millimetre-wave technology MMT

Dave Matheson

Space Science and Technology Department
Rutherford Appleton Laboratory, UK

Millimeter & sub-millimeter technology: a UK perspective

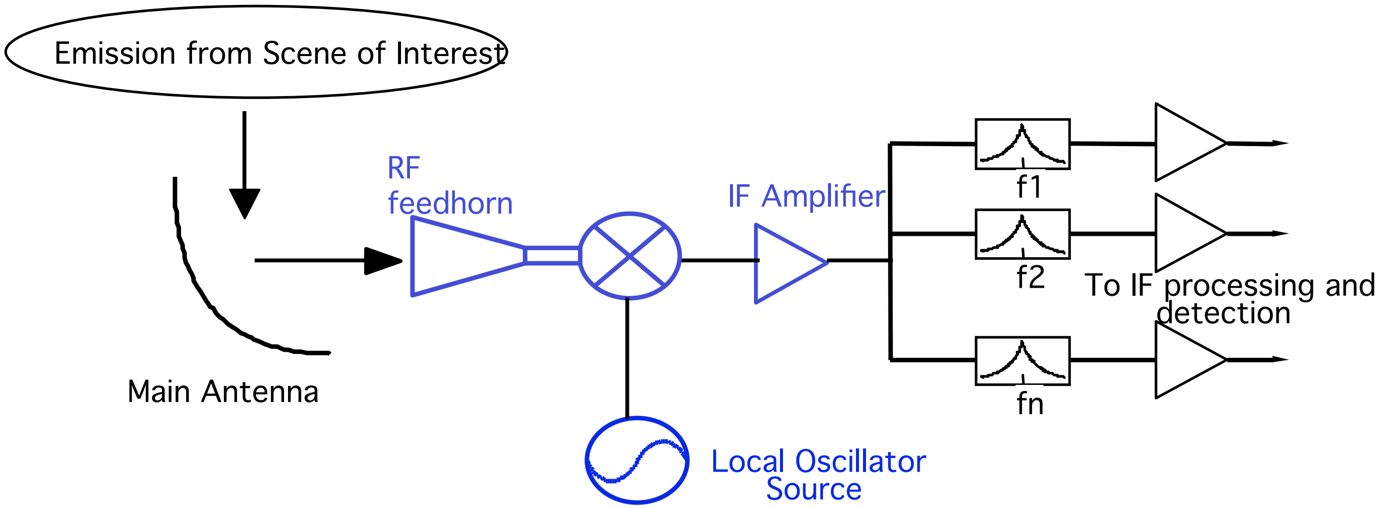
Introduction

- Development of technology in the terahertz spectral region has been largely driven by the needs of astronomy & remote sensing

- This is likely to continue. Continuing interest in astronomy and atmospheric composition and climate change require advances in critical RF technology

- Here I will briefly discuss future instruments/requirements and some trends in THz receiver development

Typical Terahertz Receiver



Mixer radiometers:

- Above ~200GHz InP amplifier noise increases rapidly with increasing frequency
- Heterodyne systems for sensitivity and spectral resolution

Generally single ‘pixel’ receivers:

- Mechanical scanning to provide 2-D imaging
- Critical technology includes the mixer, LO power generation

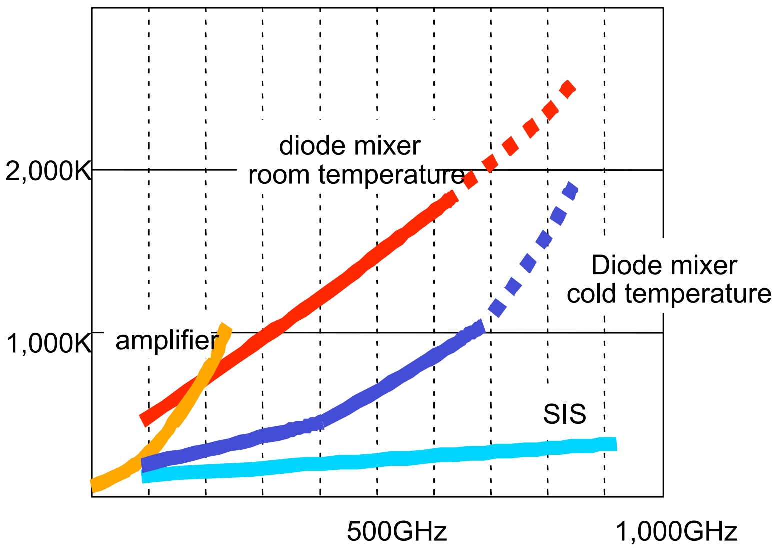
Current Receiver Technology Status - Summary

- Receiver technology is practical and demonstrated for frequencies up to at least 1THz:
    - Direct amplification (low noise InP amplifiers) realistic for frequencies up to ~200GHz
    - Mixer radiometers required from ~150GHz to 2.5THz:
        - Schottky diode technology 100 GHz to >2,500GHz
        - Superconducting SIS technology < 1,000GHz
        - Superconducting HEB technology > 1,000GHz
- Air filled waveguide/feedhorn technology is invariably preferred:
    - Best coupling from waveguide to free space
    - Low circuit losses
    - Design heritage from lower frequencies
- Focal plane receiver arrays with more than a few elements are still a problem:
    - Availability of LO power is increasingly limited at frequency increases
    - Optical LO injection into a single ended mixer is cumbersome to implement if more than a few mixing elements are involved
    - Spectrometer
- Commercial availability of critical component technology is limited - but is improving, in part because of the technology required for ALMA, HIFI, non-space applications …

Noise Performances

Freq. (GHz)	Type	Tm DSB (K)	Lm dB	IF freq. (GHz)	Reference
183	RF amplifier	~6dBNF			Scholley (2002)
183	discrete diode, SHP	450	4.2	spot	HSB (optimised performance)
215	discrete diode, SHP	~ 500	4.5	8 – 15	EOS MLS
320	integrated diode, SHP	900	6	<20	VDI (2)
330	SIS	120		4 ±1	DSB receiver (1)
380	discrete diode, SHP	1,000	7.5	4 ±1	ESA demonstrator (RAL 2006)
500	discrete diode, SHP	2300	9.5	4 ±1	ESA demonstrator (RAL 1998)
500	SIS	<500		4 ±1	SSB receiver (1)
585	Integrated diode, FP	1200	6.5	1	Hui, PhD 2001
640	QUID diode, SHP	2,500	9	8 – 15	Mehdi et al., 1998
642	SIS	<700		4 ±1	SSB receiver (1)
650	integrated diode, SHP	~2,000	<9		VDI (2)
600-900	integrated diode, SHP	5,000	13		VDI (2)
810	SIS	300		1.5 GHz	UKIRT DSB rx (RAL, 2003)

Indicative noise performance



(1) Receivers deployed on the James Clerk Maxwell Telescope

(2) Virginia Diodes Inc

Future Instruments - Astronomy

Space science missions			
Planetary atmospheres	e.g., Mars (MAMBO)	Selected atmospheric constituents in the mm/submm	Planetary atmosphere composition
	Cosmic Vision Jupiter/Europa or Tandem e.g., ORTIS	Selected atmospheric constituents in the mm/submm/FIR	E.g., Exo-planet studies
	Cosmic Vision SPICA	Infrared, (bolometers) – lw end ~200microns	Astronomy, e.g., Planet detection
Gravitational wave detection	Cosmic Vision (B-Pol)	Rx arrays (bolometers) – up to 350GHz	Polarisation Satellite
Space interferometry		Broad band receivers, up to 5THz	Planet formation

Ground based astronomy			
Focal plane arrays	Various observatories	All window frequencies to ~900GHz	Improved mapping speed for extended objetcs
Multi-channel receivers	Various observatories (notably ALMA)	Selected frequencies to ~900GHz	Simultaneous observation of molecular species

Required:

- Heterodyne receivers > 1THz (spatial resolution, planetary atmospheres)
- Array receivers (lots of elements - observing efficiency)
- Multi-frequency receivers
- Best sensitivity (speed)

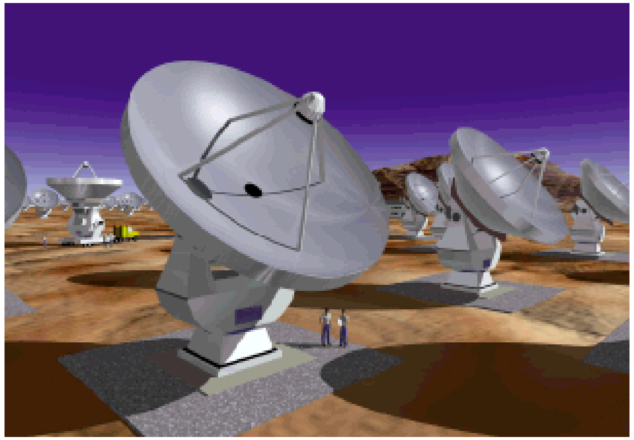
Future Instruments - Remote Sensing

Earth Remote Sensing - Satellite			
Imagers, sounders	EU/ESA GMES Sentinel Post EPS GEO, LEO sounders	Atmospheric bands up to ~900GHz (e.g., 220, 301, 462, 684, 875GHz…) Array receivers	Near time weather forecasting
Imagers, sounders	e.g., ESA Explorer CIWSIR	Several atmospheric bands up to ~900GHz	Cloud physics, climate change
Limb sounders	e.g., ESA Explorer PREMIER STEAM-R	<400GHz for UTLS, frequencies up to ~3THz (inc. OH)	Atmospheric composition, climate change

Earth Remote Sensing - Aircraft			
MARSCHALS	ESA - upgrade in hand	Atmospheric emission lines (300-350GHz)	Atmospheric composition
ISMAR	UKMO – instrument planned for FAAM (ESA Explorers - CIWSIR, GOMAS)	Several atmospheric bands up to ~900GHz	Cloud physics, climate change

Required:
- Heterodyne receivers up to and above 1THz (targeted line emission, e.g., OH at 3.5THz)
- Array receivers (lots of elements - e.g., GEO sounder sensitivity)
- Multi-frequency receivers
- High precision

Astronomy Instruments - ALMA



- Under construction at Chajnantor in the Andes of Northern Chile:
- 64 antennas, each 12 m in diameter
- Full frequency coverage (31 GHz to 950 GHz) of all atmospheric windows in nine bands
- Higher frequency bands instrumented with waveguide, cryogenic SIS, wideband single sideband receivers, using multiplied solid state LOs
- Due for completion in about 2012

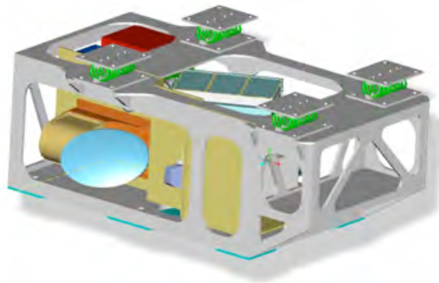
MARSCHALS

- Airborne millimetre-wave limb sounder designed to measure composition of the upper troposphere
- Designed to measure O_3, H_2O and CO in upper troposphere
- Total instantaneous RF bandwidth: 12 GHz, spectral resolution 200 MHz
- Fine spatial resolution ~2 km at 10 km limb tangent point
- Two precision calibration loads (290K and 85K)

- *RAL is about to start a programme to upgrade the receiver sensitivity*

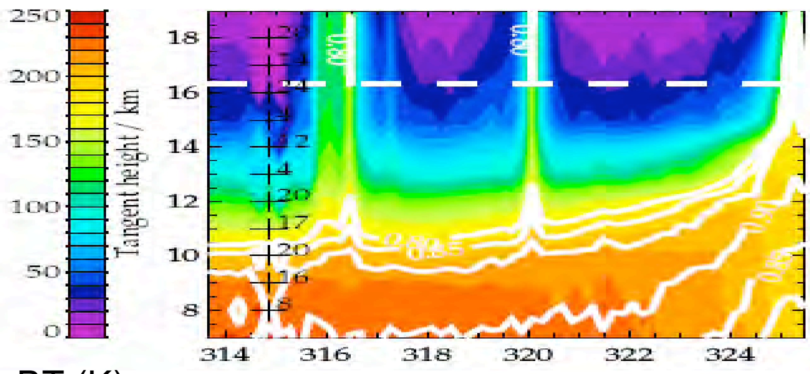
The M55 Geophysica

MARSCHALS 300GHz Atmospheric Limb Sounder

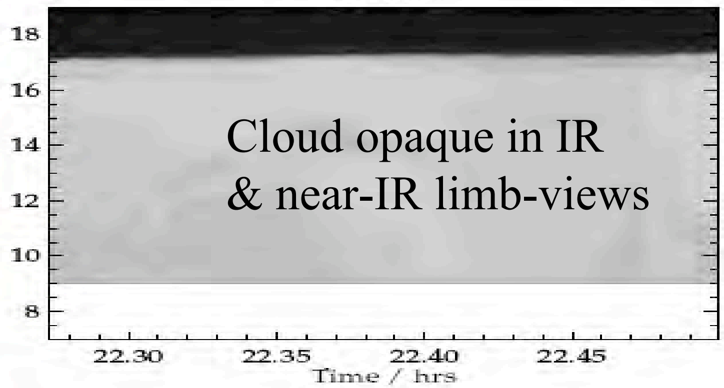


- 3 receivers in the ~300GHz band
- Demonstration that mm-wave observes H_2O & O_3 through tropical cirrus

mm-wave limb spectra

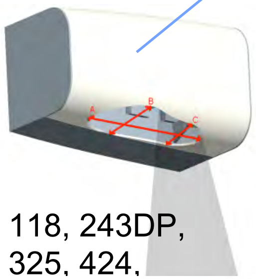


co-located 0.75mm limb imager

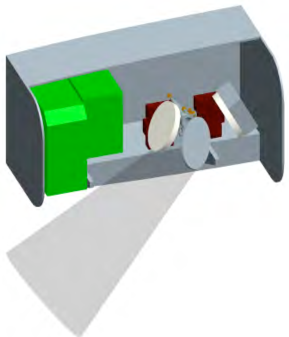


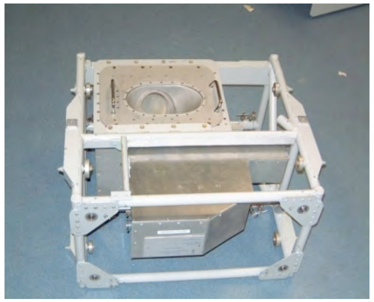
ISMAR/CIWSIR

Deimos 50 in TAFTS Bay
Max forward scan ~35°



118, 243DP,
325, 424,



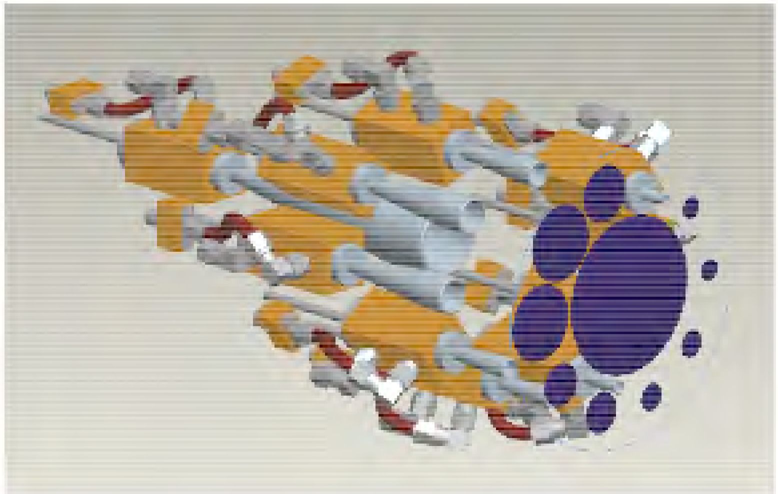


MARSS 183GHz on FAAM
Max forward scan = 54°

Frequency Coverage		**Compliant**
NEΔT		**Compliant**
Calibration	**2CT, Windowless**	**Compliant**
Cluster Diameter (HPBW 8.25°)	**70 mm**	
Scan Geometry	**Along-track 0-53° Except 0-35°@54GHz**	**90% Compliant (Requirement 0-60°)**

Sub-mm wave Airborne Demonstrator for Ice & Precipitation

ISMAR - Receiver Configuration



ISMAR cluster incorporates lenses to reduce beamwidth

FAAM Instrument	Channel ID	Centre Frequency (GHz)	Bandwidth (MHz)	Measured NEΔT (K)	ESA FOp3?
Deimos	D1	23.80±0.07	127	0.6	N
Deimos [1]	D3	50.10±0.05	82	0.6	
(Deimos) [2]	D4	50.30	180		Y
(Deimos) [2]	D5	52.825	300		Y
(Deimos) [2]	D6	53.845	190		Y
(Deimos) [2]	D7	54.40	220		Y
MARSS	M16	88.992±1.10	650	0.46	N
MARSS	M17	157.05±2.60	2600	0.72	N
MARSS	M18	183.31±1.00	450	0.62	Y
MARSS	M19	183.31±3.00	1000	0.42	Y
MARSS	M20	183.31±7.00	2000	0.33	Y
ISMAR	S1	118.75±1.10	400		Y
ISMAR	S2	118.75±1.50	400		Y
ISMAR	S3	118.75±2.10	800		Y
ISMAR	S4	118.75±3.00	1000		Y
ISMAR	S5	118.75±5.00	2000		Y
ISMAR	S6V	243.20±2.50	3000		Y
ISMAR	S6H	243.20±2.50	3000		Y
ISMAR	S7	424.763±1.00	400		Y
ISMAR	S8	424.763±1.50	600		Y
ISMAR	S9	424.763±4.00	1000		Y
ISMAR	S10	448.00±0.80	1200		N
ISMAR	S11	448.00±2.00	2000		N
ISMAR	S12	448.00±4.50	3000		N
ISMAR	S13	448.00±11.5	3000		N
ISMAR	S14V	664.00±4.20	3000		Y
ISMAR	S14H	664.00±4.20	3000		Y
ISMAR	S15V	874.40±6.00	3000		N
ISMAR	S15H	874.40±6.00	3000		N

Frequency coverage

ISMAR Receiver Front End

Generic Receiver Front End incorporates:

- Feedhorn
  - Size dependent on frequency

Subharmonic mixer

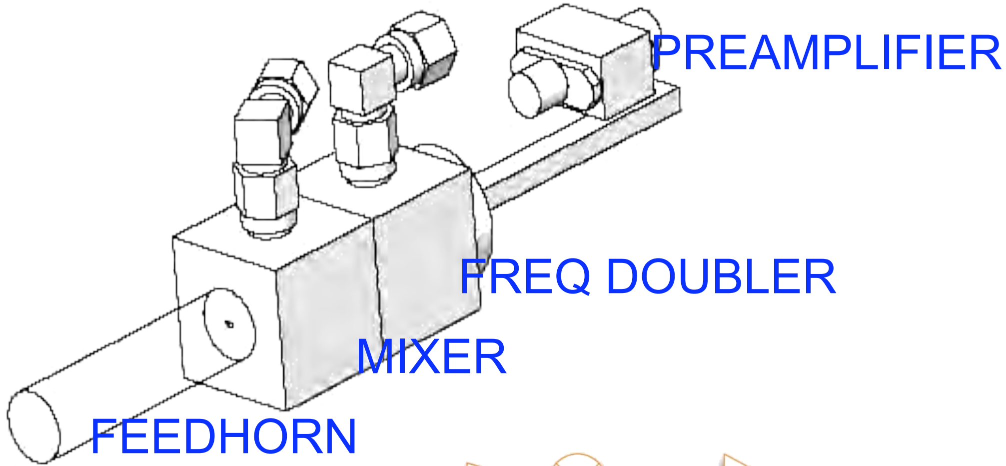
- LO frequency ~ 1/2 of RF frequency
- In-line RF & LO waveguides
- 20 x 20 x 20mm cube

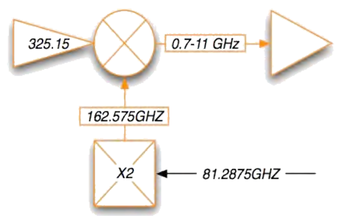
Frequency Doubler

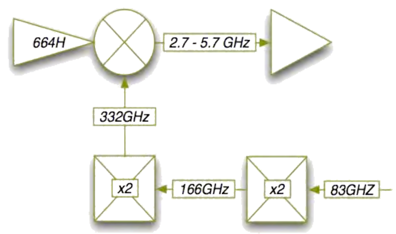
- Final stage of LO chain
- External bias
- In-line input & output waveguides
- 20 x 20 x 20mm cube
- *NB 664GHz (& 874GHz) channels would require an additional frequency multiplier stage*

Preamplifier

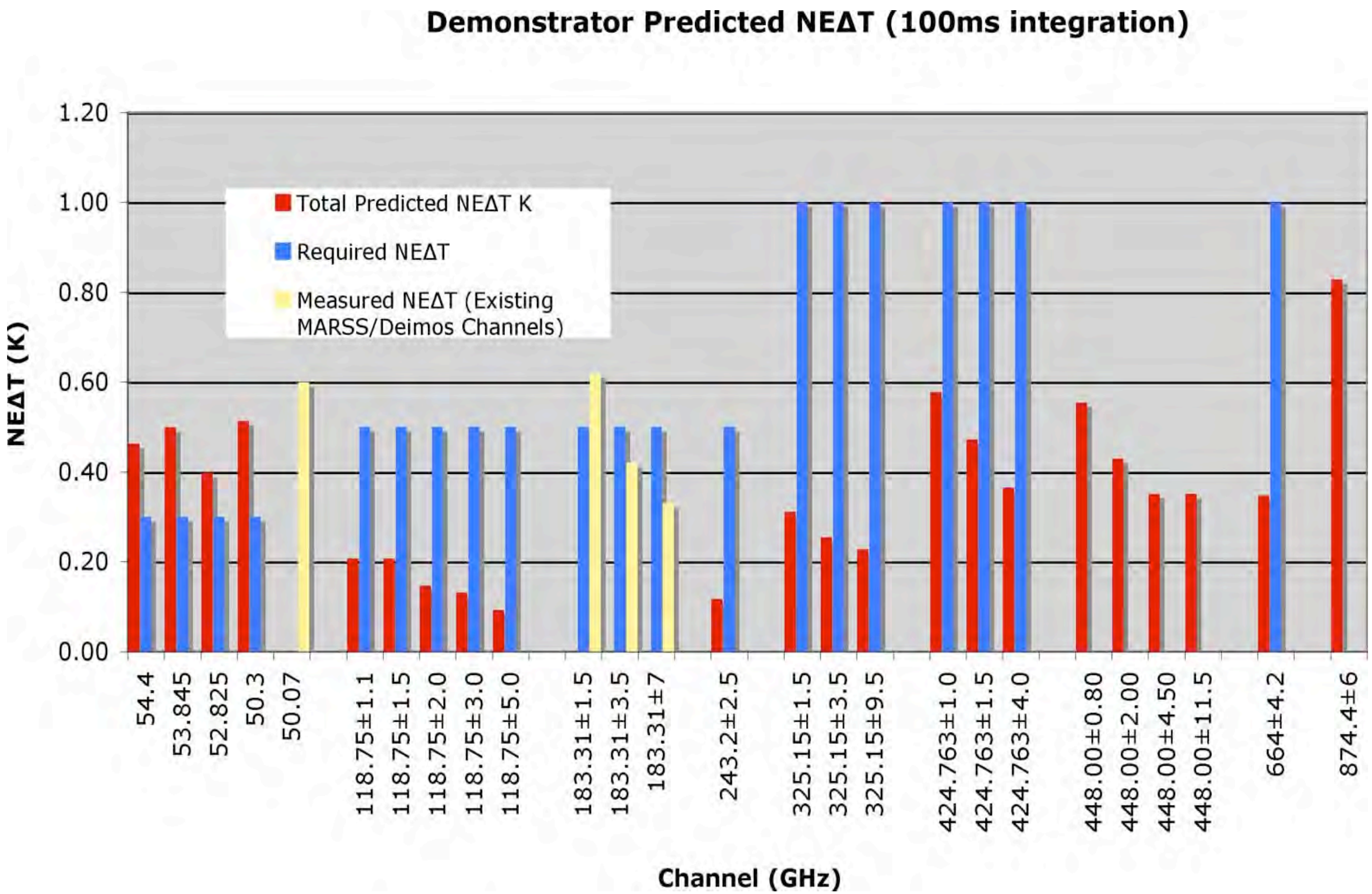
- Miteq AFS or JS series







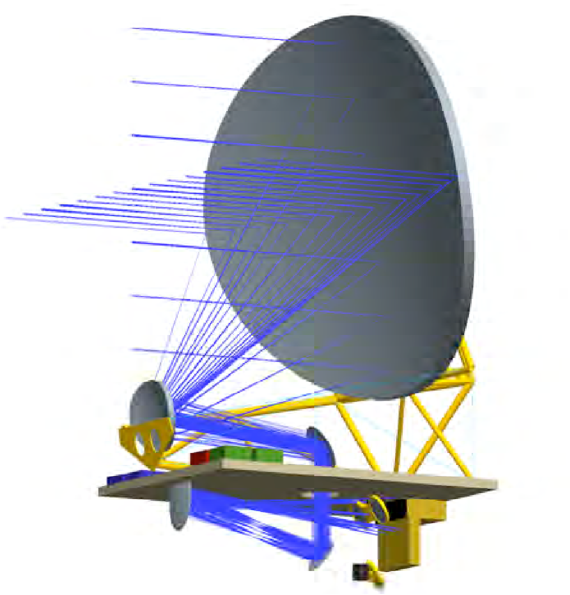
Radiometric Performance Summary



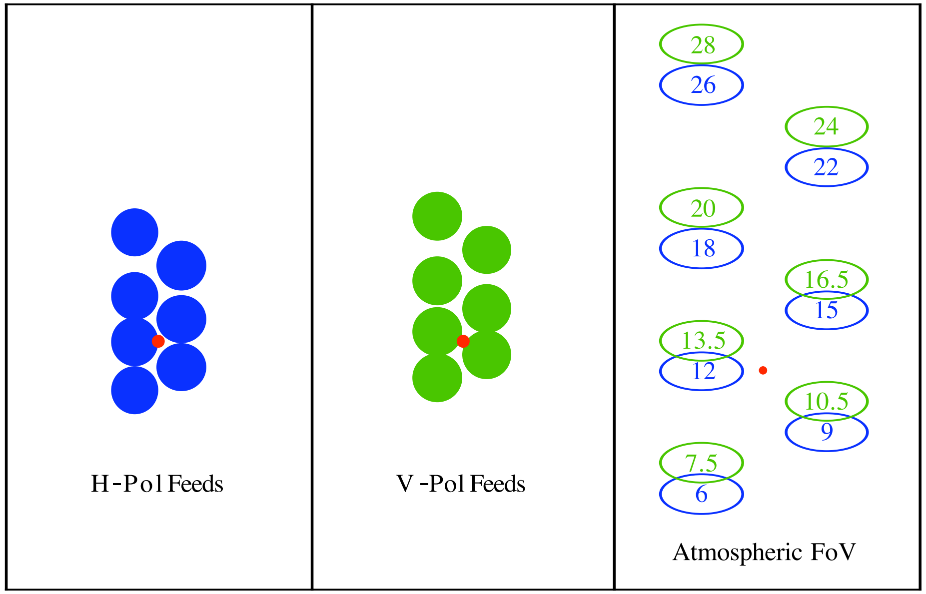
STEAM-R

- STEAM-R is a passive, millimetre-wave limb-sounding radiometer proposed by Sweden as a nationally-funded contribution to the candidate ESA Explorer mission PREMIER
- Molecular thermal emission in the frequency range 313-356GHz
- Based on ODIN
- Flight opportunity in 2014+
- Instrument includes compact receiver array, based on Schottky technology:
  - Antenna, of size 1.6x0.8 metre
  - A receiver array comprising 14 beams arranged in two orthogonal polarizations
  - Single side band (SSB) for observations below 18km tangent height
  - Double side band (DSB) for observations above 18km tangent height
  - Frequency coverage from 313 to 356GHz
  - Spectrometers that provide up to 12GHz instantaneous bandwidth

STEAM-R Instrument

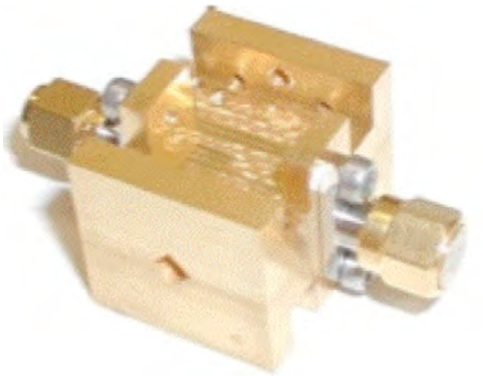


STEAM-R Beam configuration on the sky



- Blue lines indicating limb views from the array receiver
- The receiver array consists of 2 arrays of 7 receivers in orthogonal polarisations, a total of 14 view-angles/tangent-heights
- The illustration shows resulting beams on the sky, with closer beam spacing below 18 km at the limb

STEAM-R mixer technology



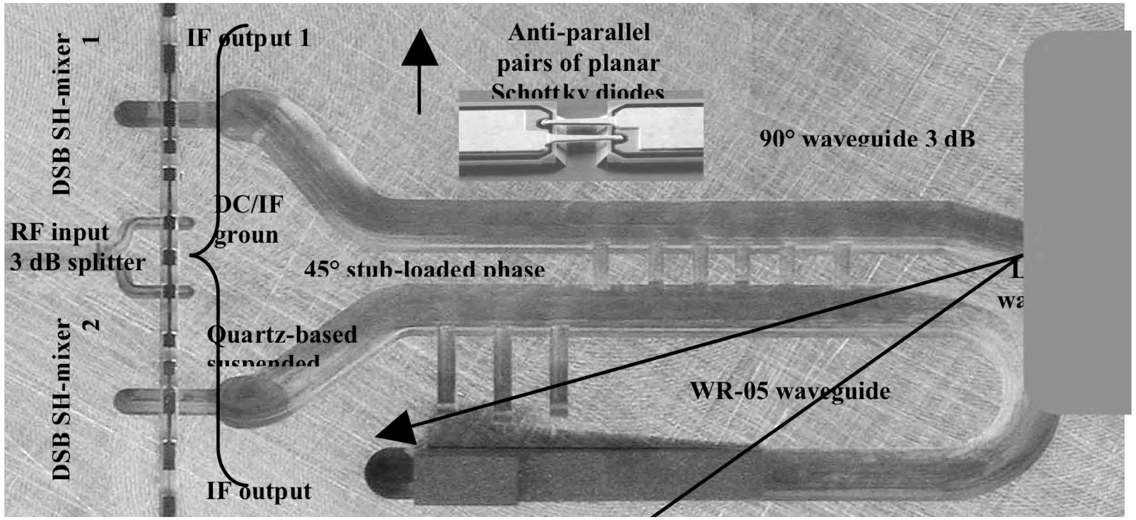


Image separating mixers at ~340GHz

Development of a 340-GHz Sub-Harmonic Image Rejection Mixer Using Planar Schottky Diodes", B. Thomas, S. Rea and D. Matheson, *Proc. of the 19th Int. Symposium on STT, Groningen, April 2008*

Limb Sounding Feasibility - Jupiter Example

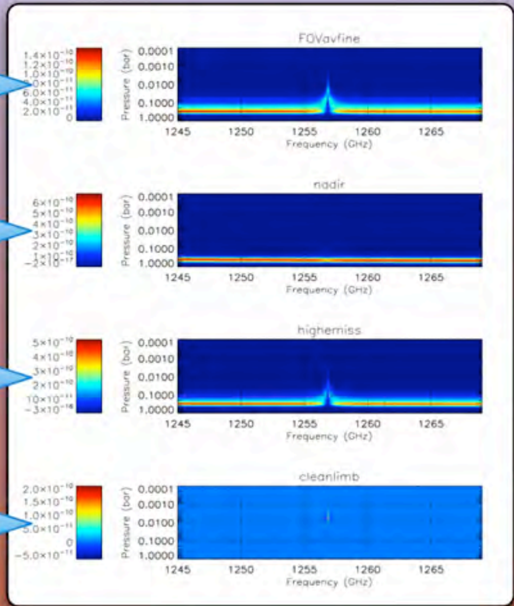
Preliminary limb calculations for Jupiter taking into account the relatively large field-of-view that a sub-mm instrument on Laplace would have (30 cm antenna diameter and 6RJ distant).

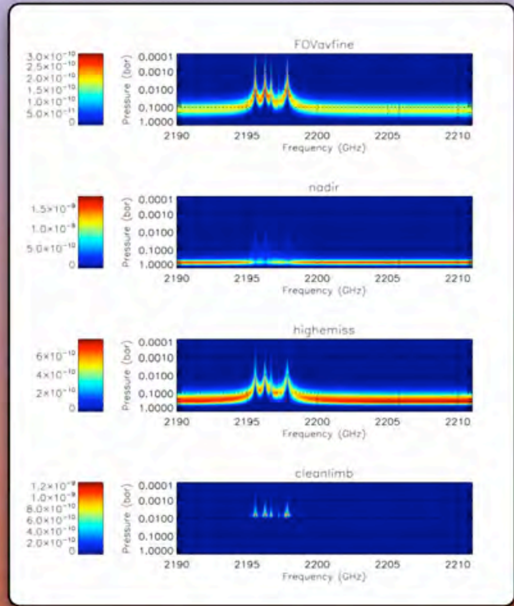
Real Beam Bore-sight at Tangent of Altitude of 100km

Nadir View

High Emission Angle of 88 Deg.

Infinitely Narrow Beam with 100km Tangent Height





Plots indicate the rate of change of radiance with respect to temperature across a) the methane absorption line near 1.2THz and b) the methane/water absorption line complex at 2.2THz. Each plot shows the sensitivity of the observed radiance to temperature at different heights. Note the improved sensitivity and and greater vertical coverage a 2.2THz compared with 1.2THz.

Observation of Jupiter/Saturn Upper Atmosphere

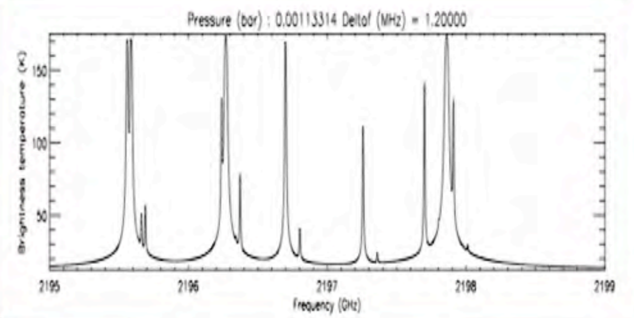
Molecular emission/absorption features allow line intensities, line shapes and Doppler wind velocities to be measured.

Atmospheric pressure and temperature profiles can be recovered.

Low scattering & absorption effects allow extensive atmospheric penetration and profiling.

Relative insensitivity to aerosols and dust.

Data provides unique information on atmospheric composition, structure, dynamics & evolution.



Example synthesised 2.2THz emission spectra calculated for CH4 and H2O for a Jupiter limb sounding geometry.

ORTIS Concept

Terahertz Atmospheric Spectrometer System Example

Preliminary System Concept

System Attributes

Designed to target key molecular species:
- e.g. H_2O, CH_4, CO etc.

Frequency of operation up to ~2.2 THz range:
- Spectral resolution of ~ 1MHz (less for wind measurements)

Antenna diameter < 0.5m:
- 10^6km above surface gives spatial resolution ~600km
- Scanning antenna with limb or nadir view

Schottky diode mixer receiver technology:
- Avoids requirement for mechanical cooling or liquid cryogens
- Quantum Cascade Local Oscillator. Cooling to ~60K required at present. Higher temp. operation anticipated.

Mass and power:
- ~ 3W, 0.5kg per receiver
- ~1.5W, 0.3Kg for digital spectrometer

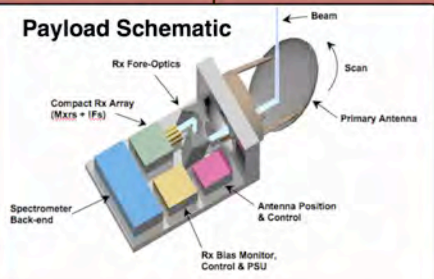
Example Single Pixel System Performance

		Demonstrated		5-10 Year Development	
Signal Freq. (THz)	IF B/W (GHz)	Rx Noise (K) (300K) DSB	NEDT (K)	Rx Noise (K) (300K)DSB	NEDT (K)
2.0	~1	9,000	~9	4,500	4.5

NEDT assume 1 sec integration time in 1MHz bandwidth.

Cooling to 100K gives factor of 2 improvement.

Payload Schematic



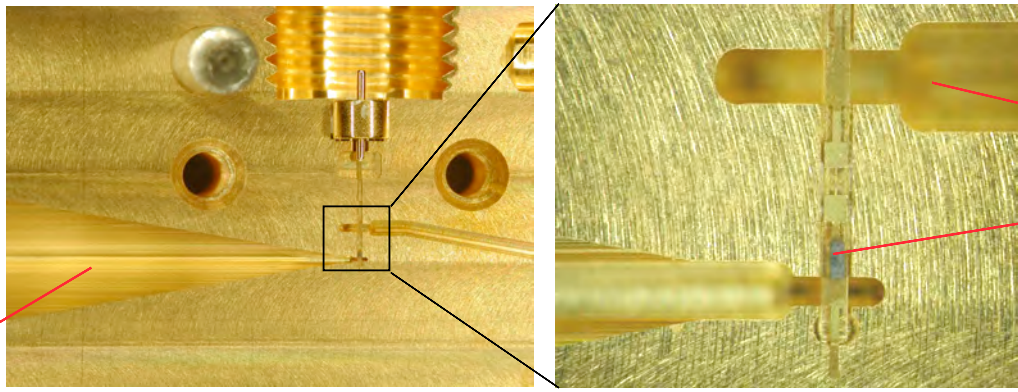
Technology Trends - Summary

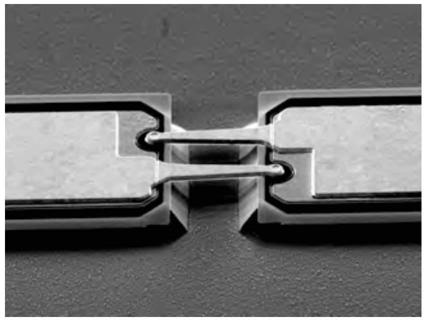
Future instruments will require more receivers, with lower resource requirements (mass & power) at frequencies up to, and above, 1THz

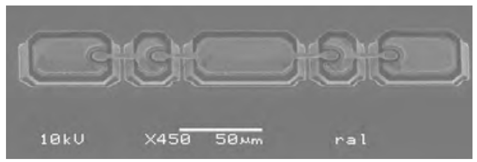
This is driving technology in directions that include:

- Better component design and manufacture (mixers, harmonic multipliers)
- New methods of LO generation:
  - Quantum Cascade Lasers (QCL)
  - Photonic mixing
- Increased circuit integration:
  - Reduced mass, improved reliability, simpler interfaces, lower cost
- New concepts for building focal plane arrays - specifically, provision and injection of LO to drive multiple mixers

Mixer/Multiplier circuit design







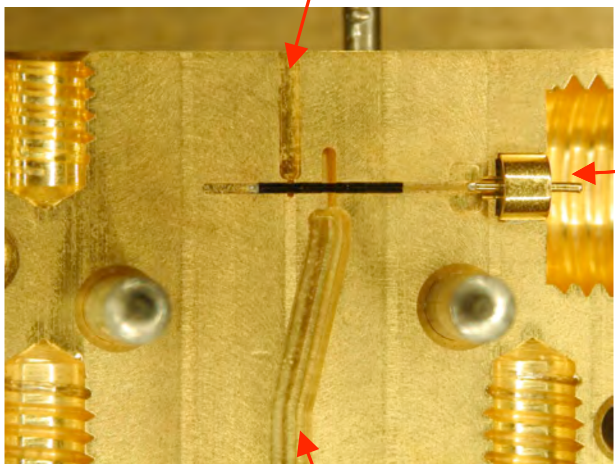
- Better design techniques - CAD
- Increasing availability of European diode structures
- Better computer controlled manufacture

Integrated Diode/Filter Circuits

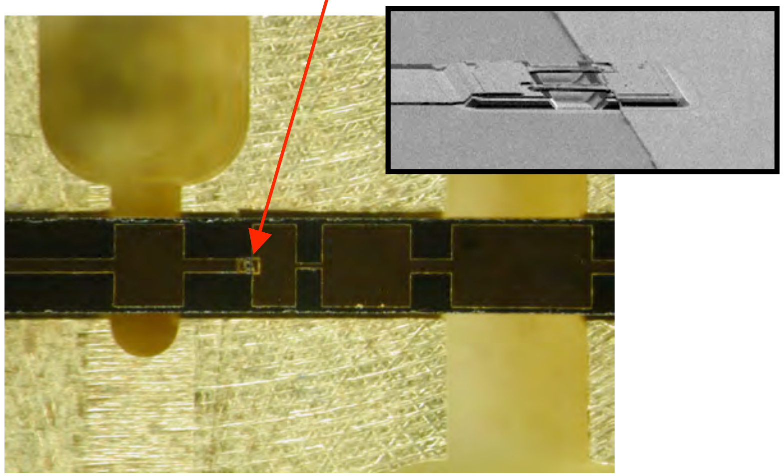
Diode and circuit integration is essential for systems operating > 400 GHz

- Increased positional accuracy
- No diode soldering
- Simple and reliable assembly

183 GHz fixed-tuned sub-harmonic mixer (Hui Wang et al):



Fixed-tuned mixer block with integrated diode/filter circuit



Circuit detail - 50micron thick GaAs

The EU AMSTAR Project: IRAM and RAL

Demonstrator 4 pixel focal plane array demonstrator for astronomy

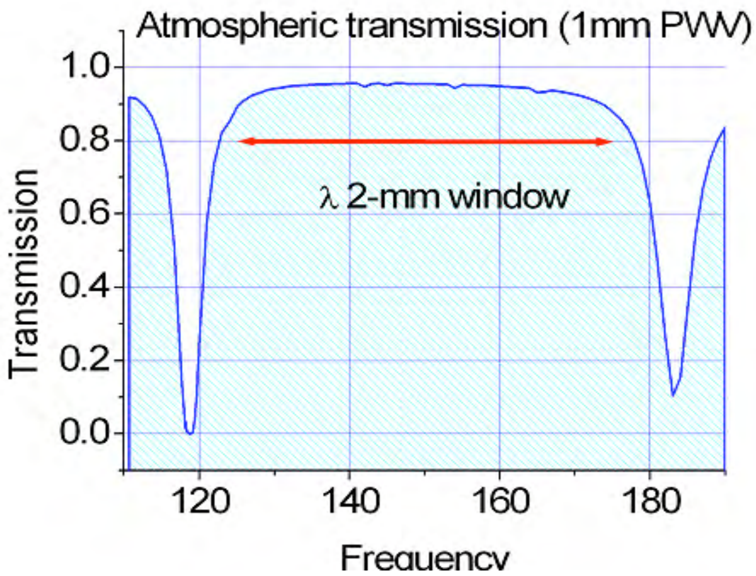
- 4 K superconductor-insulator-superconductor mixers
- LO from photomixers (mix together two 1.55micron laser signals and extract terahertz difference signal)
- λ ≈ 2 mm range: coverage 130 GHz - 170 GHz

Frequency range chosen offers good atmospheric transmission and reasonable photomixer output powers

Photomixer advantages:

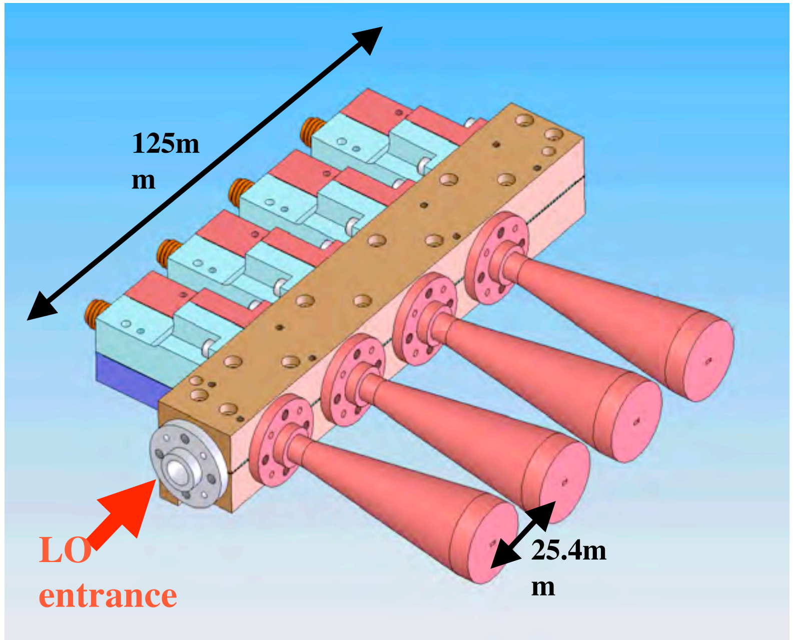
- Freedom from unwanted harmonics
- Low power dissipation in the cryostat
- Straightforward expansion for large arrays

AMSTAR is a Joint Research Activity within the European Union's FP6 Integrated Infrastructure Initiative "RadioNet"

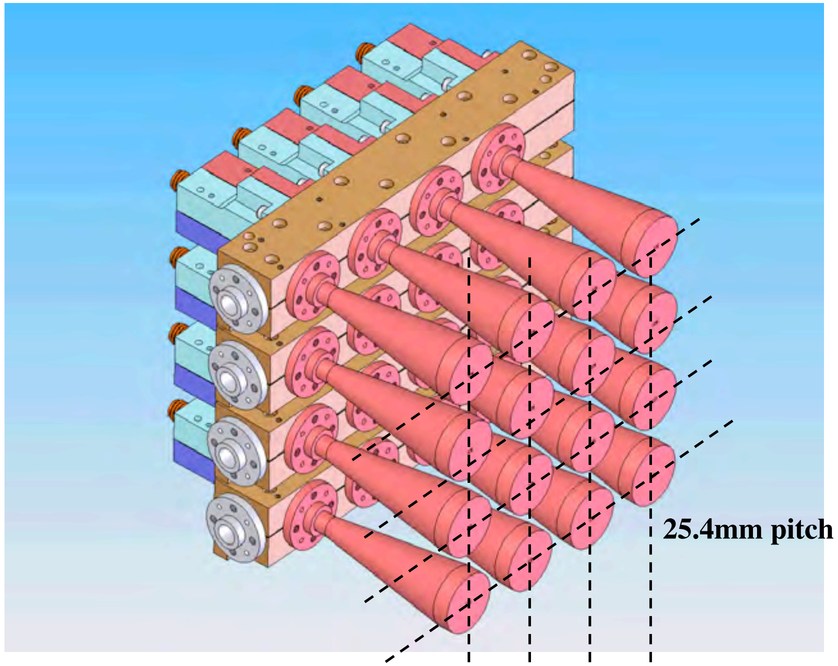


1-D and 2-D Receiver Arrays

Four pixel array:



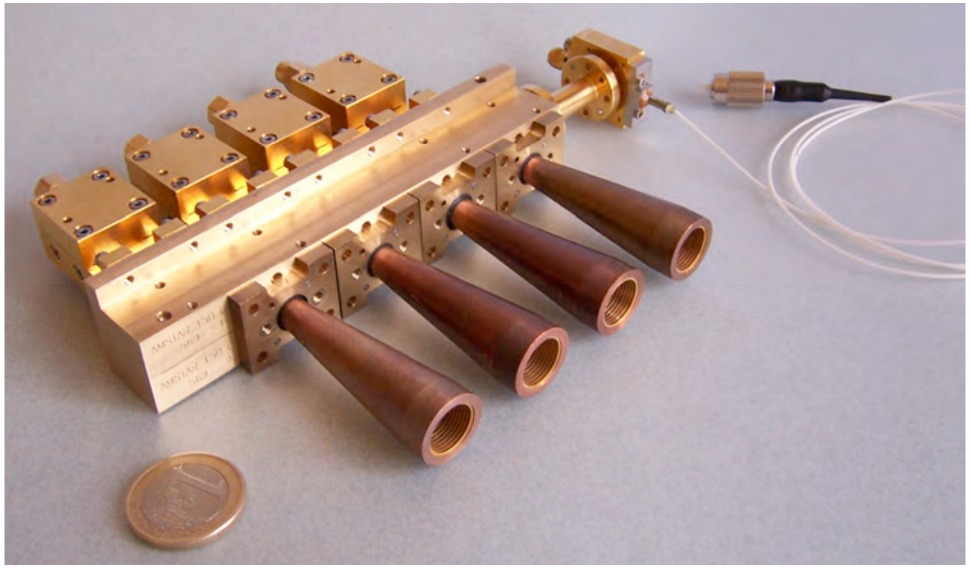
Future extension to 2-D:

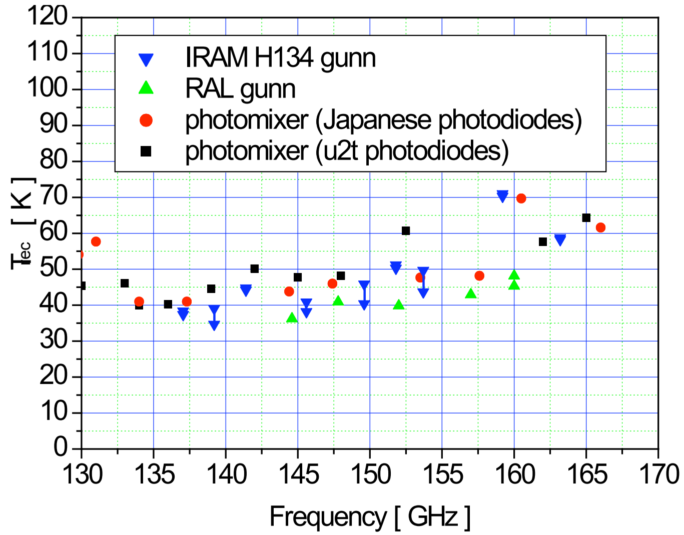


- Thermal budget considerations drive choice of 1 photomixer/row of SIS mixers
- Photomixer operating temperature between 4 K and 77 K

Prototype Array Performance

- Initial results are promising





4-element array with feedhorns, mixer blocks and photomixer

Conclusions

Both astronomy and remote sensing continue to drive improvements in Terahertz receiver technology:

- Better design techniques
- Higher frequency receivers > 1THz
- Increased range of more sophisticated receiver components, including prototype integrated circuits

But there are still problems limiting instrument design:

- LO availability, especially at short wavelengths and for array receivers
- Practical heterodyne receiver arrays
- Spectrometers (cost)
- Mass and power