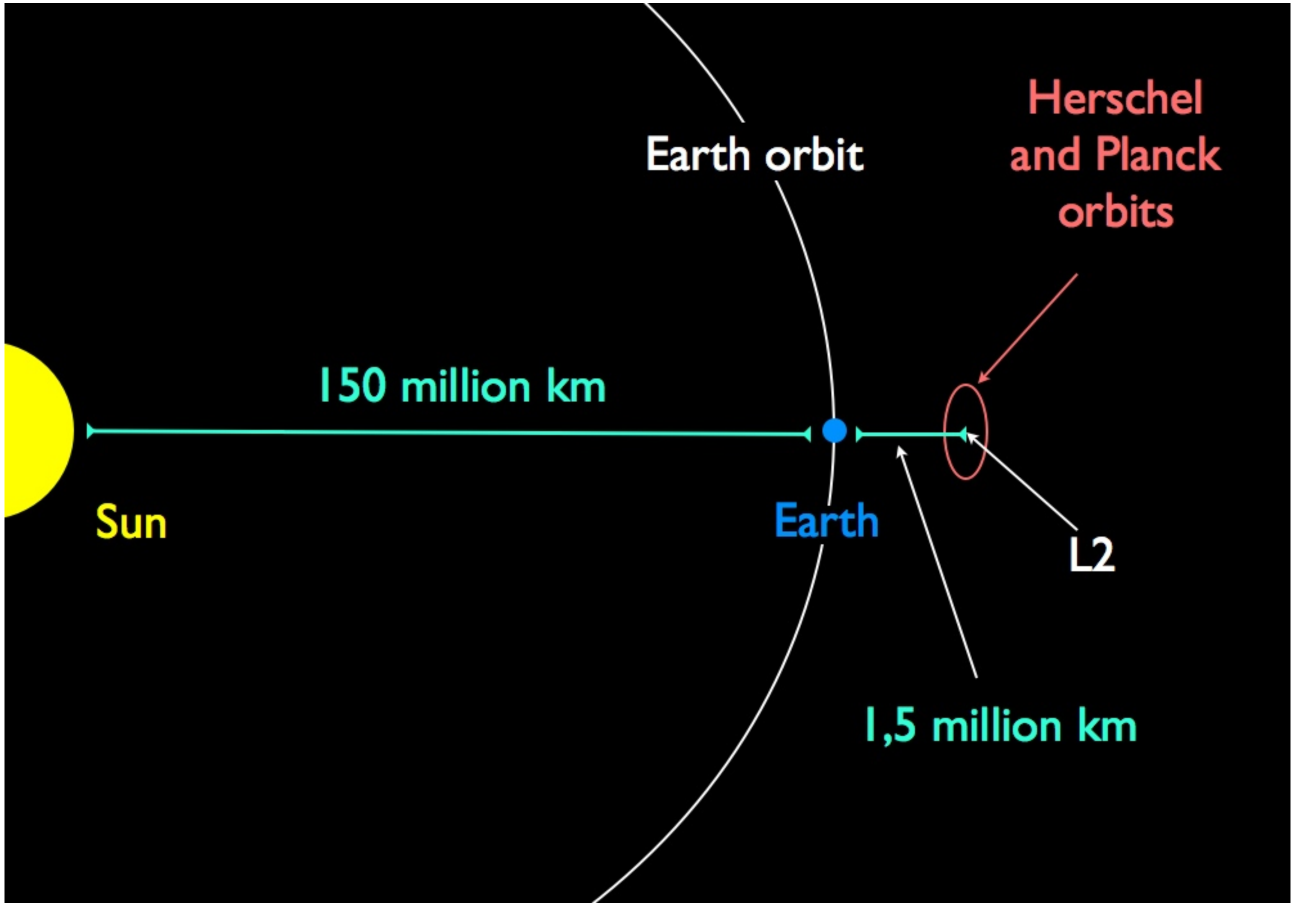


MIRO analog tray

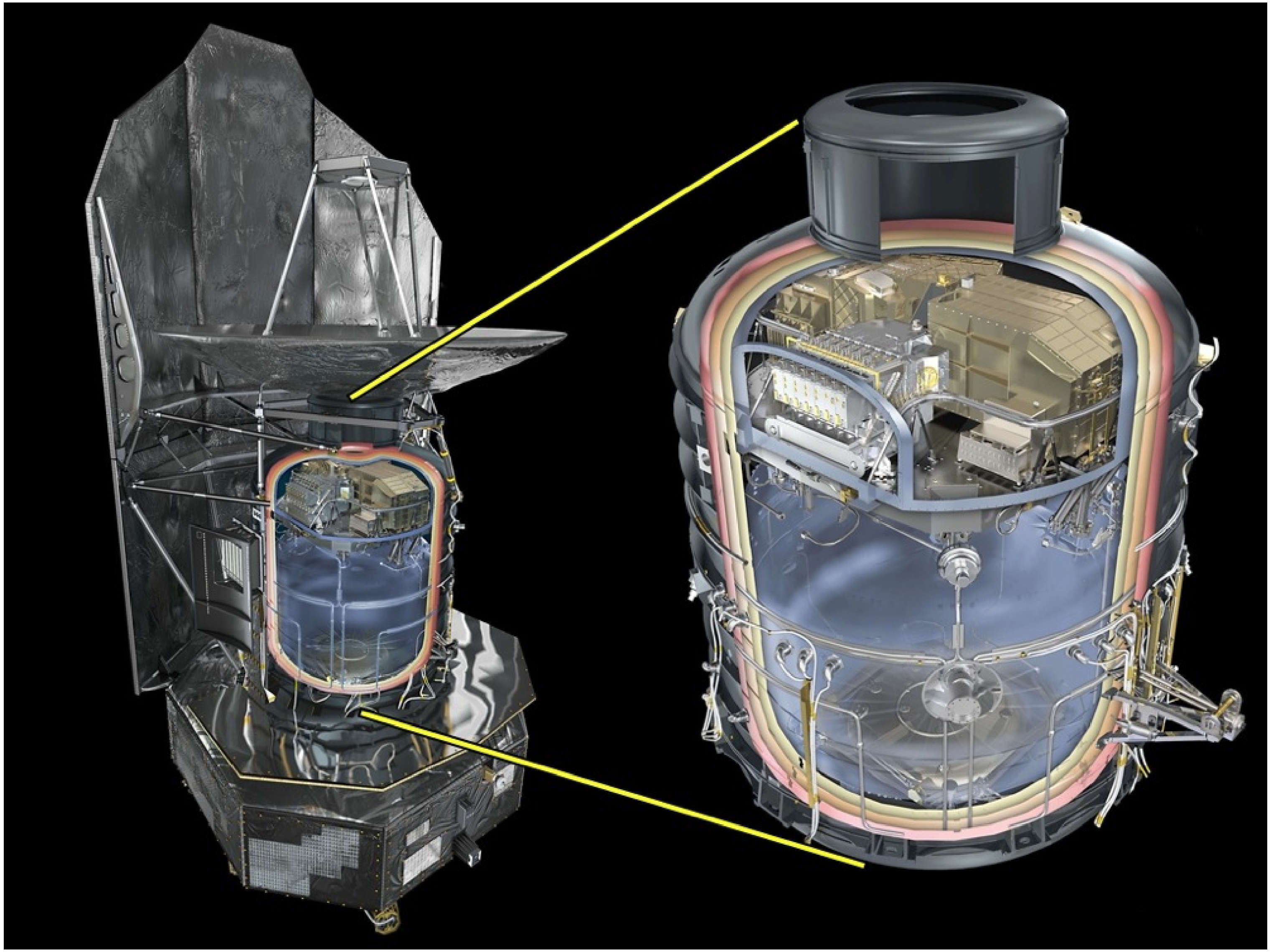


HERSCHEL Specifications

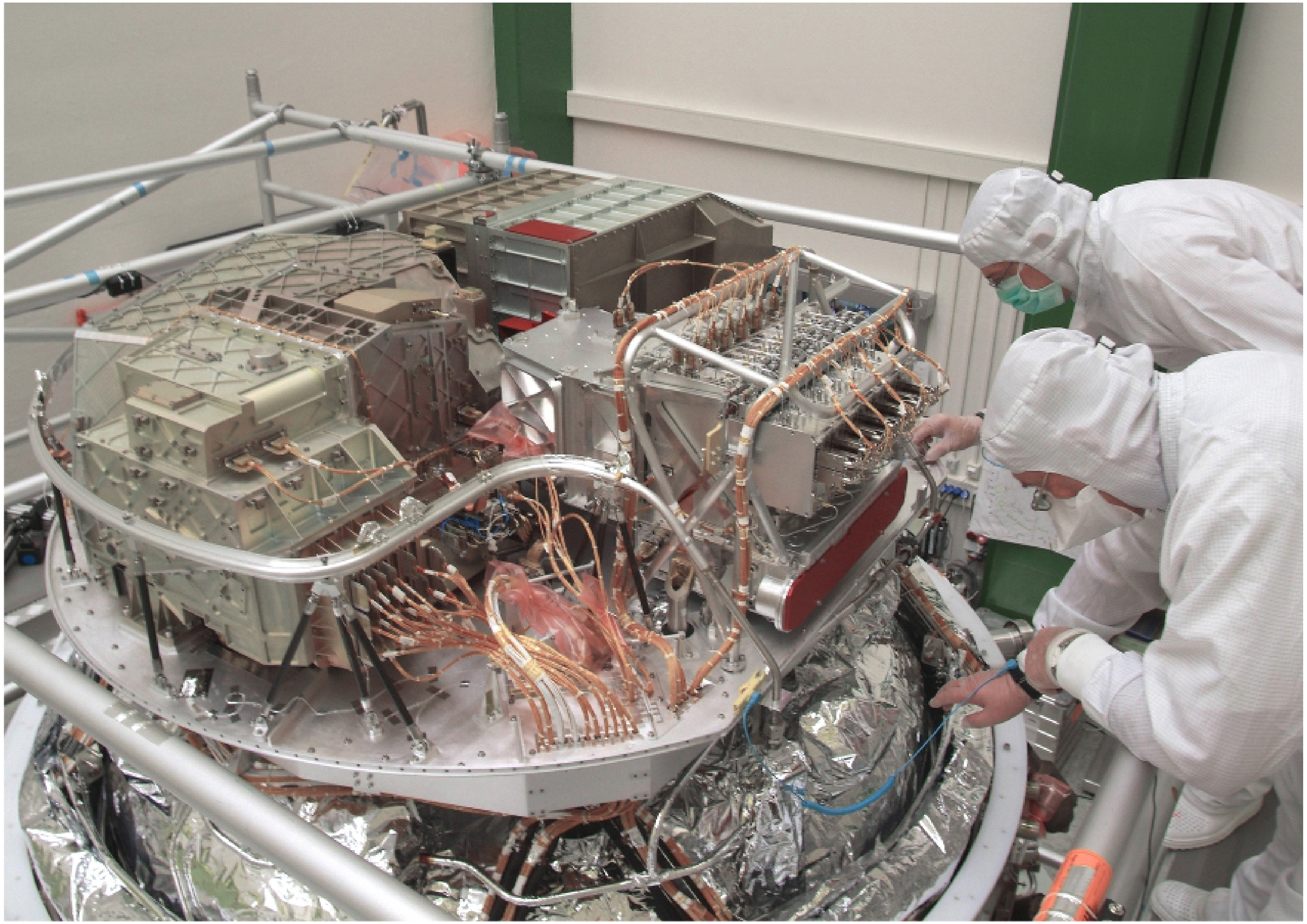
Height	9 m (29.53 ft)
Width	4.5 m (14.76 ft)
Launch Mass	3300 kg (7275.25 lbs)
Power	1 kW
Launch Vehicle	Ariane 5
Orbit	Lissajous around L2
Science Data Rate	100 kbs
Telescope Diameter	3.5 m (11.48 ft)
Telescope WFE	0 μm (goal 6 μm)
Telescope Temperature	0 to 90 K (-334° to -298° F)
ABS Pointing (68%)	3.7” (goal $<$ 1.5”)
REL Pointing (68%)	0.3”
Helium II Temperature	1.65 K (-456.7° F)
Lifetime in L2 (spec)	3 yrs



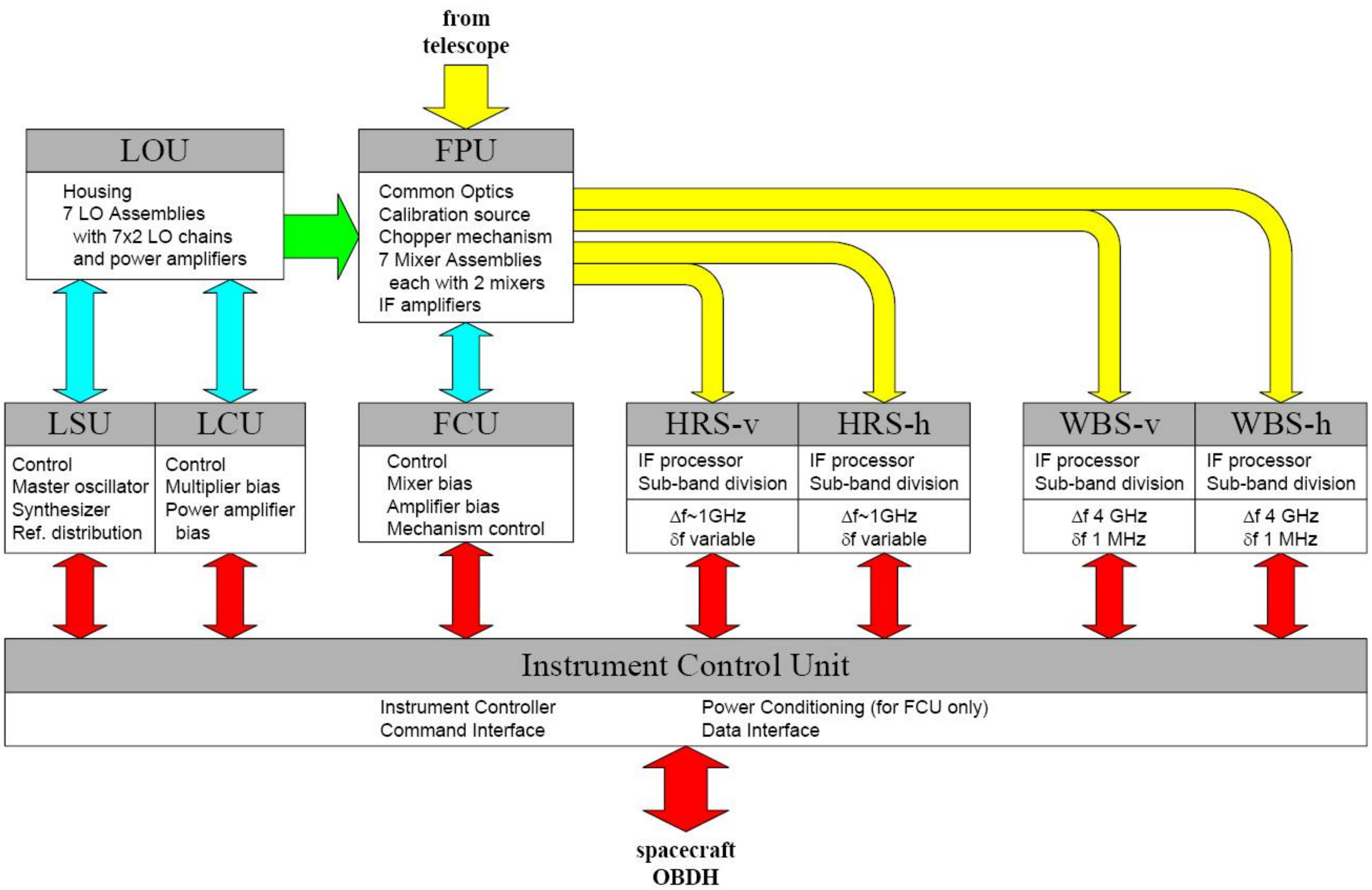
Herschel is orbiting the sun at the second Lagrangian point **L2**.



Details of the HERSCHEL cryostat. It contains the three instruments HIFI, PACS, SPIRE, and about 2300 litres of superfluid Helium for detector cooling.

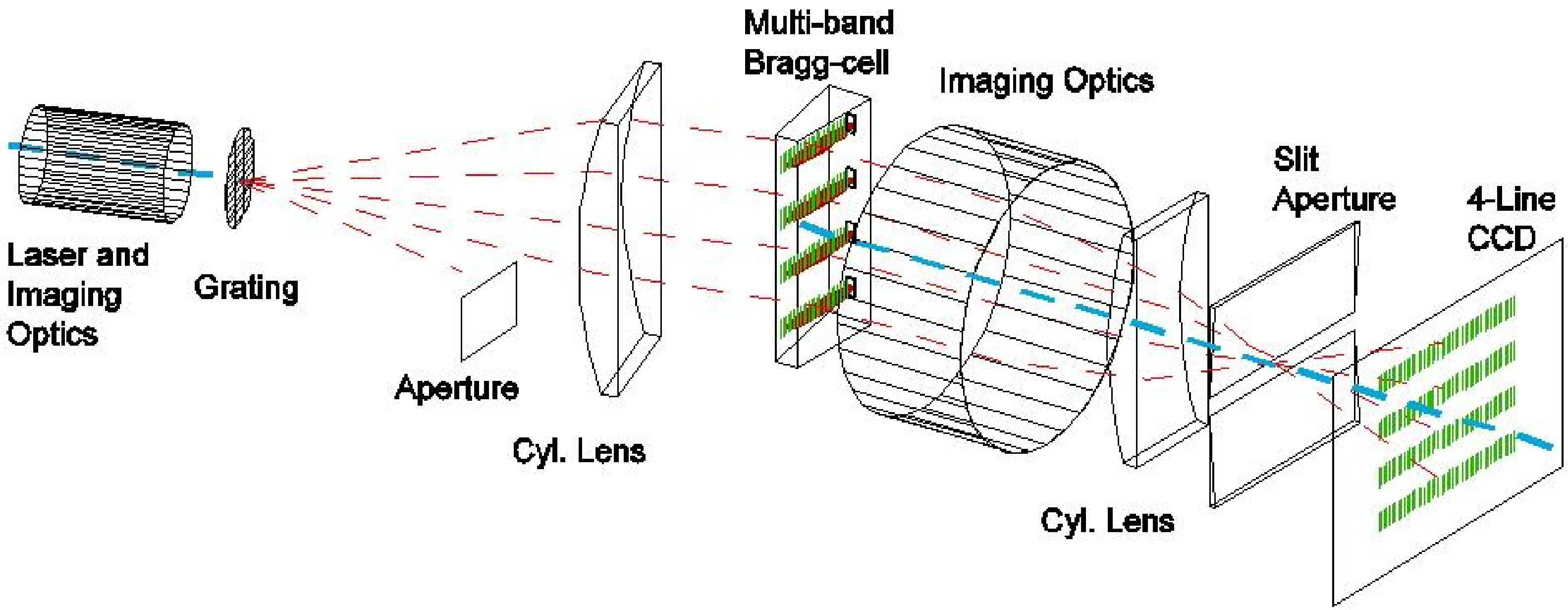


Integration of the three instruments HIFI, PACS, SPIRE into the cryostat. The HIFI Focal Plane Unit (FPU) can be seen close to the center of the image.

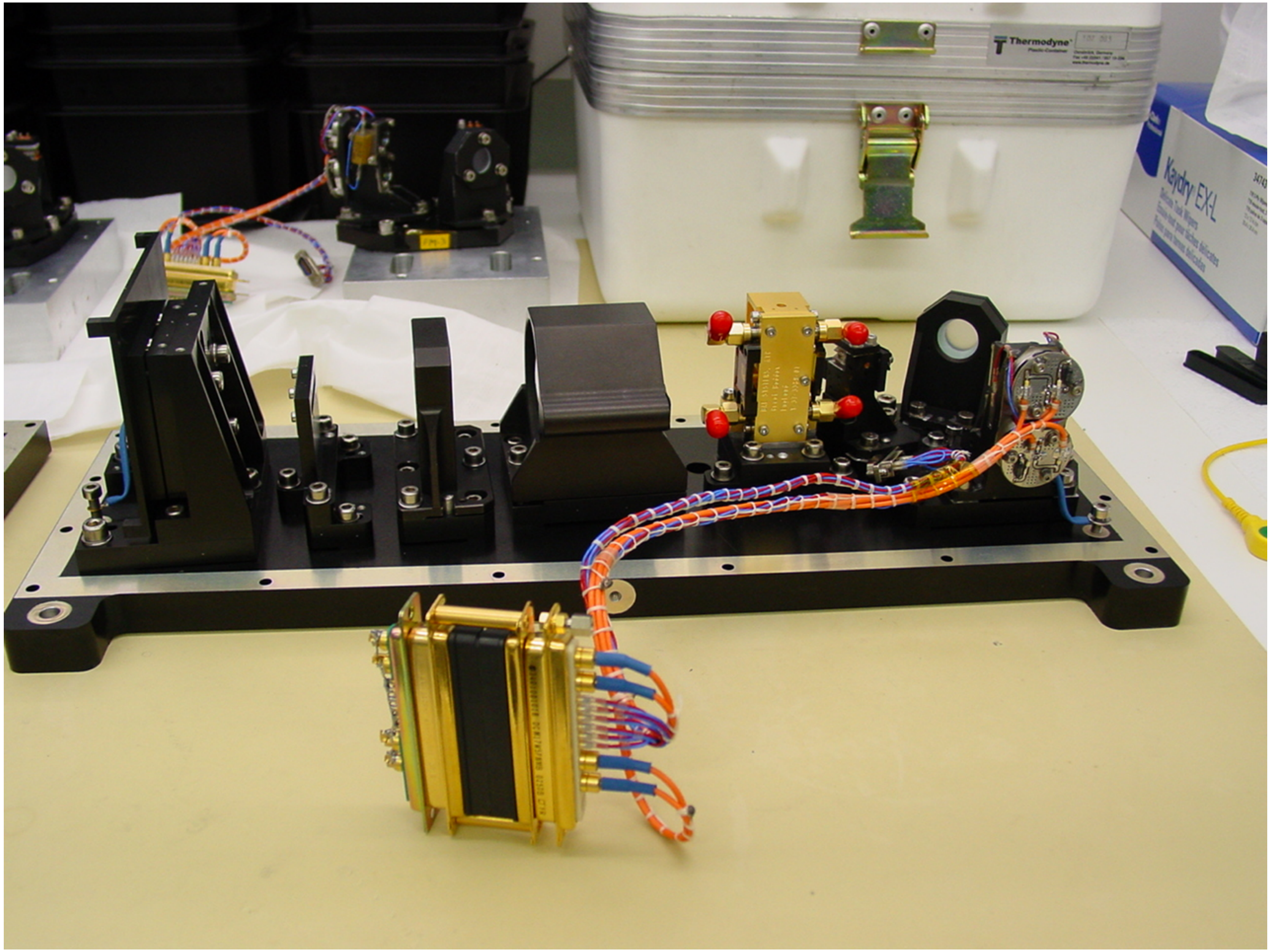


HIFI blockdiagram showing the various sub systems and their interconnections.

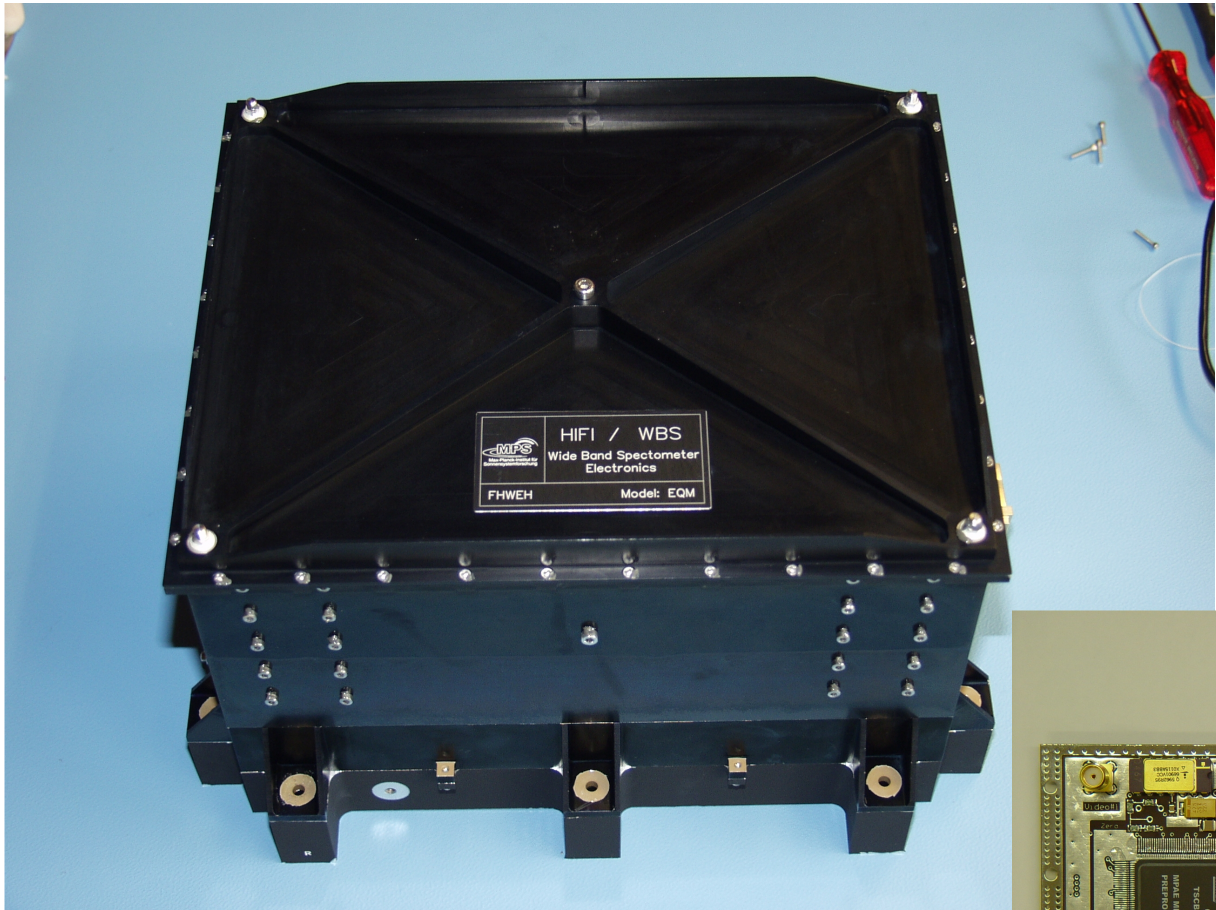
HIFI observes two polarizations with two different spectrometers: The High Resolution Spectrometer (HRS) is a digital autocorrelator, the Wideband Spectrometer (WBS) is an acousto-optical spectrometer. Only the FPU needs to be cooled and is placed inside the cryostat.

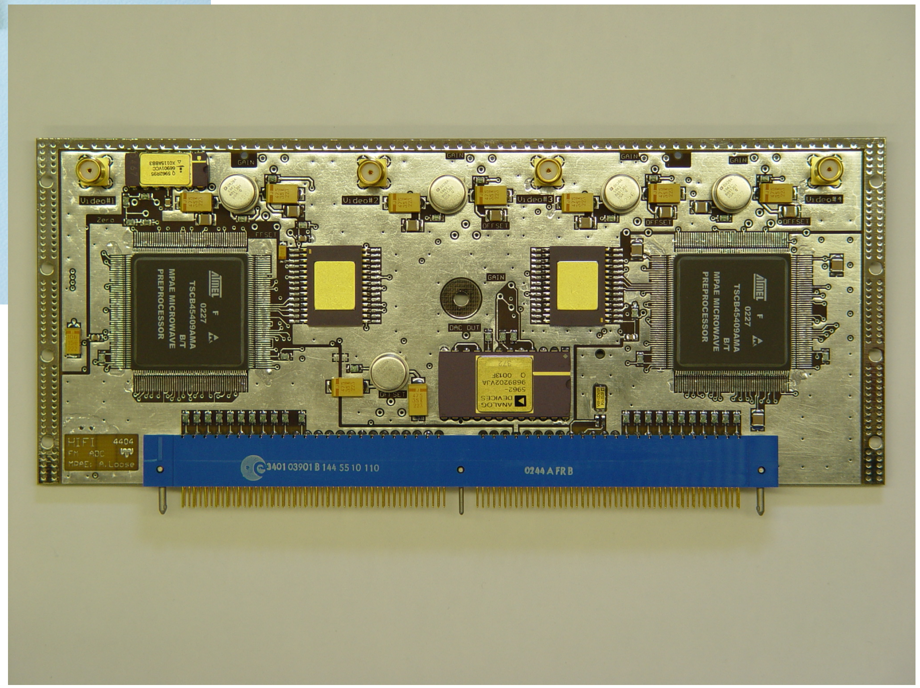


Optical design of the Wideband Spectrometer (WBS).



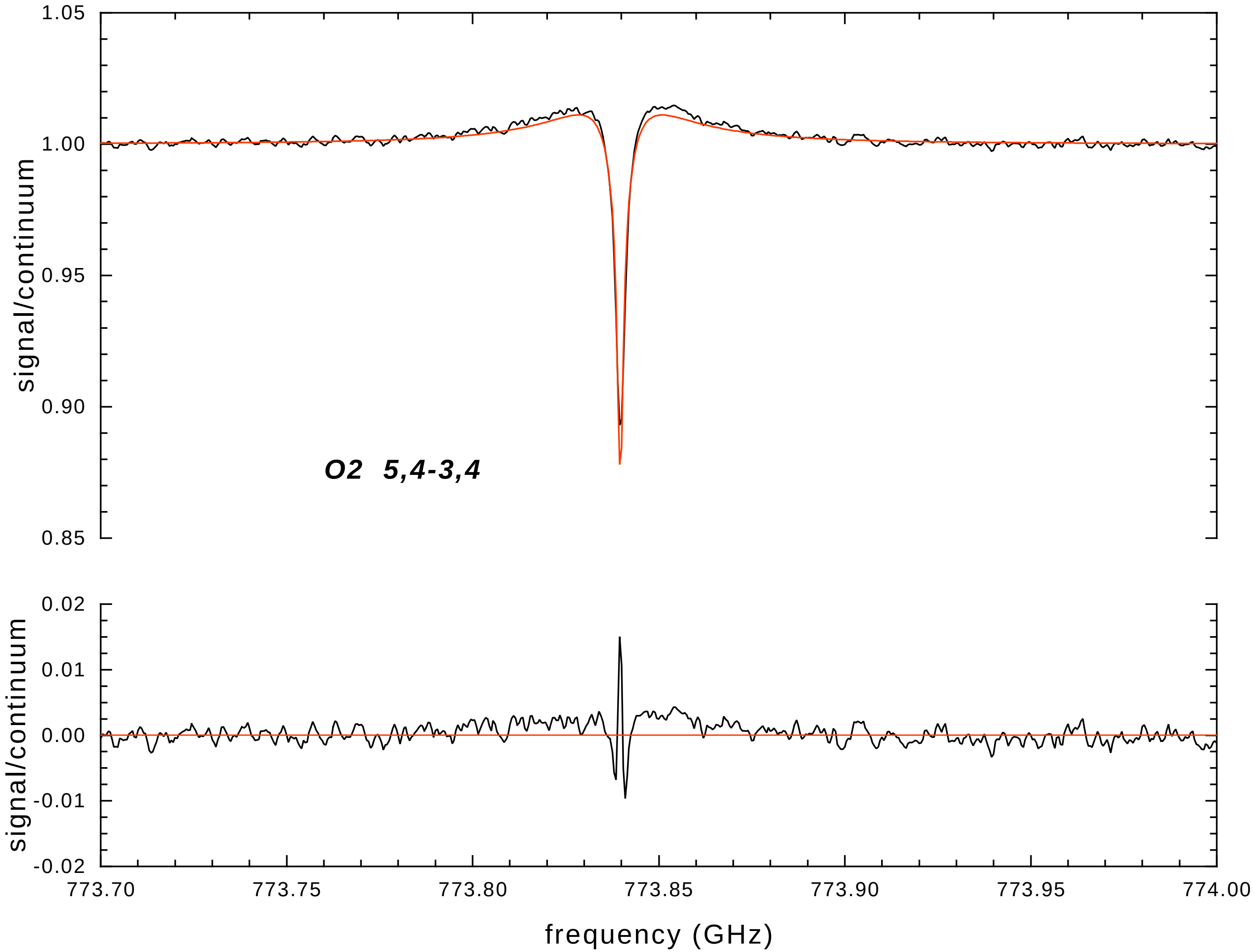
Technical realization of the optical bench of the Wideband Spectrometer WBS. The laser is at the right and the four-line CCD at the left.





The HIFI / WBS Electronics Box was built at MPS.

Functional testing of the WBS electronic box at the MPS in the microwave laboartory (R-Building).



First results: Molecular oxygen (O_2) on Mars observed with HIFI / WBS; 1400 ± 120 ppm confirmed.

Thank You!