Earth Observation by Passive MM-Wave Radiometry

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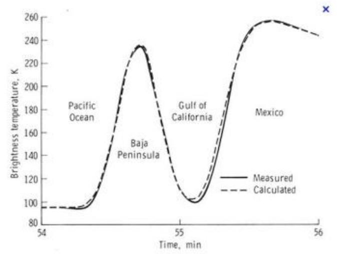
Presentation Outline

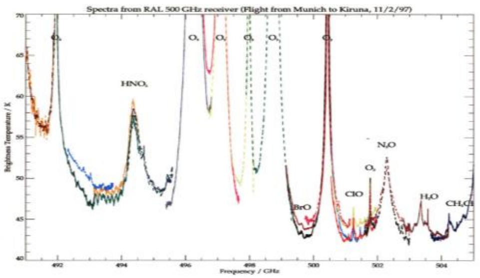
- Introduction to passive remote sensing.
- Basic concept of radiometry.
- Spectral region of observation.
- The approach to detector selection.
- Radiometer (receiver) architectures for mm-wave Earth Observation:
  - Direct detection attributes.
  - Heterodyne detection attributes.
- Example mission drivers.
- Example technology.
- Summary.

Introduction

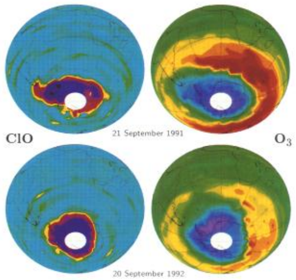
- Earth observation by passive remote microwave and millimetre-wave radiometry employs a combination of detection methods.
- Passive means that a radiometer solely detects, i.e. it does not illuminate the scene under observation.
- Radiometer system architecture selection is dependent on the mission science requirements and instrument level constraints.
- Radiometer systems can be used to;
    - measure scene temperature;
    - detect spectral signatures (molecules);
    - produce images.



Skylab L-band Radiometer Data



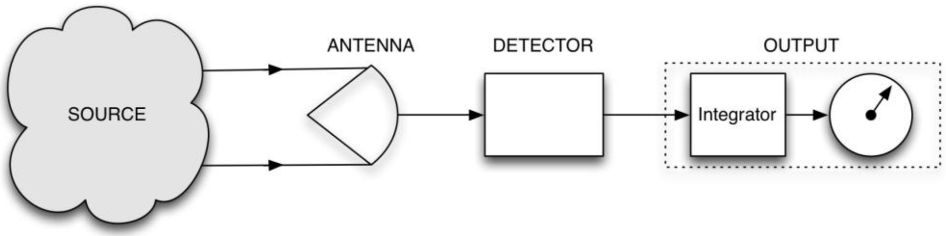
Terrestrial atmospheric spectra in region of 500GHz



Enhanced ClO & depleted ozone in the Earth's atmosphere (UARS MLS)

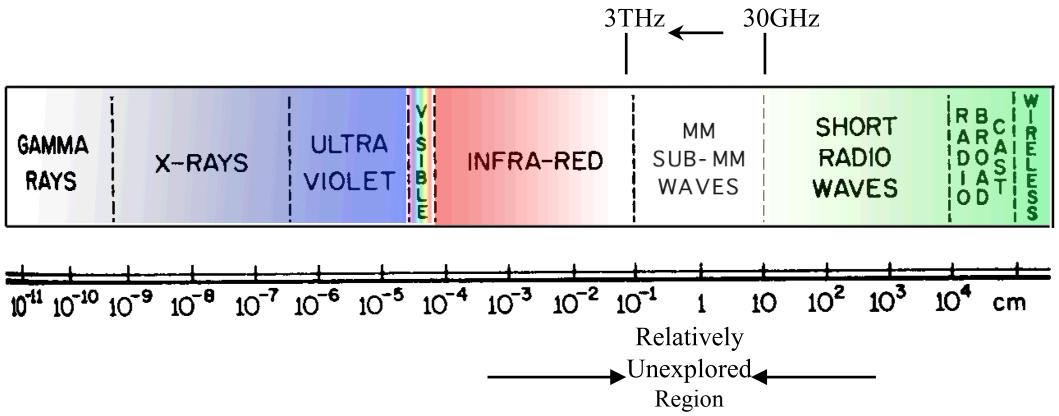
Radiometry – what is it?

- Radiometry is the measurement of radiant energy from a source.
- The distribution of the radiant energy is characterised.
- At micro and mm wavelengths, a basic radiometer consists of three core components:
  - Antenna, which collects the radiation.
  - Detector, which responds to the applied radiation.
  - Output indicator, which is proportional to the input signal intensity.



- Using radiometry detection techniques, we can determine the spatial and spectral characteristics of the source.

The wavelength region



- Part of the electromagnetic spectrum that is not yet fully exploited:
  - Rotational and rotation-vibration transitions of molecular species (O3, ClO, CO, CH4…...
  - Allows fundamental studies of the Earth's atmosphere (and the interstellar medium).
  - Regions of the Earth's atmosphere transparent to the radiation.
  - Depending on frequency selection, can view from top of atmosphere to ground.

- Technology and instrumentation that is still being invented and improved:
  - Detector limited.
  - Opportunities for novel technical development and scientific exploration.
  - New technical development promises improved frequency range, improved signal-to-noise, multi-pixel imagers, reduced mission payload demands.

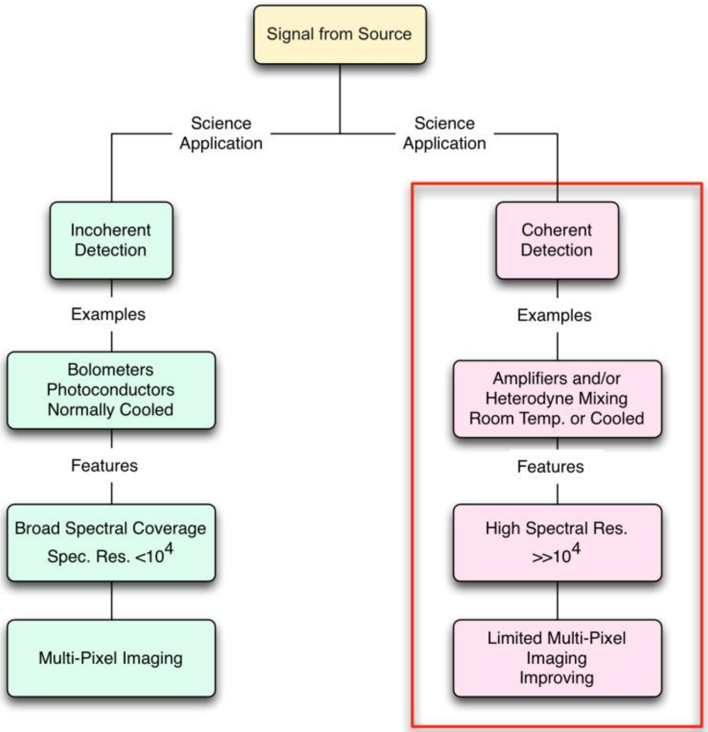
What are the main system parameters?

Depends on the application, but for EO usually:

- Frequency (wavelength).
  - Allows region of the micro/mm/submm-wave electromagnetic spectrum to be studied.
- Sensitivity.
  - Ability to distinguish source signal from background detector noise. Signal to Noise ratio (S/N).
- Stability.
  - Influences sensitivity by limiting system integration time.
- Resolution.
  - Angular, set by antenna size. Spectral, set by detection method.

Fundamental techniques?

- **Two primary detection types:**
  - **Coherent and Incoherent.**
- **Both methods measure the source brightness temperature, be it continuum or spectral.**
- **Coherent (amplifiers and frequency mixers):**
  - Fine resolving power.
  - Phase information preserved.
  - Room temp or cryogenic instrumentation.
- Incoherent (e.g. bolometric or photo-conductive):
  - Broad spectral range.
  - Relatively simple technology.
  - Phase information lost.
  - Usually cryogenic.



Will not consider bolometric detection further in this presentation.

Coherent Radiometer Performance

Normally can use Rayleigh-Jeans approximation:

Brightness = $2kT_{source}/\lambda^2$

Can represent radiometer performance in terms of noise equivalent system temperature by the relationship:

Noise Power = $k\,T_{sys}$ per unit bandwidth

Can show that the minimum detectable signal is given by:

$\Delta T_{source} \approx k\,T_{sys}/(\tau.\Delta f)^{1/2}$

Thus, to provide best sensitivity we need to:

Minimise T_{sys}, and/or maximizse τ and Δf.

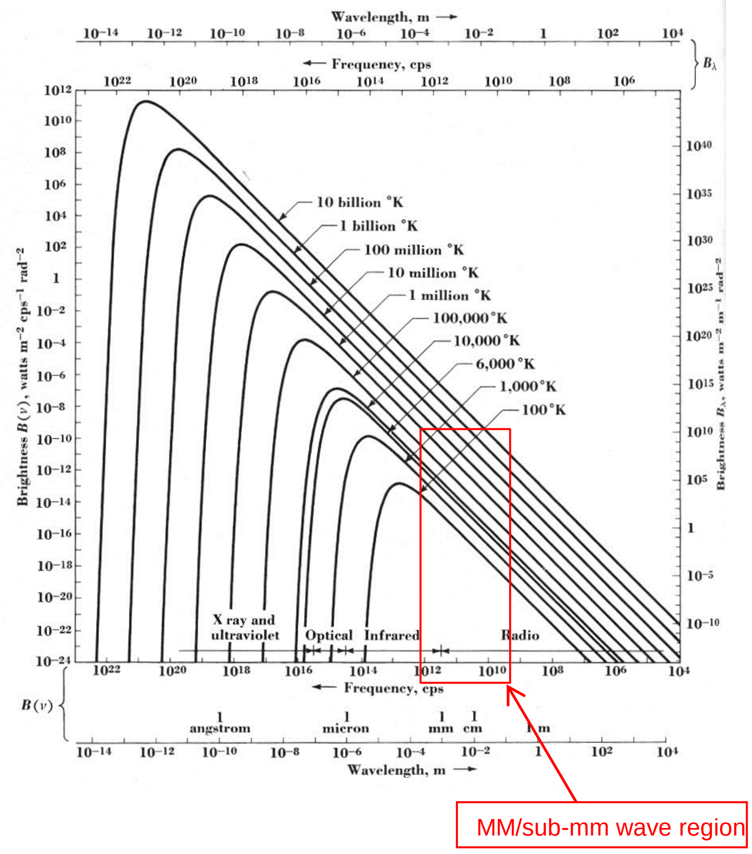
But τ and Δf are often observation dependent &

Tsys depends on the detector noise and config.

Therefore need to consider overall system.

k= Boltzmann's constant, λ= wavelength, τ = integration time and Δf = bandwidth.

Planck Radiation Curve Ref: Kraus Radio Astronomy



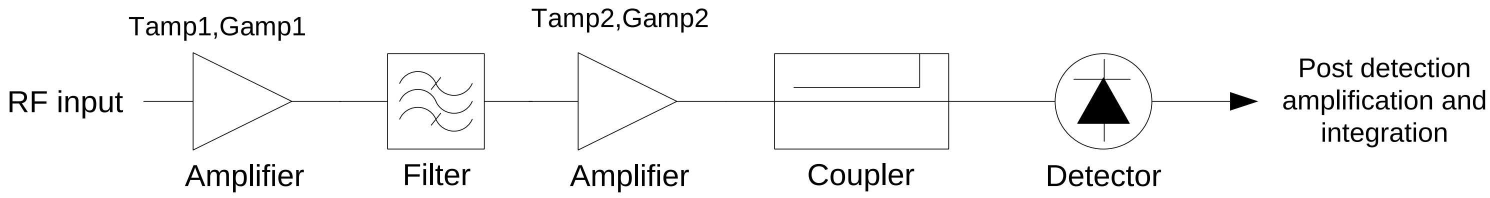
Note that in the THz region, and for lower temperature sources, we do have to consider Planck effects.

Coherent Radiometer (Receiver) Architectures

Direct Amplification & Detection

$T_{sys} = T_{amp1} + T_{amp2}/G_{amp1}$

$G_{amp1} >> 1$



Main characteristics/advantages:

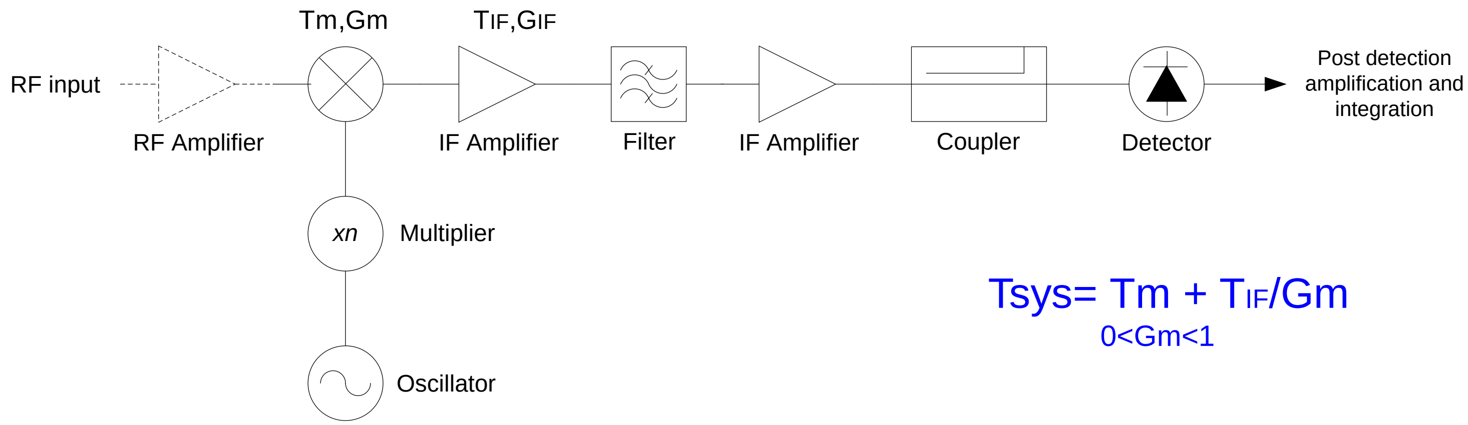
- *Detection performed directly at the frequency of the input signal.*
- *Noise of first amplifier normally defines system sensitivity.*
- *Filter used to define system bandwidth.*
- *Simpler approach than heterodyne.*

Main disadvantages:

- *Availability of low noise amplifiers and detectors >~130GHz limited.*
- *Narrow band filters difficult to make for high-spectral resolution requirements*

Common Receiver Architectures

Heterodyne Receiver



$$T_{sys} = T_m + T_{IF}/G_m$$

$$0 < G_m < 1$$

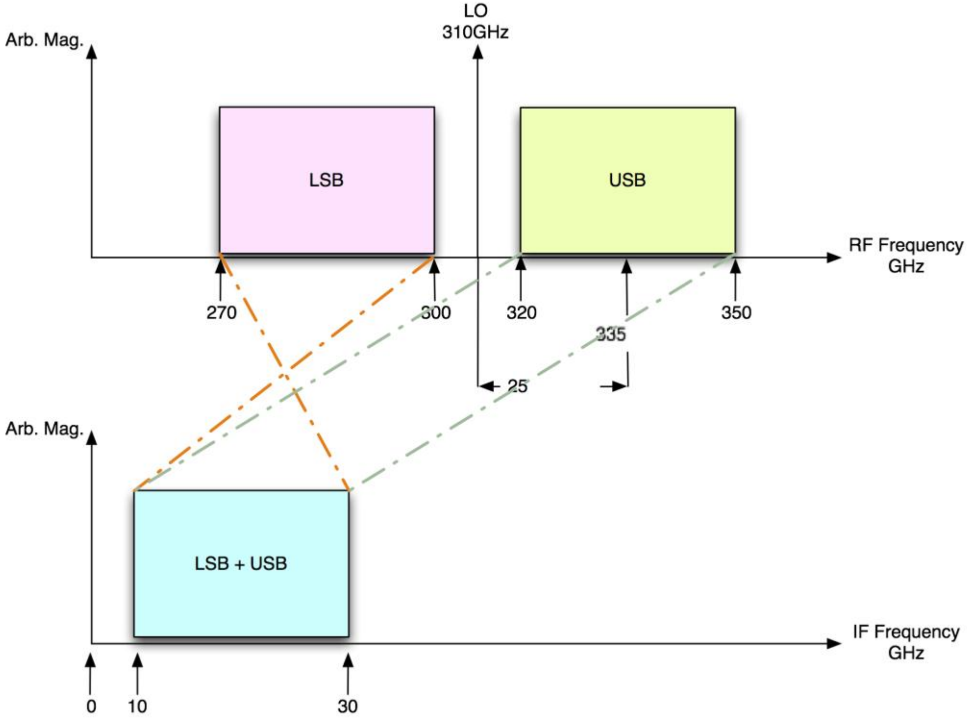
Main characteristics/advantages

- *At >~130GHz, heterodyne receiver uses "mixer-first" topology.*
- *Input signal is down-converted to a lower Intermediate Frequency (IF).*
- *Frequency conversion can provide very high spectral resolution via narrow band filtering or high-speed digital sampling.*

Main disadvantages

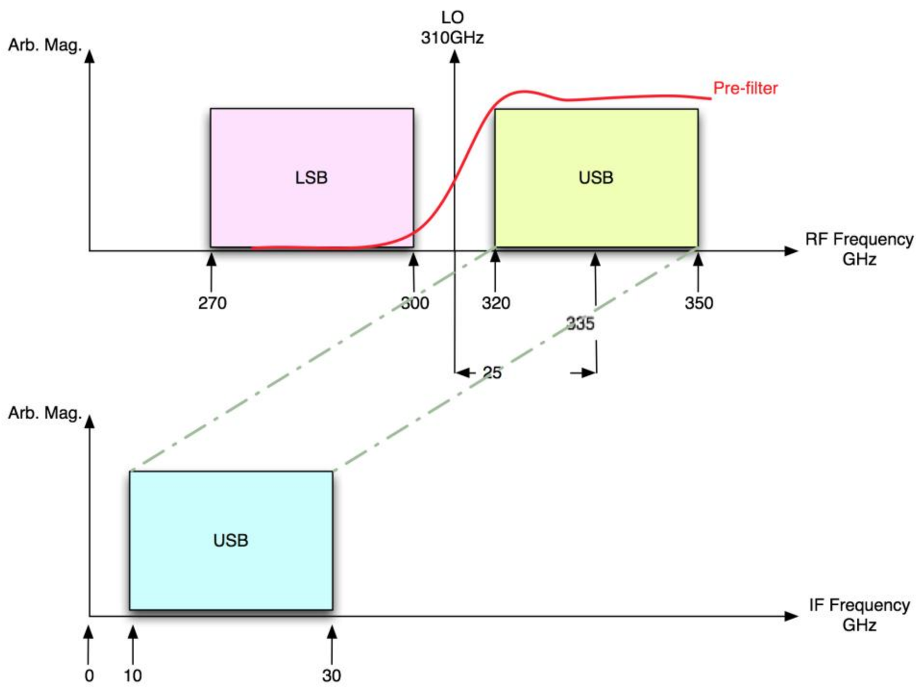
- *Increased system complexity.*
- *IF amplifier adds to system noise and limits total instantaneous bandwidth.*
- *Requires stable local oscillator (frequency and power).*
- *Potential signal confusion due to presence of sideband response.*

Heterodyne Technique – Double Sideband



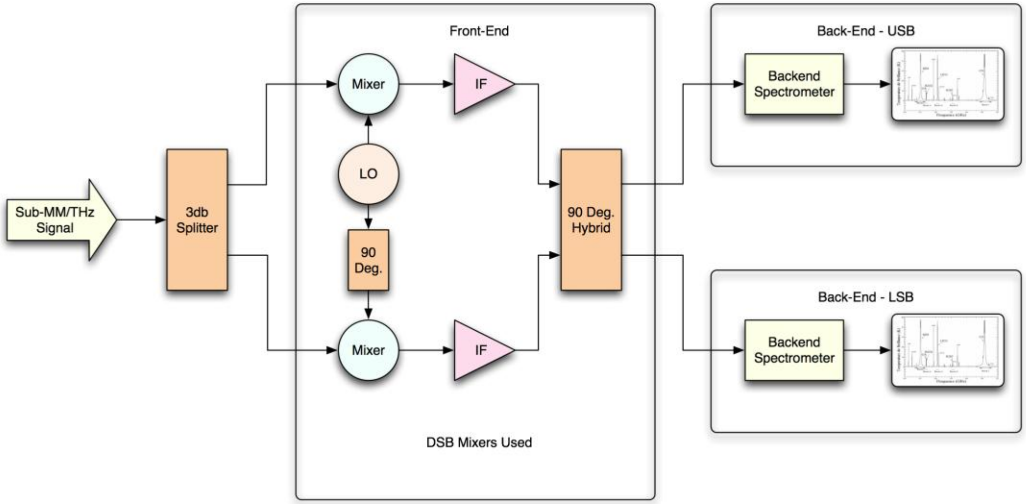
- **All signals in lower sideband (**LSB**) and upper sideband (USB) transformed to IF. Therefore two 'images' mapped to the IF.**
- **Provides broader bandwidth, but potential exists for spectral signature confusion.**

Heterodyne Technique – Single Sideband



- **Use optical filtering (dichorics, frequency selective surfaces, interferometers) or first amplifier to remove one sideband (LSB or USB).**
- **Enhances spectral precision.**
- **Difficult at increasing frequencies and can degrade system performance.**

Heterodyne Image Rejection System



- **Use two heterodyne systems to provide sideband separation.**
- **Provides separation of sidebands into two output channels.**
- **Offers increased spectral bandwidth with spectral separation.**
- **Increased system complexity and limited of sideband rejection.**

SubHarmonically pumped Image Reject Mixer – SHIRM considered excellent candidate for EO missions >~130GHz.

Requirements Driving Receiver Architecture

- Mission Level
  - *Channel centre frequency*
  - *Channel bandwidth (spectral resolution)*
  - *Frequency stability*
  - *Receiver noise temperature*
  - *RFI immunity*
- Instrument Level
  - *Mass, power, volume*
- Component Level
  - *Availability*
  - *Performance*
  - *Reliability*
  - *Heritage (especially for space use)*
  - *Cost*

MetOp SG Mission

- MetOp SG is Europe's next-generation platform for Operational Meteorology
- Mission is currently undergoing Phase A/B1 industrial studies
- Three passive millimetre-wave missions with contrasting requirements
  - *Microwave Sounder (MWS): atmospheric temperature & humidity sounding*
  - *Microwave Imager (MWI): precipitation monitoring & sea ice extent*
  - *Ice-Cloud Imager (ICI): monitoring of clouds and ice particles*

MWS – Selected Requirements

Table 4 MWS Channels, bandwidth and frequency stability

Channel name	Frequency (GHz)	Bandwidth (MHz)	Frequency Stability (MHz)
MWS-1	23.8	270	±5
MWS-2	31.4	180	±10
MWS-3	50.3	180	±5
MWS-4	52.8	400	±3
MWS-5	53.246±0.08	2x140	±5
MWS-6	53.596±0.115	2x170	±2
MWS-7	53.948±0.081	2x142	±1
MWS-8	54.4	400	±2
MWS-9	54.94	400	±2
MWS-10	55.5	330	±2
MWS-11	57.290344	330	±0.5
MWS-12	57.290344±0.217	2x78	±0.5
MWS-13	57.290344±0.3222±0.048	4x36	±1.2
MWS-14	57.290344±0.3222±0.022	4x16	±1.2
MWS-15	57.290344±0.3222±0.010	4x8	±0.5
MWS-16	57.290344±0.3222±0.0045	4x3	±0.2
MWS-17	89	4000	±130
MWS-18	165.5±0.725	2x1350	±40
MWS-19	183.311±7.0	2x2000	±30
MWS-20	183.311±4.5	2x2000	±30
MWS-21	183.311±3.0	2x1000	±30
MWS-22	183.311±1.8	2x1000	±30
MWS-23	183.311±1.0	2x500	±30
MWS-24	229	2000	±100

Channel centre frequency

- 23.8 GHz – 229 GHz
- Wide coverage

Channel bandwidth

- 3 MHz – 2000 MHz
- High resolution required at ~57 GHz

Frequency stability

- ±0.2 MHz – ±100 MHz
- High stability required at ~57 GHz

MWI – Selected Requirements

Table 4 MWI Channels, bandwidth and frequency stability

Channel name	Frequency (GHz)	Bandwidth (MHz)	Frequency Stability (MHz)
MWI-1	18.7	200	±50
MWI-2	23.8	400	±50
MWI-3	31.4	200	±50
MWI-4	50.3	400	±10
MWI-5	52.61	400	±5
MWI-6	53.24	400	±5
MWI-7	53.75	400	±5
MWI-8	89	4000	±100
MWI-9	118.7503±3.2	2x500	±15
MWI-10	118.7503±2.1	2x400	±15
MWI-11	118.7503±1.4	2x400	±15
MWI-12	118.7503±1.2	2x400	±15
MWI-13	165.5±0.725	2x1350	±100
MWI-14	183.31±7.0	2x2000	±70
MWI-15	183.31±6.1	2x1500	±70
MWI-16	183.31±4.9	2x1500	±70
MWI-17	183.31±3.4	2x1500	±70
MWI-18	183.31±2.0	2x1500	±30

Channel centre frequency

- 18.7 GHz – 183 GHz
- Wide coverage

Channel bandwidth

- 200 MHz – 2000 MHz
- Moderate resolution

Frequency stability

- ±5 MHz – ±100 MHz
- Moderate stability

ICI – Selected Requirements

Table 4 ICI Channels, bandwidth and frequency stability

Channel name	Frequency (GHz)	Bandwidth (MHz)	Frequency Stability (MHz)
ICI-1	183.31±7.0	2x2000	±100
ICI-2	183.31±3.4	2x1500	±100
ICI-3	183.31±2.0	2x1500	±100
ICI-4	243.2±2.5	2x3000	±100
ICI-5	325.15±9.5	2x3000	±200
ICI-6	325.15±3.5	2x2400	±200
ICI-7	325.15±1.5	2x1600	±200
ICI-8	448±7.2	2x3000	±200
ICI-9	448±3.0	2x2000	±200
ICI-10	448±1.4	2x1200	±200
ICI-11	664±4.2	2x5000	±400

Channel centre frequency

- 183 GHz – 664 GHz
- High frequency

Channel bandwidth

- 1200 MHz – 2000 MHz
- Moderate resolution

Frequency stability

- ±100 MHz – ±400 MHz
- Moderate stability

Mission Level Requirements

Channel Centre Frequency

- As channel frequency increases, availability of key components becomes a driving factor in choice of receiver architecture
  - *RF LNAs & detectors available to ~200 GHz, however TRL is low*
  - *Mixers/LO chain components available to ~700 GHz*

- Current breakpoint for direct detection / heterodyne receiver selection is ~130 GHz
  - *RF LNA performance better than mixer/IF LNA to ~130 GHz (dependent on channel bandwidth)*

Mission Level Requirements

Channel Bandwidth

- Extensive range of filter topologies available at microwave and low millimetre wavelengths, e.g. to 40 GHz
  - *At higher frequencies range of filter topologies is limited and fabrication/machining is more specialised*

- For channels with low fractional bandwidth requirements ($f_{BW}/f_c < 0.01$), it is preferable to employ a heterodyne receiver
  - *Filtering performed at low IF frequency*
  - *Difficult to realise filter at RF frequency*

Mission Level Requirements

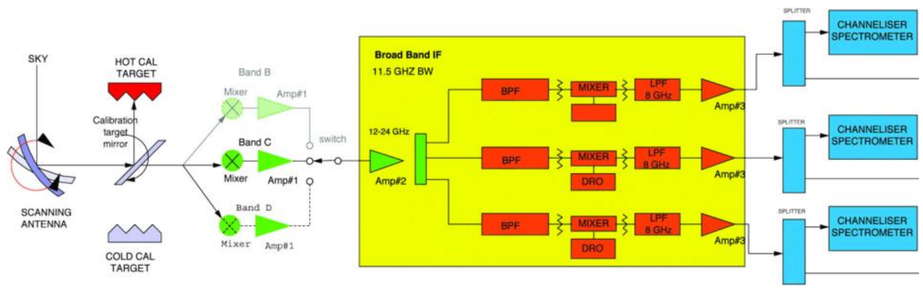
Frequency Stability

- Frequency stability of a Direct Detection Receiver is defined by the temperature stability of its channel definition filter bandwidth
  - *Filter stability depends on the material used*
  - *Aluminium alloy filter stability ~23ppm/ °C*
  - *SiO2 filter stability ~10ppm/ °C*
  - *Invar filter stability ~2ppm/ °C*

- Frequency stability of a Heterodyne Receiver is defined by the temperature stability of the fundamental oscillator of the LO chain
  - *Multiplication in LO chain will degrade stability*
  - *Free-running DROs have stability ~3ppm/°C*
  - *Phase-locked DROs have stability ~1ppb/°C*

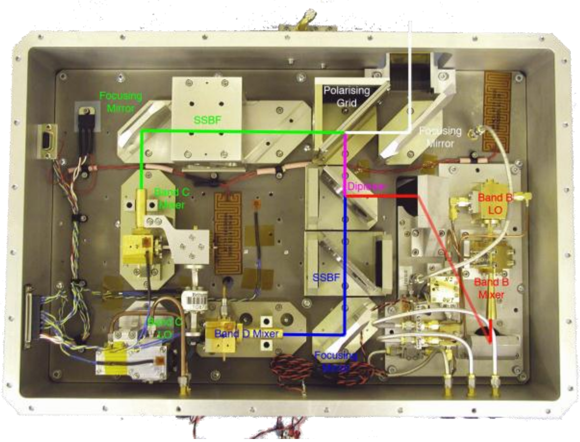
- Heterodyne receivers must be selected when high frequency stability is required

MMTG System Technology Examples: MARSCHALS



The quasi-optical network splits the signal into three frequency bands around 300 GHz, 325 GHz and 345 GHz. This allows the detection of O_3, H_2O, CO, N_2O and some other minor trace gases

Geophysica M55



MARSCHALS receiver front-end unit

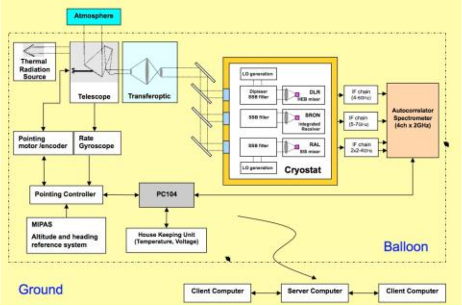
MARSCHALS on Geophysica M55

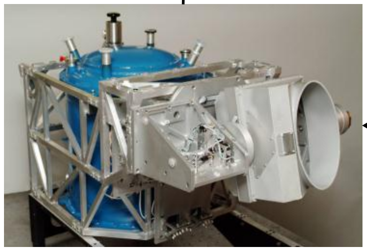
MMTG System Technology Examples:
TELIS (TErahertz & submm LImb Sounder)

RAL/DLR SRON collaboration produced a THz superconducting remote sounder operating in spectral regions from 0.5THz to 1.8THz.

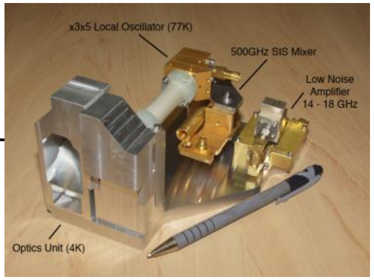
THz observations from balloon platforms using superconducting heterodyne receivers allow the detection of molecular species in the stratosphere.

Flown three times, and again after this event!





TELIS Receiver System – Blue Unit is a LHe Cryostat containing all THz Receivers

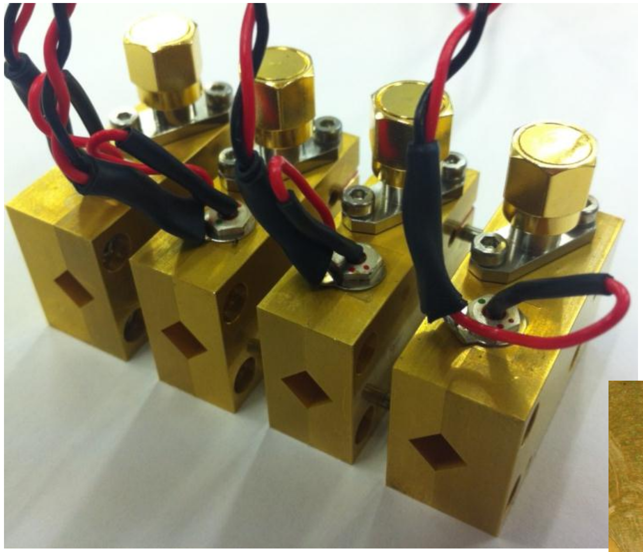


RAL ultra-compact 500 GHz SIS radiometer subsystem

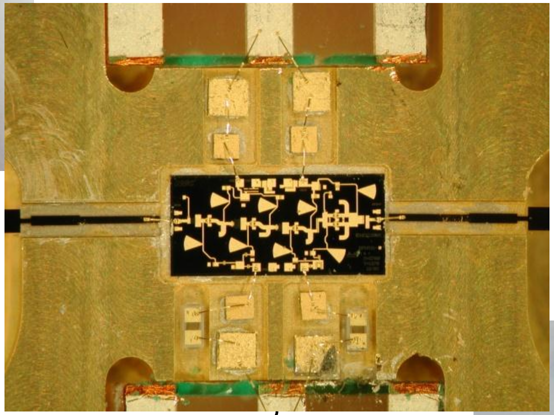
MMTG Component Technology

MMTG is developing component technologies in support of its various programmes. These include, for example:

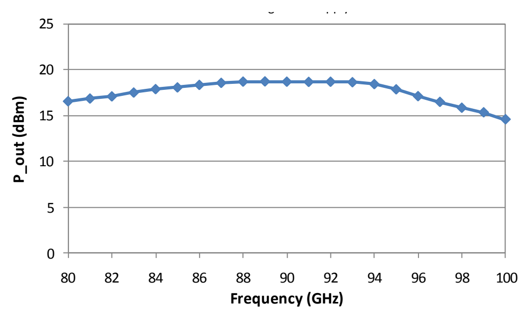
- Schottky diode mixer focal plane imaging arrays.
- MM Wave Integrated Circuit Amplifiers – packaging
- Photomixers for conversion of IR laser tones to mm-wave

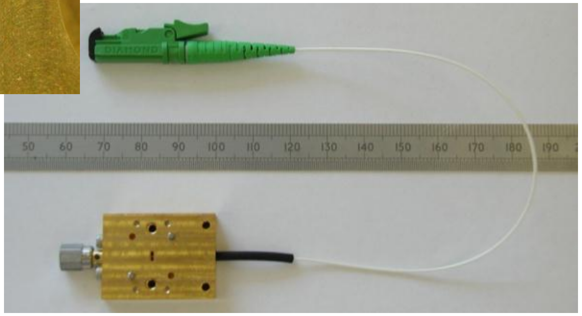


Four element array receiver



Packaged mm-wave amplifier





Photomixer

Summary

- Current and future passive microwave and millimetre-wave radiometry provides and important Earth observation tool.
- Provides scene temperature and imaging.
- Allows high-resolution spectroscopy.
- Trade-off between detection methods is essential in selecting the most appropriate instrument configuration.
- Direct amplifier detection up to ~130GHz.
- Heterodyne detection best >~130GHz.
- Future EO mission (MWI/MWS, ICI and STEAM-R) will use both types.
- RAL Millimetre-Wave Technology Group at the forefront of such development

Thank you