Space Instrumentation: Microwave Spectroscopy

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Outline

- *History of Microwave Remote Sensing*
- *Fundamentals of Microwave Remote Sensing*
- *Microwave Instrumentation*
- *Application on Planet Earth*
- *Observations of Extraterrestrial Objects in the Solar System*
- *New Missions and Future Projects*

What is Microwave Remote Sensing ?

- *Detection of electromagnetic radiation emitted, scattered or reflected from remote sources.*

- *Definition of wavelength range: changed in the last decades. Now perhaps 100 mm to 0.05 mm (3 GHz to 6000 GHz).*

Pre-History: Important Dates I

- *Gen 1:3 "And God said 'Let there be light' "*
- *4th Century BC Aristotle recognizes that light was necessary for color to exist*
- *AD 1300 first recorded use of lenses for eyeglasses*
- *1600 Hans Lippershey makes first telescope after two children playing in his shop put two lenses in front of each other*
- *From referee report of first patent application for remote sensing by Hans Lipperhey on 25 September 1608:*
  *“who claims to have a certain device by means of which **all things at a very great distance can be seen as if they were nearby**, by looking through glasses which he claims to be a new invention."*
- *1609 Galileo produces telescope of power of 30x*

Pre-History: Important Dates II

- *1666 Newton observes **spectrum** obtained from a prism; publishes Principia*

- *1678 Huygens proposed **wave theory** of light*

- *1800 F.W. Herschel notes that different amounts of heat passed through different colored glasses: discovery of **infrared radiation***

- *1801 J.W. Ritter discovers UV*

- *1817 Josef Fraunhofer maps details of absorption lines in solar spectrum*

Pre-History: Important Dates III

- *1820 C. Oerstedt finds relationship between **electricity and magnetism***

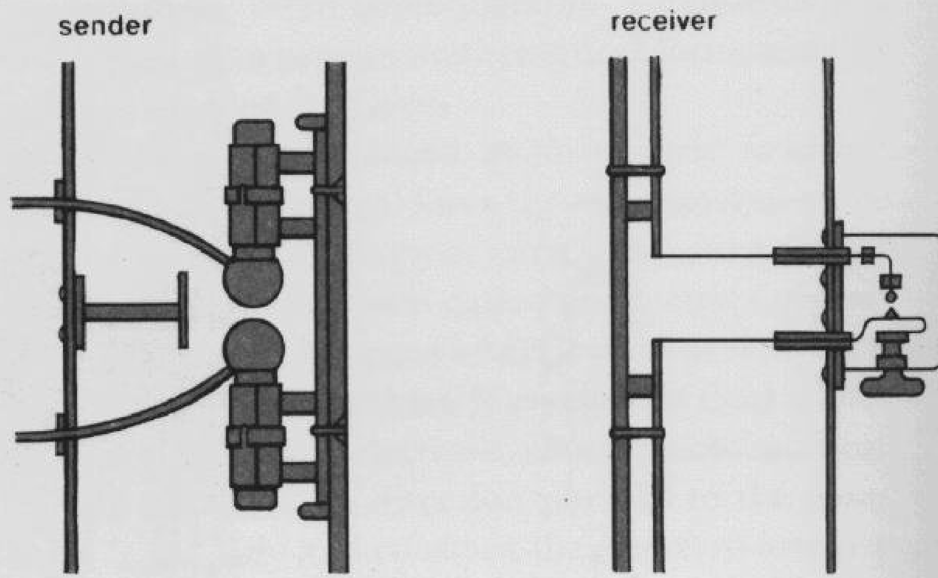
- *1836/37 M. Faraday proposes the existence of **electric and magnetic fields** that permeate space*

- *1864/65 J.C. Maxwell develops a theory about Faraday's idea and predicts the existence of **electromagnetic waves**. He concludes that **light is an electromagnetic wave***

- *1887/88 H. Hertz generates and receives for the first time cm-**(micro) waves** and proves the prediction of J.C. Maxwell. He finds that **they propagate with the speed of light** . Hertz also builds the first focusing antenna*

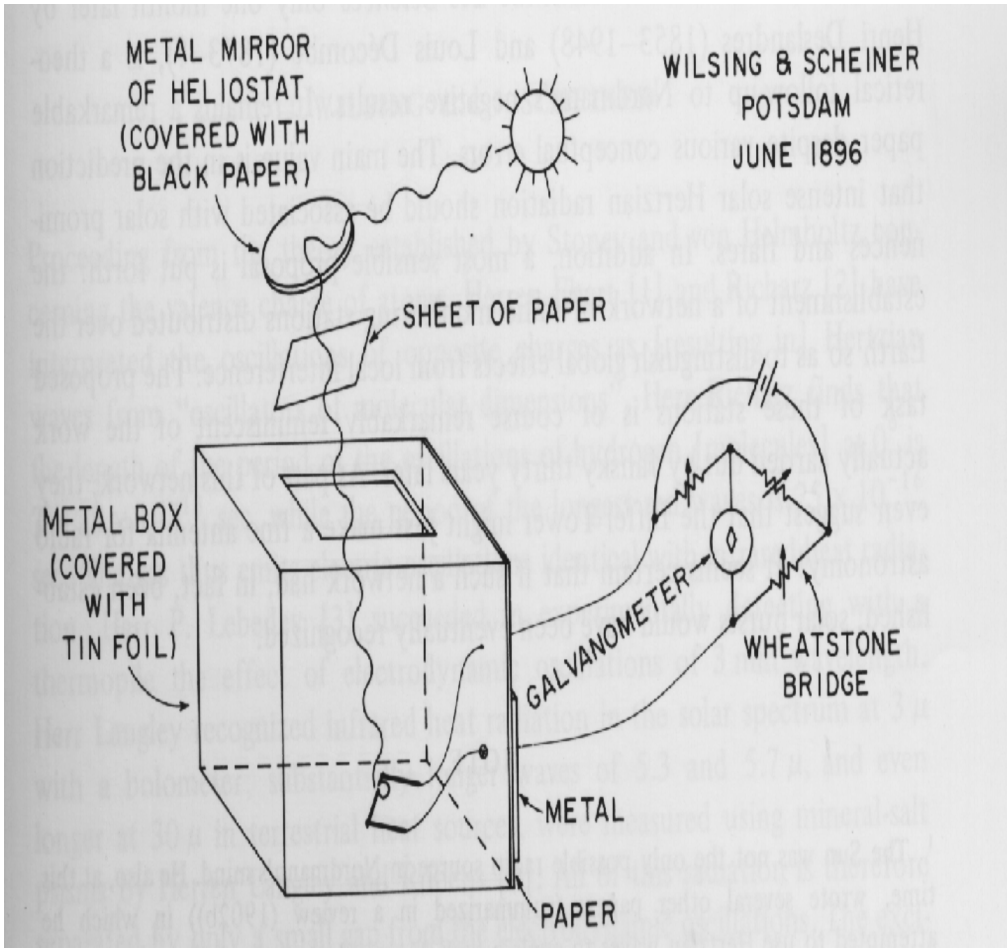
Pre-History: Important Dates IV

Since 1935 "Hertz" (Hz) is the official unit for frequency



Once it was shown that the quantity that oscillates in a light wave is the electric field or the magnetic field, Heinrich Hertz artificially produced waves of different wave-length from those of visible light. Above are his oscillator, or sender, and his resonator, or receiver.

Pre-History: Important Dates V



Wilsing and Scheiner (1896) were the first proposing to receive radio wave emissions from an extraterrestrial object (the sun) [Ann.Phys.Chem.59, 782, 1896].

They built the experiment and tried to measure solar radiation without success, since their apparatus was not sensitive enough. The first detection of solar radio emissions was made by J.S. Hey in 1942

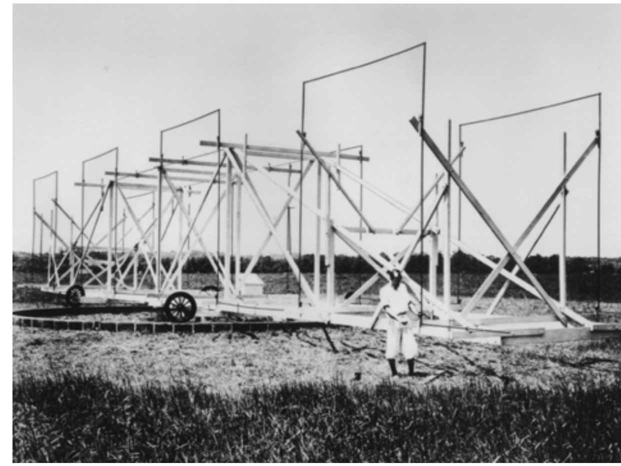
Pre-History: Important Dates VI

- *1896 First message sent by radio wave telegraphy: “Heinrich Hertz” through A. Popov. Distance: 250 m*

1901 Marconi improved radio transmission and receiver designs and developed the first practical systems for long distance communication by radio. In 1901 he was the first to send and receive signals across an ocean, from Newfoundland to Cornwall. As a result of his pioneering efforts, commercial radiotelephone service became available in later years. In the 1930s the Bell Telephone company was working on improving their transatlantic telephone service when they assigned Karl Jansky to investigate sources of radio static.

History: Important Dates I

1932: First detection of extraterrestrial radio emissions by K. Jansky



Karl Jansky found 3 sources of disturbances: 1) nearby thunderstorms, 2) distant thunderstorms and 3) emissions from the center of the Milky Way

[New York Times, 5 May 1933]

["Electrical disturbances apparently of extraterrestrial origin", Proc.IRE, 21, p.1387, 1933.]

Flux density unit "Jansky" (JY) = 10E-26 W /Hz /m^2

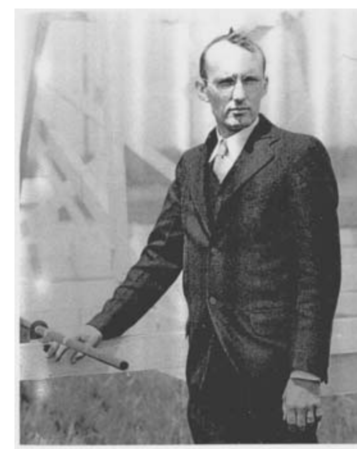


Fig. 1—Karl Guthe Jansky, about 1933.

History: Important Dates II

1937 G. Reber built the first parabolic radio telescope, operated at 3.3 GHz

1942 J.S. Hey discovered microwave emissions of the Sun

1943 G. Reber provided first radio map of the Milky Way

–Grote Reber, about 1937.

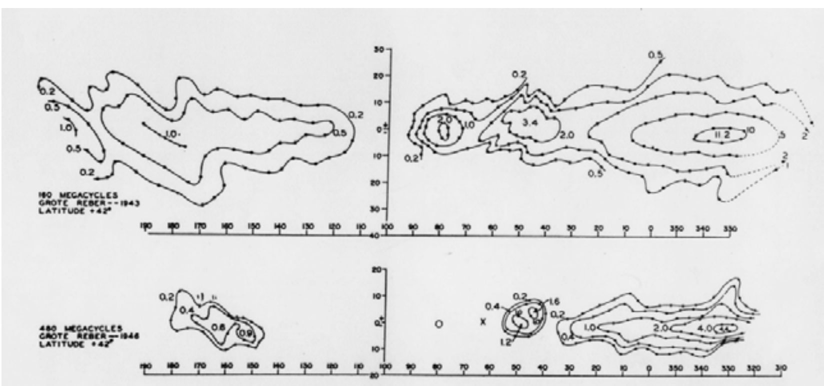


FIG. 7—Contours of constant intensity at 160 MHz and 480 MHz, taken at Wheaton, Illinois.

["Cosmic Static", Astrophysical Journal, 91, p.621, 1940] "

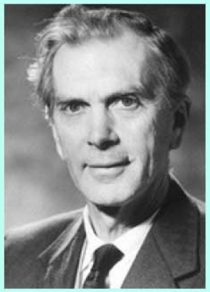
[Solar Radiation at 480 MHz.", Nature, 158, 945, 1946]

History: Important Dates III

- *1944 Prediction of hyper fine structure line of hydrogen at 21 cm by van Hulst and Oort.*
- *1946 First detection of discrete sources (Cygnus) by Hey, Parson and Phillips*
- *1951 First detection of a spectral line, namely hydrogen on 21 cm by Ewen and Purcell => determination of galactic structure*
- ***1955 Burke and Franklin discover synchrotron emission of Jupiter and determine 10 hours rotation period***
- ***1962 Barrett and Chung propose a new method to determine vertical profiles of atmospheric molecules by ground-based microwave observations***
- *1963 Penzias and Wilson discover the cosmic background radiation*
- ***1965 Groom determines for the first time vertical profiles of stratospheric water vapor by ground-based 22 GHz measurements, rather poor results however.***

History: Important Dates IV

Sir Martin Ryle (1918 – 1984)



3C Survey,
Apertursynthese,
Erdrotation-Synthese,
Phase-switching …

Nobelpreis 1974
… for their pioneering research in radio astrophysics: Ryle for his observations and inventions, in particular of the aperture synthesis technique, and Hewish for his decisive role in the discovery of pulsars.

John Kraus (1910 – 2004)

1962 Polarisation (Weterhout, Wielebinski, Shakeshaft)
1963 erstes Molekül OH (Weinreb [Shklovski '49])
1965 Radiorekombinationslinien (Mezger, Höglund)
1965 Kosmischer Hintergrund (Penzias, Wilson)
1967 VLBI (Brown, Carr, Block, Broten)
1967 Pulsare (Jocelyn Bell, Hewish)
1968 Ammoniak (Townes)
1970 CO (Wilson, Penzias)
Ab 1970 …. mm und submm Fenster

History: Important Dates V

- ***1968 Caton, Manella, Kalaghan, Barrington and Ewen detect atmospheric ozone line for the first time (101,7 GHz). Rather poor results however***
- ***1973 Staelin et al: first microwave spectrometer on a satellite for meterological applications***
- ***1975 Shimabukuro, Smith and Wilson determine first stratospheric vertical ozone profile from ground-based 101,7 GHz observations.***
- ***1976 Penfield Litvak, Gottlieb and Lilley provide first mesospheric ozone profiles derived from ground-based 110,8 GHz observations***
- ***1976 Waters, Wilson and Shimabukuro detected mesospheric carbon monoxide at 115 GHz for the first time.***
- ***1976 Kakar, Waters and Wilson detect the microwave emission of carbon monoxide of Mars' atmosphere at 115 GHz***
- ***1981 Parish, de Zafra, et al. detect chlorine oxide at 278 GHz for the first time and report 6 years later about the relationship between chlorine activation and Antarctic ozone destruction***

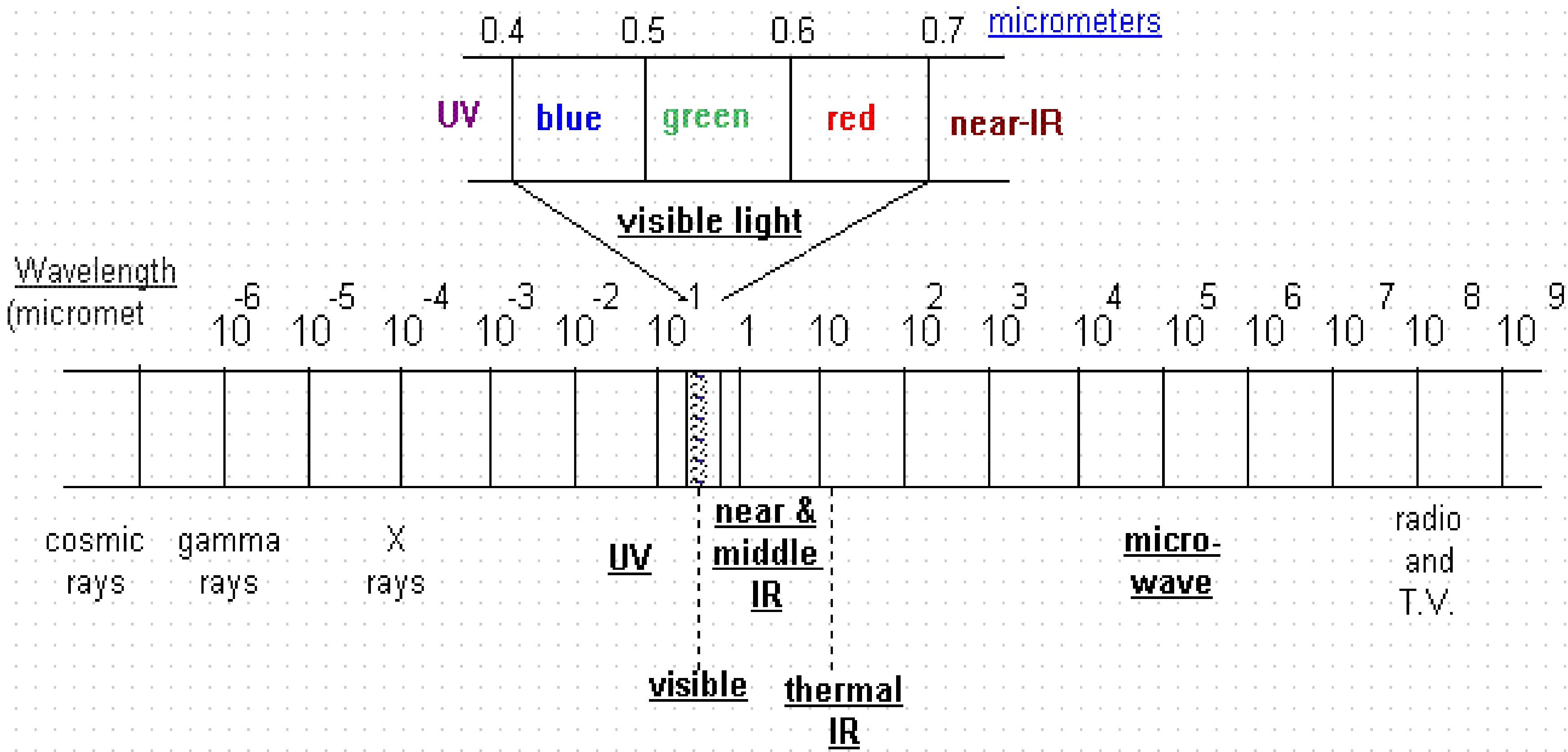
History: Important Dates VI

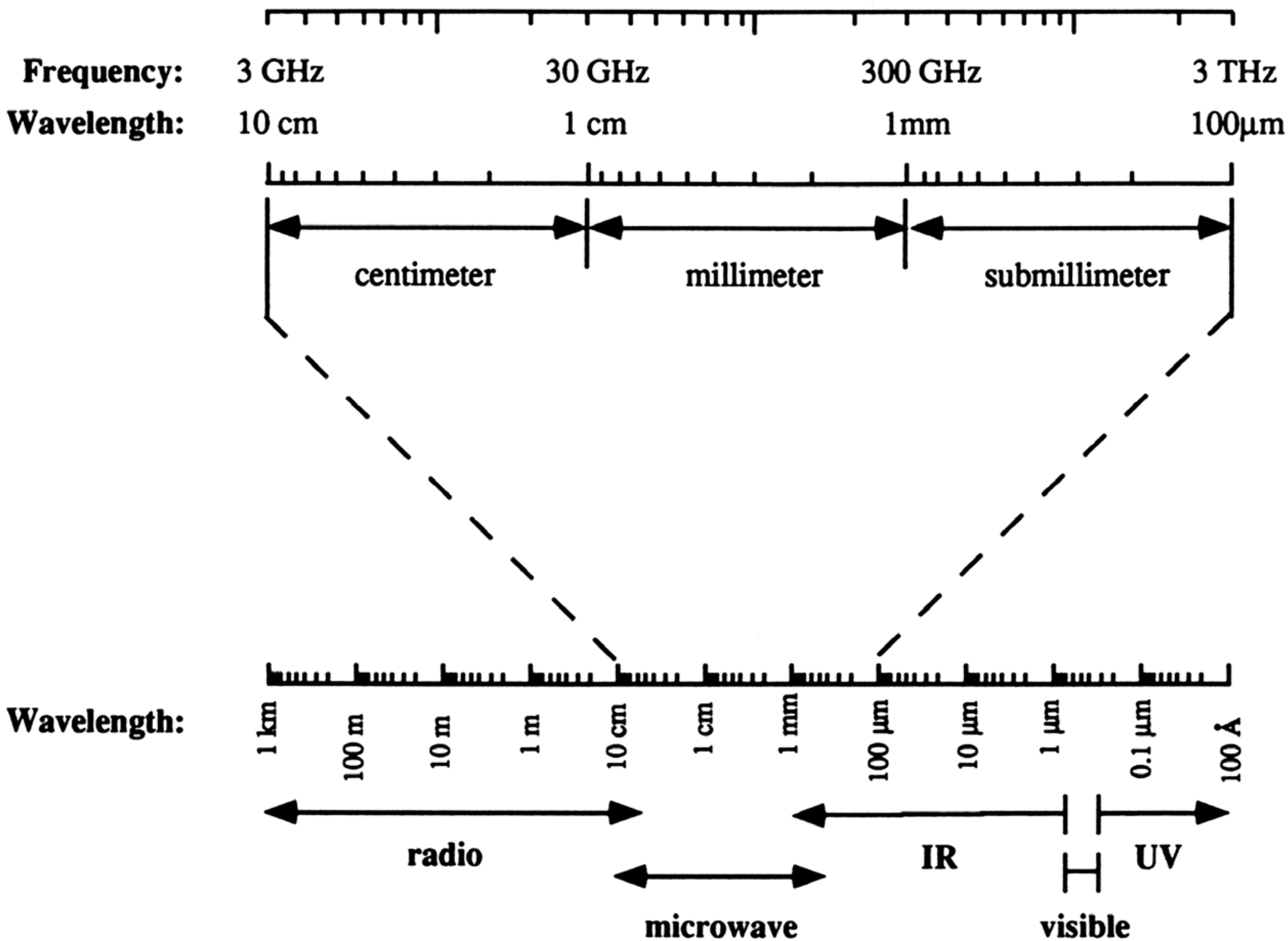
- ***1981 Wilson et al. provide vertical CO distribution in Venus mesosphere from 115 GHz measurements.***
- ***1983 Clancy, Muhleman and Jakosky provide data about temperature variations in Martian atmosphere derived from 115 GHz CO detections***
- ***1984 Muhleman, Berge and Clancy detect the microwave emission of carbon monoxide on Titan at 115 GHz using an interferometer***
- ***1985 Clancy and Muhleman discover diurnal variation of CO in the atmosphere of Venus derived from 115 GHz measurements***
- ***1986 Despois discovers HCN in Comet Halley from 88.6 GHz observation***
- ***1990 Martin et al. detect mm emission lines of CO at 345 GHz and HCN at 354 GHz in the atmosphere of Neptune***
- ***1990 Lellouch et al. find SO_2 source on Io from 222 GHz measurements***
- ***1990 Shah, Muhleman and Berge measure wind in Venus' upper mesosphere from 115 GHz CO measurements***

Fundamentals of Microwave Remote Sensing

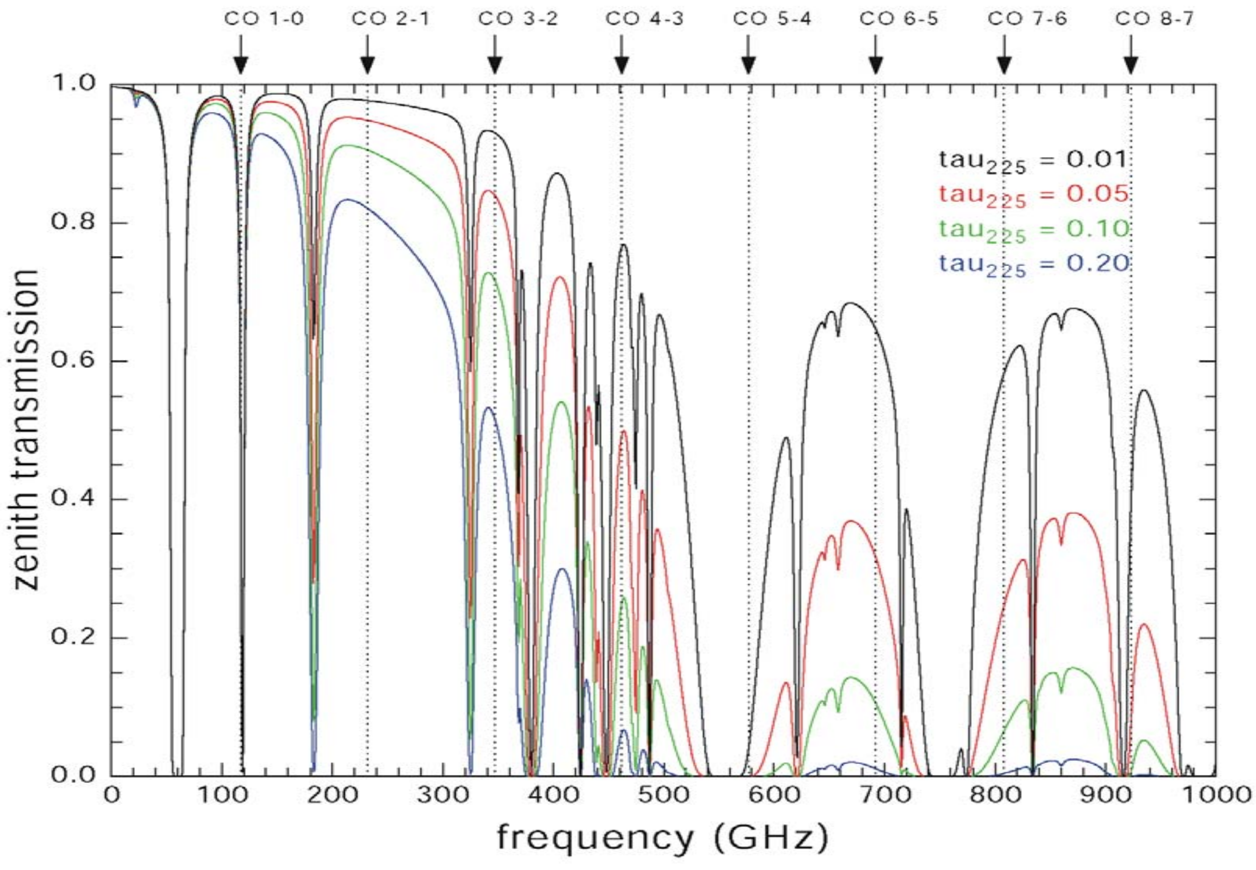
- The electromagnetic spectrum
- Atmospheric transparency in the microwave range
- Heterodyne principle
- Receivers and sensitivity: the noise temperature
- Real time spectrometers: bandwidth and spectral resolution
- Calibration and linearity
- Radiometer formula
- Fundamentals of microwave radiative transfer
- Retrieval of atmospheric information from microwave spectra

The Electromagnetic Spectrum

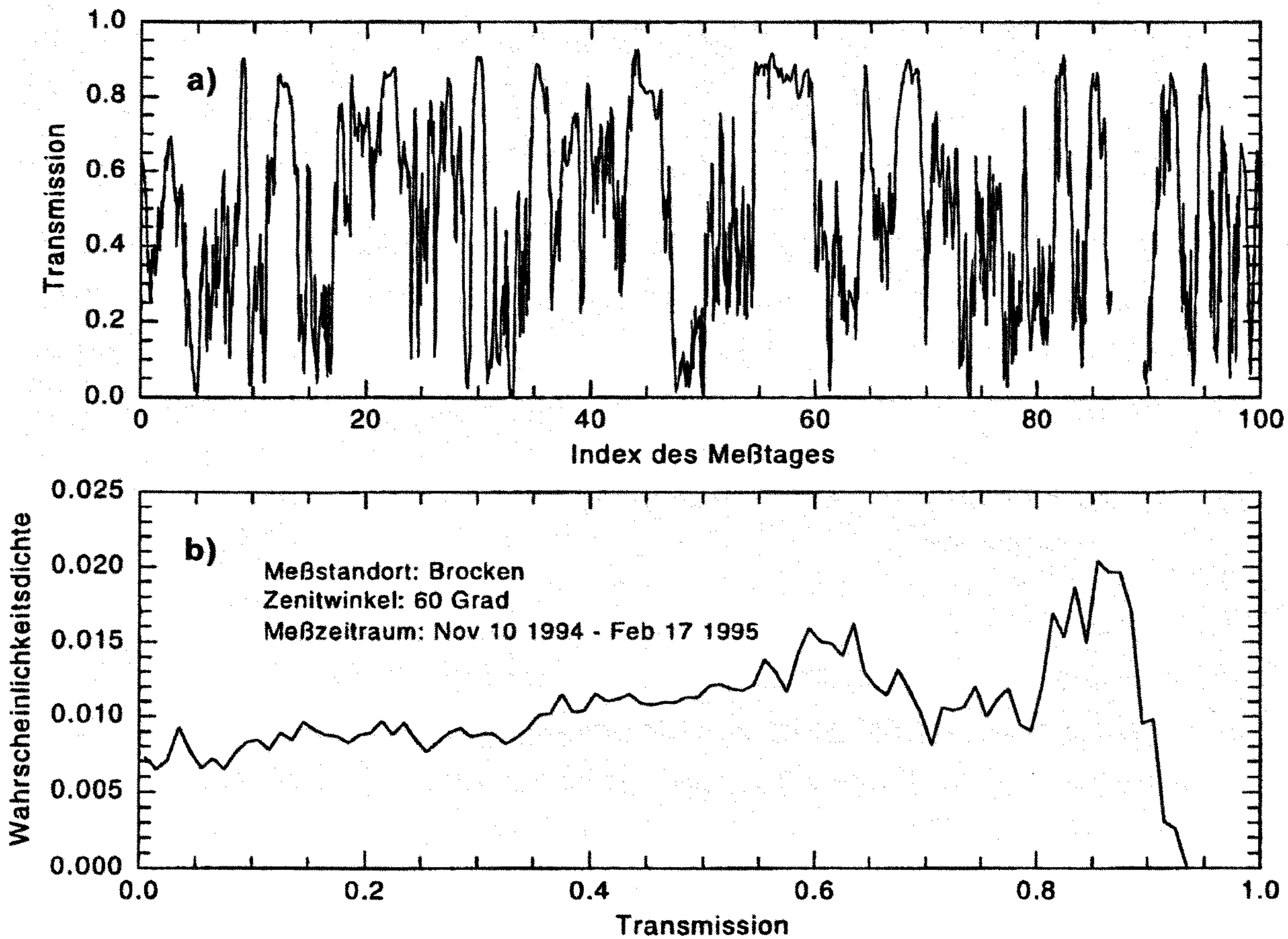



Frequency:
3 GHz
30 GHz
300 GHz
3 THz
Wavelength:
10 cm
1 cm
1mm
100µm
centimeter
millimeter
submillimeter
Wavelength:
1 km
100 m
10 m
1 m
10 cm
1 cm
1 mm
100 µm
10 µm
1 µm
0.1 µm
100 Å
radio
microwave
IR
visible
UV

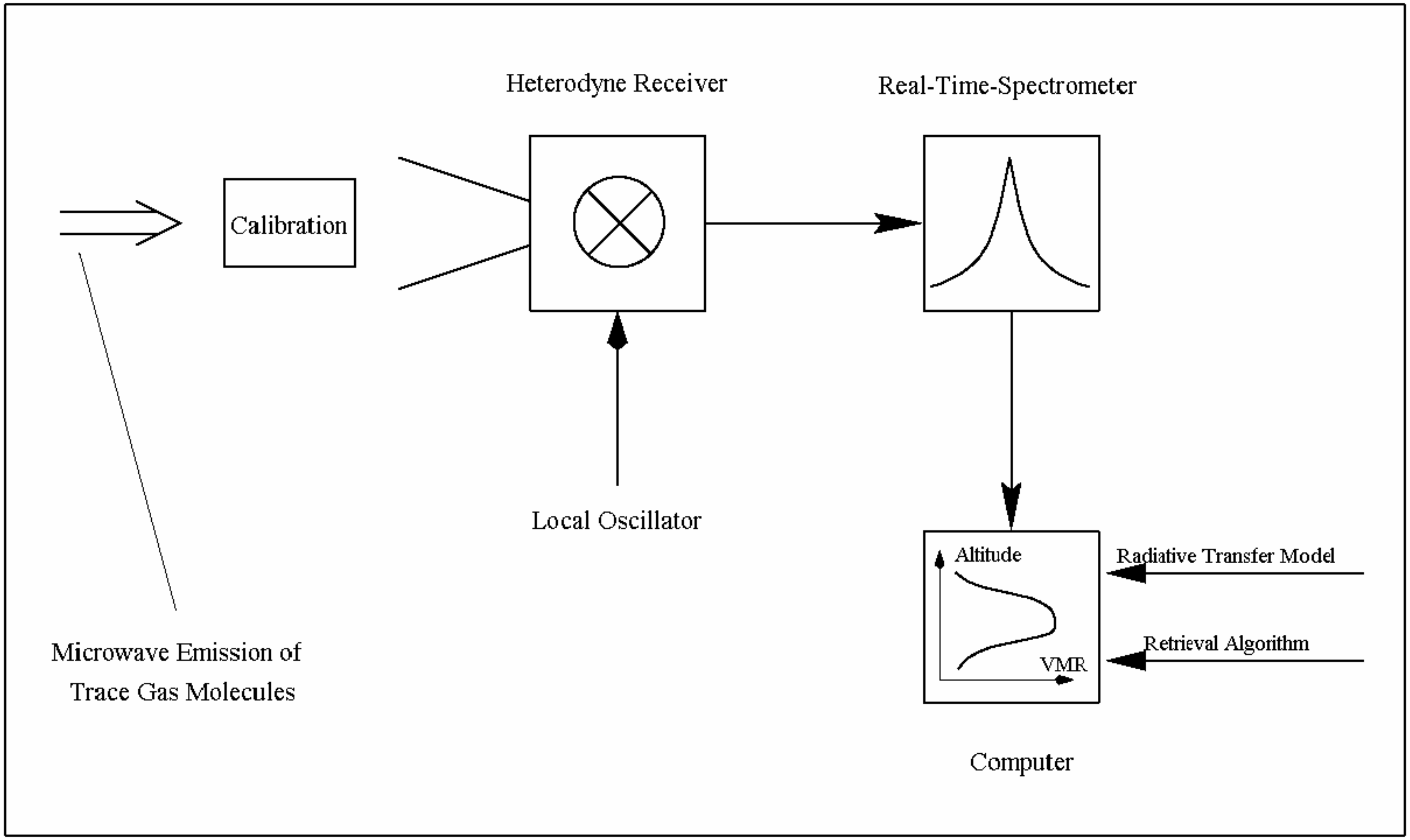
Tropospheric Transmission 0 – 1000 GHz from Ground



Zenith Transmission on 142 GHz, Brocken 1142 m



How does a microwave spectrometer work?



Heterodyne Principle I

High microwave frequencies cannot be processes electronically, a conversion to lower frequencies is required.

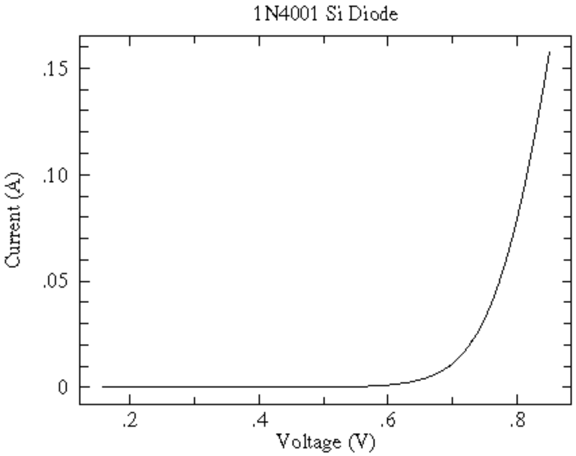
This is achieved by multiplying the received signal (RF) by a local oscillator signal (LO). Multiplication is done by a non-linear element, for instance a diode. Its I-V curve can be described by a power series. I as function of U denotes to:

$$I(U_0 + \Delta U) = I(U_0) + \frac{dI}{dU}\Delta U + \frac{1}{2!}\frac{d^2 I}{dU^2}\Delta U^2 + \frac{1}{3!}\frac{d^3 I}{dU^3}\Delta U^3 + \ldots$$

with ΔU being the sum of RF- and LO - signal

$$\Delta U = A \sin \omega_{RF} t + B \sin \omega_{LO} t$$

for the multiplication (mixing) process we just consider the quadratic term:

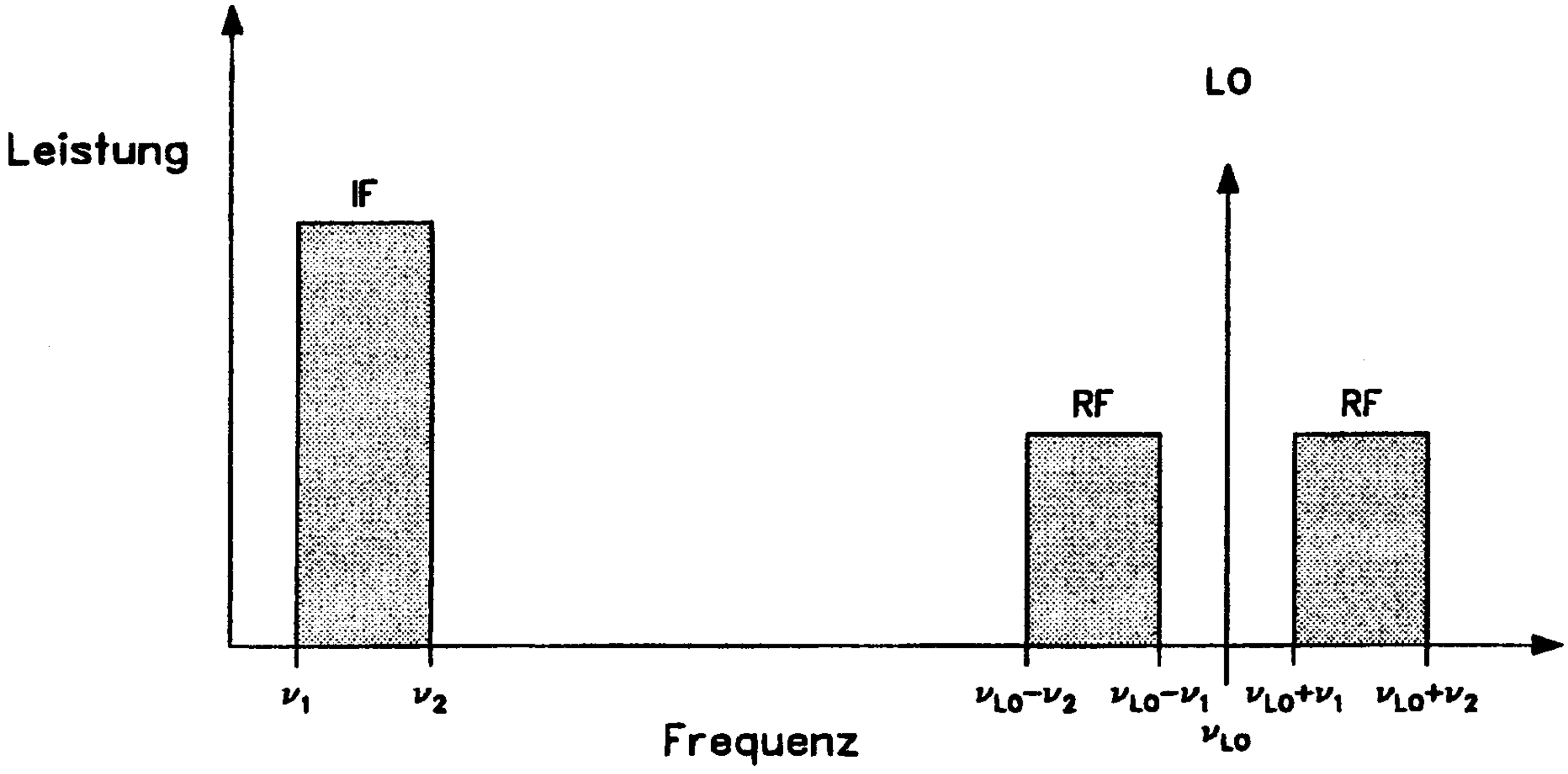


Heterodyne Principle II

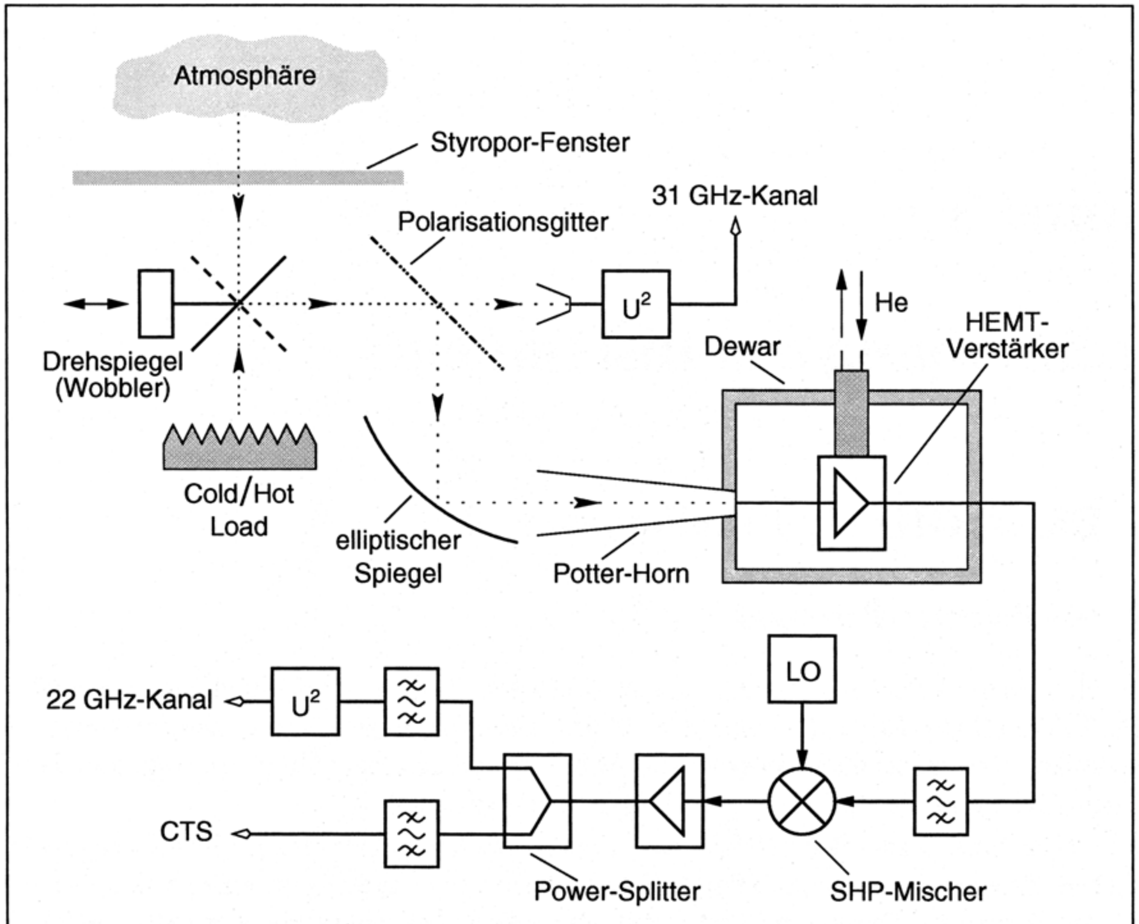
$$\begin{aligned}
\Delta U^2 &= (A \sin \omega_{RF} t + B \sin \omega_{LO} t)^2 \\
&= A^2 \sin^2 \omega_{RF} t + 2AB \sin \omega_{RF} t \sin \omega_{LO} t + B^2 \sin^2 \omega_{LO} t^2 \\
&= \frac{1}{2} A^2 (1 - \cos 2\omega_{RF} t) + \frac{1}{2} B^2 (1 - \cos 2\omega_{LO} t) \\
&\quad + AB \Big[\cos(\omega_{RF} - \omega_{LO}) t - \cos(\omega_{RF} + \omega_{LO}) t \Big] \\
&= \frac{1}{2}(A^2 + B^2) - \frac{1}{2} A^2 \cos(2\omega_{RF}) t - \frac{1}{2} B^2 \cos(2\omega_{LO}) t \\
&\quad + AB \cos(\omega_{RF} - \omega_{LO}) t - AB \cos(\omega_{RF} + \omega_{LO}) t
\end{aligned}$$

Heterodyne Principle III

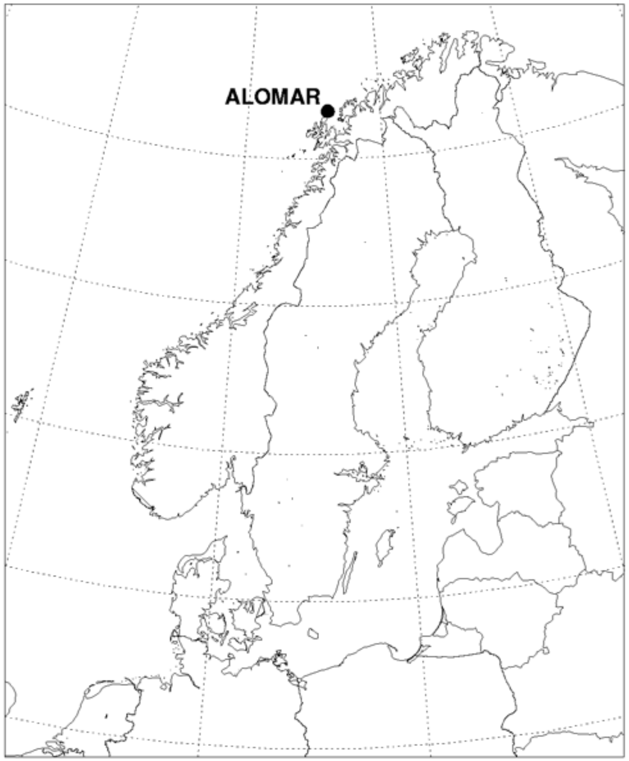
- *Result: we get a DC – component, the doubled RF and LO frequencies and finally the sum and difference frequiencies of LO and RF signal. The difference frequency is called intermediate frequency (IF) , the component we use for further processing, i.e. the spectroscopy. Consider, that in principle 2 bands around the LO frequency can result in the same IF. They are called upper and lower sideband (USB, LSB).*

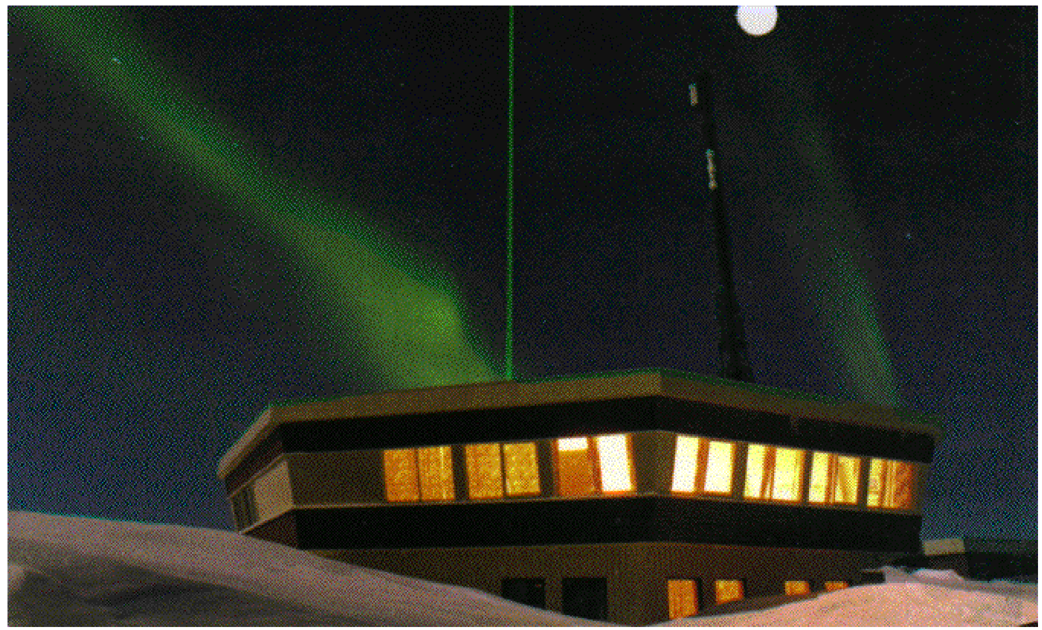


Example: 22 GHz Water Vapor System

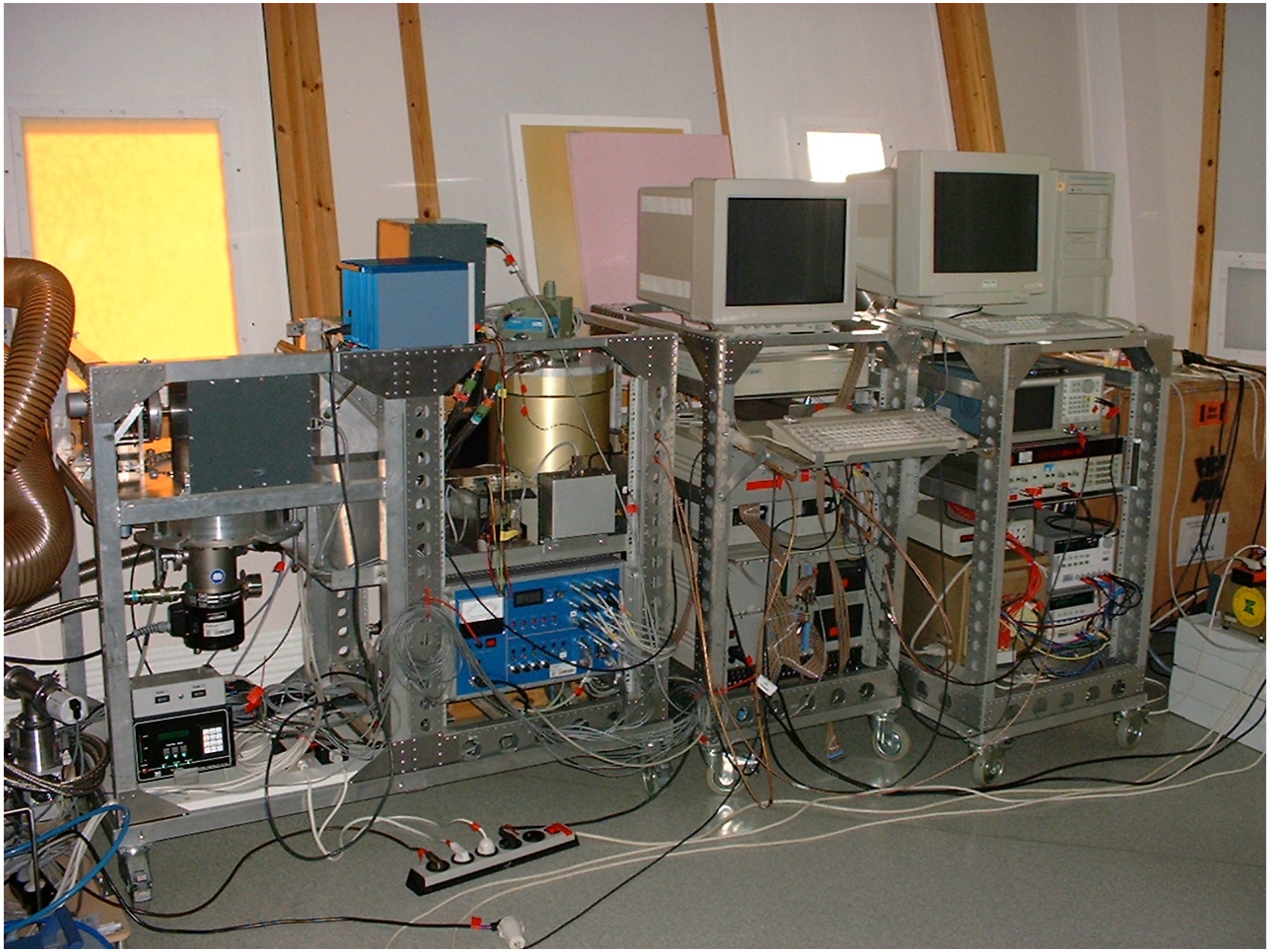


ALOMAR SITE at 69° N, 16° E

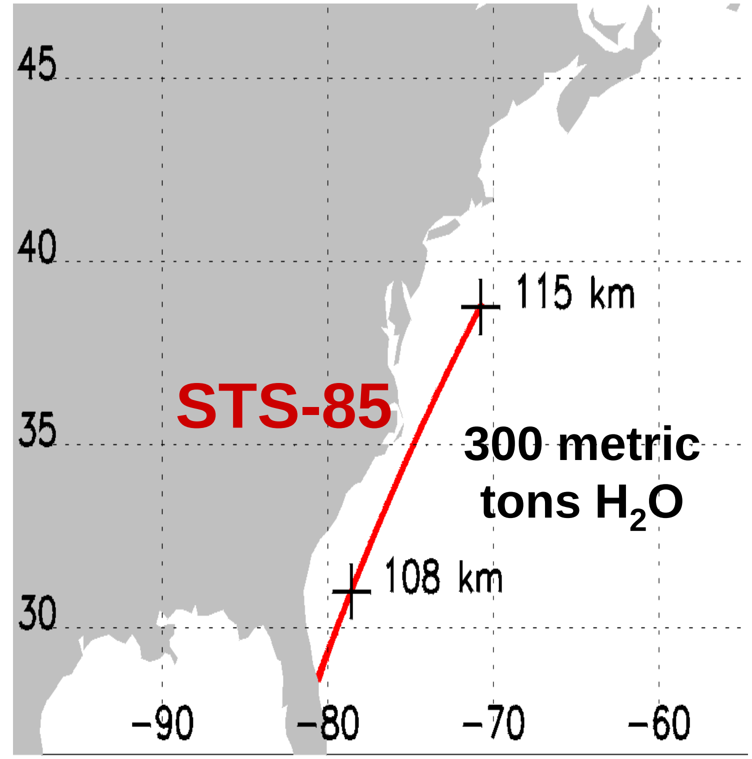




ALOMAR 22 GHz System

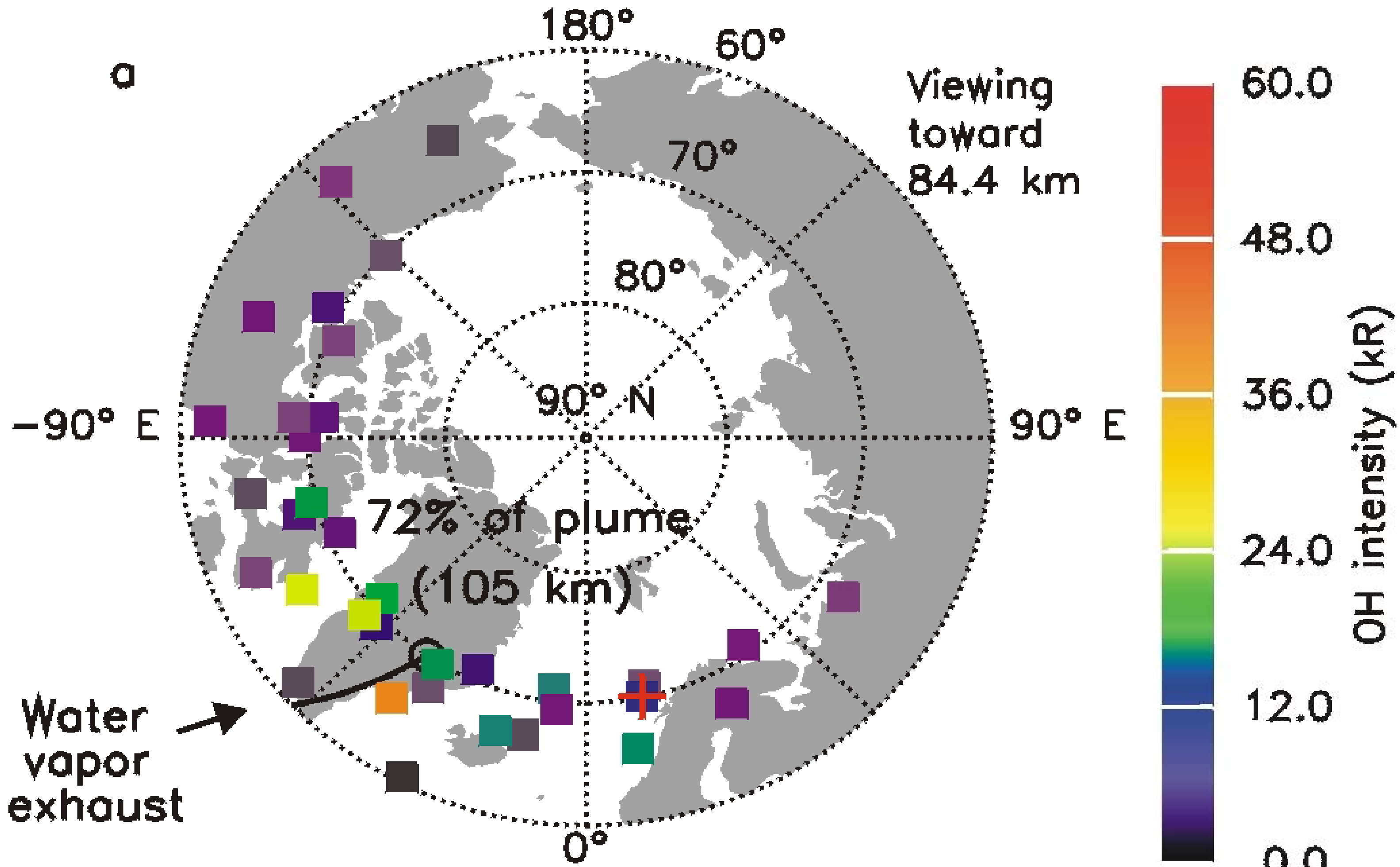


CRISTA-SPAS 2: August, 1997

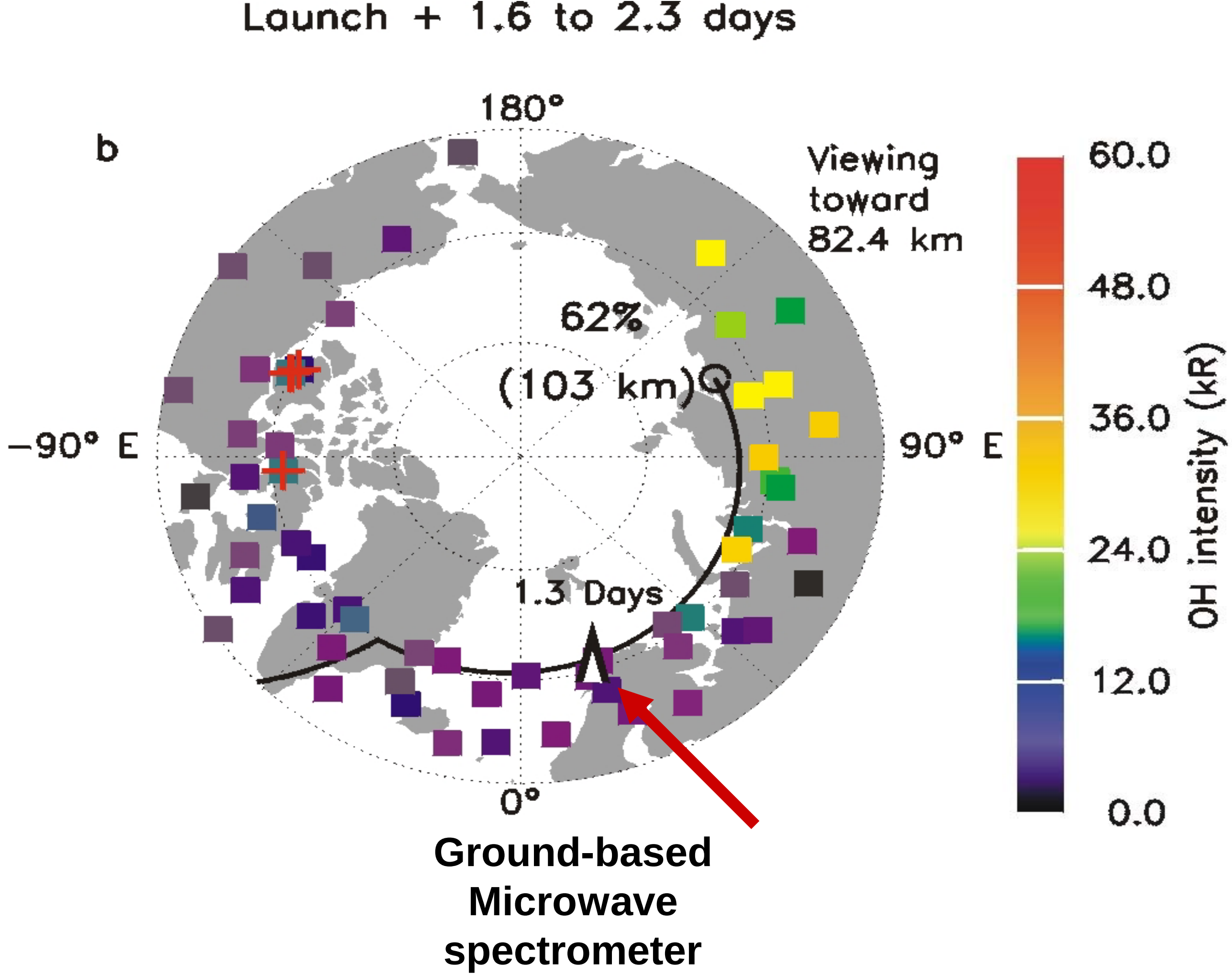


What can happen to the water exhaust in the summer?

STS-85 Launch + 0.9 to 1.3 days

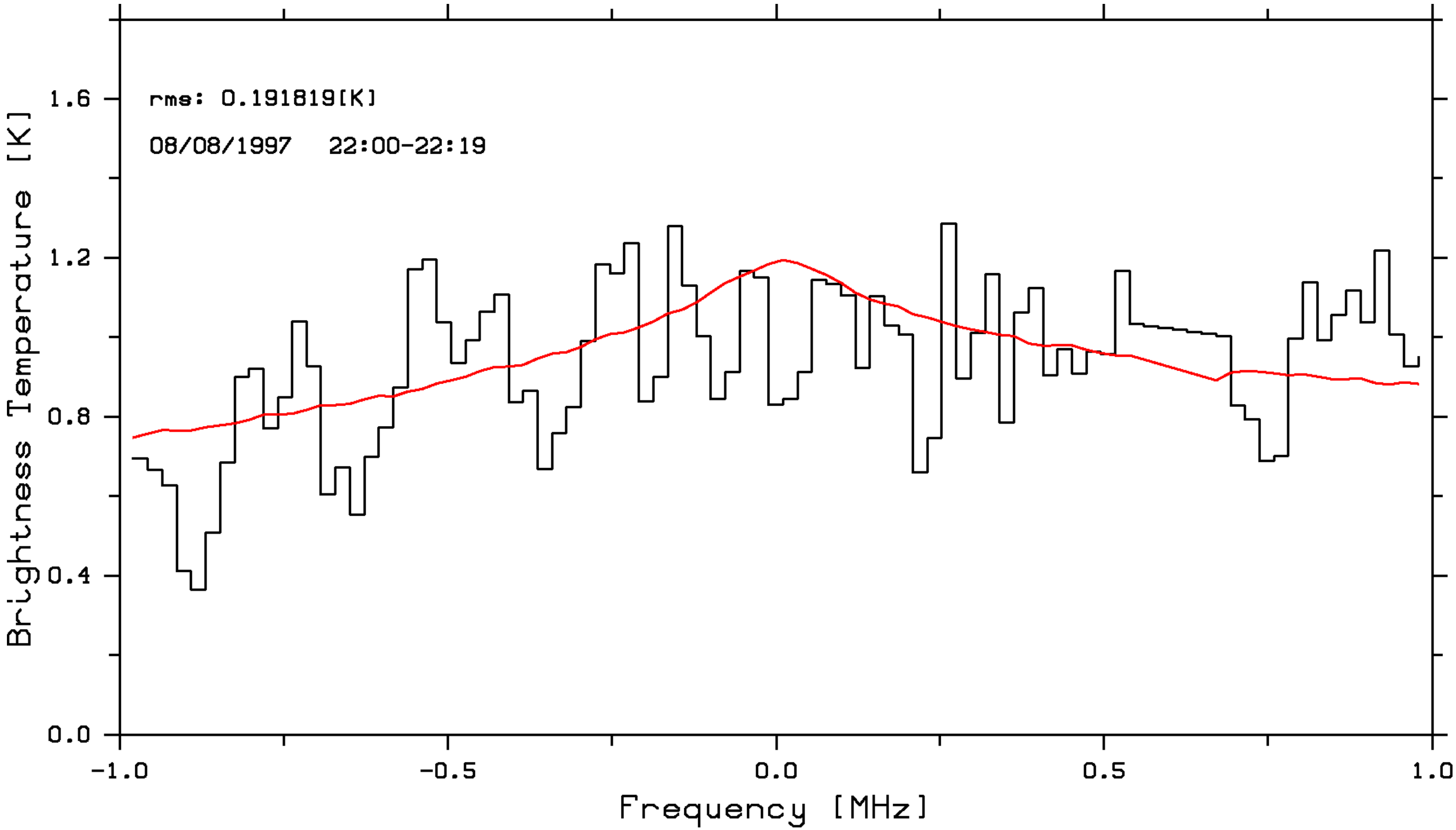


MAHRSI observed bright OH intensities in the Arctic a day after launch of STS-85.

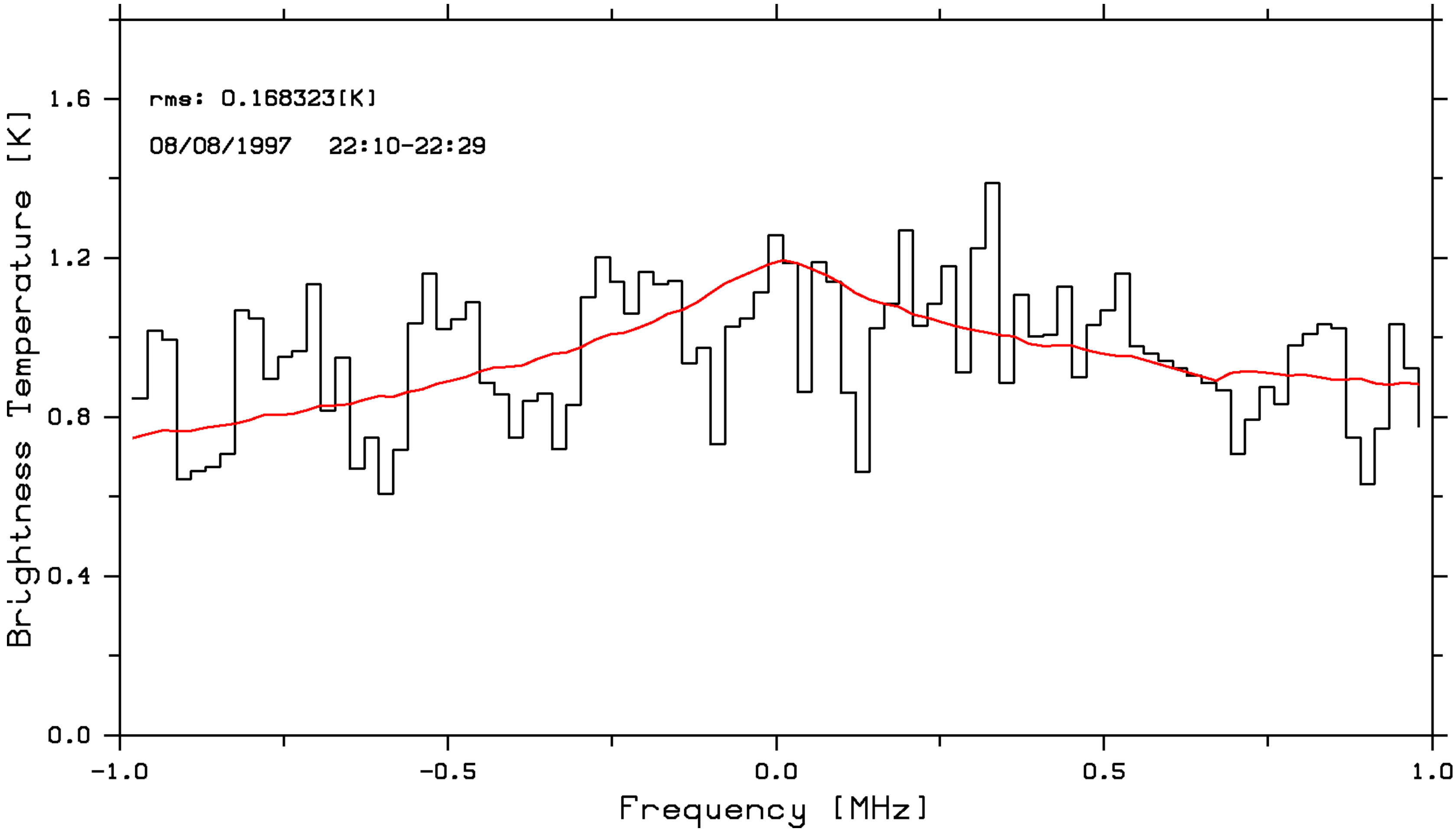


- **Bright OH intensities are observed over Siberia ~2 days after launch**
- **Vertical motion is <u>downward</u> in the lower thermosphere during the Arctic summer [Lieberman et al., 2000].**

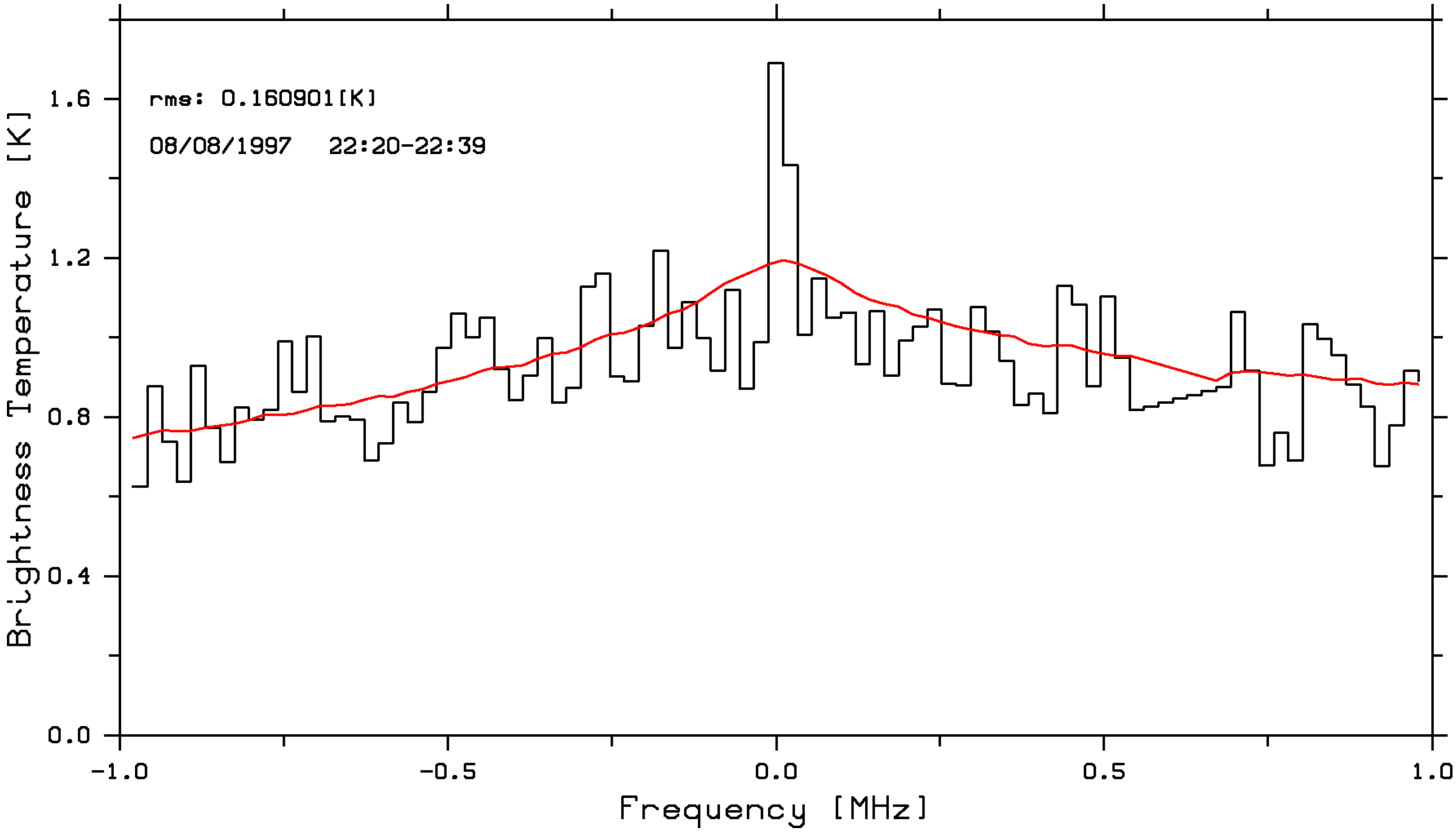
Average August and 20 Minute Spectrum (1)



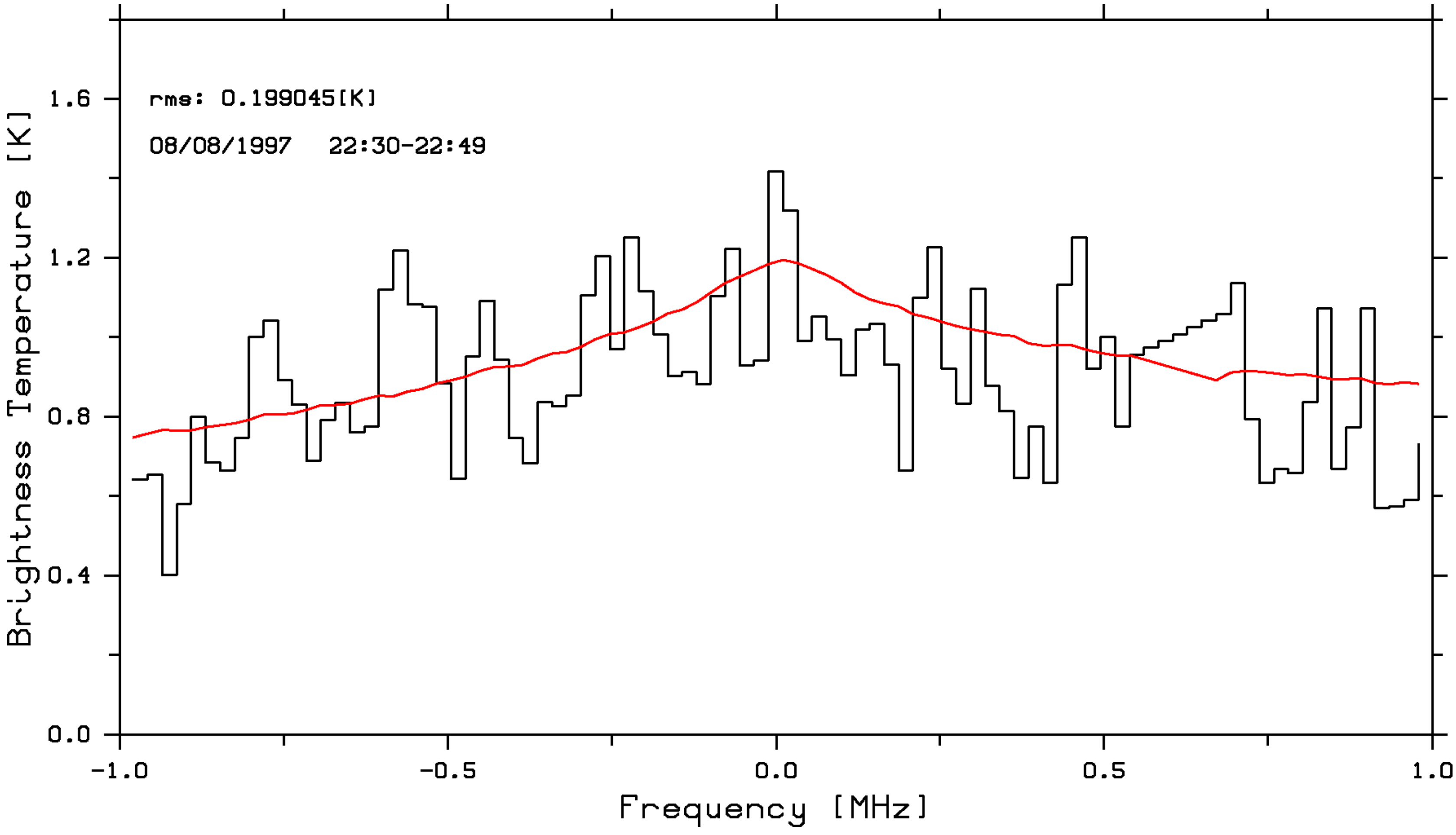
Average August and 20 Minute Spectrum (2)



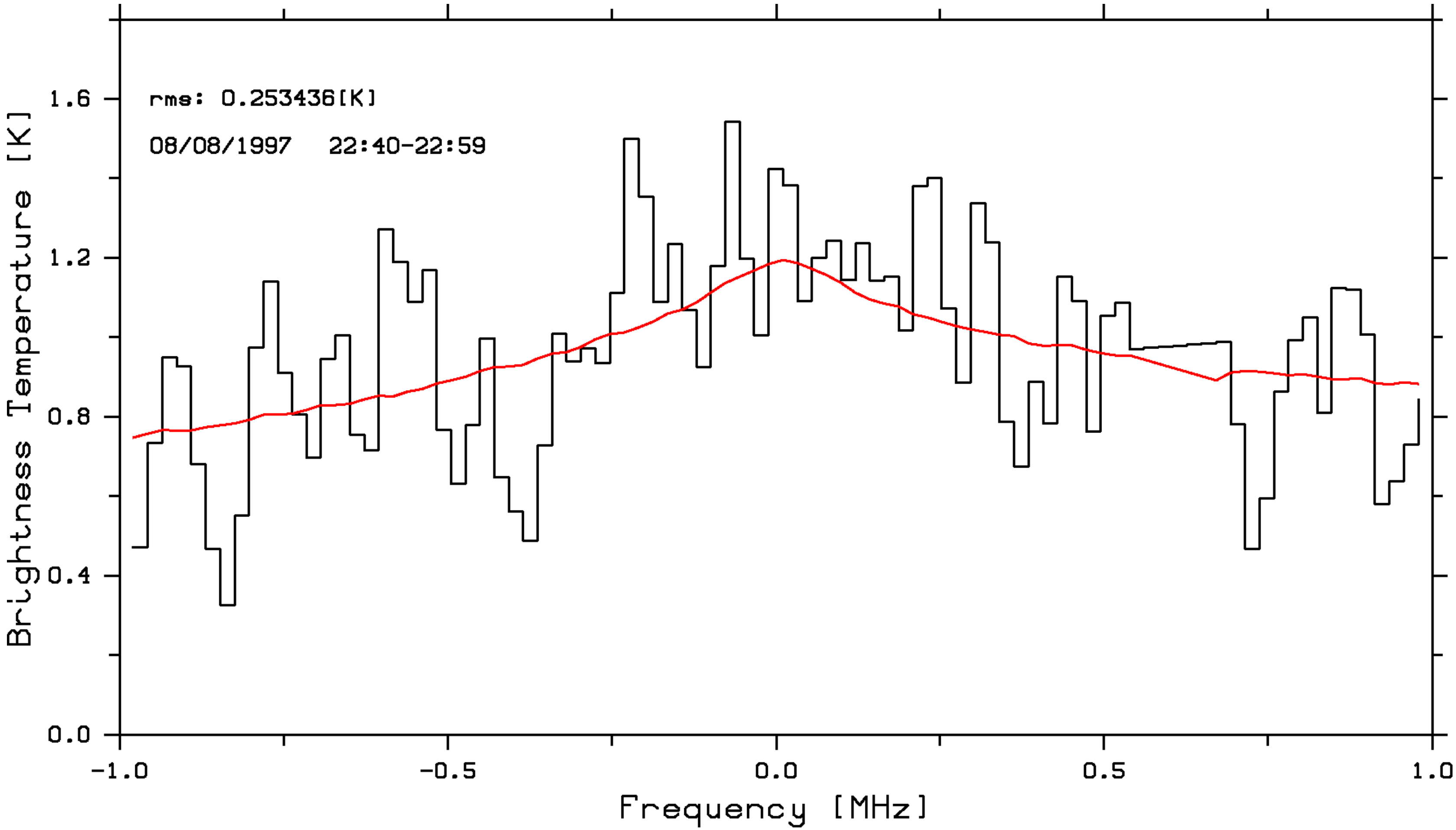
Average August and 20 Minute Spectrum (3)



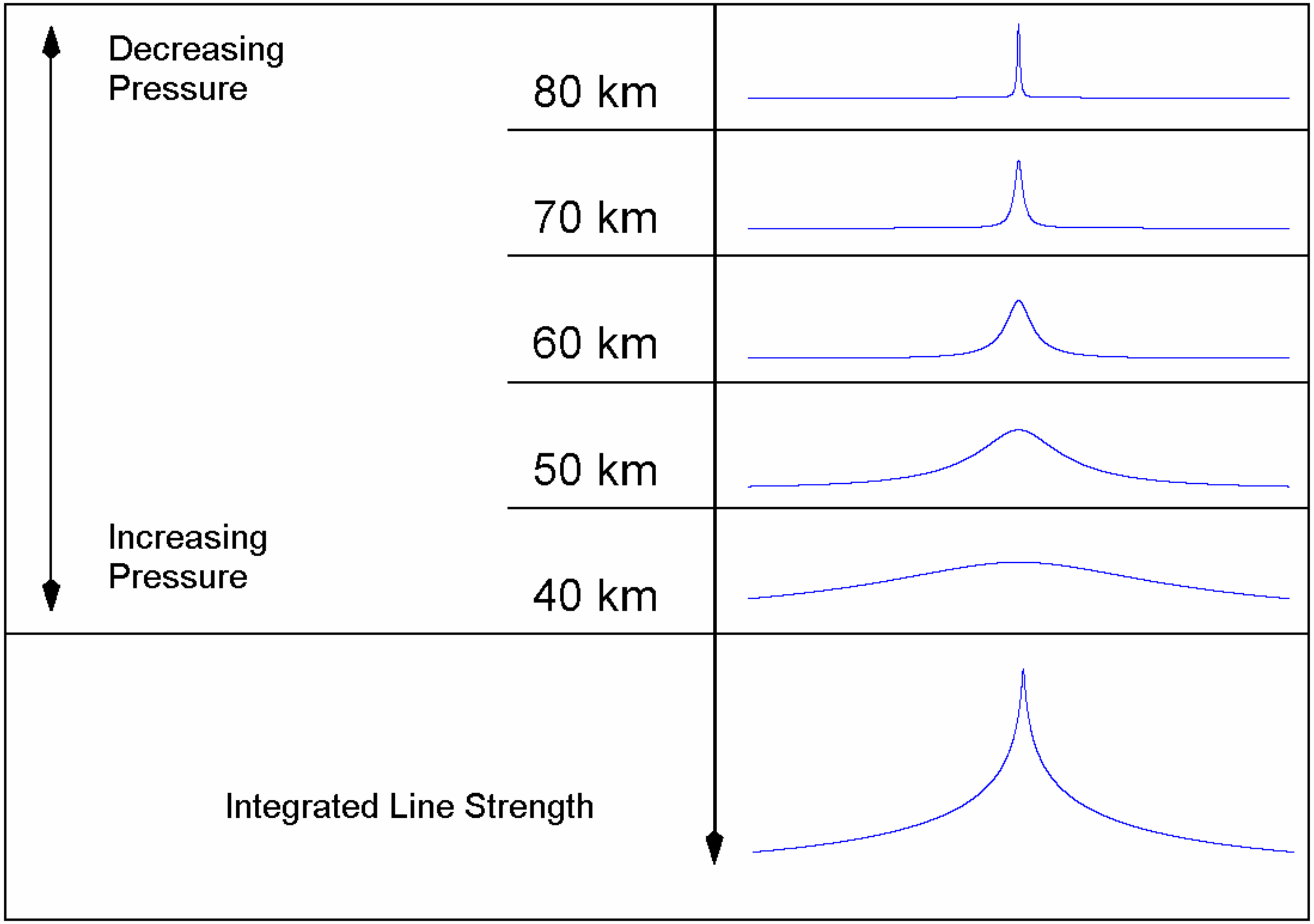
Average August and 20 Minute Spectrum (4)



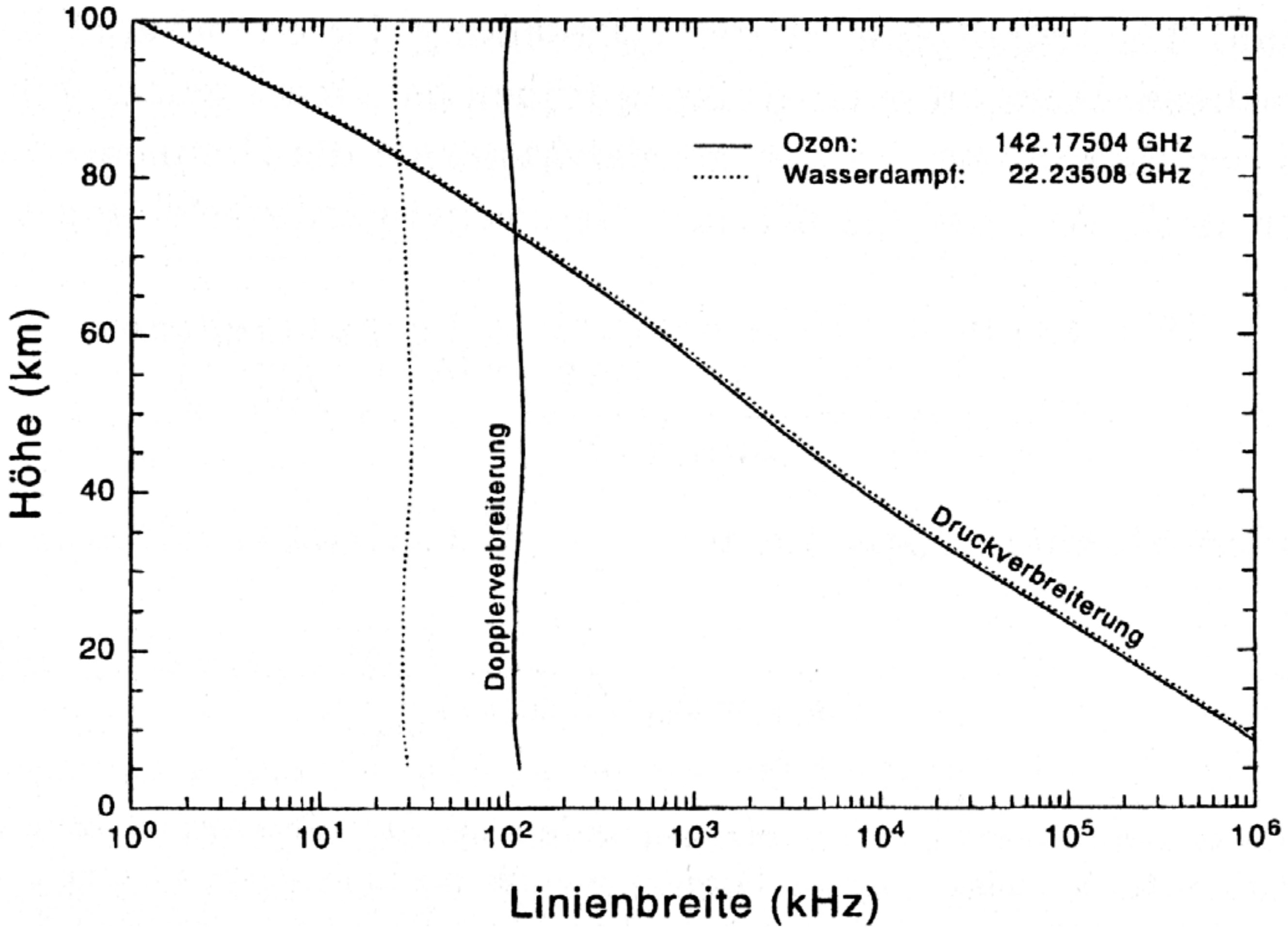
Average August and 20 Minute Spectrum (5)



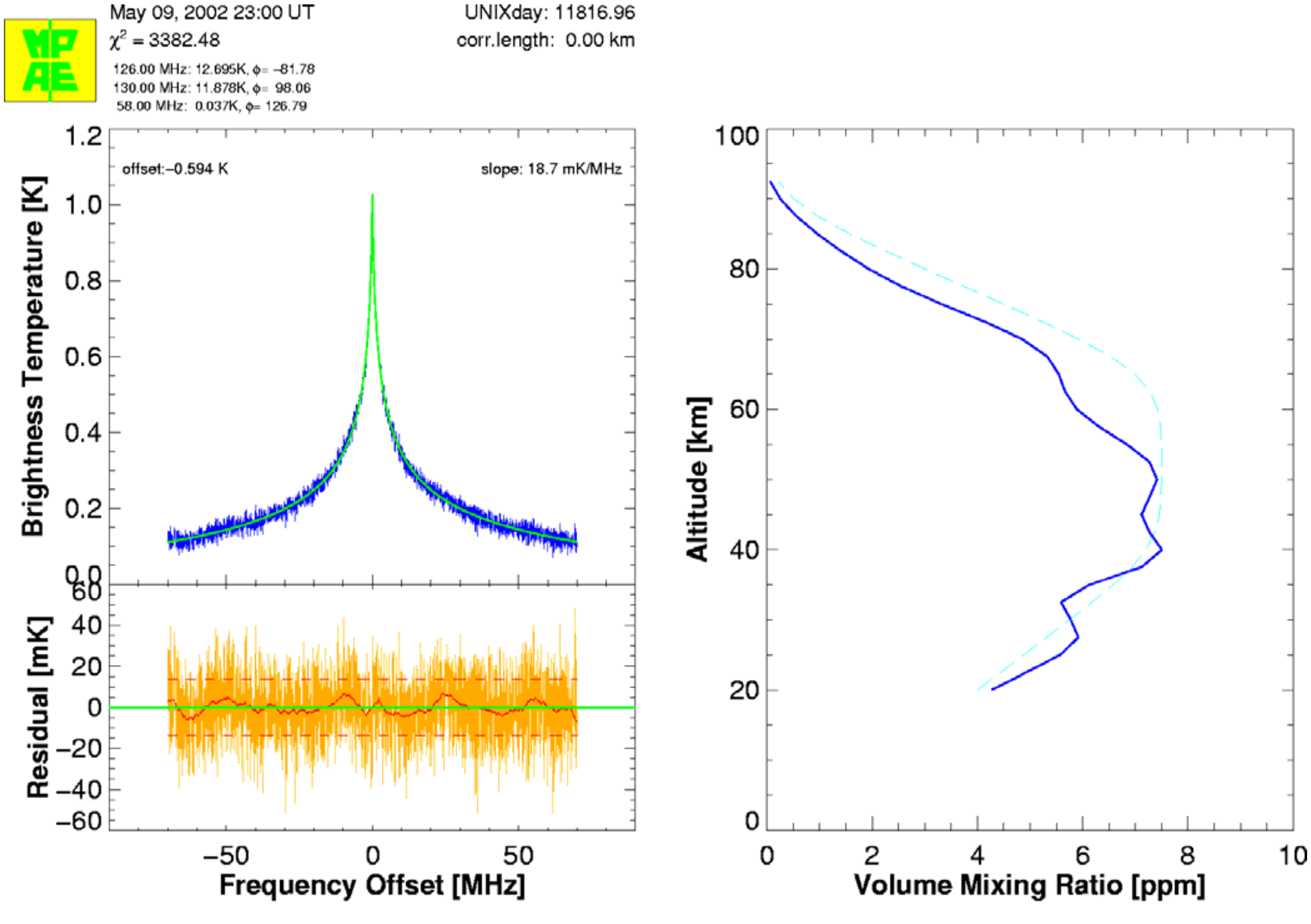
Synthesis of Molecular Emission measured from Ground



Broadening for Ozone and Water Vapor at 22 and 142 GHz



WASPAM Water Vapor Observation from ALOMAR



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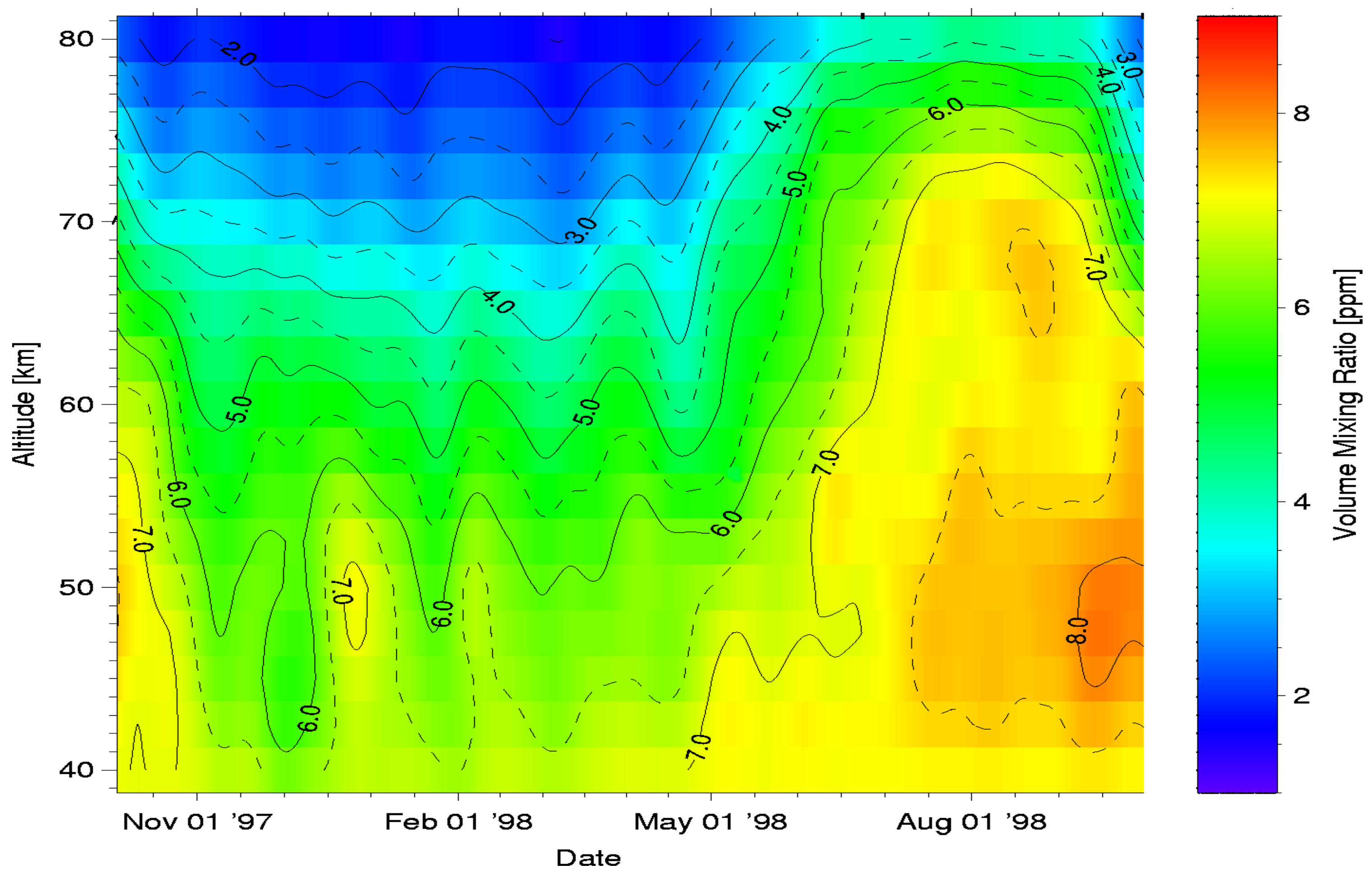
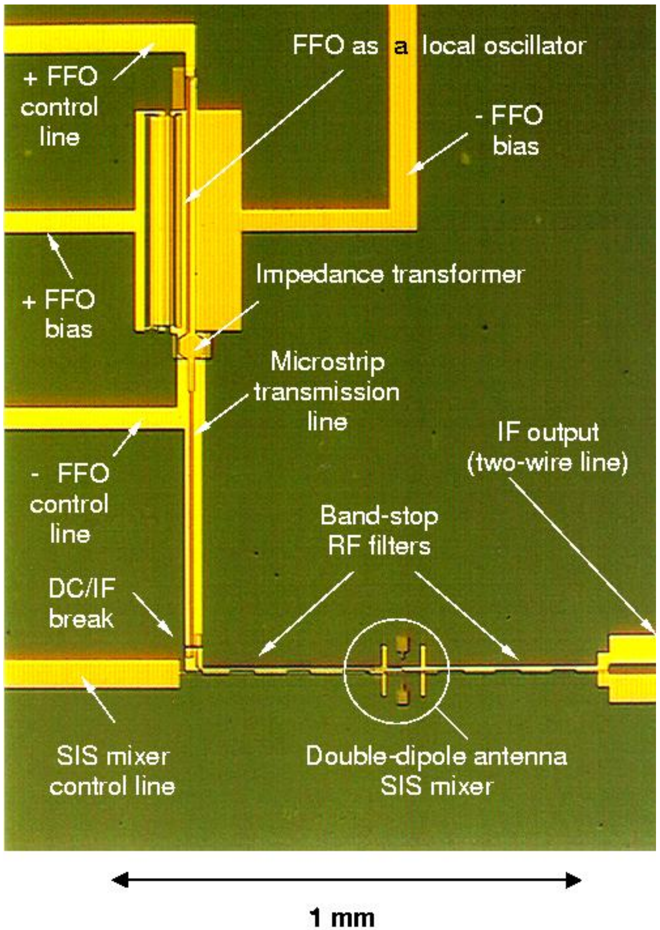
Annual Variation of Water Vapor Volume Mixing Ratio with 1 day Time Resolution



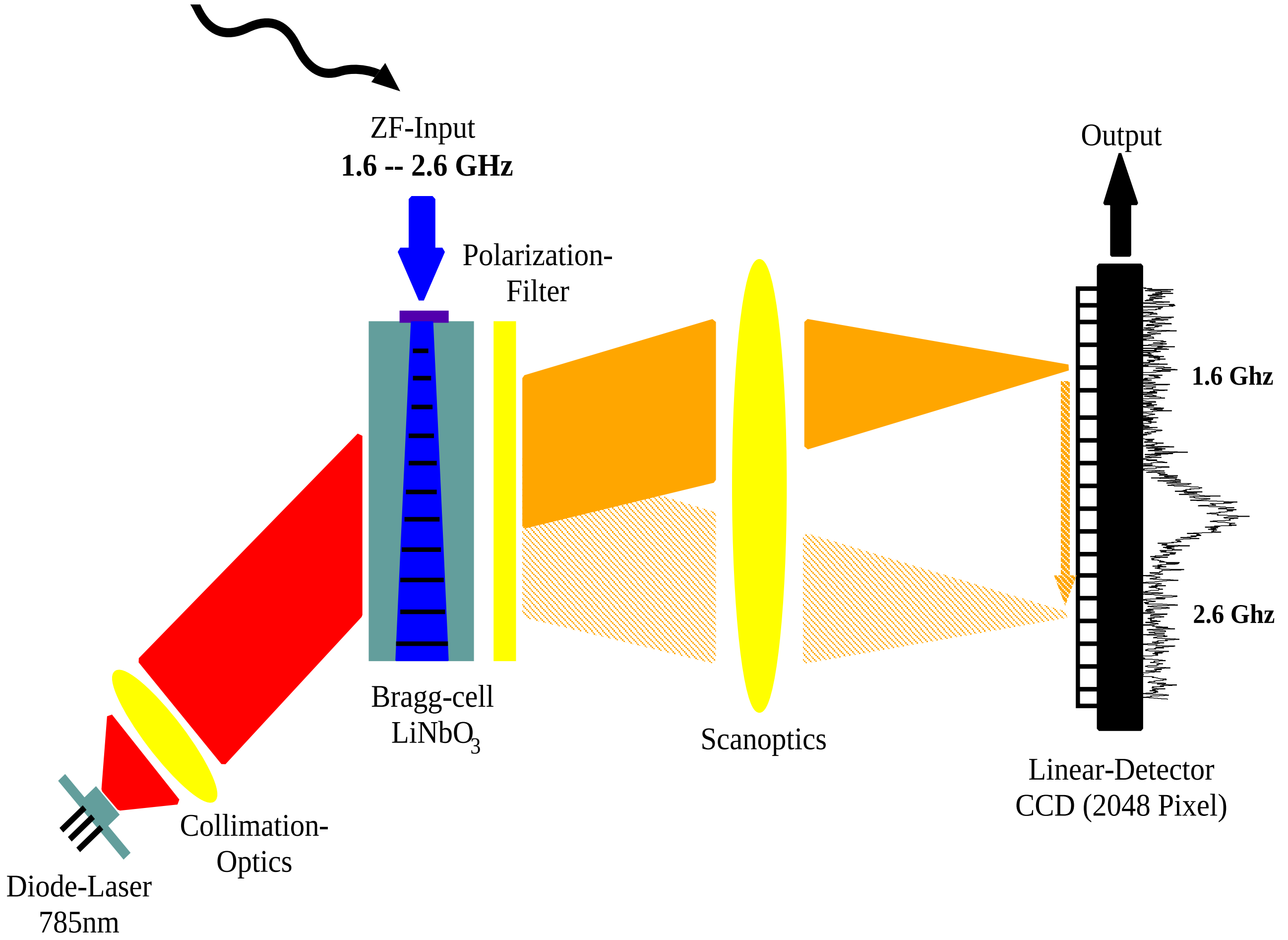
Instrumentation: Frontend

- *Front end amplifier up to 150 GHz (followed by mixer). Type: High Electron Mobility Transistor (HEMT). Today highest performance HEMTs are based on InP semiconductor material.*
- *Above 150 GHz front end mixer instead followed by HEMT*
- *Basically 3 types of mixers: Schottky, superconductor - insulator - superconductor (SIS) and Hot Electron Bolometers (HEB)*
- *Schottky- mixers: work at room temperature, however not that sensitive (about 100 times quantum limit hv/k, e.g. 2500 K at 500 GHz)*
- *SIS – mixers: work typically at 4 K, very sensitive (2 hv/k, e.g. 50 K@500 GHz), need low LO-signal only*
- *HEB – mixers: useful above 1000 GHz since SIS at their limit, operate at 4 K, rather sensitive (5 – 20 hv/k, e.g. 500 – 2000 K @ 2000 GHz), very low LO-signal required.*

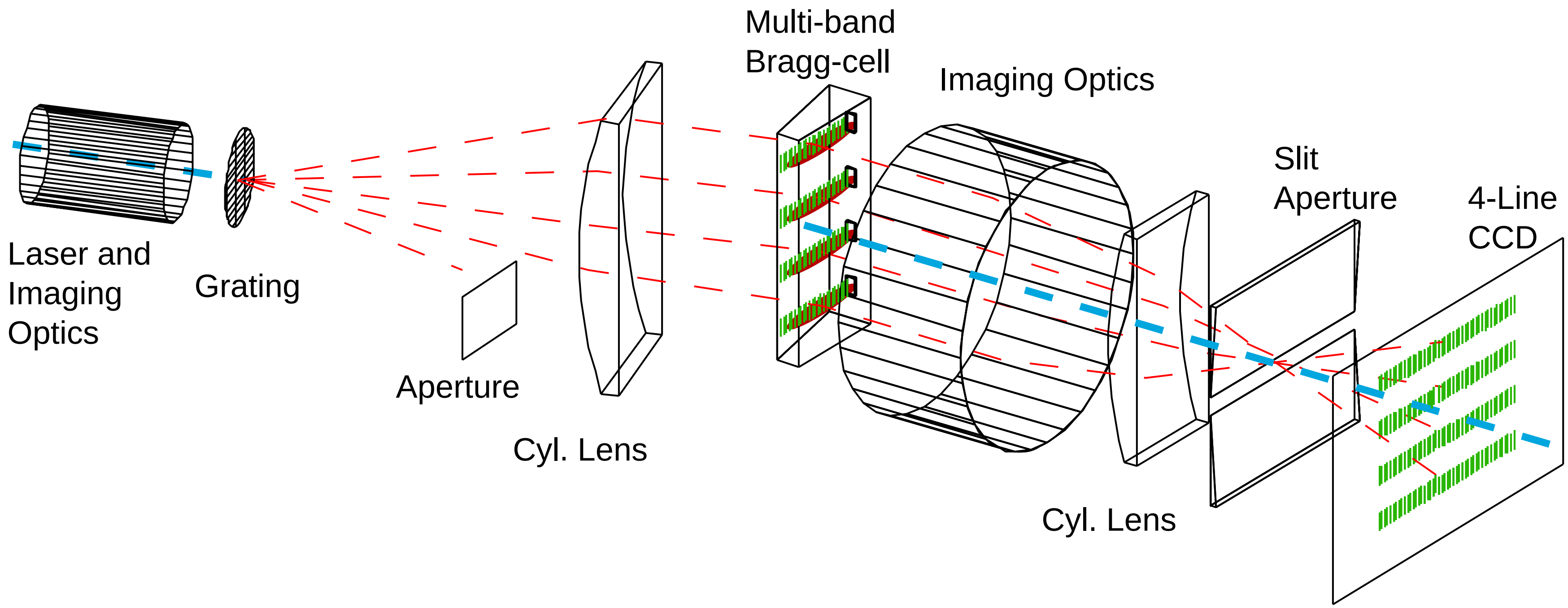
Submm integrated receiver (SRON/IREE)



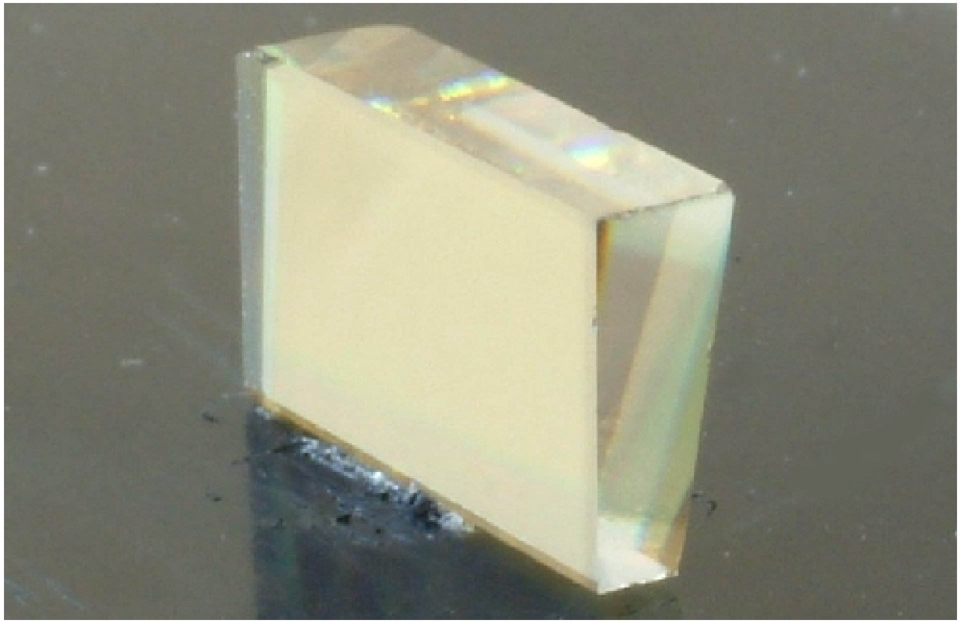
Instrumentation: Backends, the Acousto Optical Spectrometer (AOS)



Instrumentation: Backends, the Array-AOS

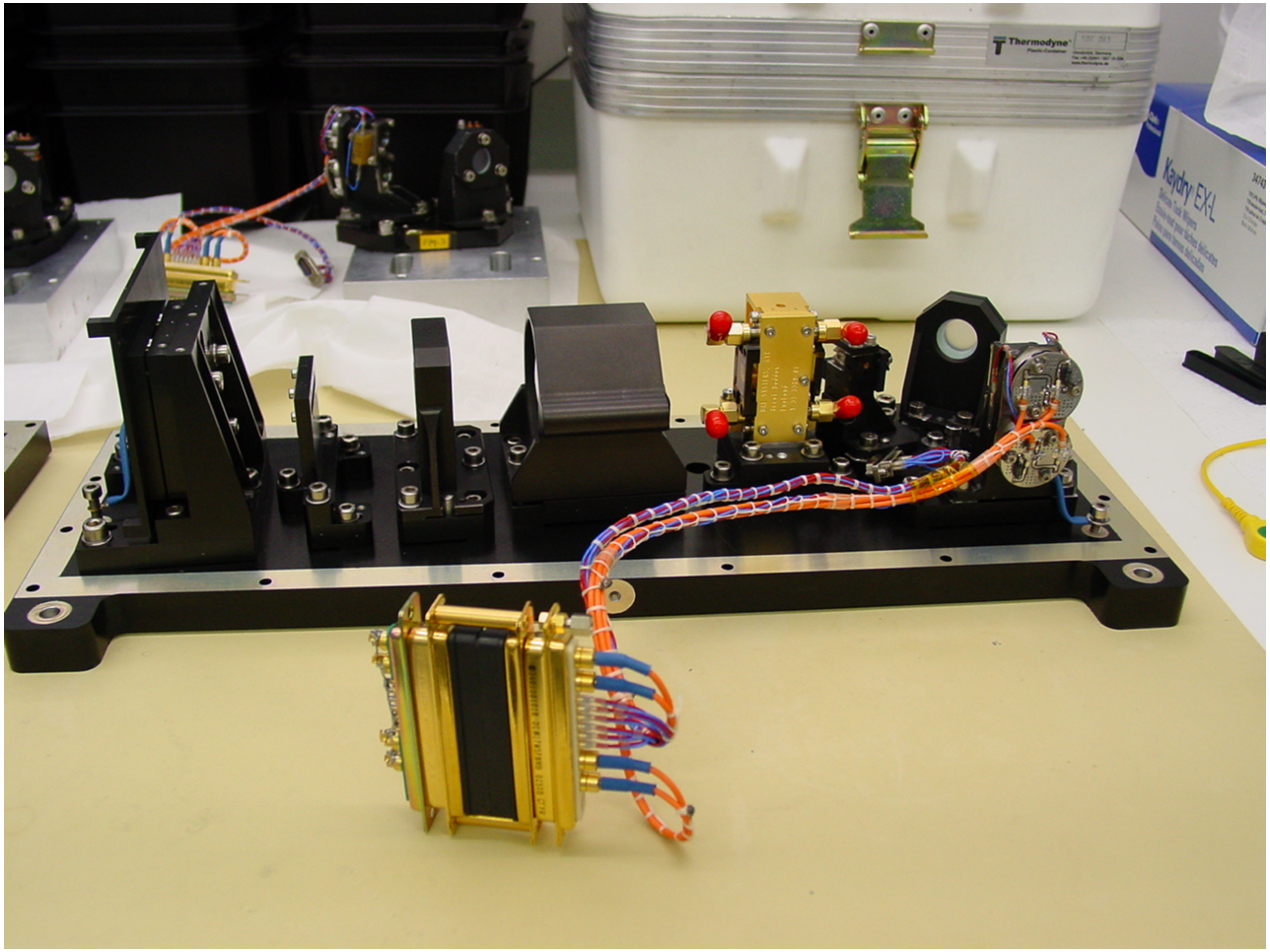


Bragg Cell Material Properties

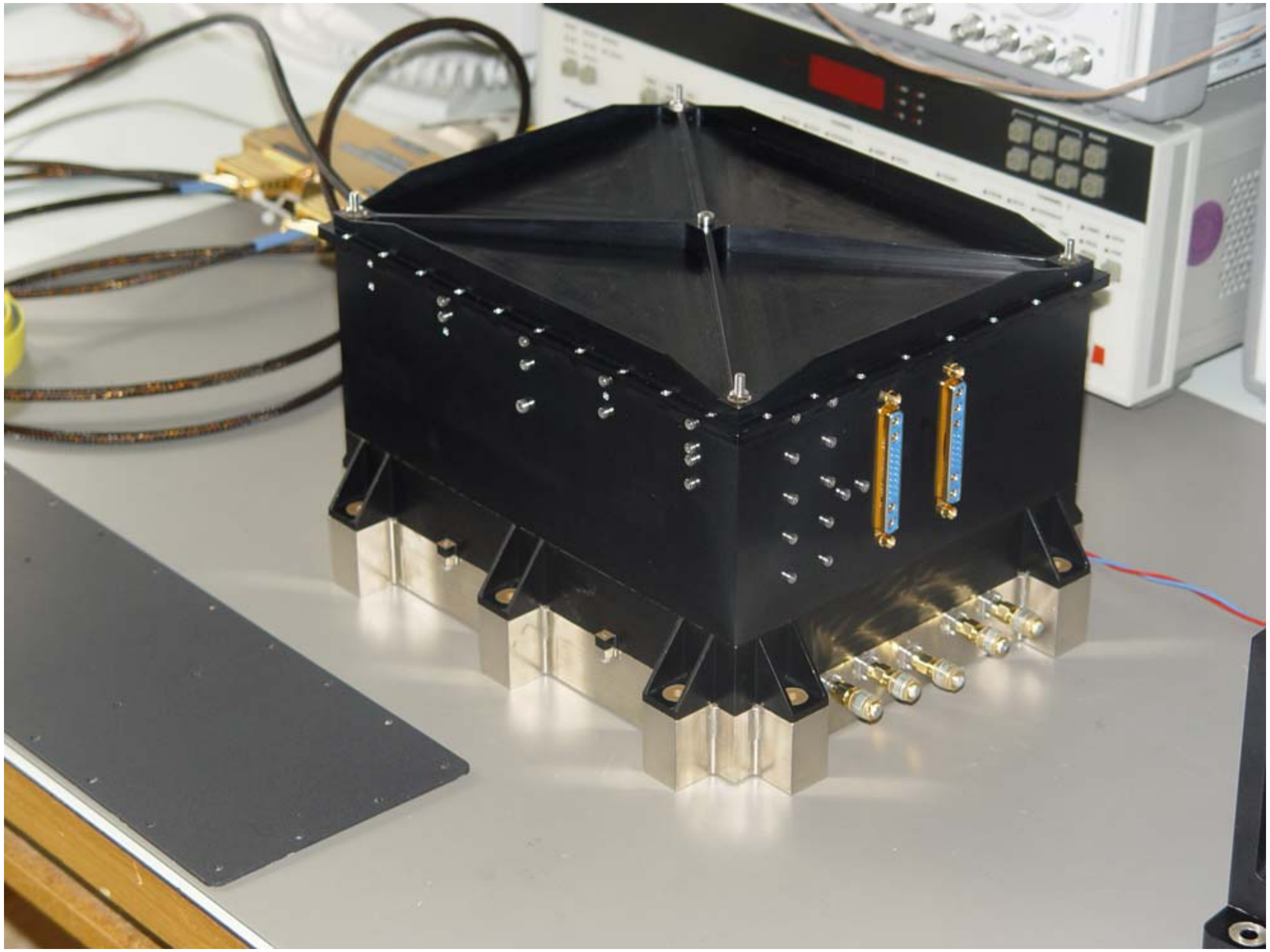


Parameter	$LiNbO_3$	TiO_2
Max. bandwidth	2 GHz	4 GHz
Attenuation @ 2 GHz	5.6 dB/µsec	1.1 dB/µsec
v_{sonic}	3445 m/sec	3200 m/sec

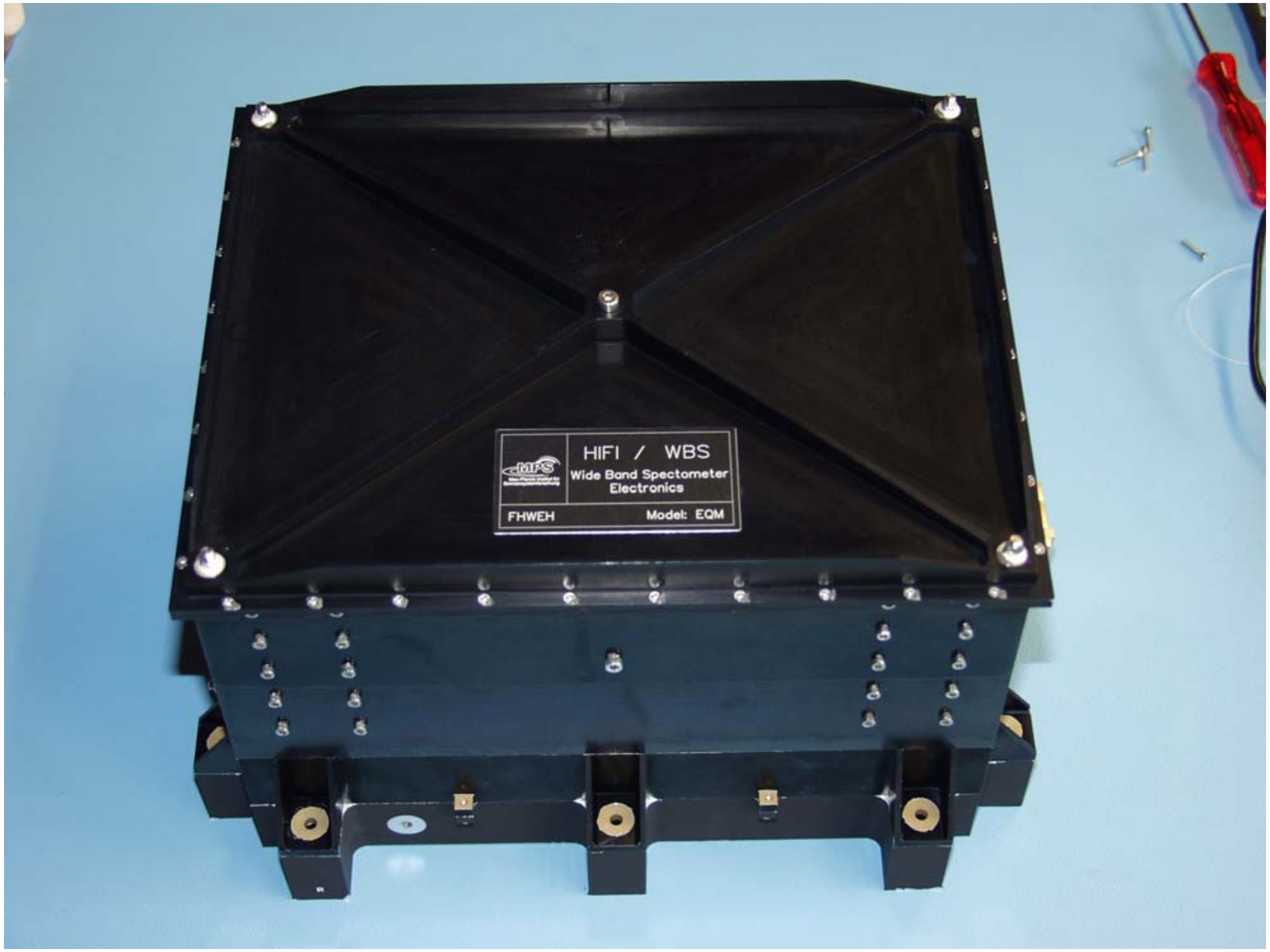
HIFI-AOS Optical Unit



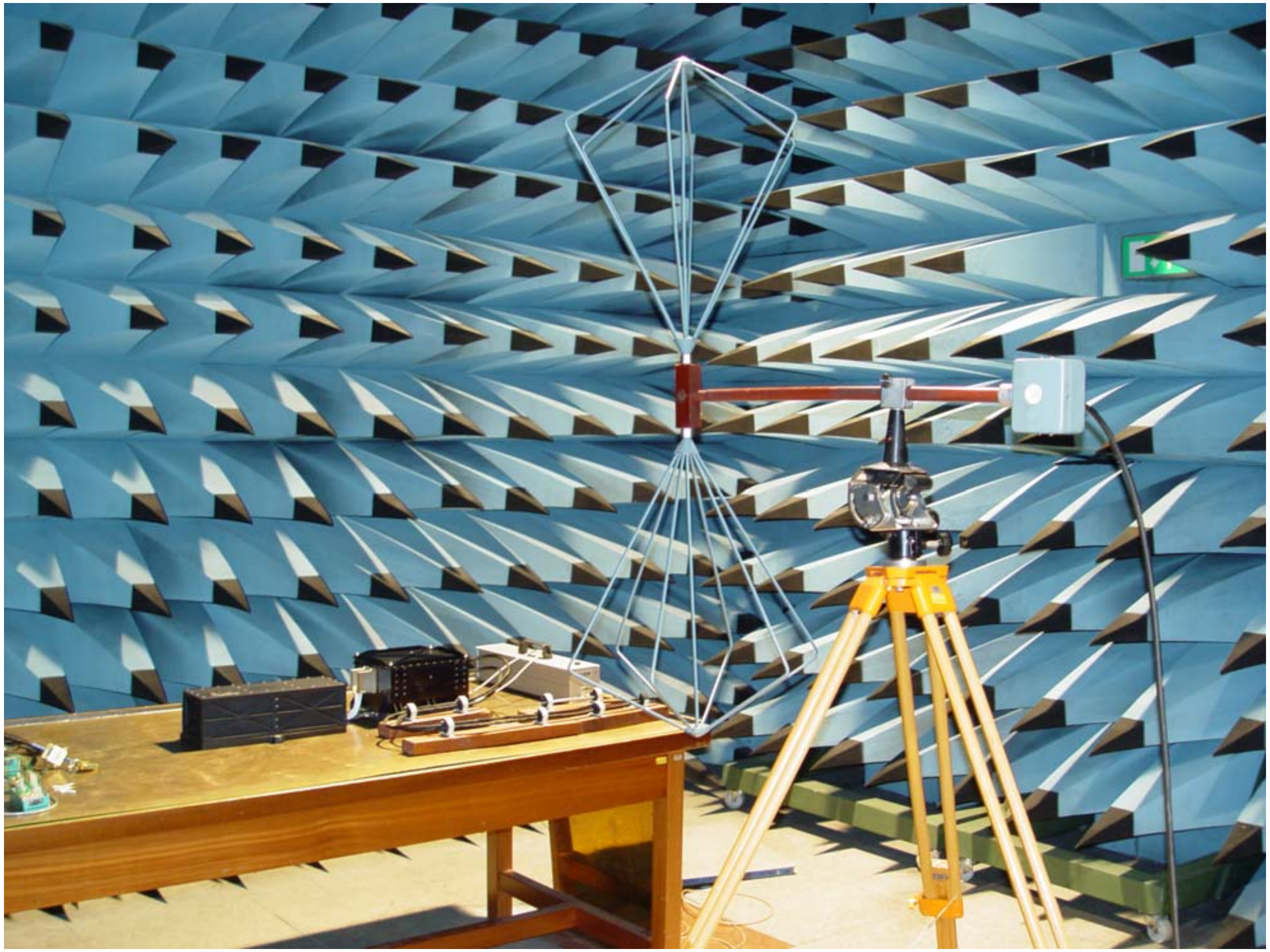
HIFI-AOS Electronic Unit



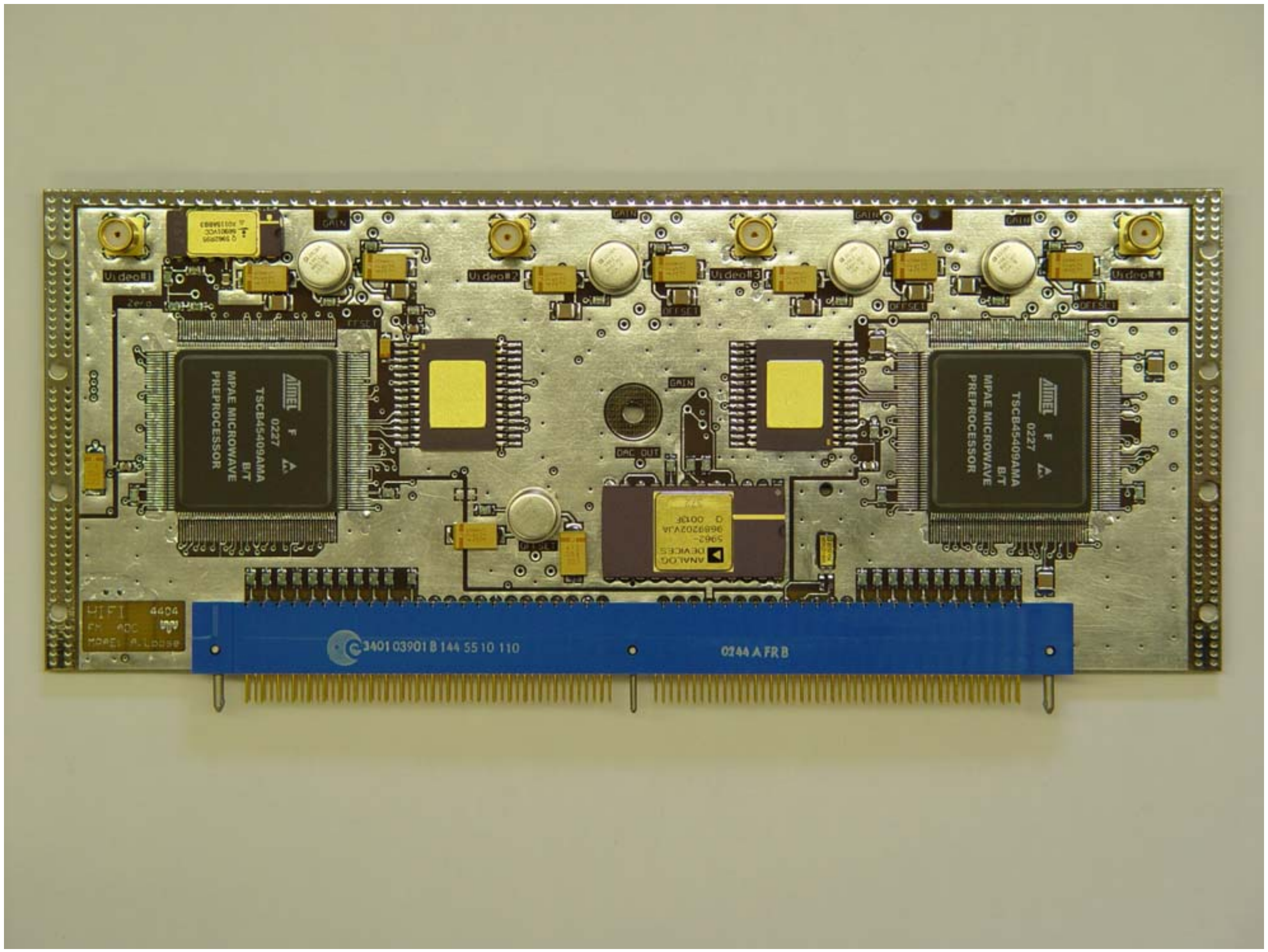
HIFI WBE/WBI


HIFI / WBS
Wide Band Spectometer
Electronics
FHWEH
Model: EQM

HIFI AOS EMC - Test

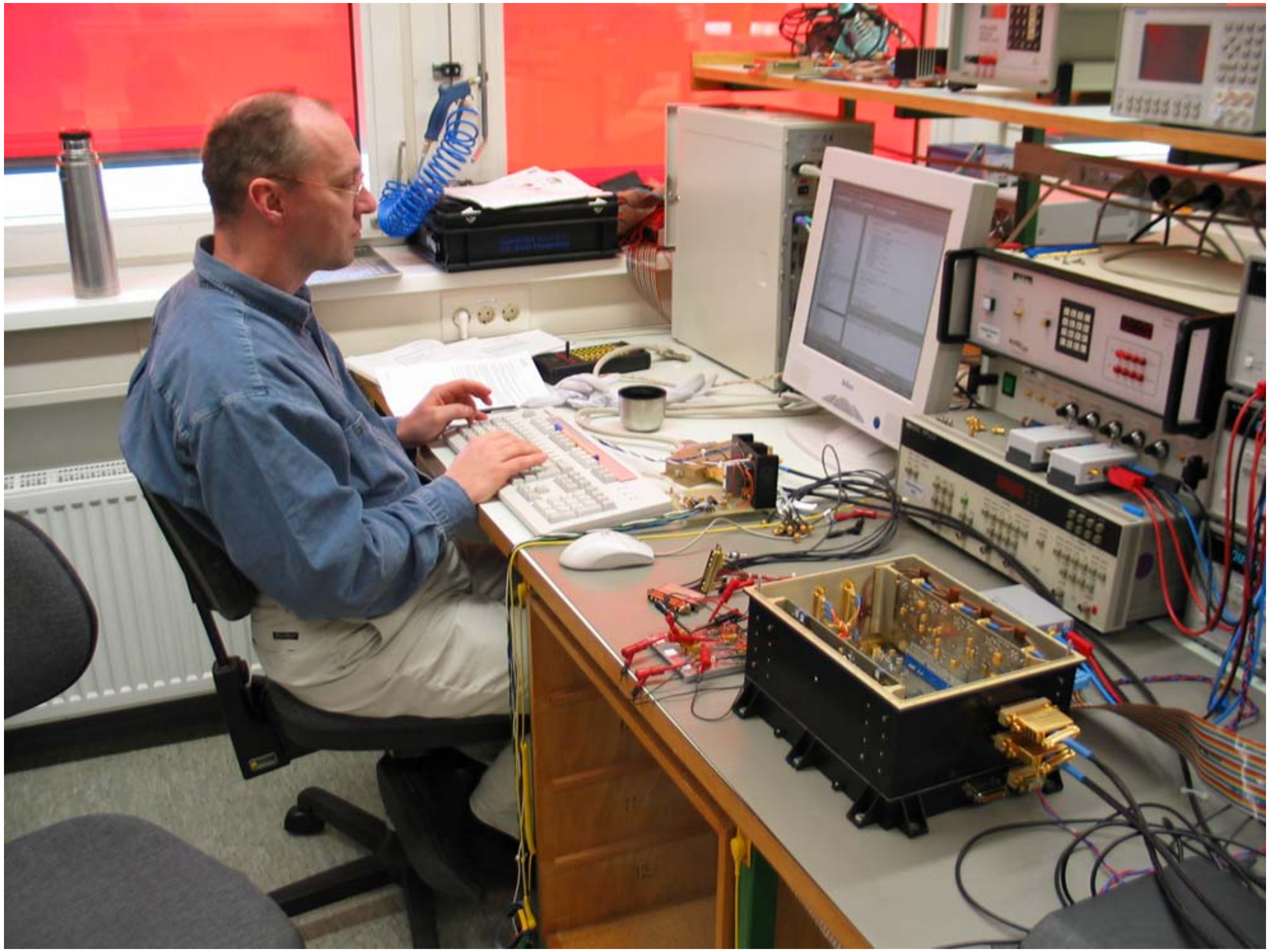


HIFI – AOS ASIC-Board



HIFI AOS CCD

Test of Electronic Unit



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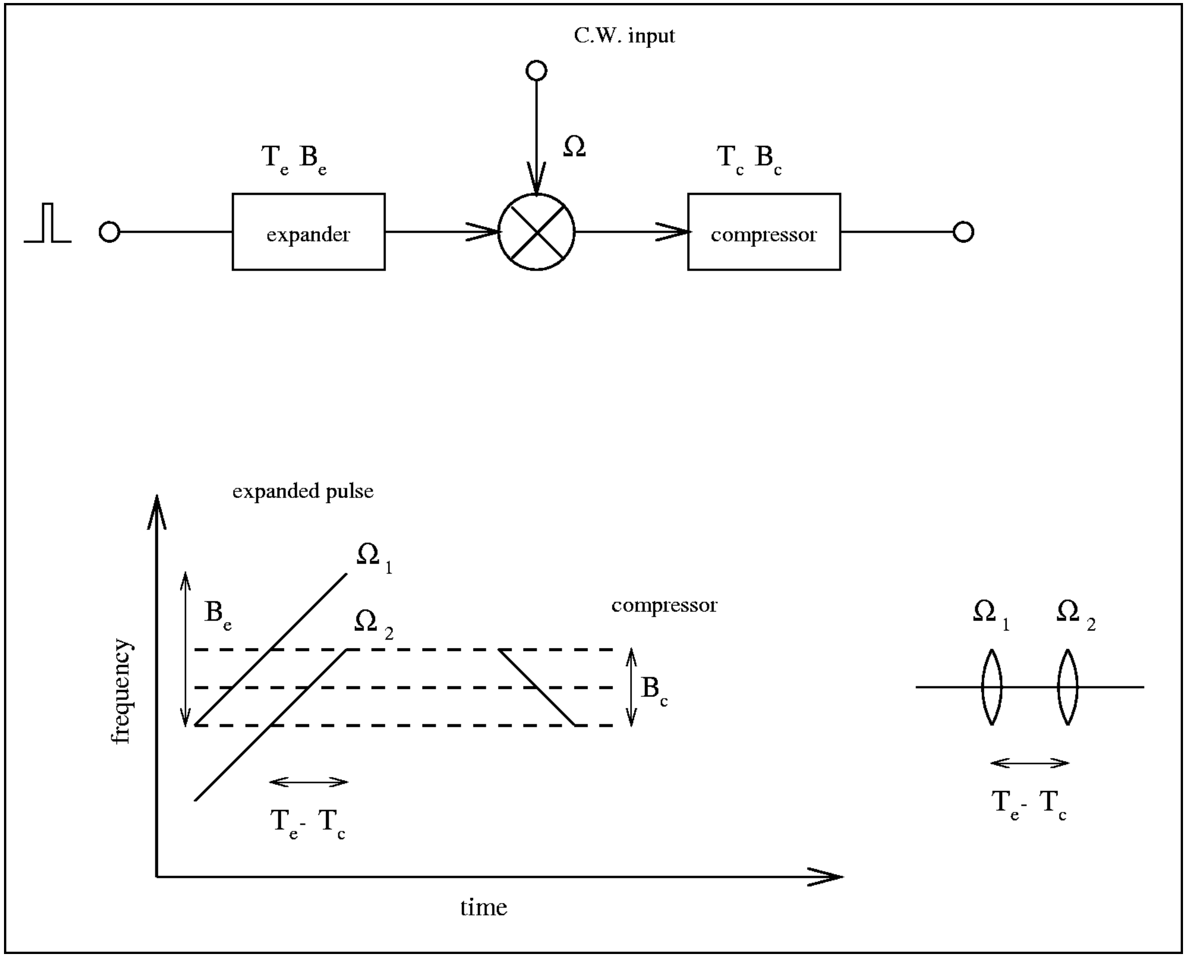
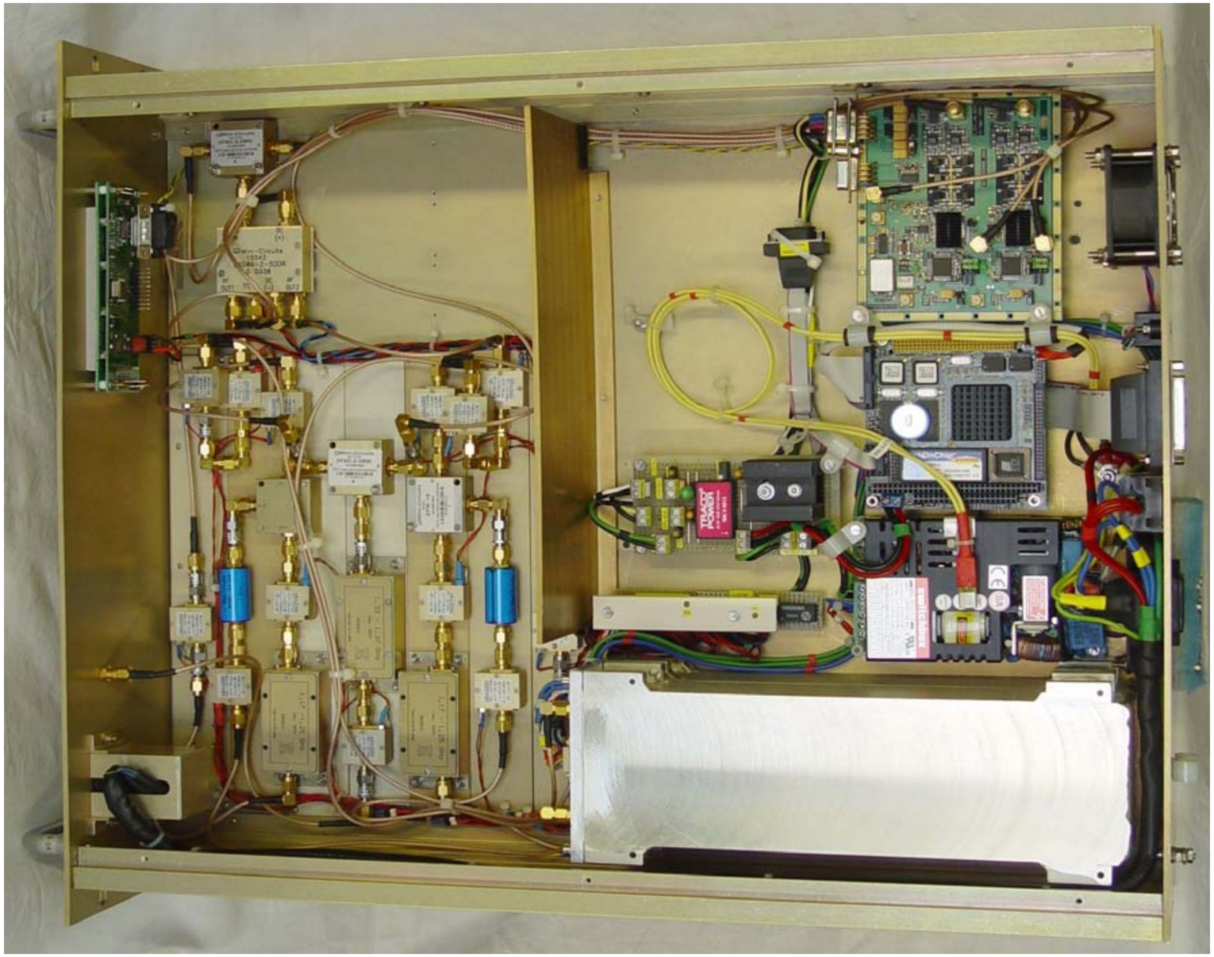
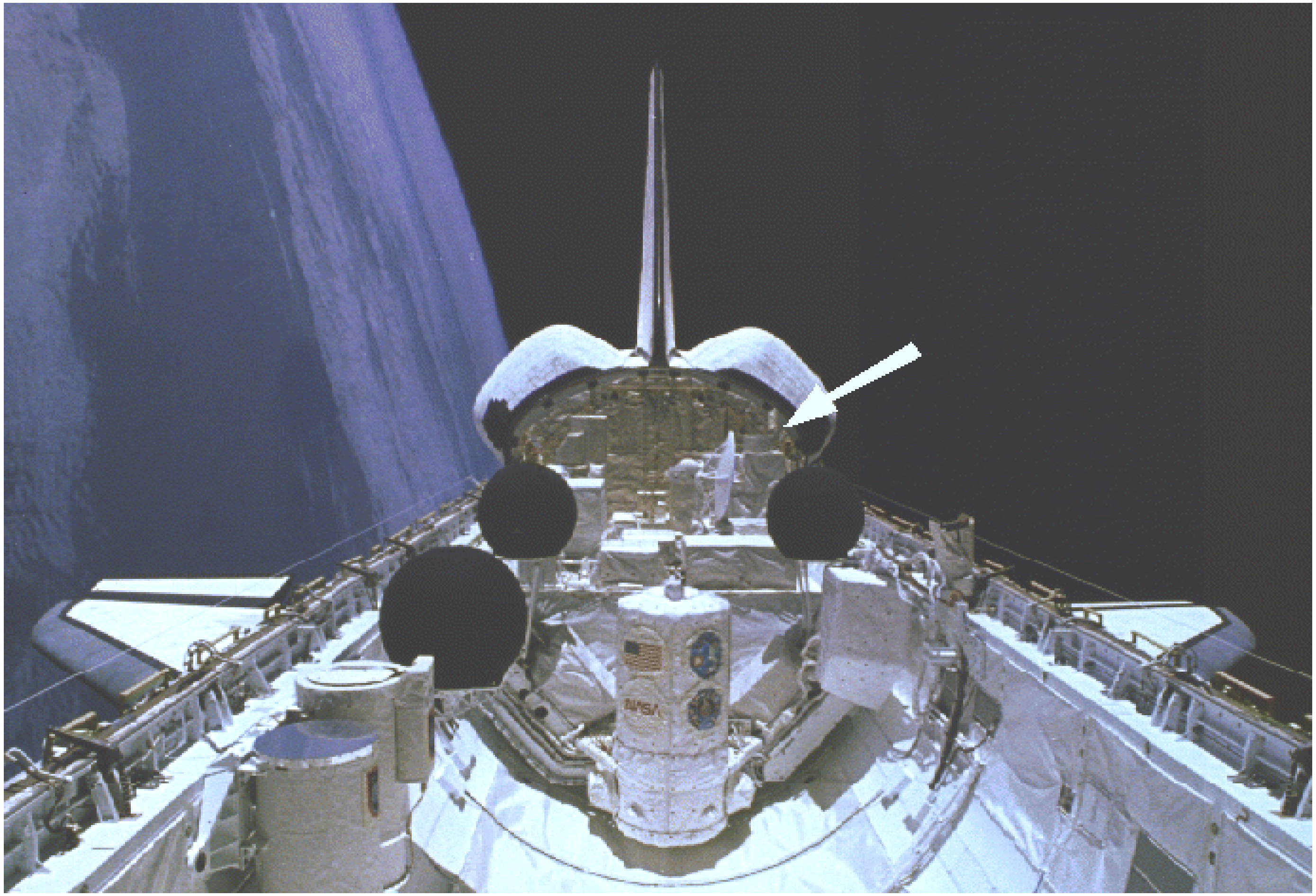
Chirp Transform Spectrometer Functional Principle



CTS for 22 GHz Instrument at ALOMAR



MAS – Limb Sounding Experiment

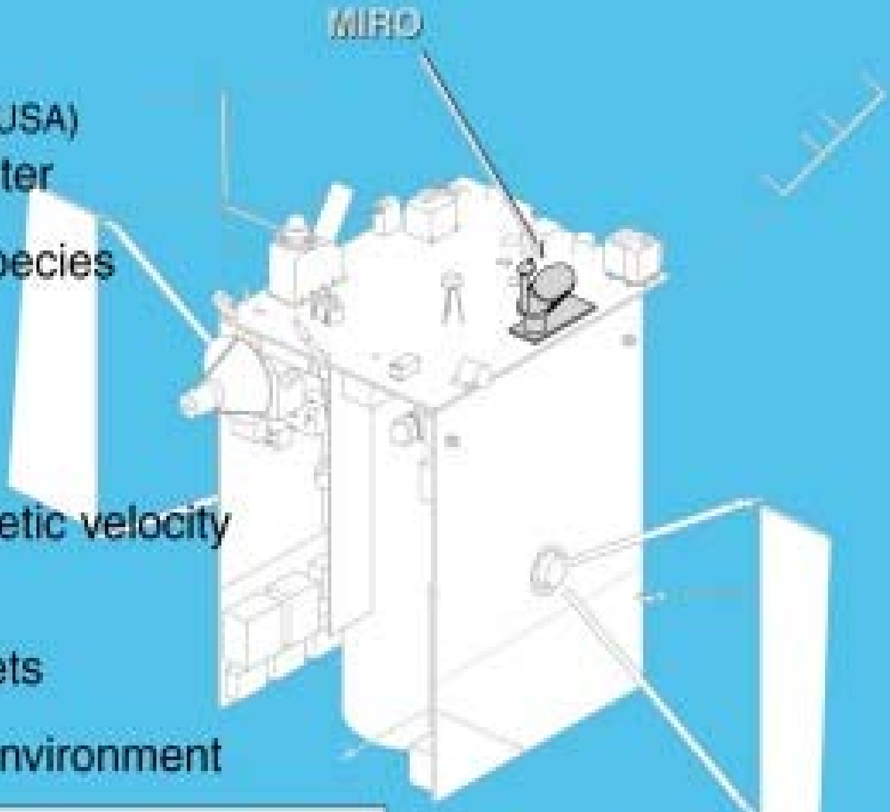


MIRO

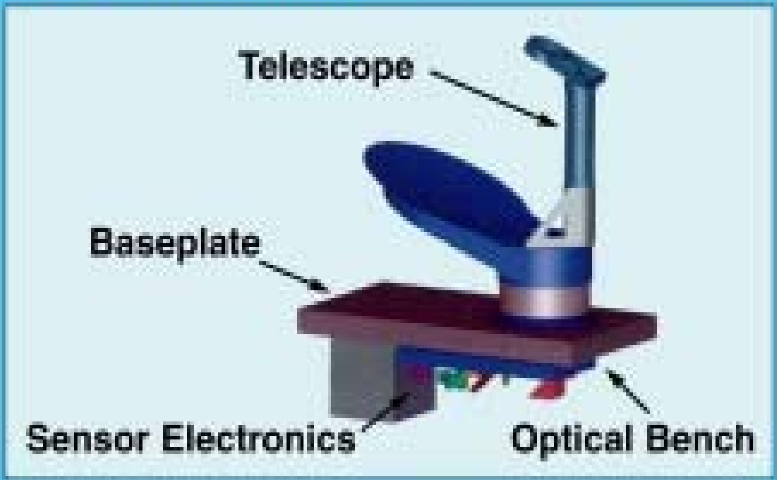
PI: S. Gulkis (JPL, California Institute of Technology, USA)

Microwave Instrument for the Rosetta Orbiter

- Absolute abundances of major volatile species
- Fundamental isotope ratios
- Surface outgassing rate
- Nucleus subsurface temperature and kinetic velocity close to nucleus surface
- Subsurface temperature of asteroid targets
- Search for low levels of gas in asteroid environment



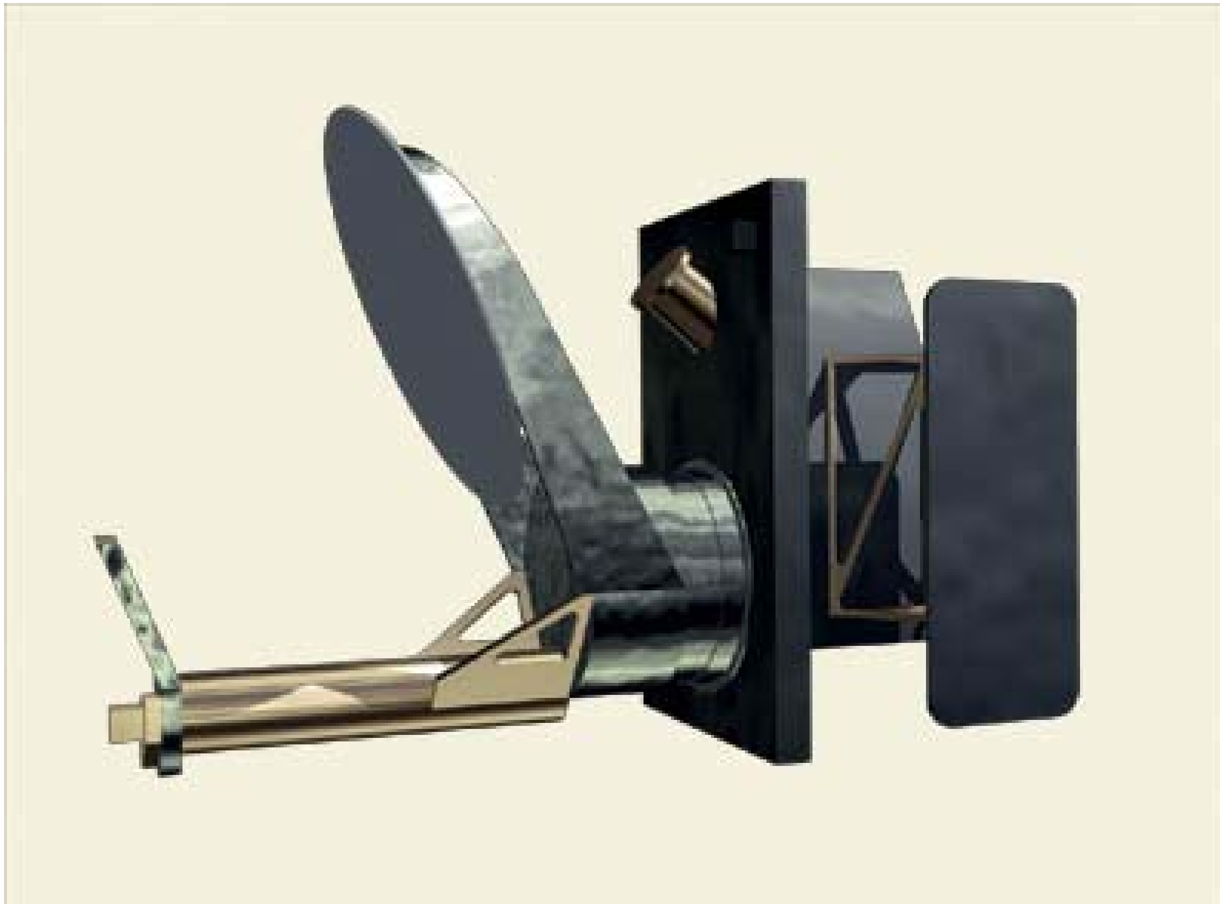
Co-Investigators
USA
France
Germany



esa

Rosetta

MIRO



Launched 03/04

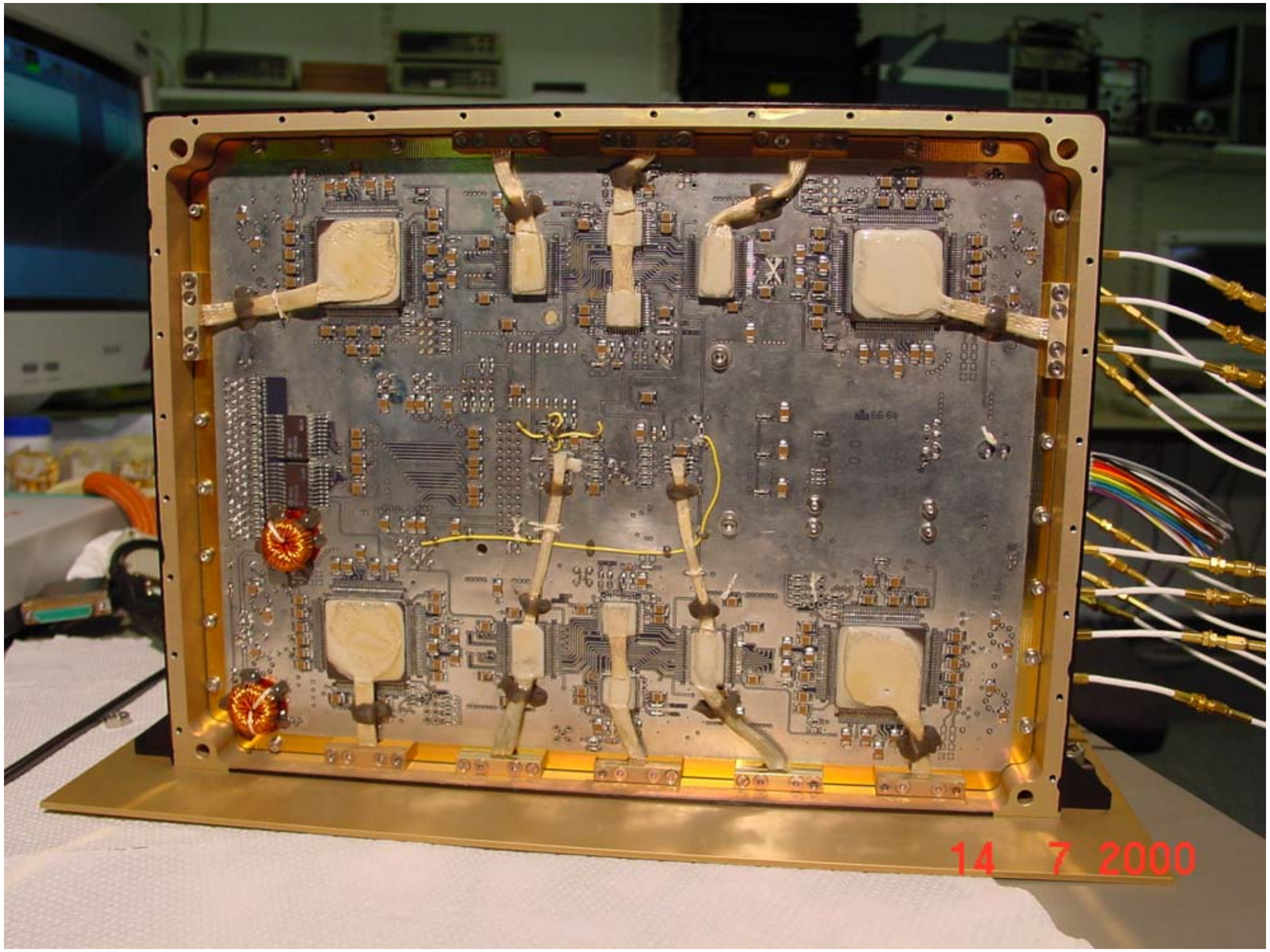
First Spectra: 05/04

Earth flyby: 04-Mar-05: mesospheric water vap.

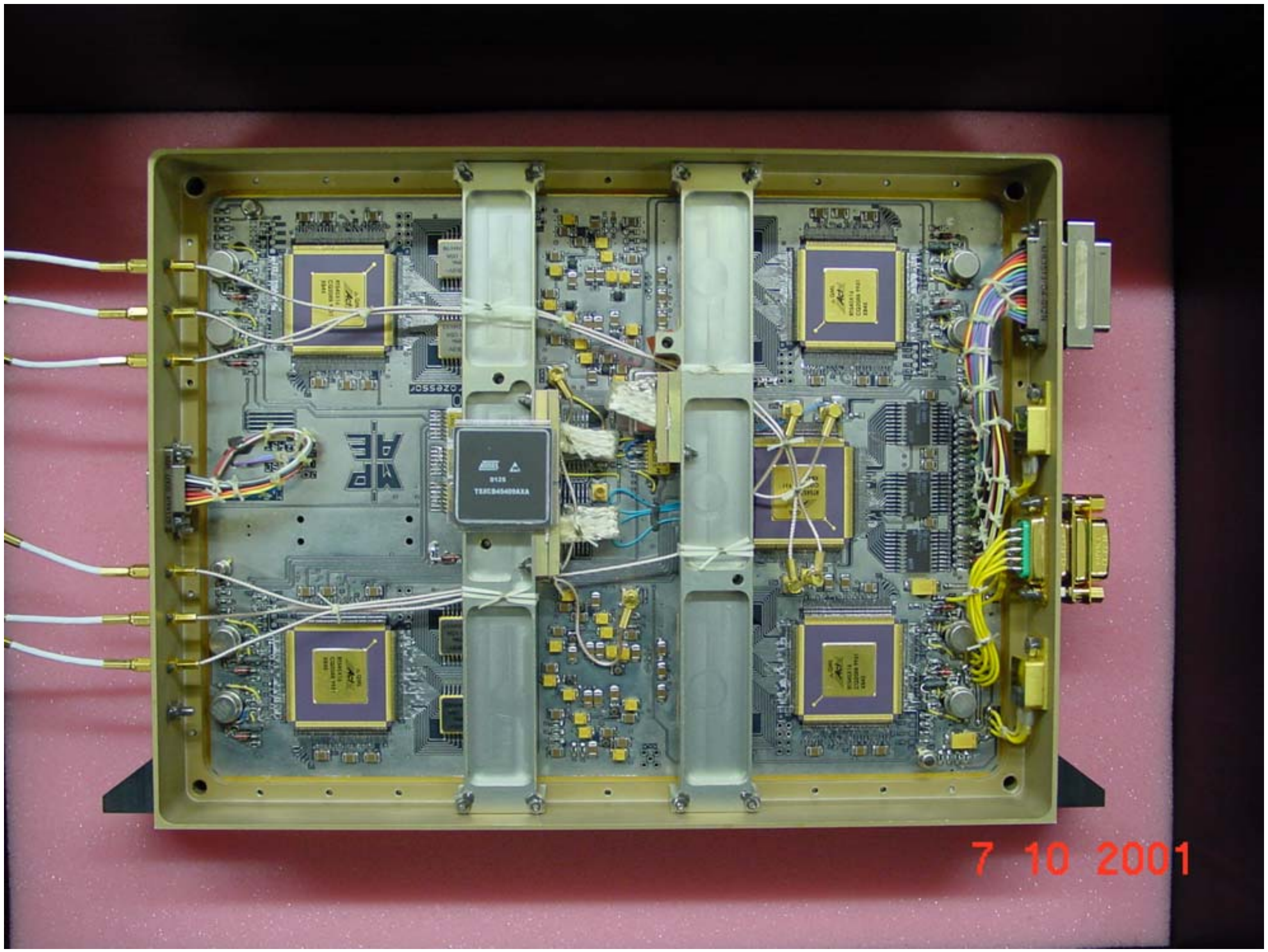
Mars flyby: Feb 07: wv- and wv-isotopes profiles

Other molecules: ammonia, methane, carbon monoxide (comets)

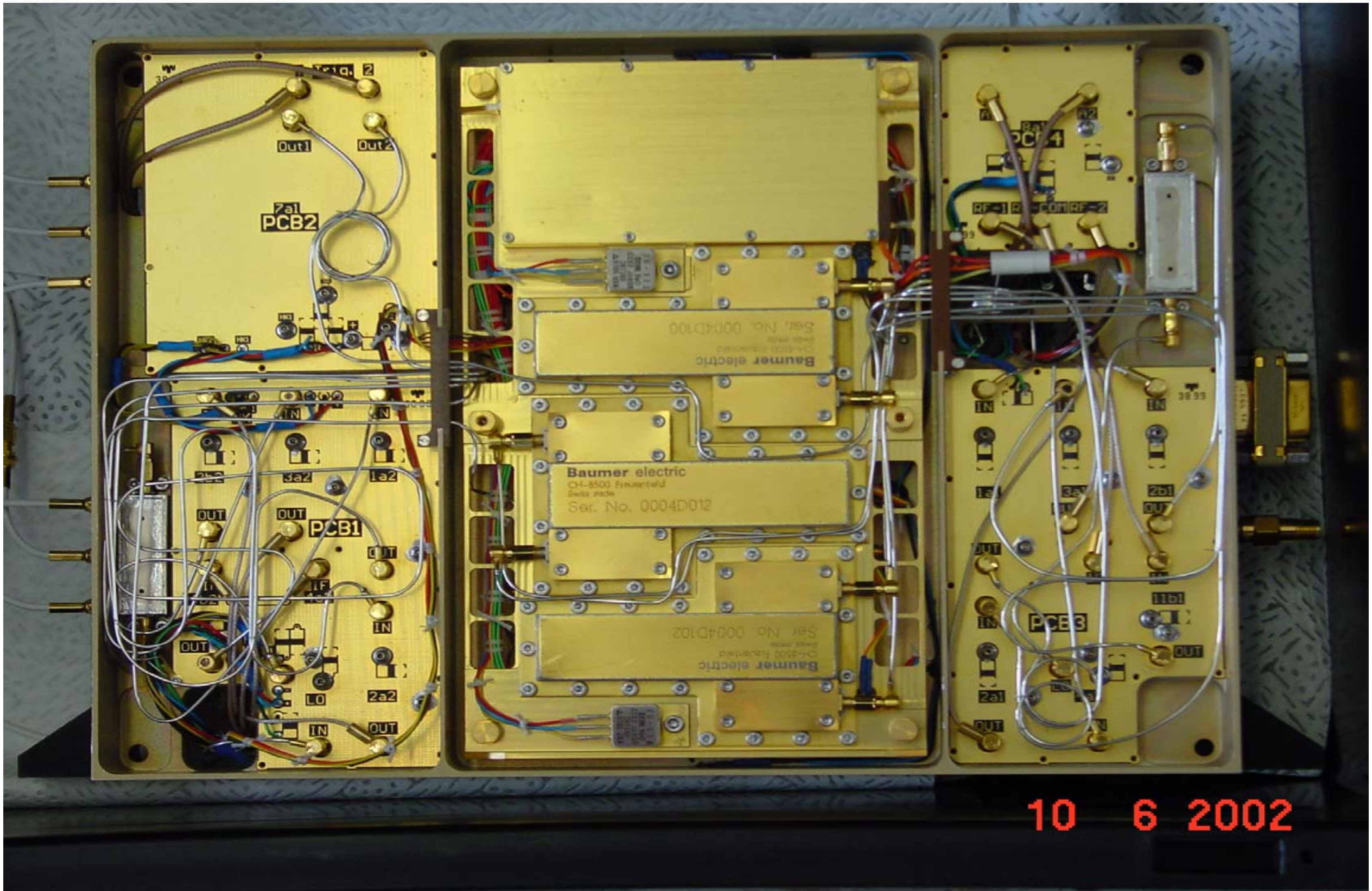
MIRO-CTS Digital Tray (back)



MIRO digital tray (front) + CMOS-ASIC



MIRO analog tray including DDLs

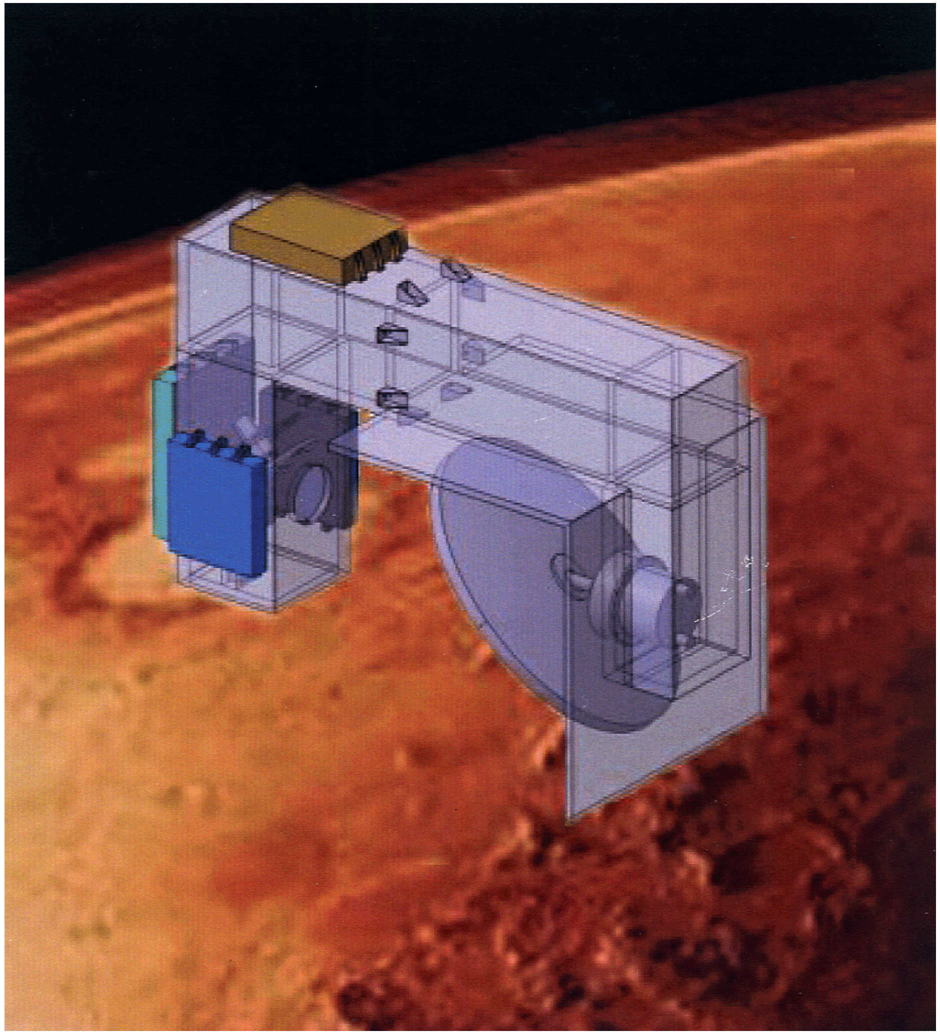


MIRO (Rosetta) Launch

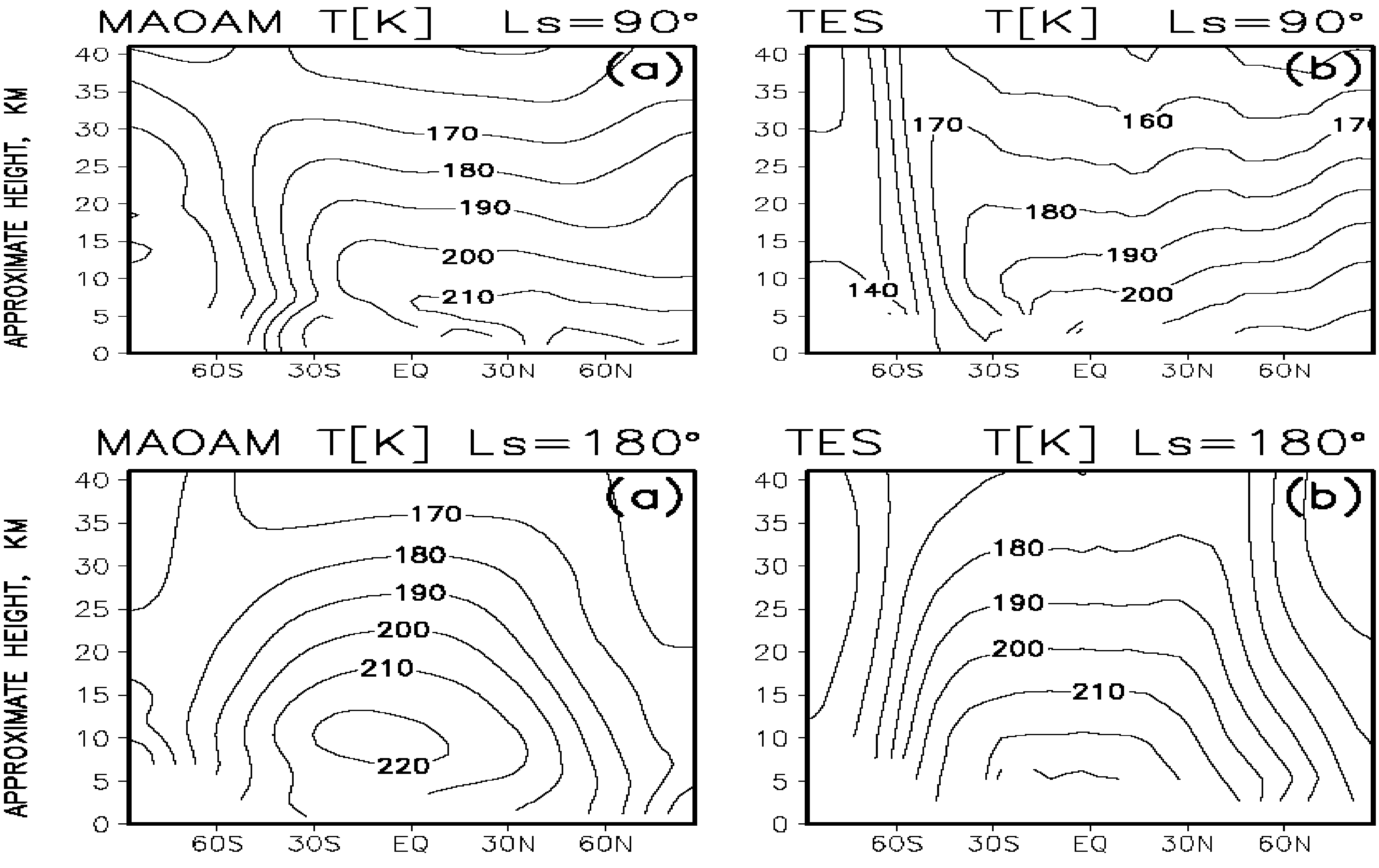
CTS-Developments at MPAE: Past Achievements and Future Prospectives

PARAMETER	1983	1984	1985	1987	1991	1992	1996	2003	2003	2006	UNIT
Input Center Frequency	180	300	1350	300	300	1350	1350	3000	2100	15000	MHz
Input Bandwidth	25	22	40	40	40	40	178	400	200	2000	MHz
Spectral Resolution	500	150	50	50	22	50	43	100	50	500	kHz
Passband Ripple	3	6	1	1	1	1	2	2	1	2	dB
Dynamic Range	18	27	26	15	30	30	29	25	40	25	dB
Frequency Linearity	20	8	1	1	1	1	2	2	0,5	2	kHz
Absolute Allan Variance	100	1100	900	100	1000	900	300	300	600	300	S
Frequency Scale Stability	50	1	5	2	2	2	5	10	5	25	kHz
Power Consumption	420	520	530	430	50	30	< 15	5	> 10	2	W
Mass	22	20	20	25	10	10	2,3	1	> 10	0,2	kg

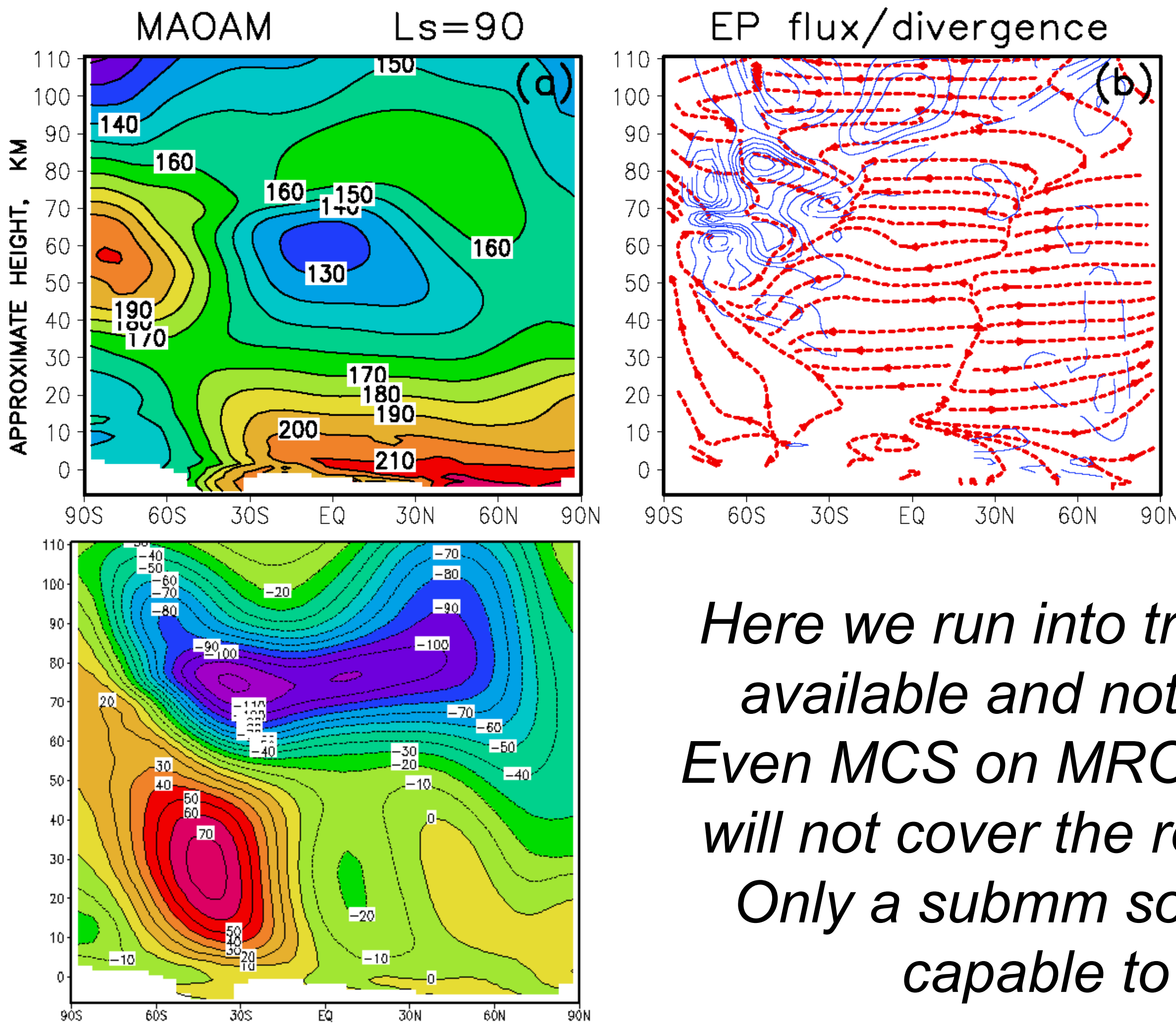
(SWI) Submm Wave Instrument



Comparison MAOAM-TES for summer solstice and fall equinox



MAOAM simulation of warming during dustless season (Ls=90)

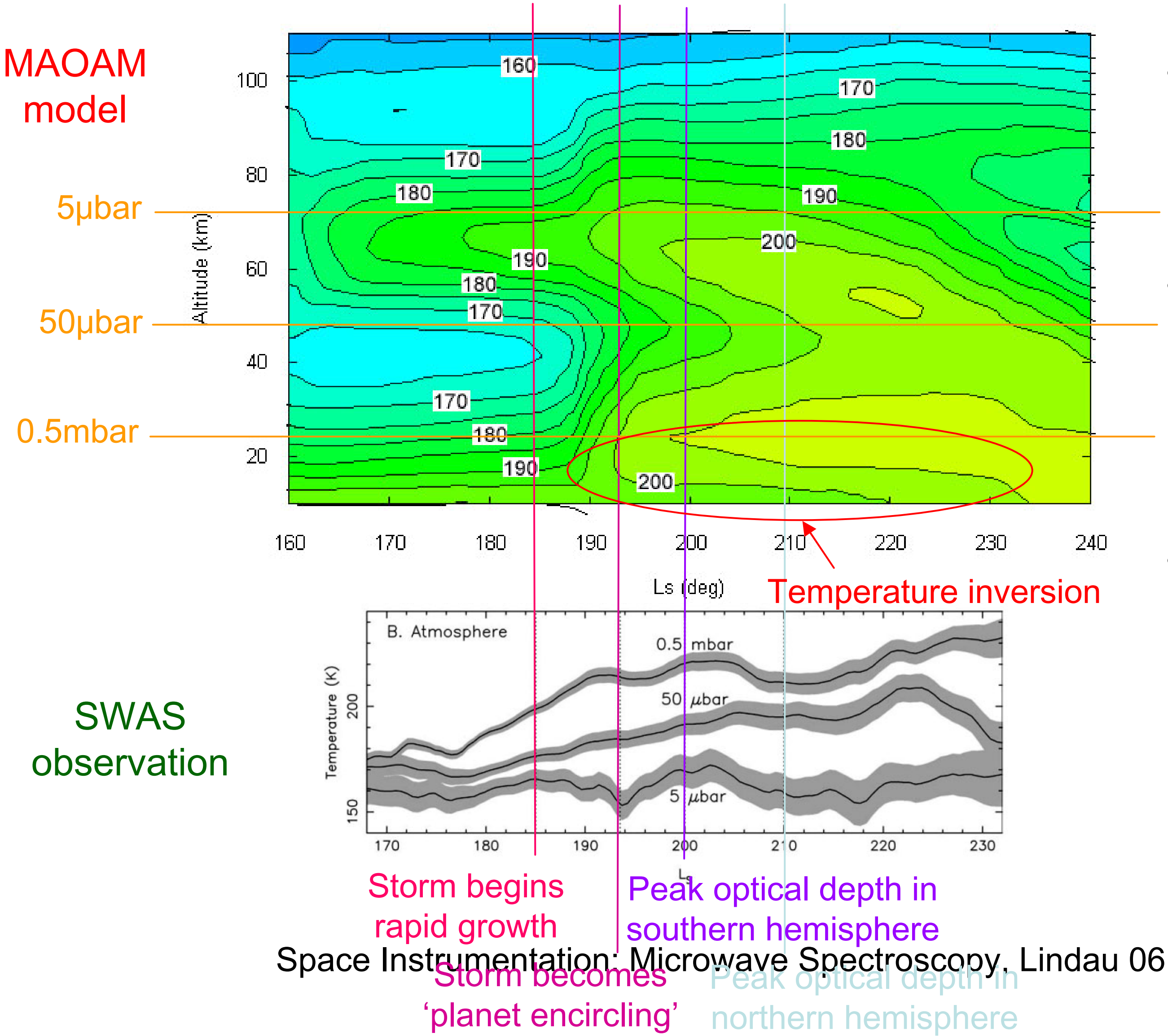


Here we run into trouble: no data available and nothing in sight. Even MCS on MRO, just launched will not cover the required range. Only a submm sounder will be capable to do so.

Validation and Application:

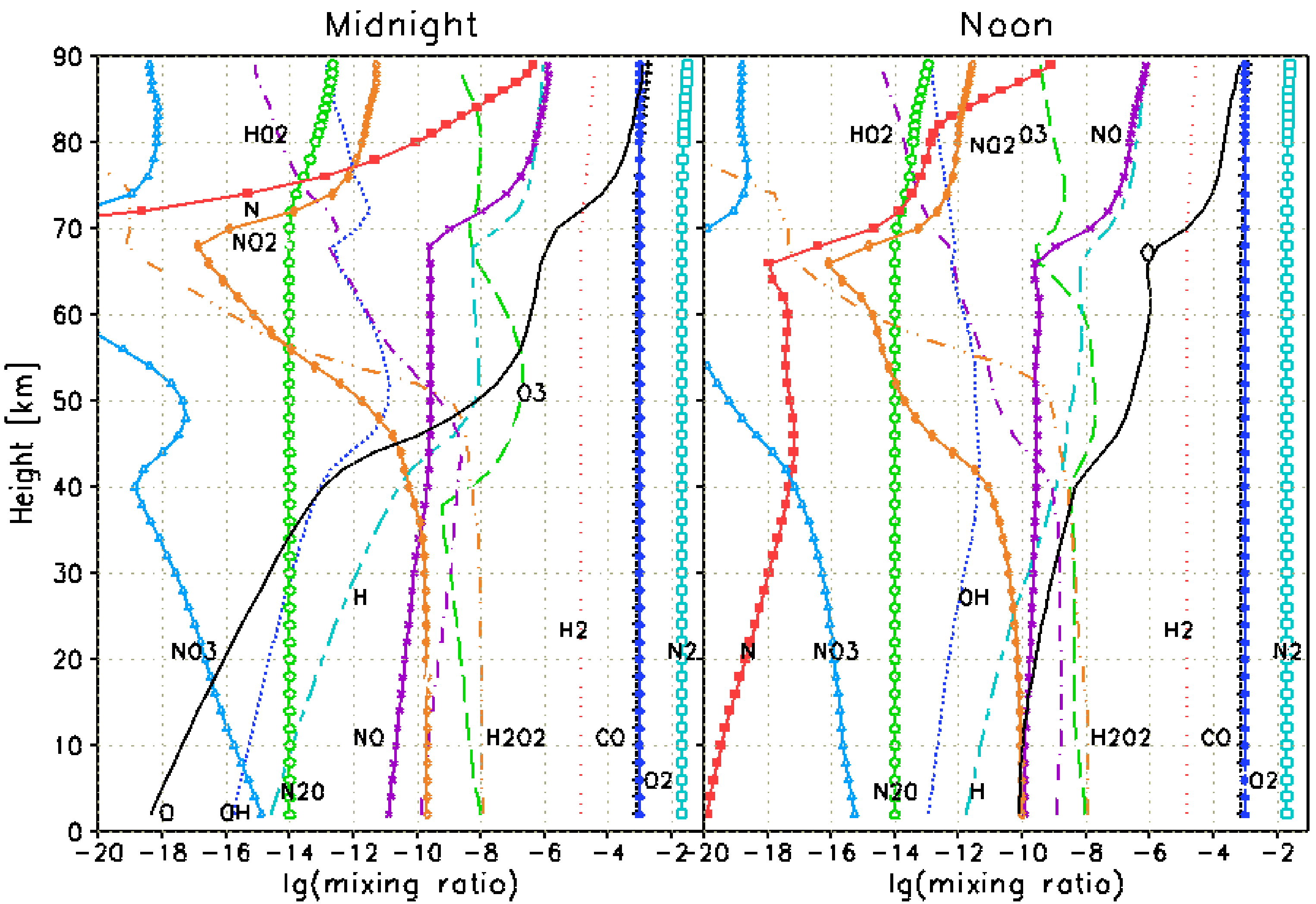
comparison with the SWAS (Sub-millimeter Wave Astronomy Satellite)

Kuroda, Medvedev, Hartogh, Adv.Geosc. 2006

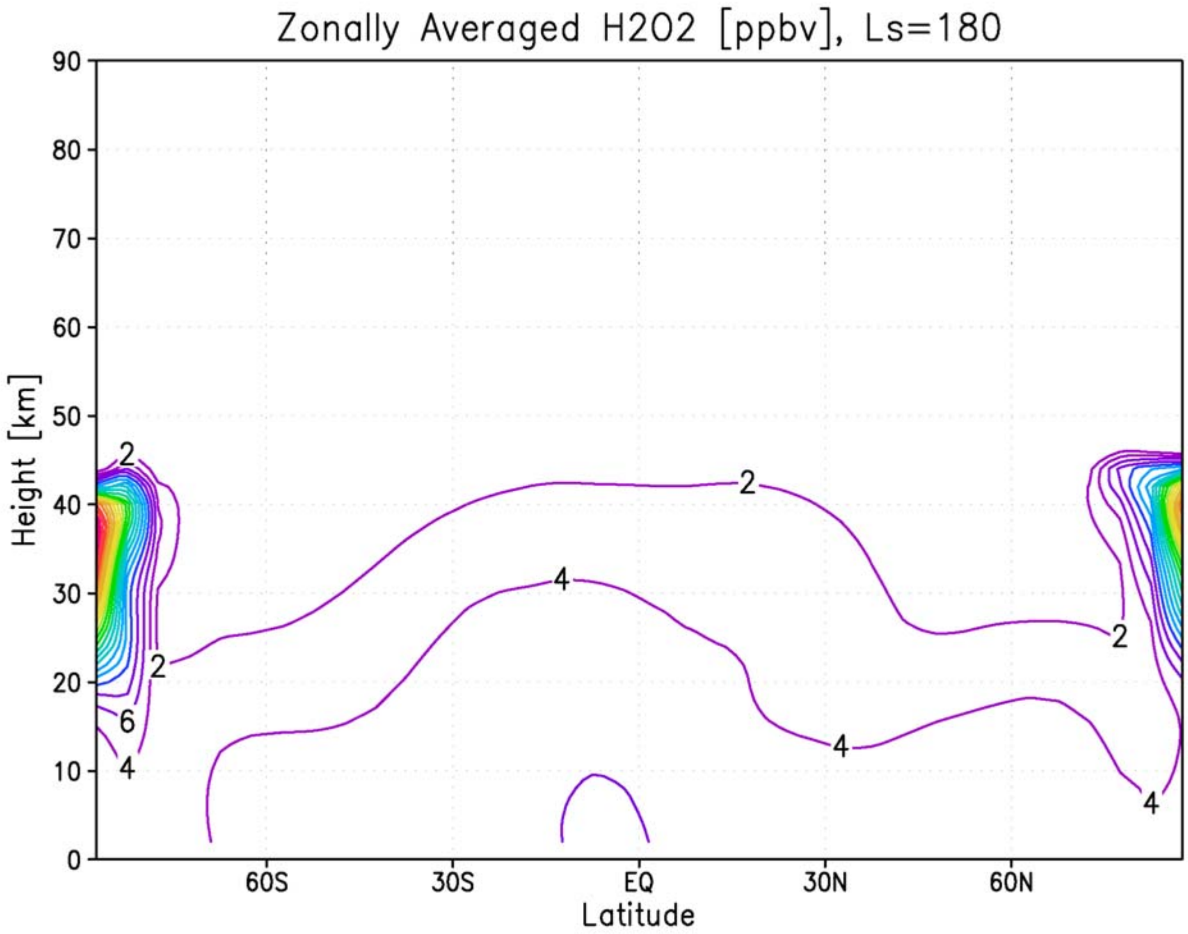


- At 50µbar, the temperature profile is consistent with SWAS observation.
- At 0.5mbar, 10~20K lower than observation during global dust storm.
- At 5µbar, the temperature doesn't change so much between before and after global dust storm, as well as observation, though ~20K higher in all times.

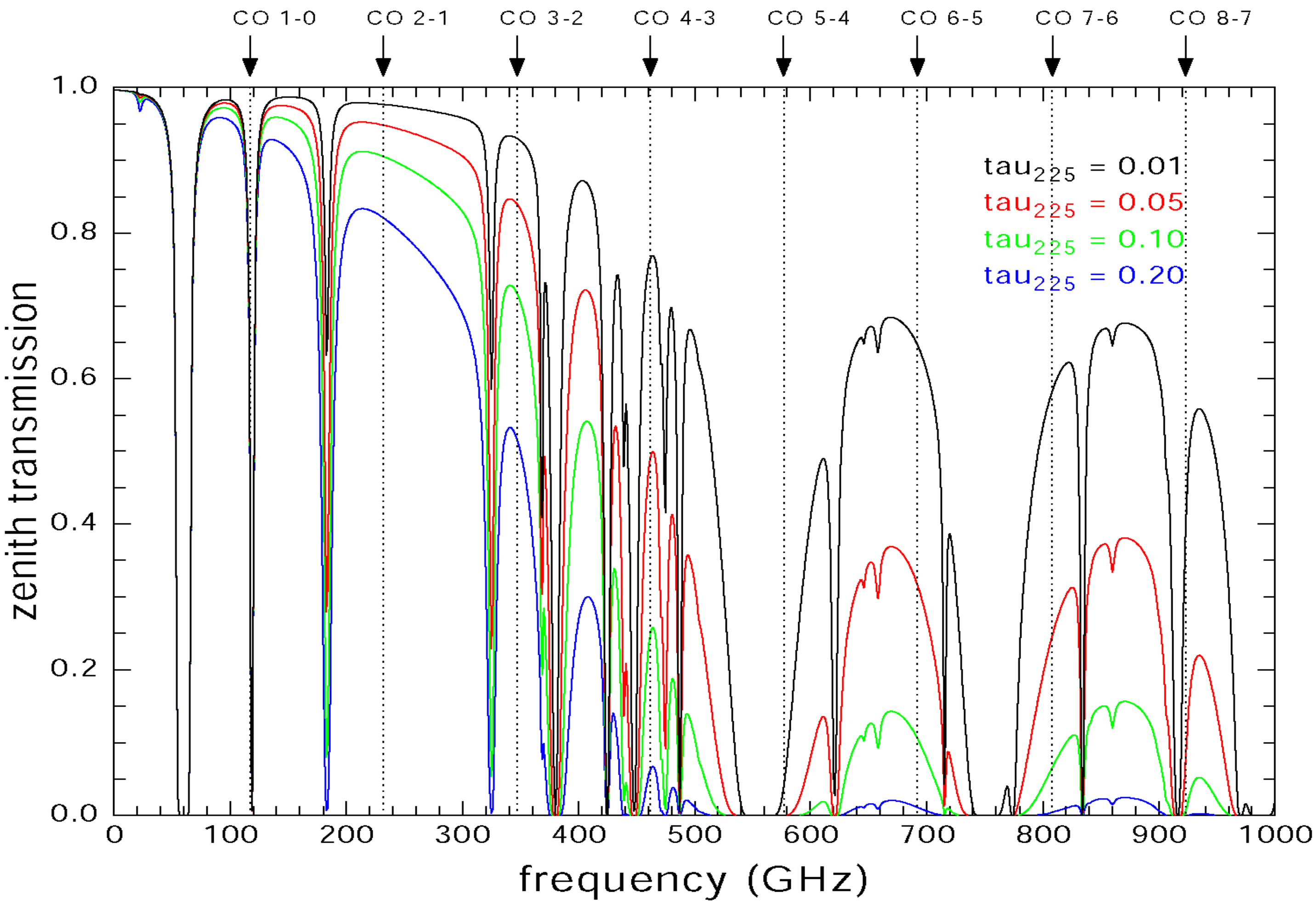
Zonally averaged mixing ratios for midnight and noon



Fall equinox H_2O_2 (zonally averaged)



Transmission & CO-transitions



Heinrich Hertz Telescope

Elevation: 3178 m,
Latitude: 32d 42m North,
Longitude: 109d 53m West

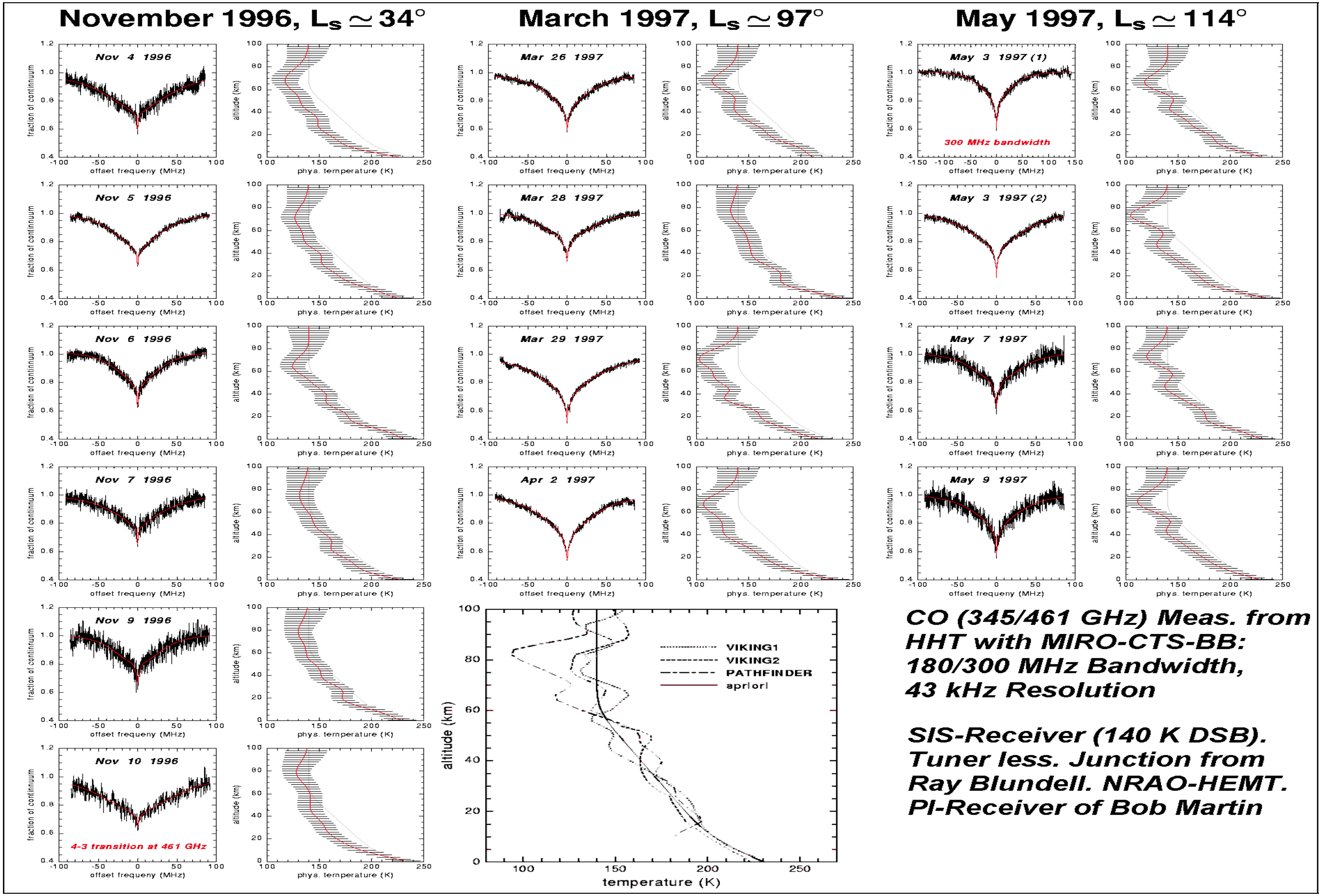
Wavelength Range:
0.3 - 2.0 mm

Main Reflector: paraboloid, D=10 m, F/D=0.35

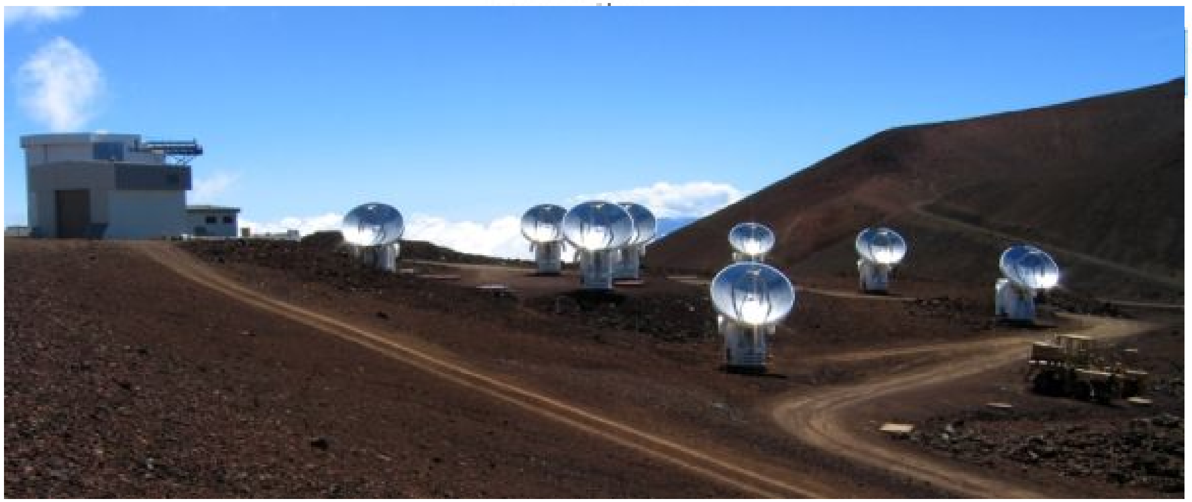
Subreflector: hyperboloid, d=0.69, Focus: Nasmyth or bent Cassegrain foci

Mount weight: 41.5 tons.

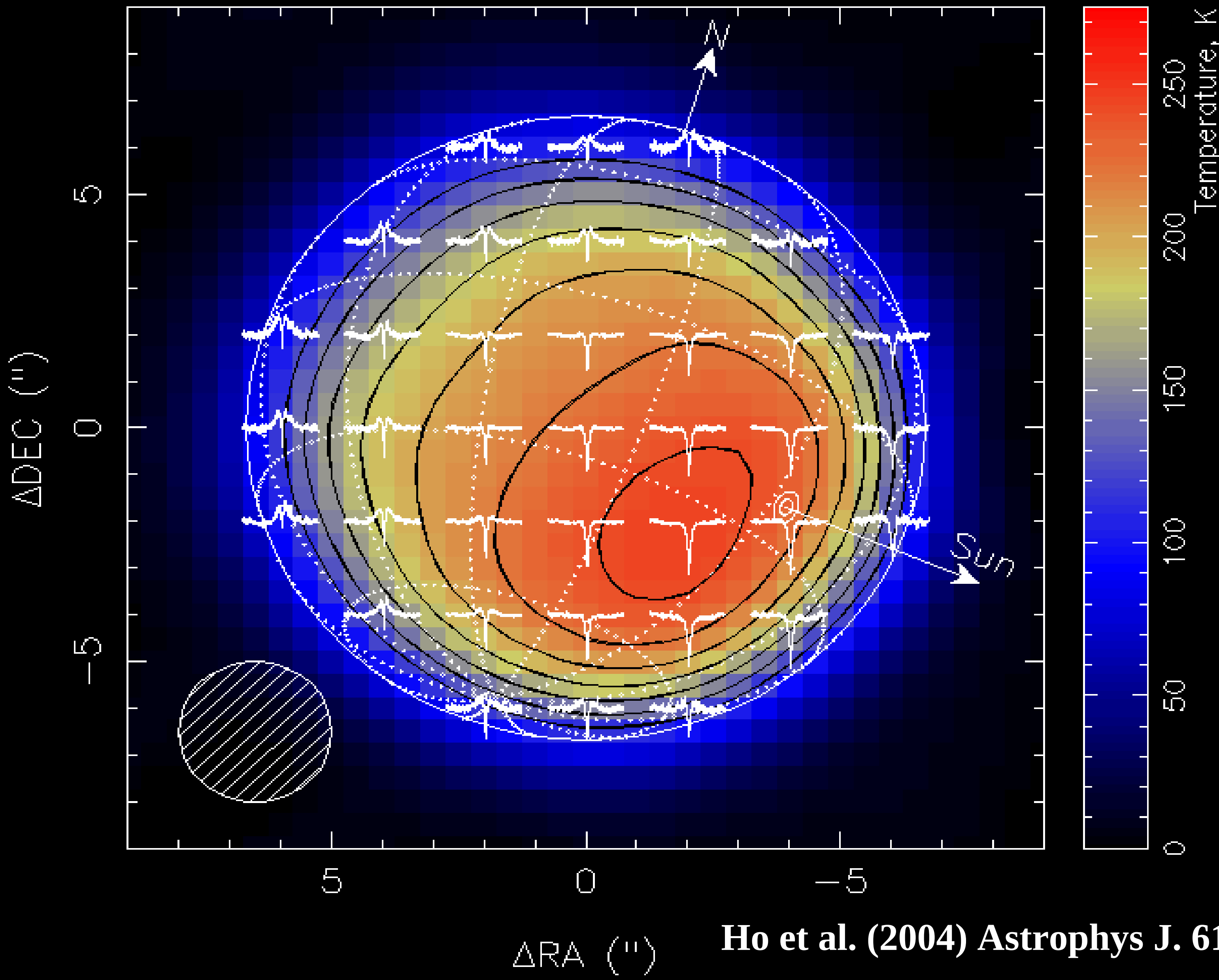
Mars Microwave Temperature Profiles (HHT)



Ground-based sub arc-sec observations (e.g. ALMA or SMA)

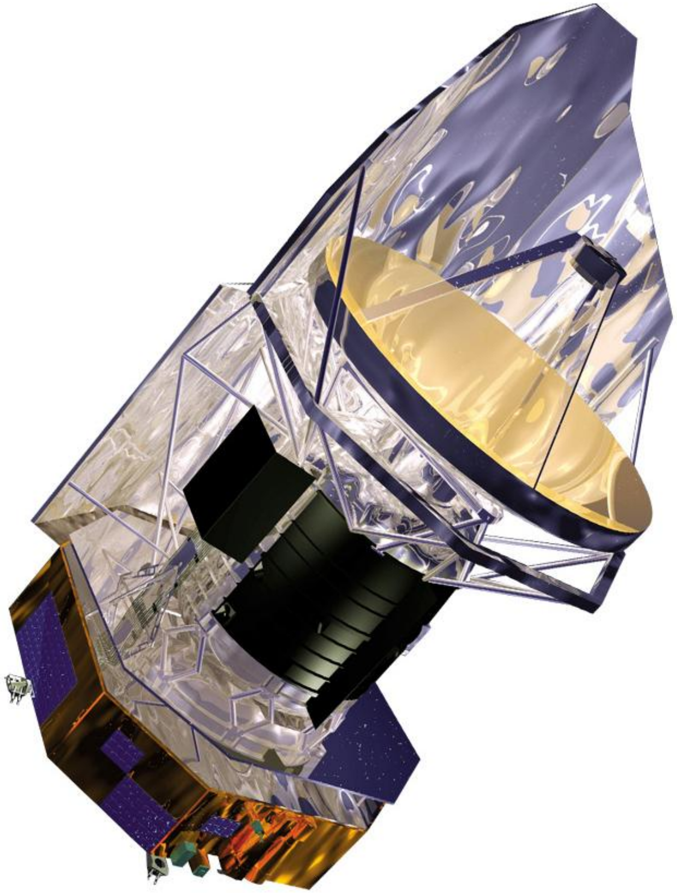


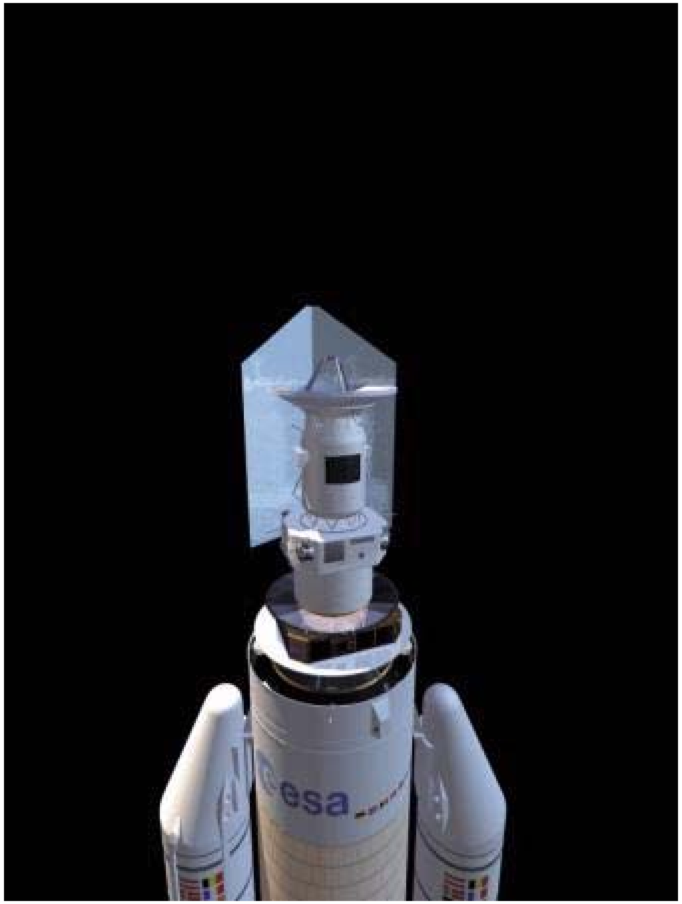
First SMA Image with all 8 Antennas: Mars can be used to map both T(p) and T_{surf}



Ho et al. (2004) Astrophys J. 616, 61.

Herschel Space Observatory

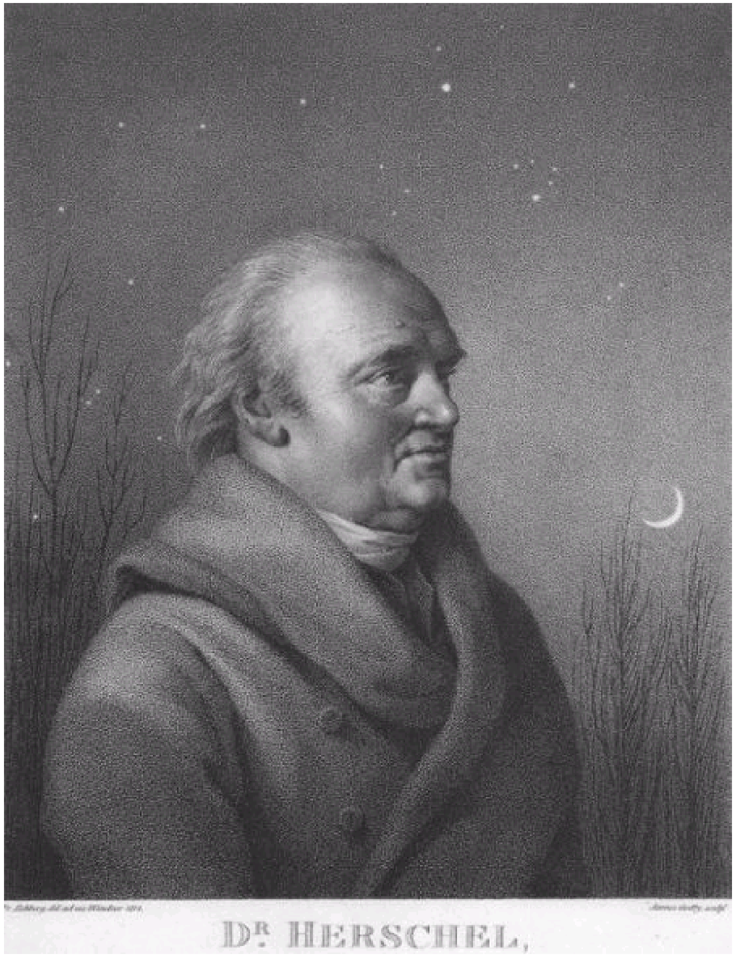




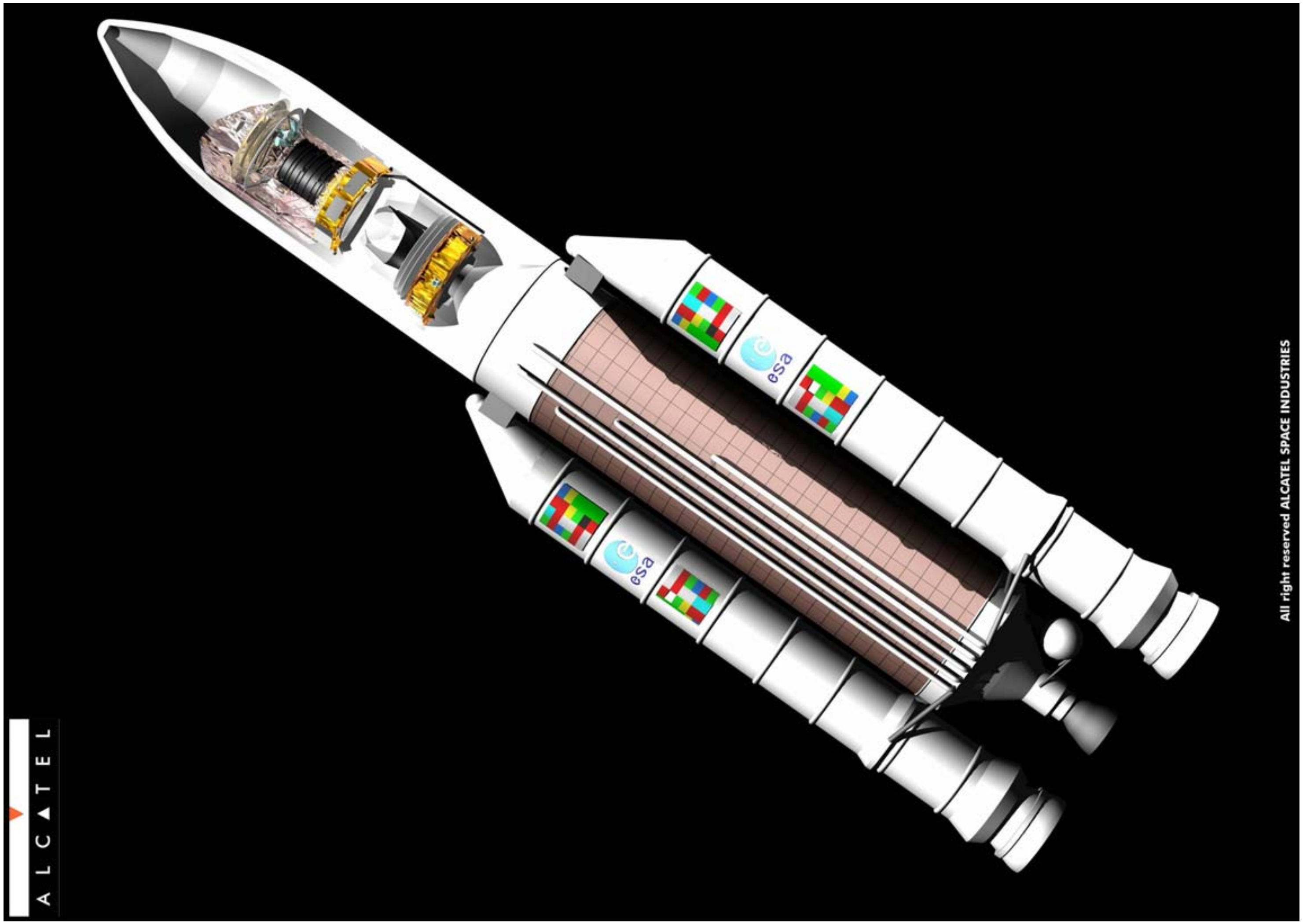
Why Herschel

- Friedrich Wilhelm Herschel (1738 – 1822) was the first Infrared Astronomer. He discovered the IR – radiation in 1800

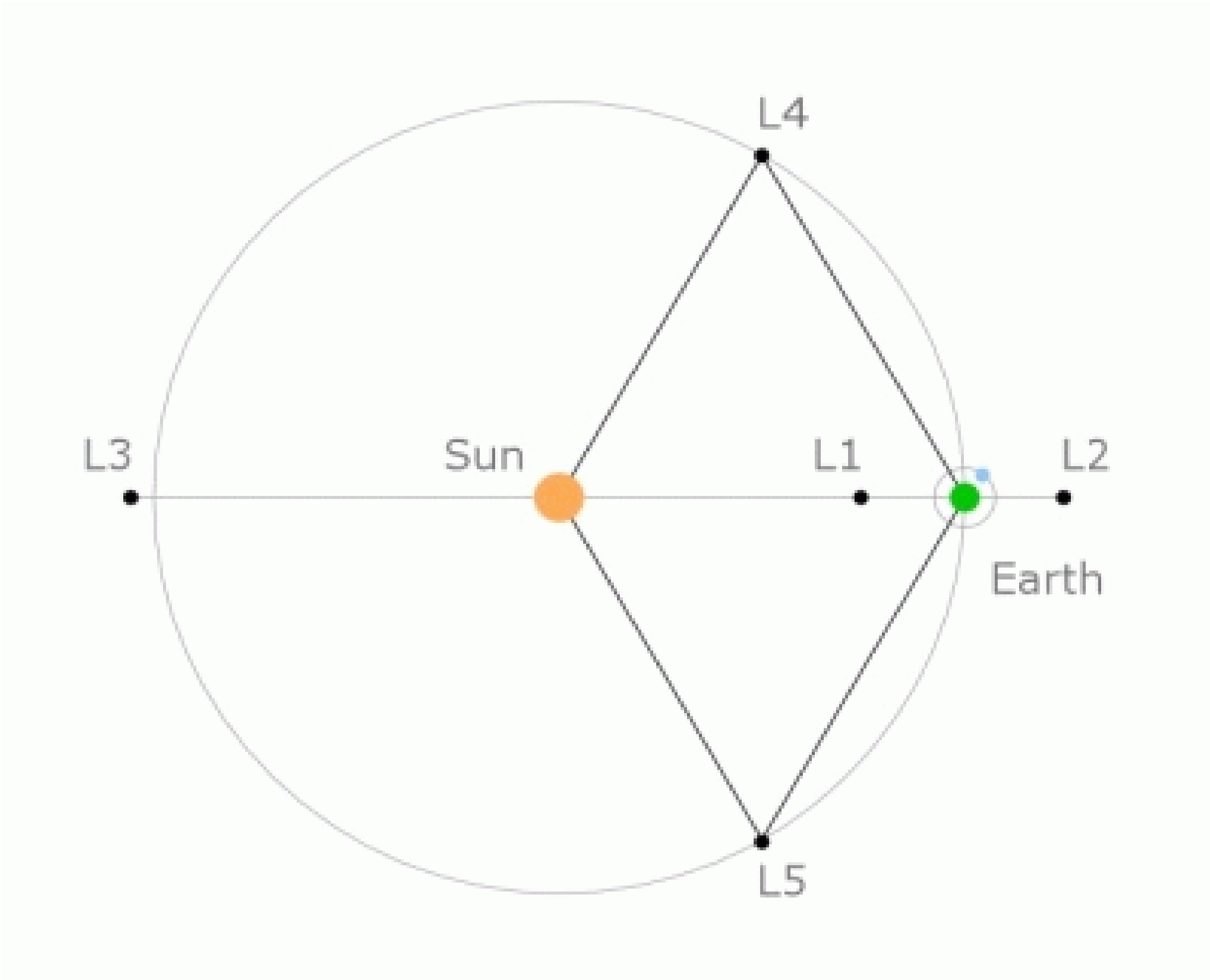
- Herschel also discovered the planet Uranus



Ariane 5 Launch together with Planck

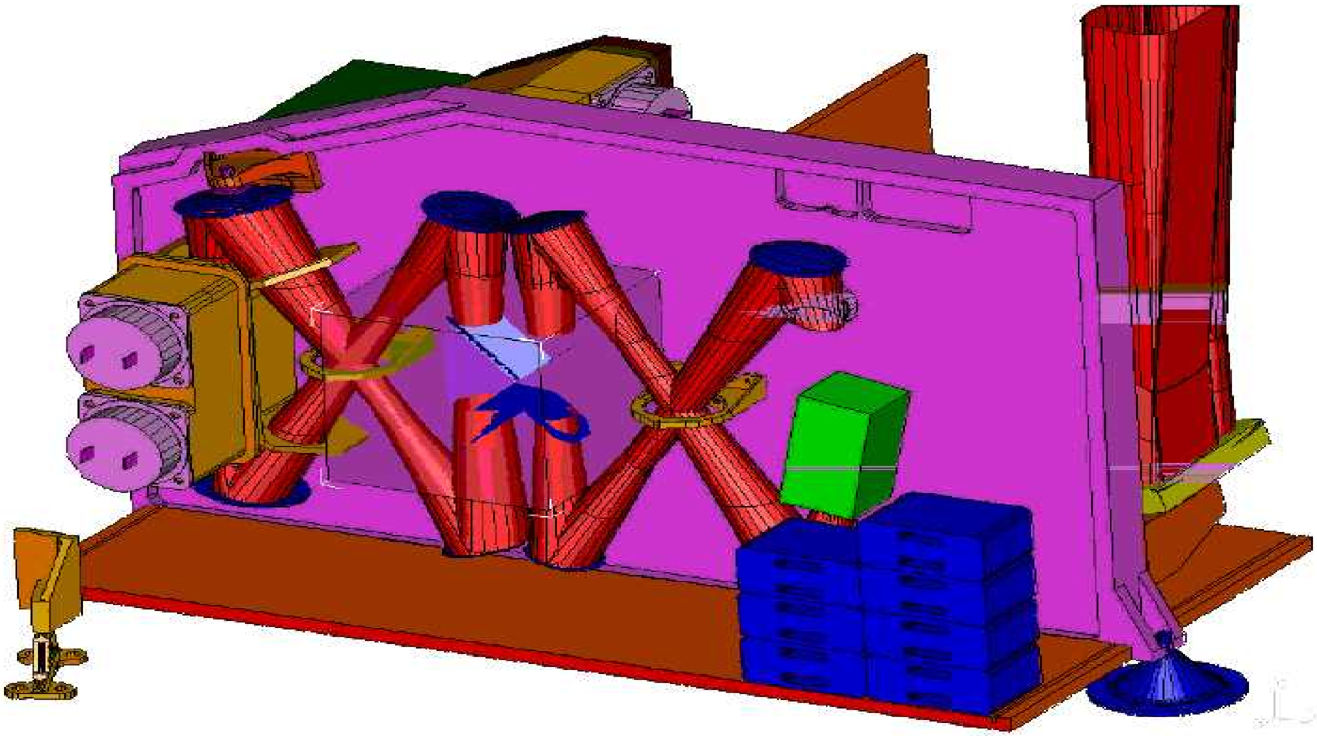


L2 - Orbit of Herschel



Instruments on Herschel

- Spectral Photometric Imaging Receiver (SPIRE)



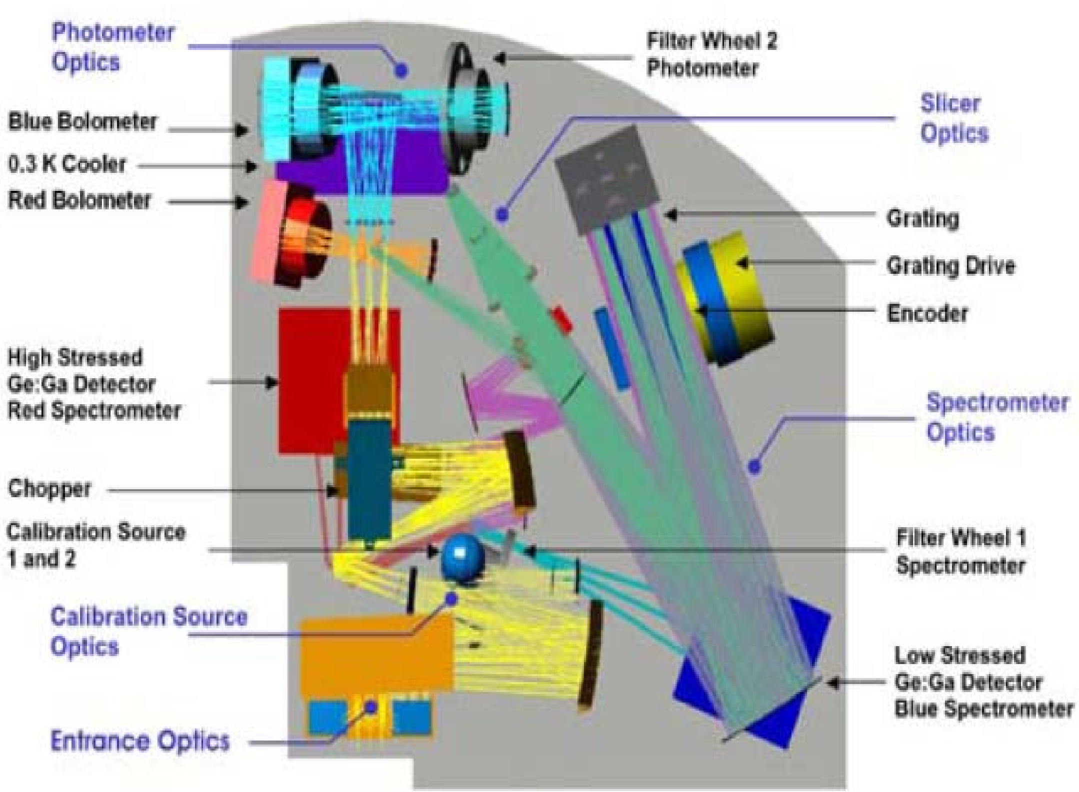
SPIRE -Features

- **3-band imaging photometer (simultaneous observation in 3 bands)**
  Wavelengths (μm): 250, 350, 500
  Beam FWHM (arcsec.): 71, 24, 35
  Field of view (arcmin.): 4 x 8

- **Imaging Fourier Transform Spectrometer (FTS)**
  Wavelength Range (μm): 200-400 (req.) 200-670 (goal)
  Simultaneous imaging observation of the whole spectral band
  Field of view (arcmin): 2.0 (req.) 2.6 (goal)
  Max. spectral resolution (cm-1): 0.4 (req.) 0.04 (R~1000)
  Min. spectral resolution (cm-1): 2 (req.) 4

Instruments on Herschel

Photodetector Array Camera & Spectrometer (PACS)



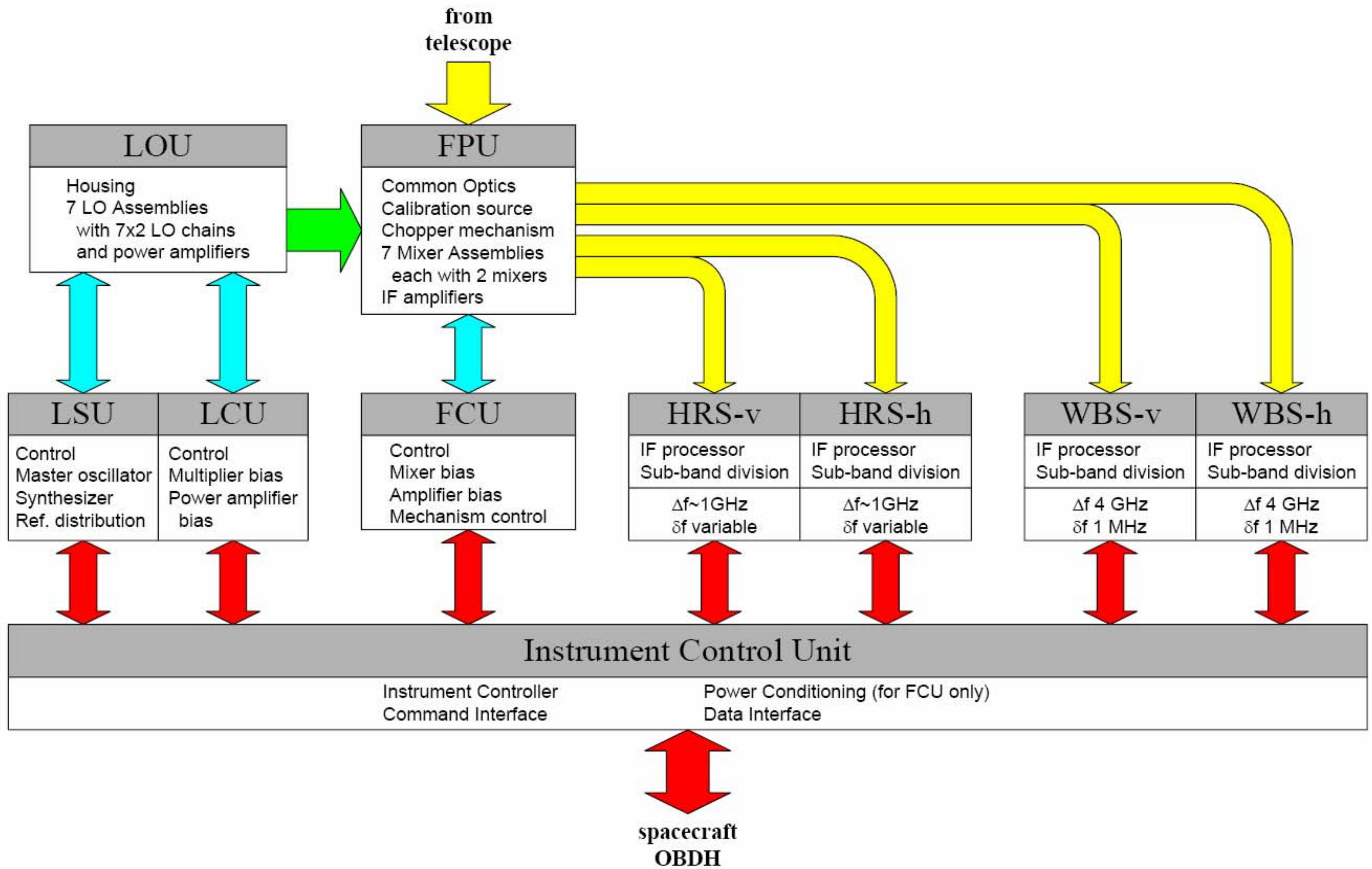
PACS Features

- **Imaging photometry**
  – two bands simultaneously (60-90 or 90-130 μm and 130-210 μm) with dichroic beam splitter
  – two filled bolometer arrays (32x16 and 64x32 pixels, full beam sampling)
  – point source detection limit ~3 mJy (5σ, 1h)

- **Integral field line spectroscopy**
  – range 57 - 210 μm with 5 x 5 pixels, image slicer, and long-slit grating spectrograph (R ~ 1500)
  – two 16x25 Ge-Ga photoconductor arrays (stressed/unstressed)
  – point source detection limit 2…8 x 10^{-18} W

Instruments on Herschel

Heterodyne Instrument for the Far Infrared (HIFI)

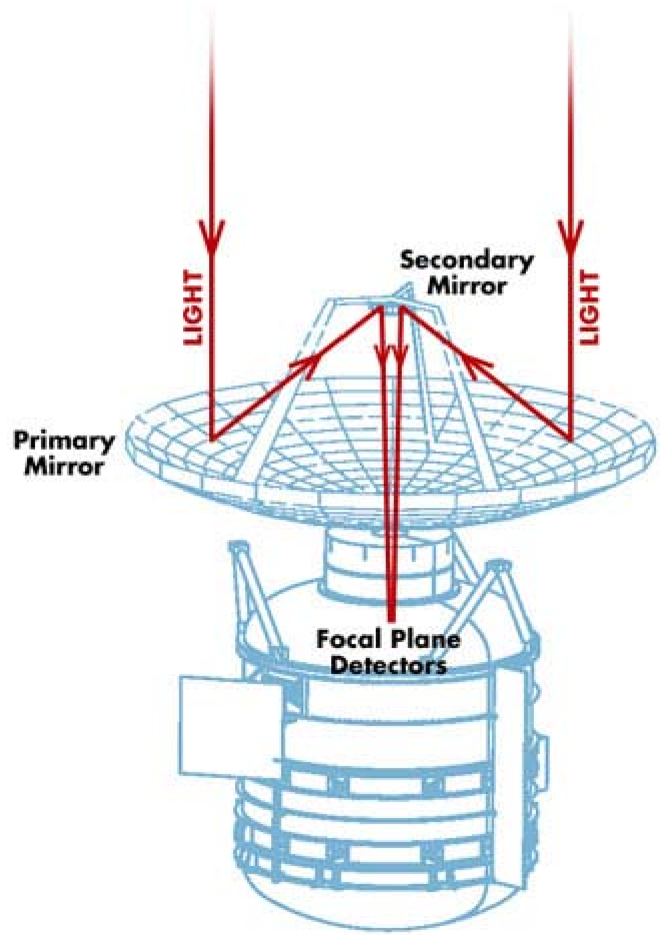


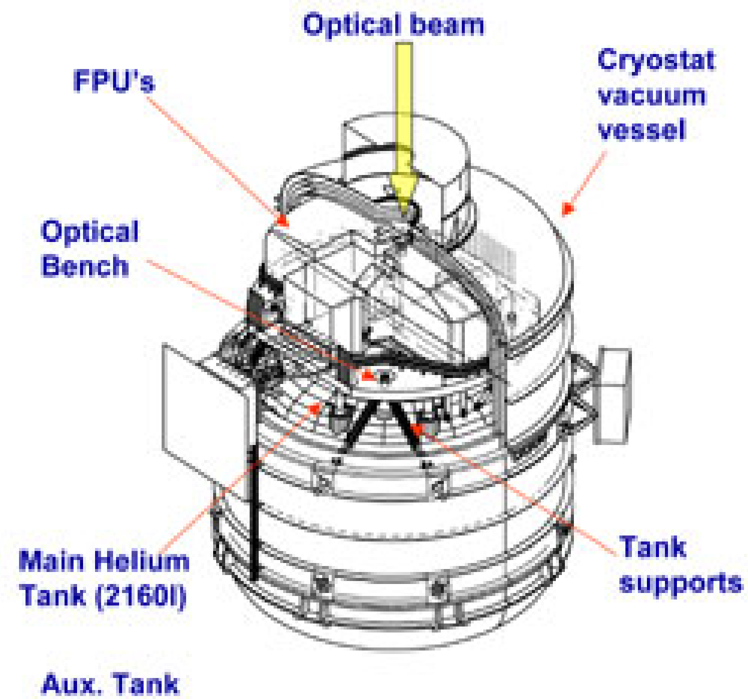
HIFI Features

- **6 – band Heterodyne Spectrometer**
- **Extremely high spectral resolution**

dual polarization	
wavelengths range:	157 – 625 µm
Spectral resolution:	***10^7***
Beam size:	12 – 40 arc sec
Sensitivity:	3 hv/k
IF - bandwidth:	4 GHz

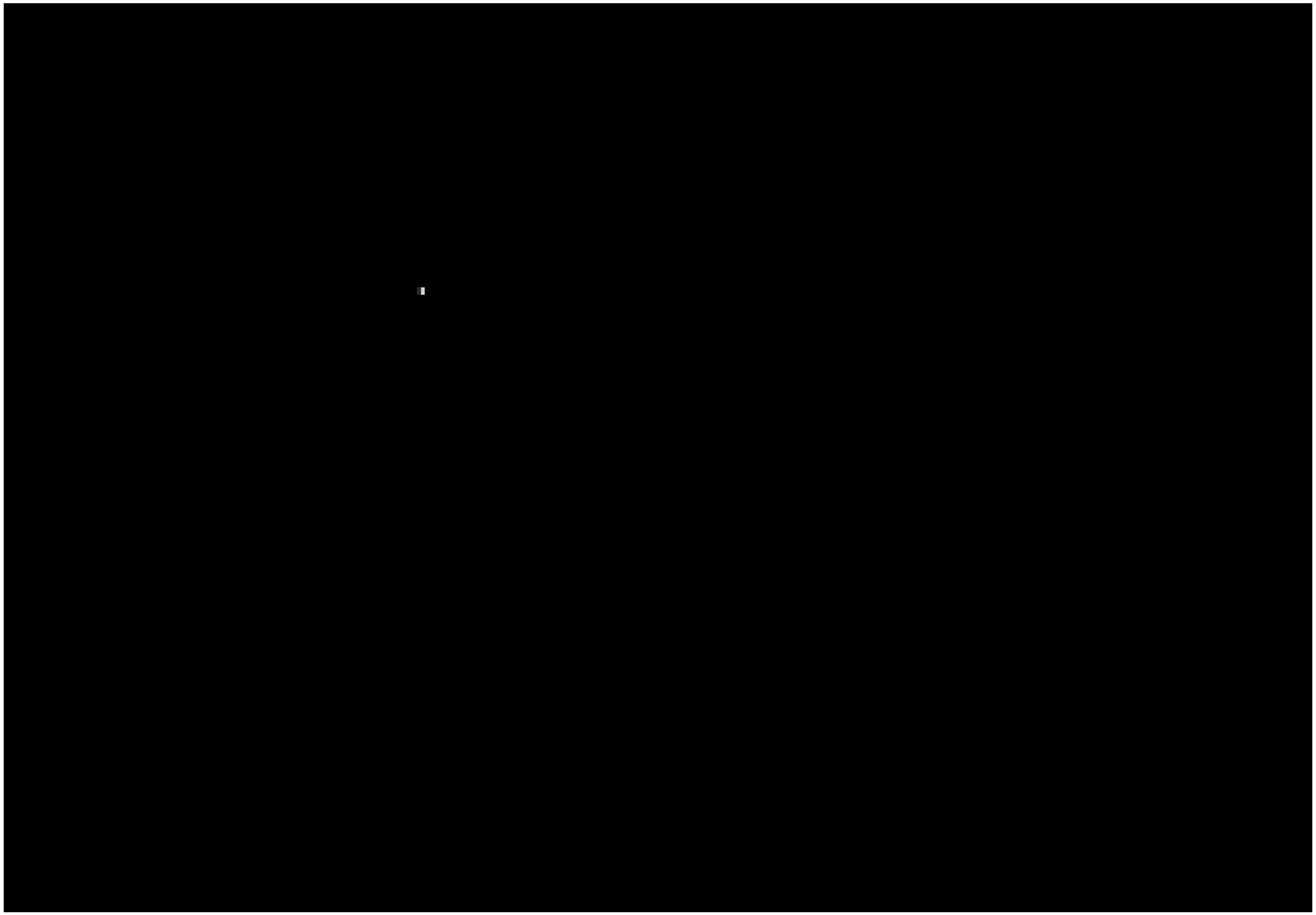
Herschel Space Observatory



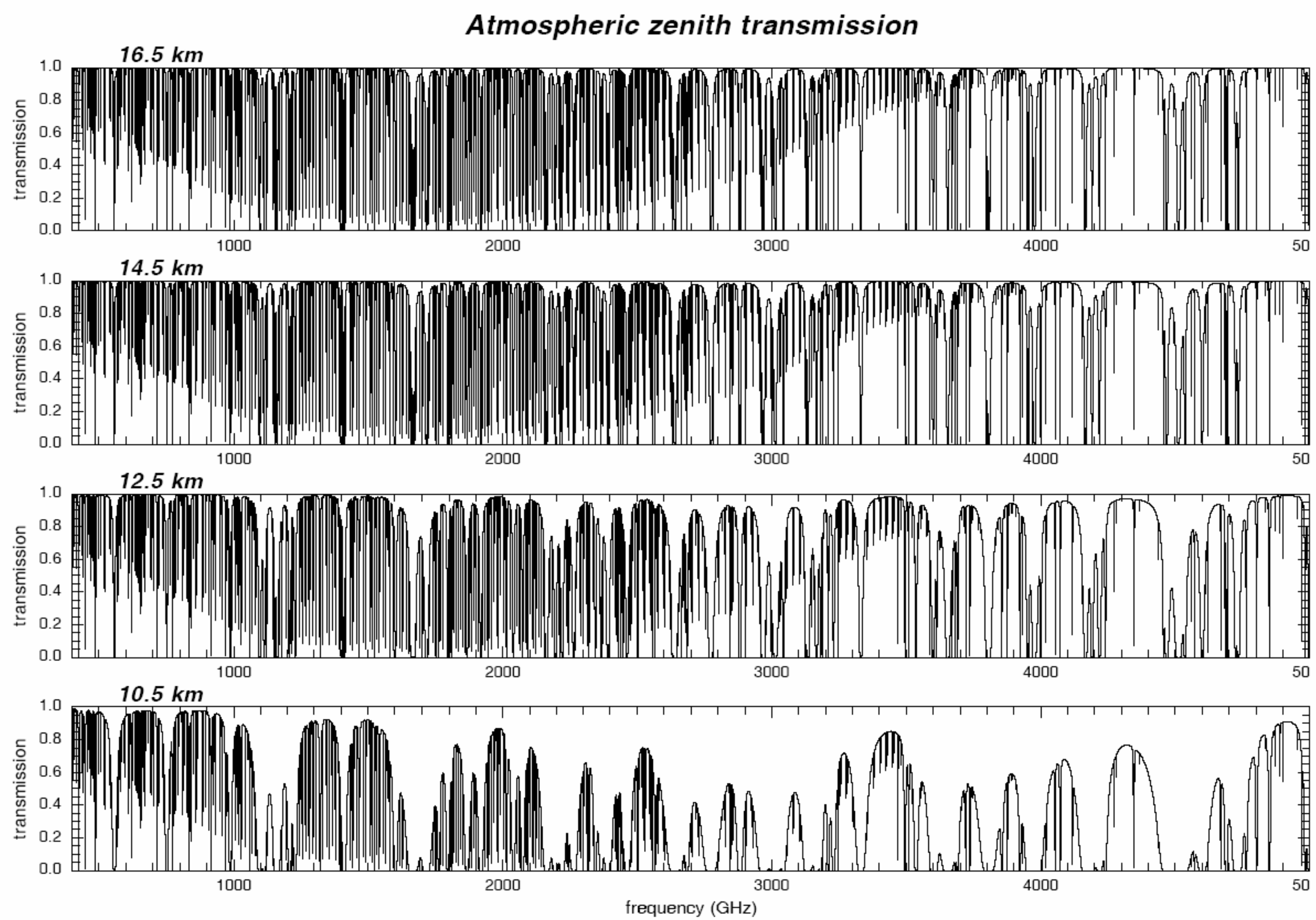


Spacecraft 4.5 m diameter, 9 m high, 3.3 tons, 1 kW, 3 years lifetime in L2

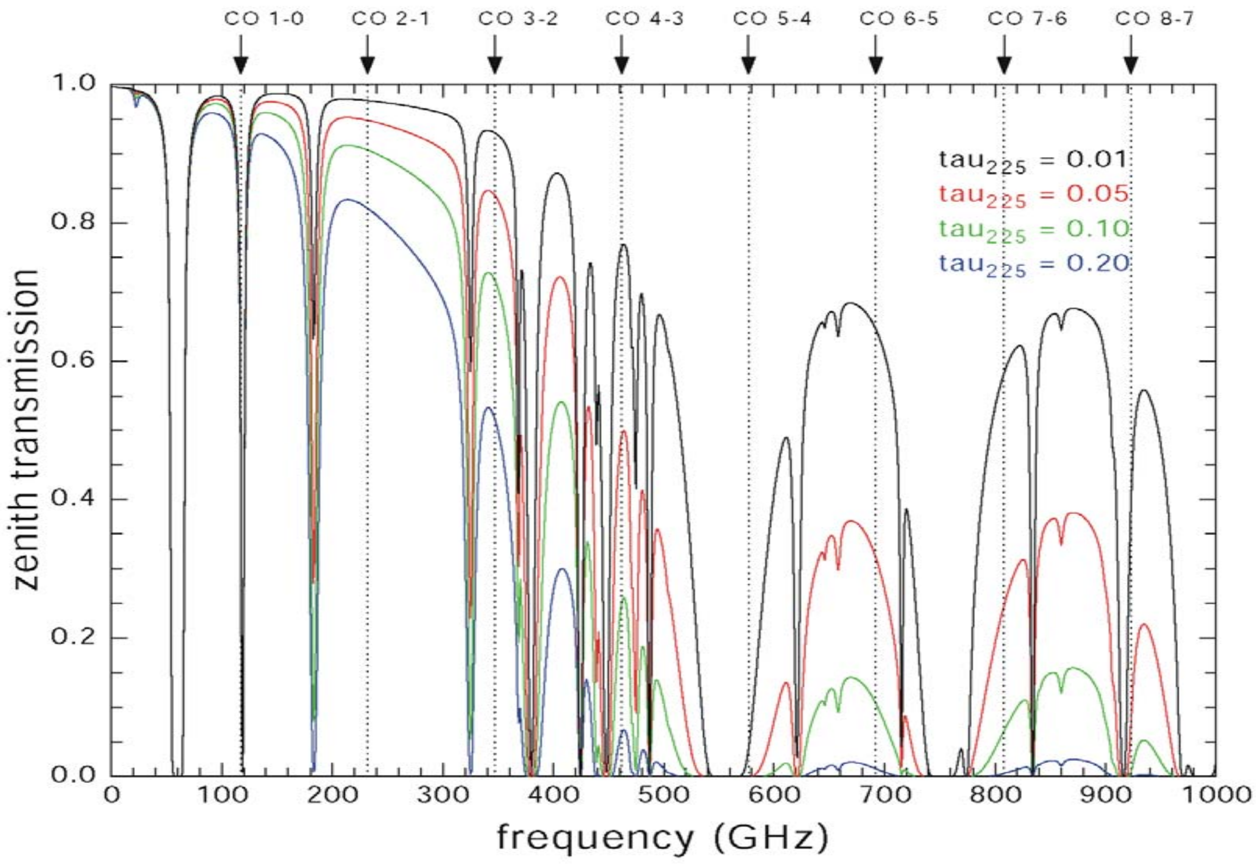
Stratospheric Observatory for Infrared Astronomy (SOFIA)



Transmission above the Troposphere (0 – 5000 GHz)



Tropospheric Transmission 0 – 1000 GHz from Ground



Science Objectives and Goals

- The Martian water cycle and atmospheric chemistry
- Origin of water in the upper atmospheres of the outer planets
- Water in distant comets
- Excitation of water in comets
- The D/H ratio and minor species

Water and Chemistry in the Martian Atmosphere

- Water cycle: vertical profile function of solar longitude (Ls), cut off at 10 km at aphelion and 50 km at perihelion: *variable hygropause from ground-based low quality measurements.* **If true, strong impact on general circulation: TBC by HIFI**

- History of Martian atmosphere: D/H about 5 times higher & $^{18}O/^{16}O$ about 10% and $^{17}O/^{16}O$ about 5 % lower than on Earth. **TBC by HIFI, i.e. observe CO, O_2 and O_3**

- HO_x-chemistry: H_2O, OH, HO_2,H_2O_2: confirm expected anti-correlation with O_3

- Chemistry: Search for minor components possibly based on PACS (2.2h) survey and moderate deep line survey in bands 4 and 5

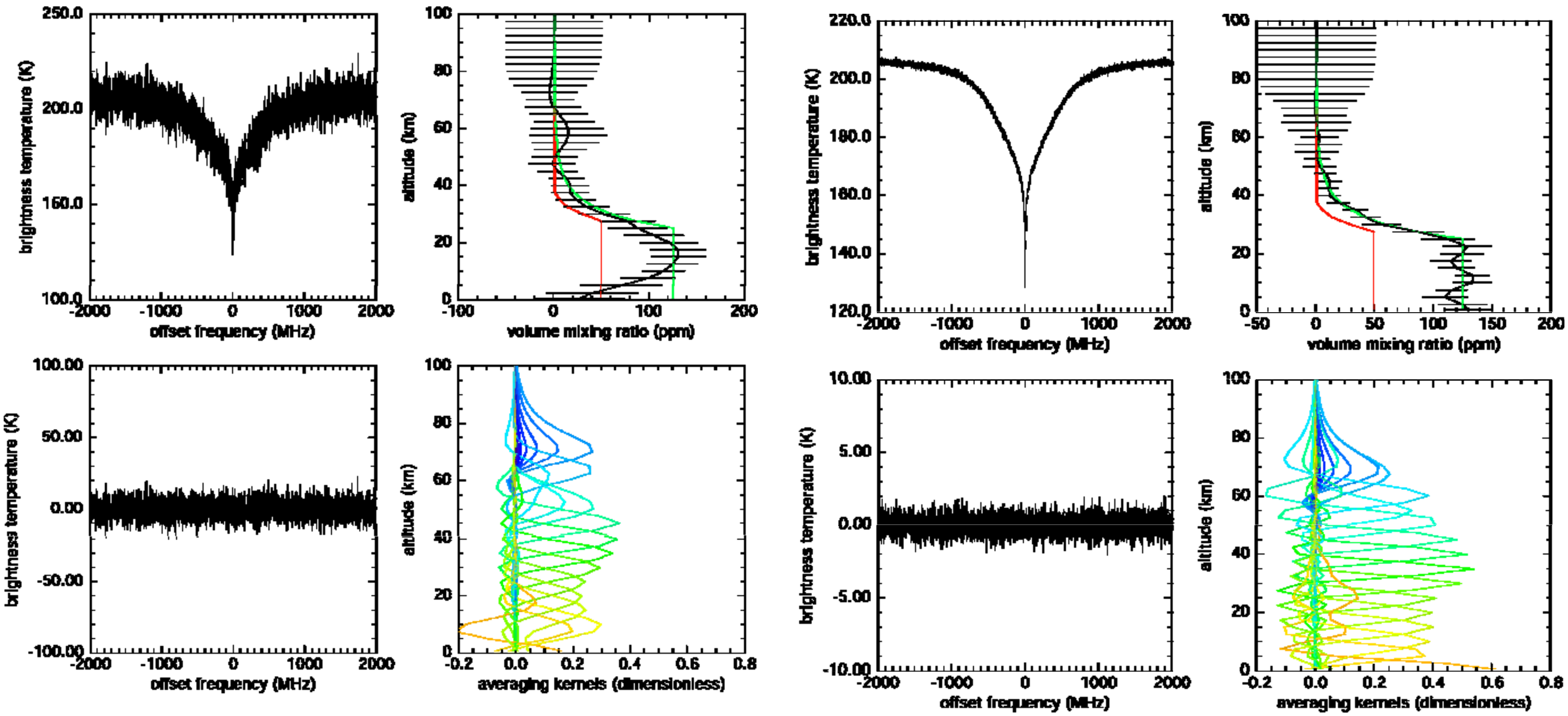
Mars Radiative Transfer Model Inputs

- T-profile: own ground-based measurements, Pathfinder and Viking entry profiles, TES-data, GCM output (MAOAM)
- Spectral line parameters: JPL 1991
- Line shape: Voigt-function
- ***Pressure broadening: 5,963 MHz/hPa (calculated)***
- Collision induced absorption: negligible for Mars
- Layer thickness: 2 km, T, p = const. within each layer
- TB-unit: Planck and Rayleigh-Jeans
- Trx: Rayleigh Jeans (SNR definition)
- Disk averaged spectrum (32 rings nadir & 32 rings limb

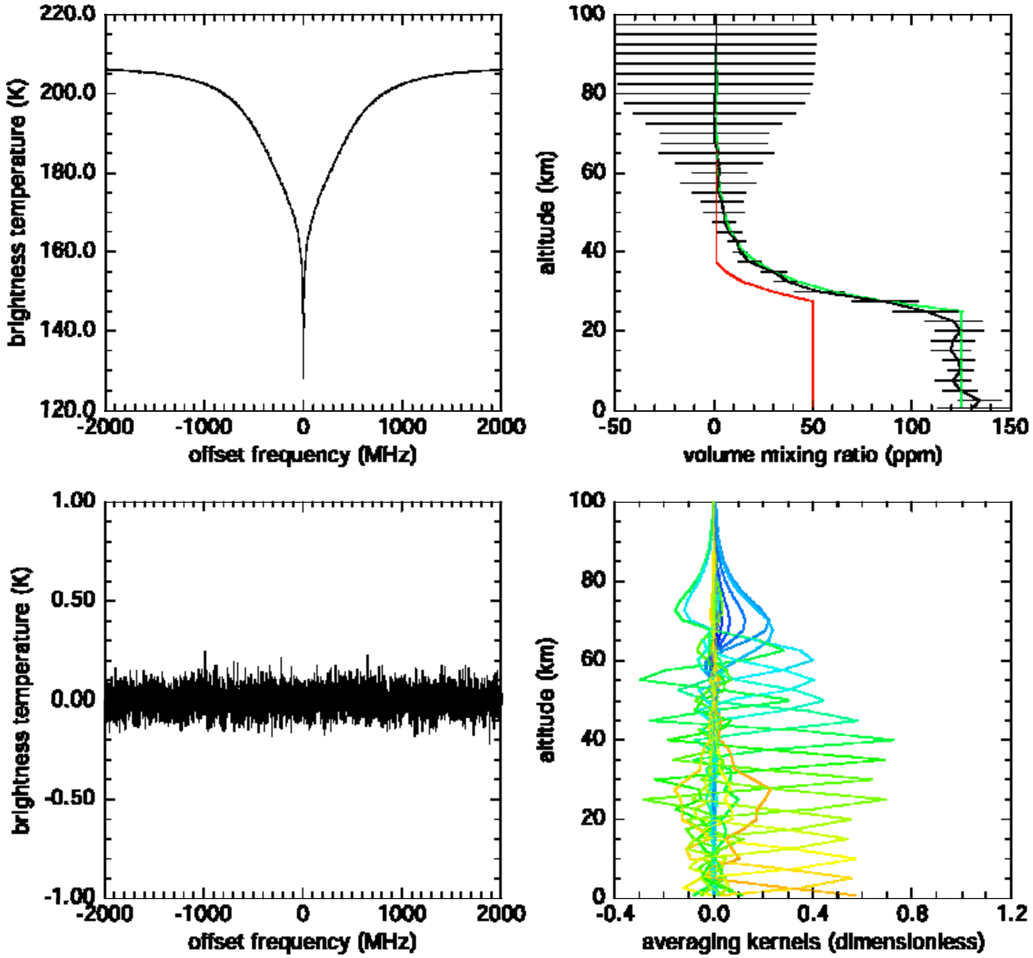
Retrieval-Method

- *Optimal Estimation: updates a priori profile with info from measured spectrum. A priori given with error covariance matrix of describing the variance in each single layer and the correlation between the layers.*
- *Use of artificial apriori profiles close to zero to test who well the true profile can be retrieved*
- *Equal error in each layer of apriori profile*
- *Correlation length about 5 km for Mars and 10-20 km for the Giant Planets.*

Mars H_2O 557 GHz Retrieval Simulation for SNR 10 and 100



Mars H_2O 557 GHz Retrieval Simulation for SNR 1000



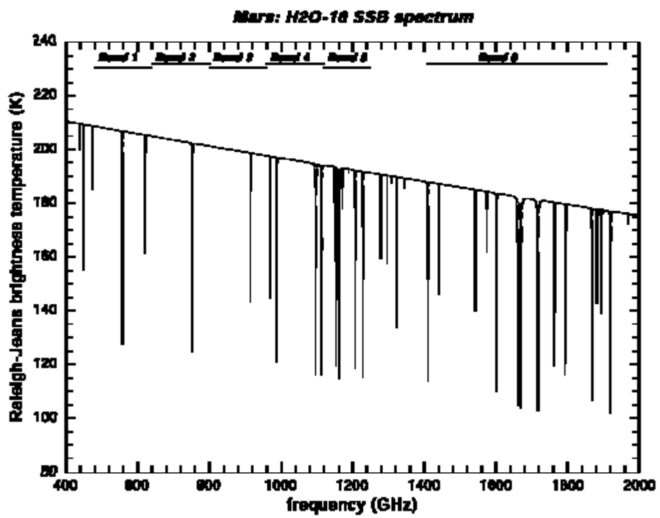
Integration times:

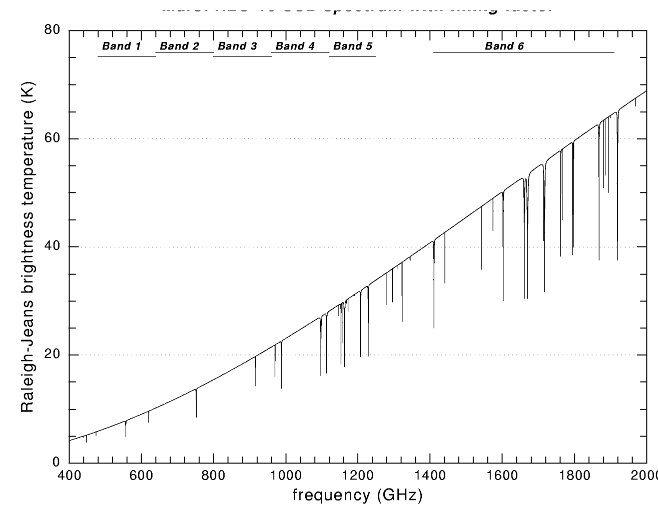
SNR 10 = 5.4 s

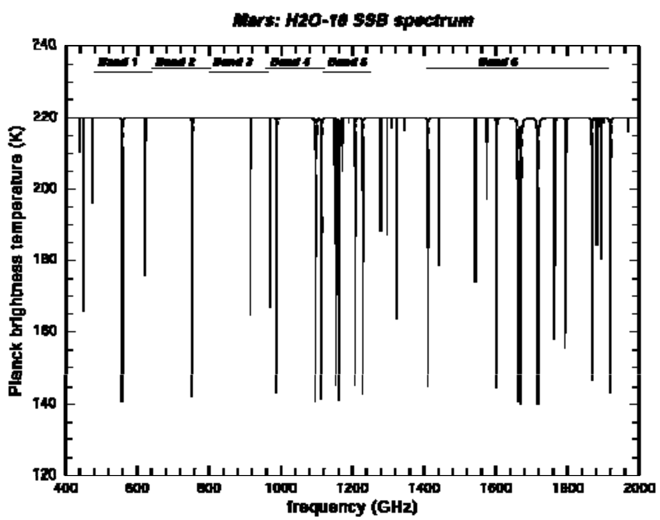
SNR 100 = 9 min

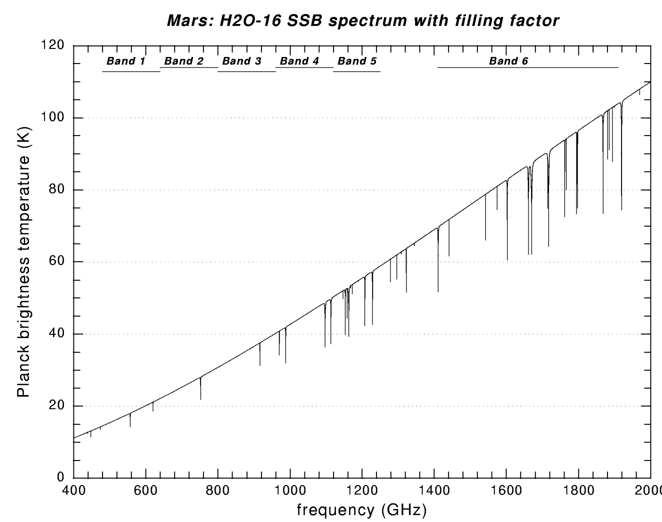
SNR 1000 = 15 h

HIFI Mars water lines w/o and with filling factor









Origin of water in the stratospheres of the outer planets

- *External sources required in order to explain the column amount found by ISO:*

  *Permanent **I**nterplanetary **D**ust **P**article flux (IDP)*

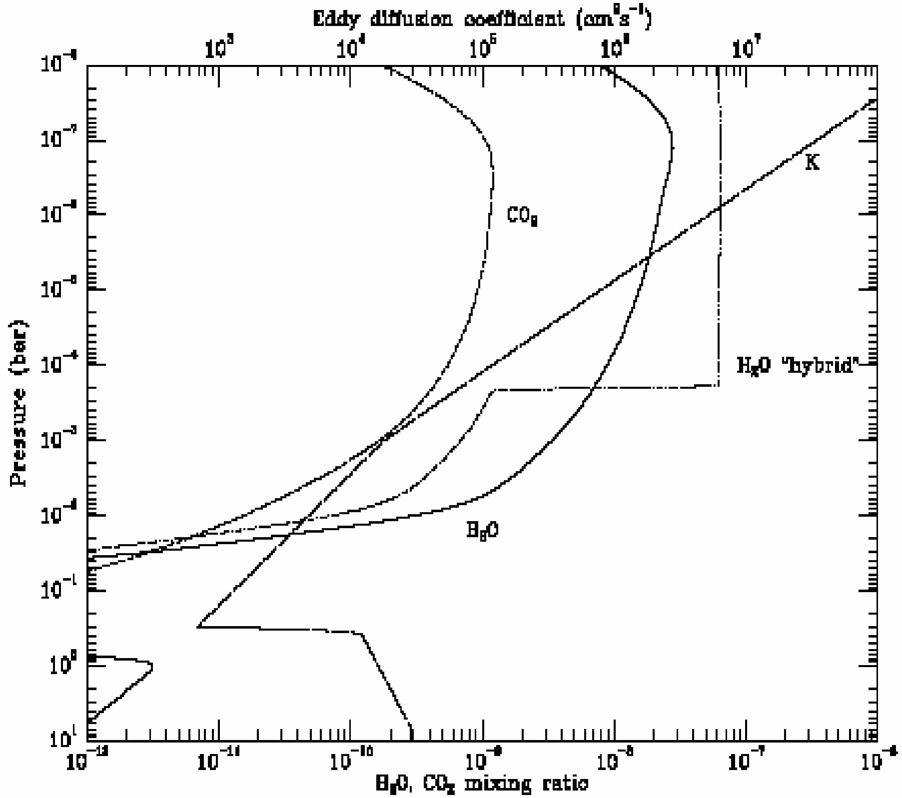
  Local sources (rings, satellites)

  cometary collisions

- *Impacts on production mechanism of dust, transport and ionization of gas/solid material in planetary magnetospheres, frequency of cometary collision events.*

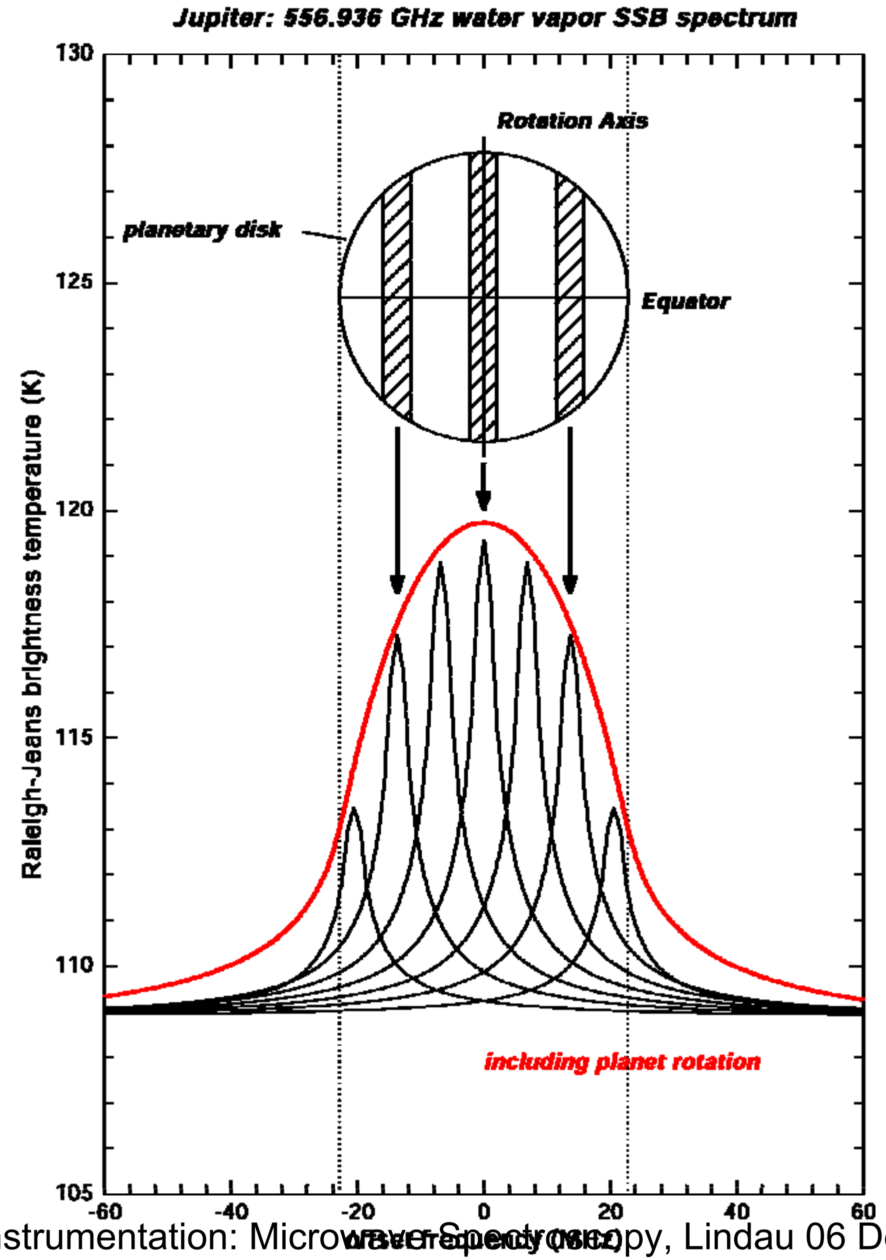
Science Goals of the Program

- *Improve accuracy of disc-average water abundances to better characterize the budget of input fluxes*
- *Determine vertical profiles: helps to discriminate between sources*
- *Map latitudinal distribution of water at Jupiter: > @ poles → source= high lat. satellites connected via magnetic field*
- *Get isotopic ratios of oxygen and hydrogen (latter with help of ALMA, since H/D ~ 40000*

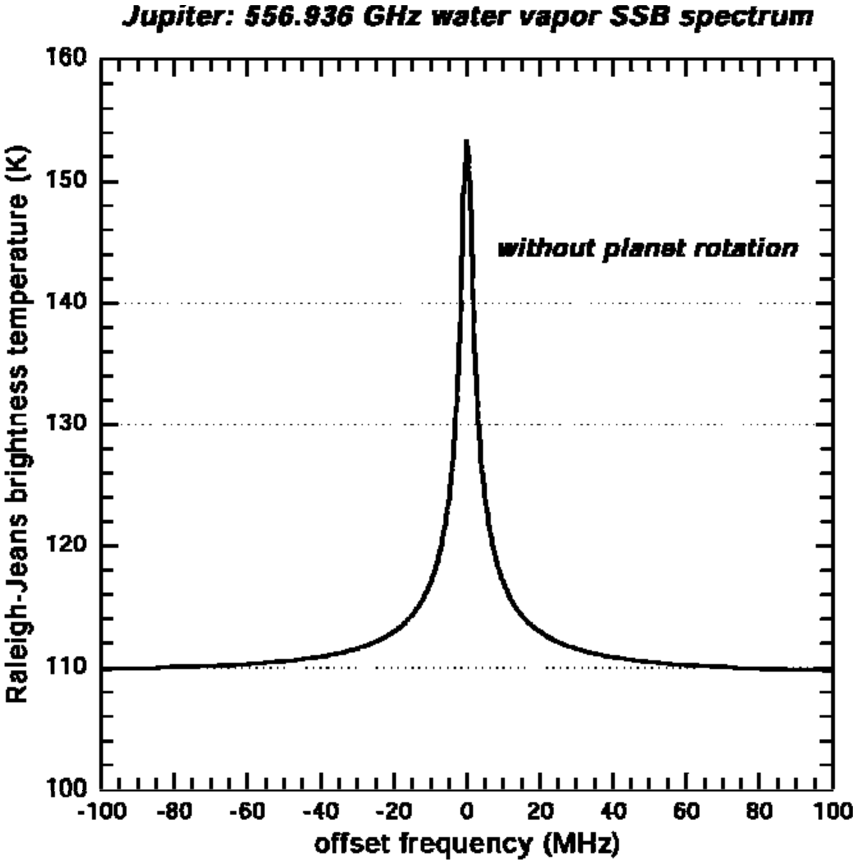


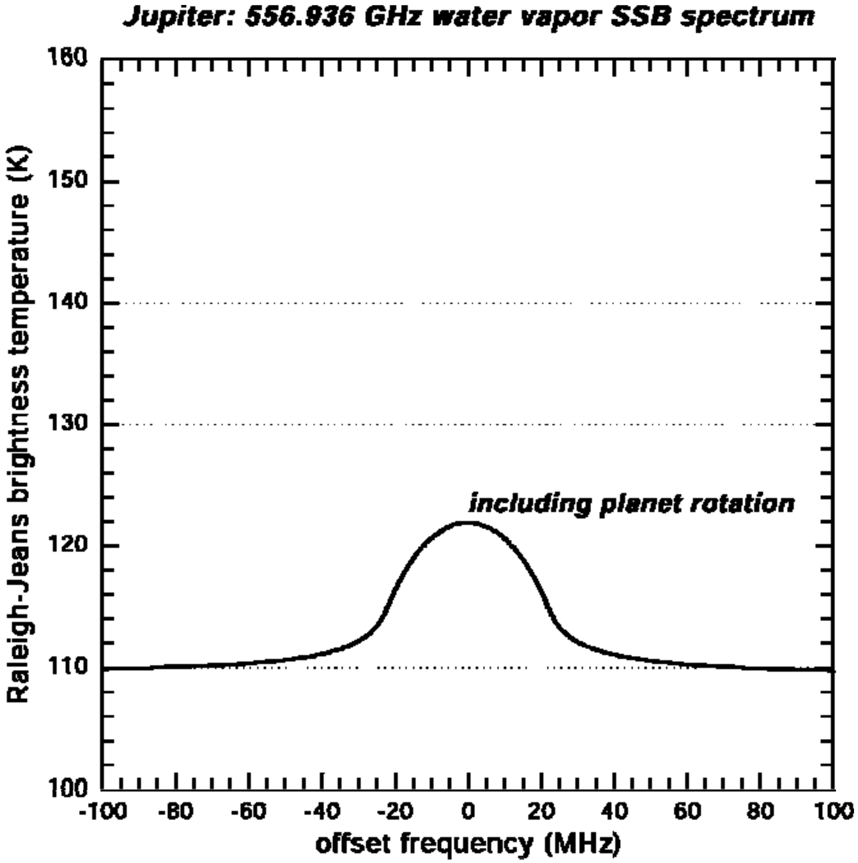
Jupiter Radiative Transfer Model Inputs

- T-profiles: Th. Encrenaz et al, 1995 (Planet Space Sci.)
- NH_3 and PH_3 profiles: Fouchet et al, Icarus 2000
- H_2O profiles: Feuchtgruber et al, Nature 1997
- Pressure broadening: 2 MHz/hPa
- H_2-H_2 CIA: Borysow et al, AJ 1985,
- H_2-He CIA: Birnbaum et al, Icarus 1996
- Layer thickness: 5 km, T, p = const. within each layer
- TB-unit: Planck and Rayleigh-Jeans
- Trx: Rayleigh Jeans (SNR definition)
- Disk averaged spectrum (32 rings nadir & 32 rings limb) and resolved disk (as function of frequency)
- Rotational broadening (rot. period 9.925 h)

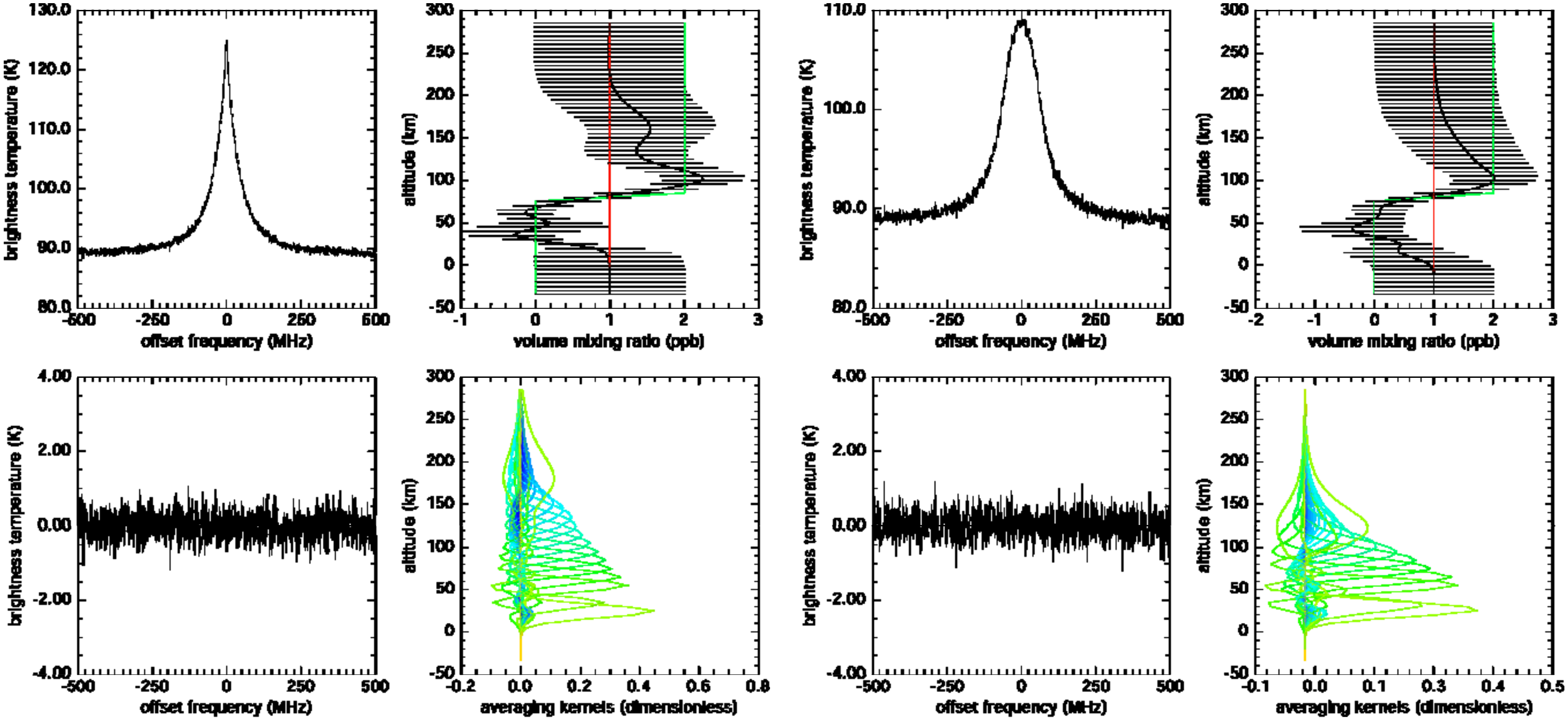

Jupiter: 556.936 GHz water vapor SSB spectrum
Rotation Axis
planetary disk
Equator
including planet rotation
Raleigh-Jeans brightness temperature (K)
130
125
120
115
110
105
-60
-40
-20
0
20
40
60
offset frequency (MHz)

Water with and without Jupiter rotation



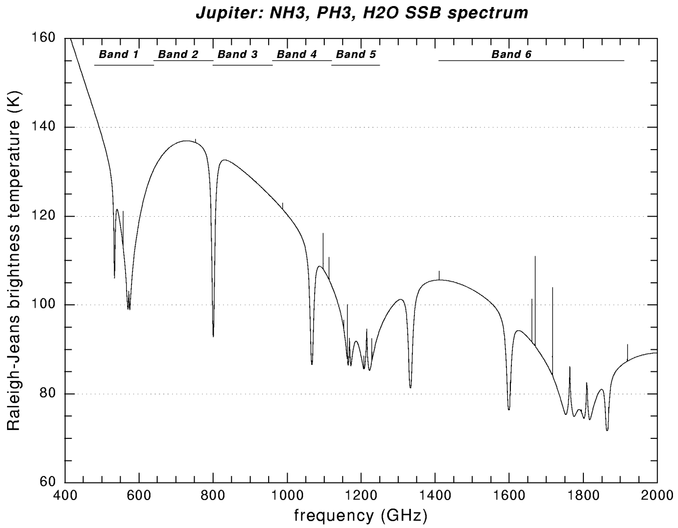


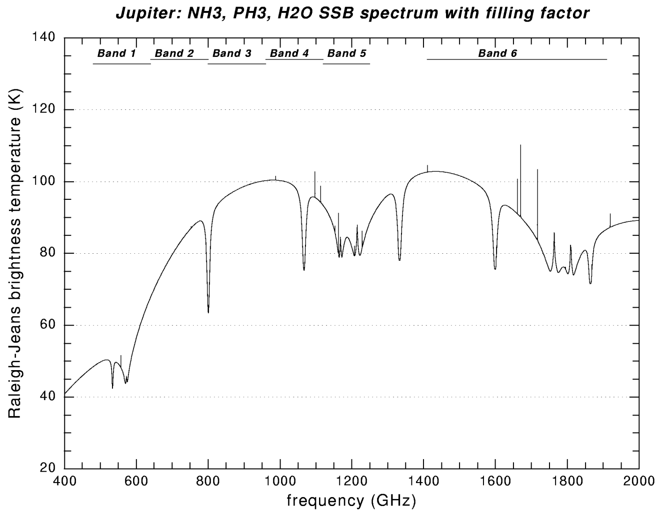
HIFI 1670 GHz Water spectra of Jupiter

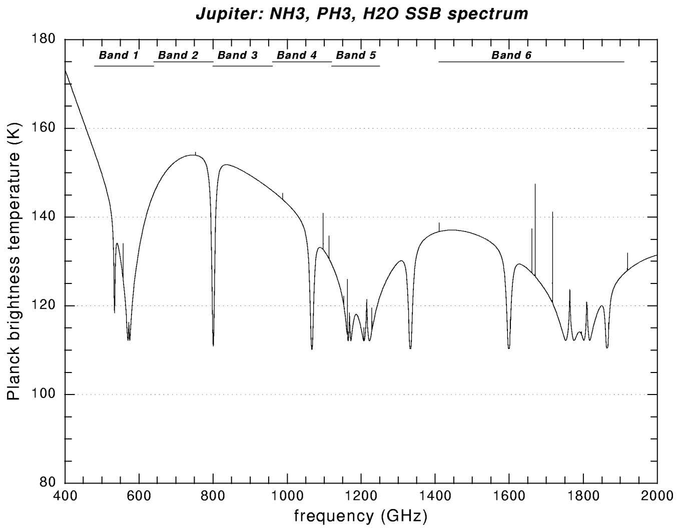


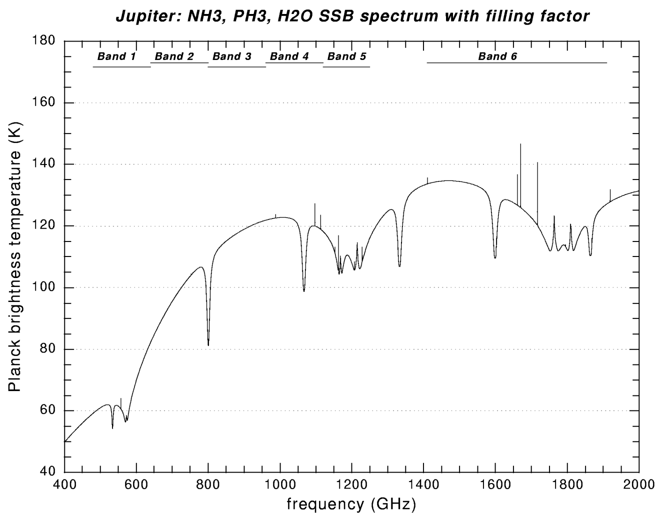
Space Instrumentation: Microwave Spectroscopy, Lindau 06 December 2006

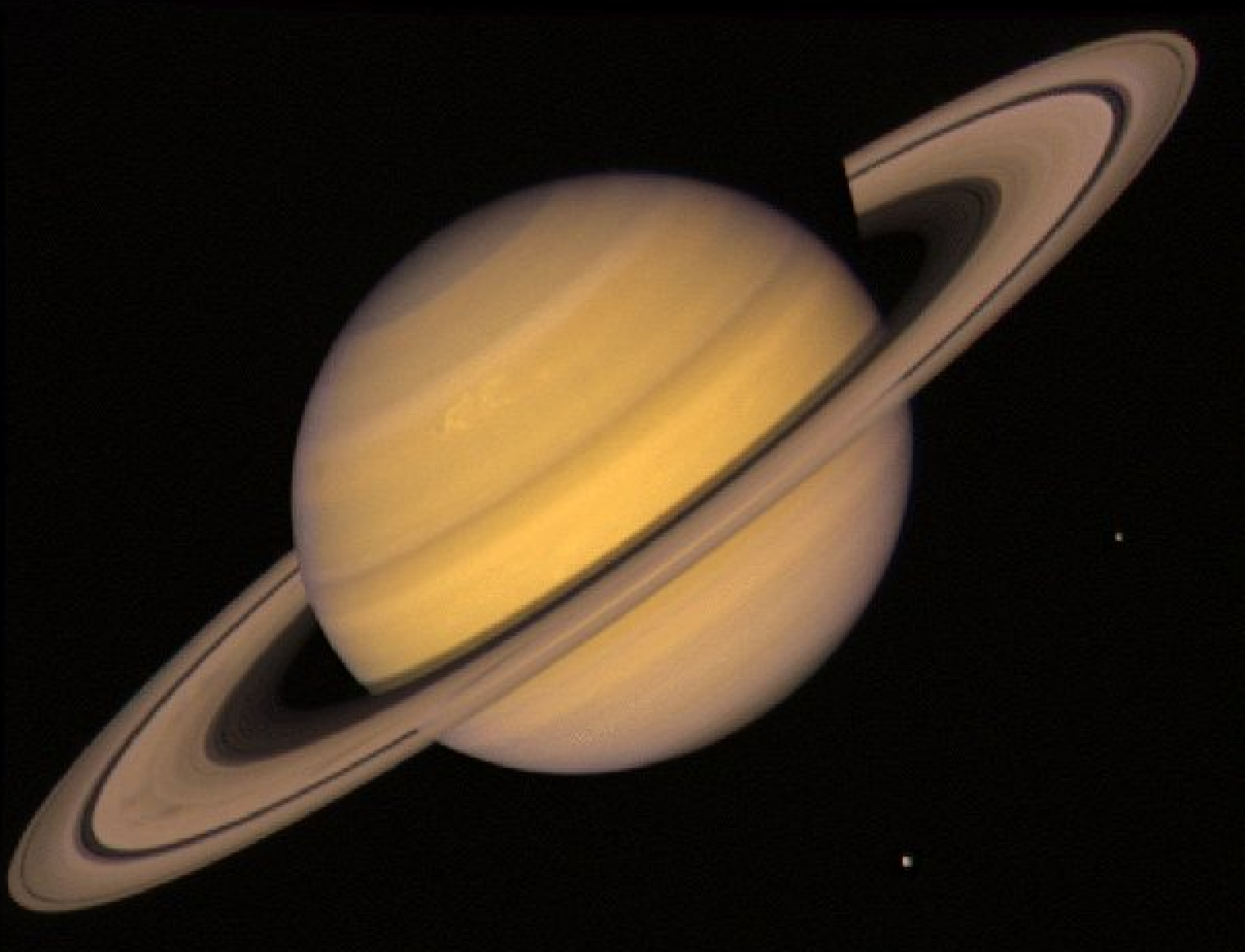
HIFI Jupiter NH_3, PH_3 and H_2O lines w/o and with filling factor



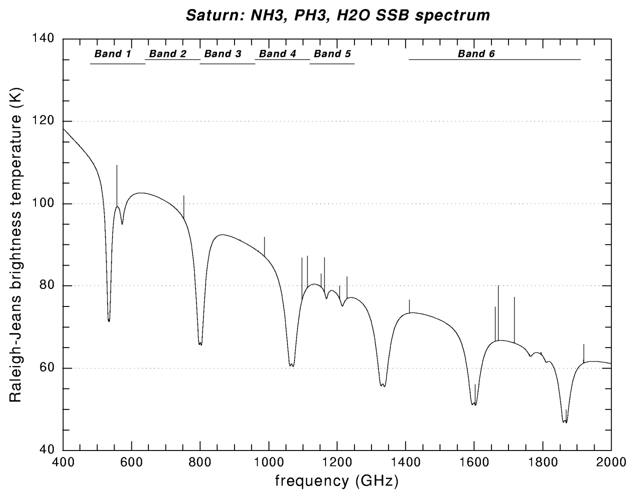


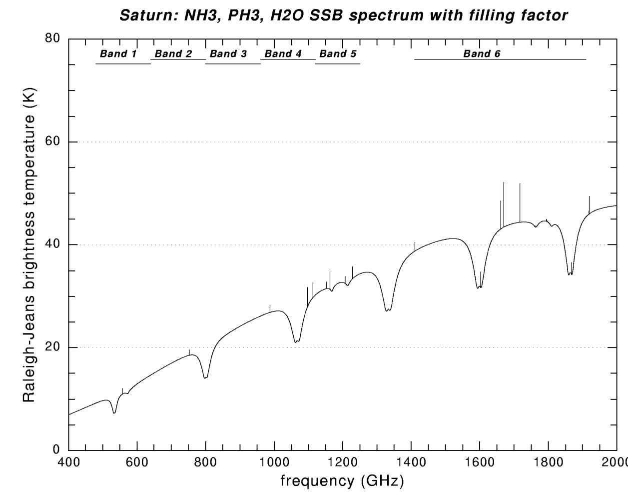


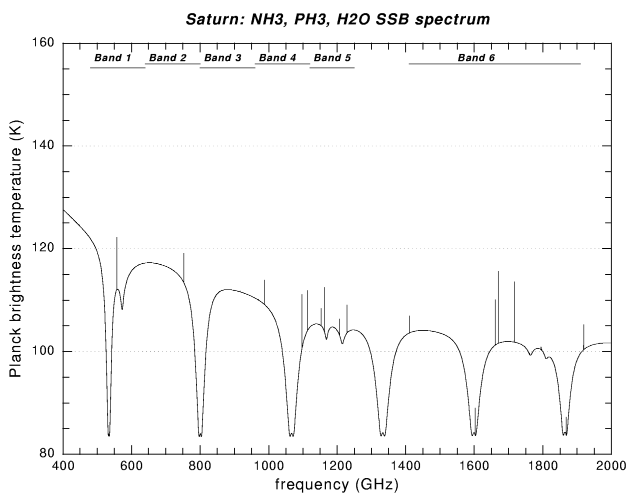


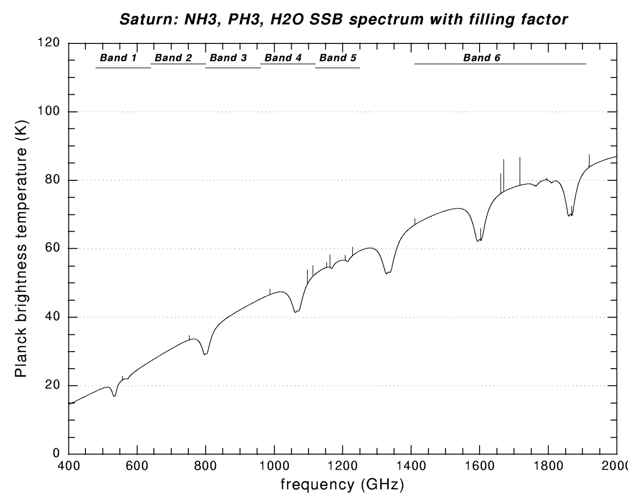


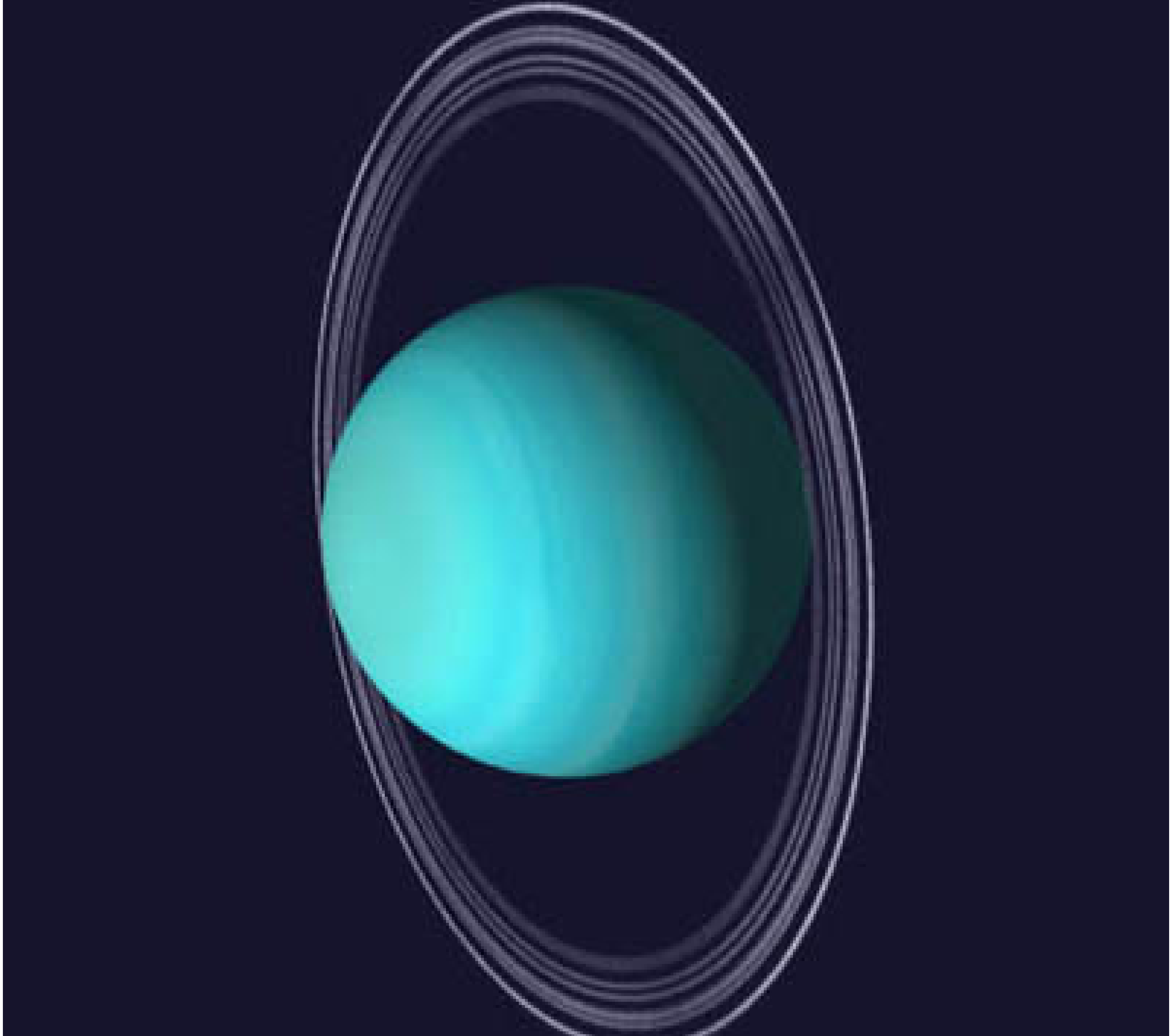
HIFI Saturn NH_3, PH_3 and H_2O lines w/o and with filling factor



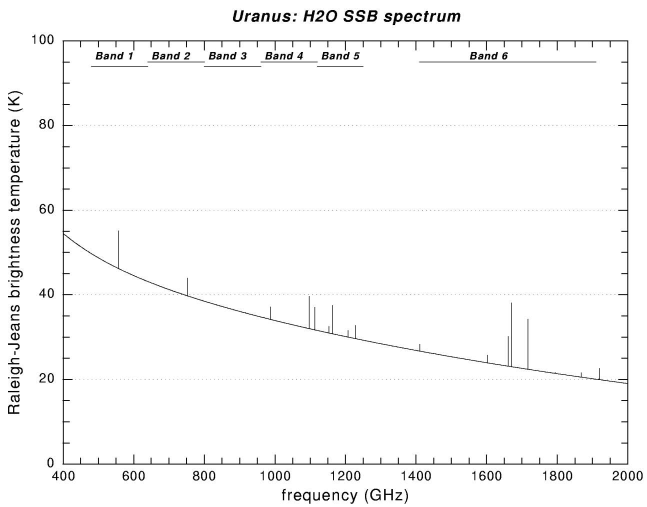


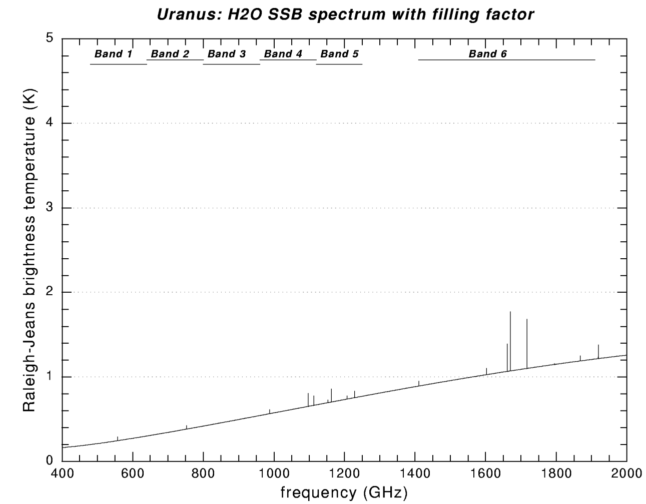


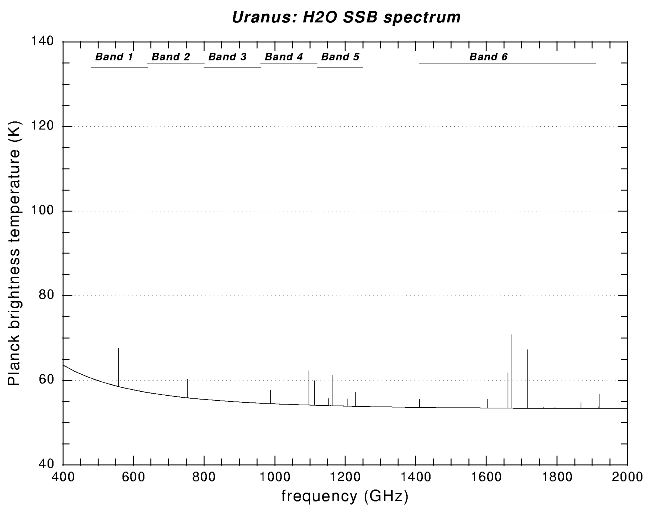


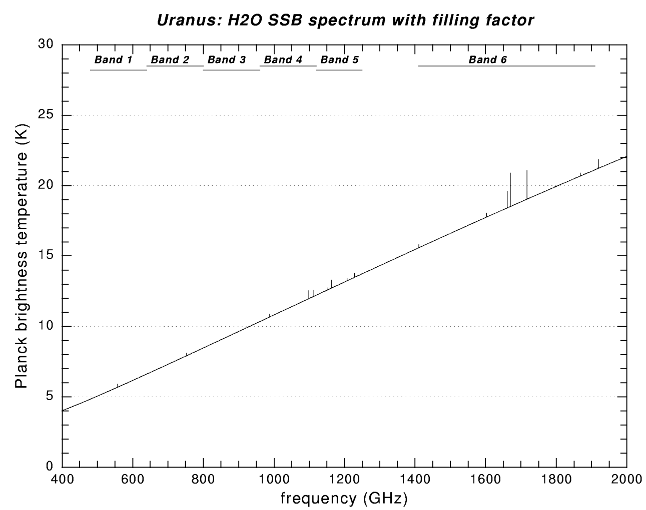


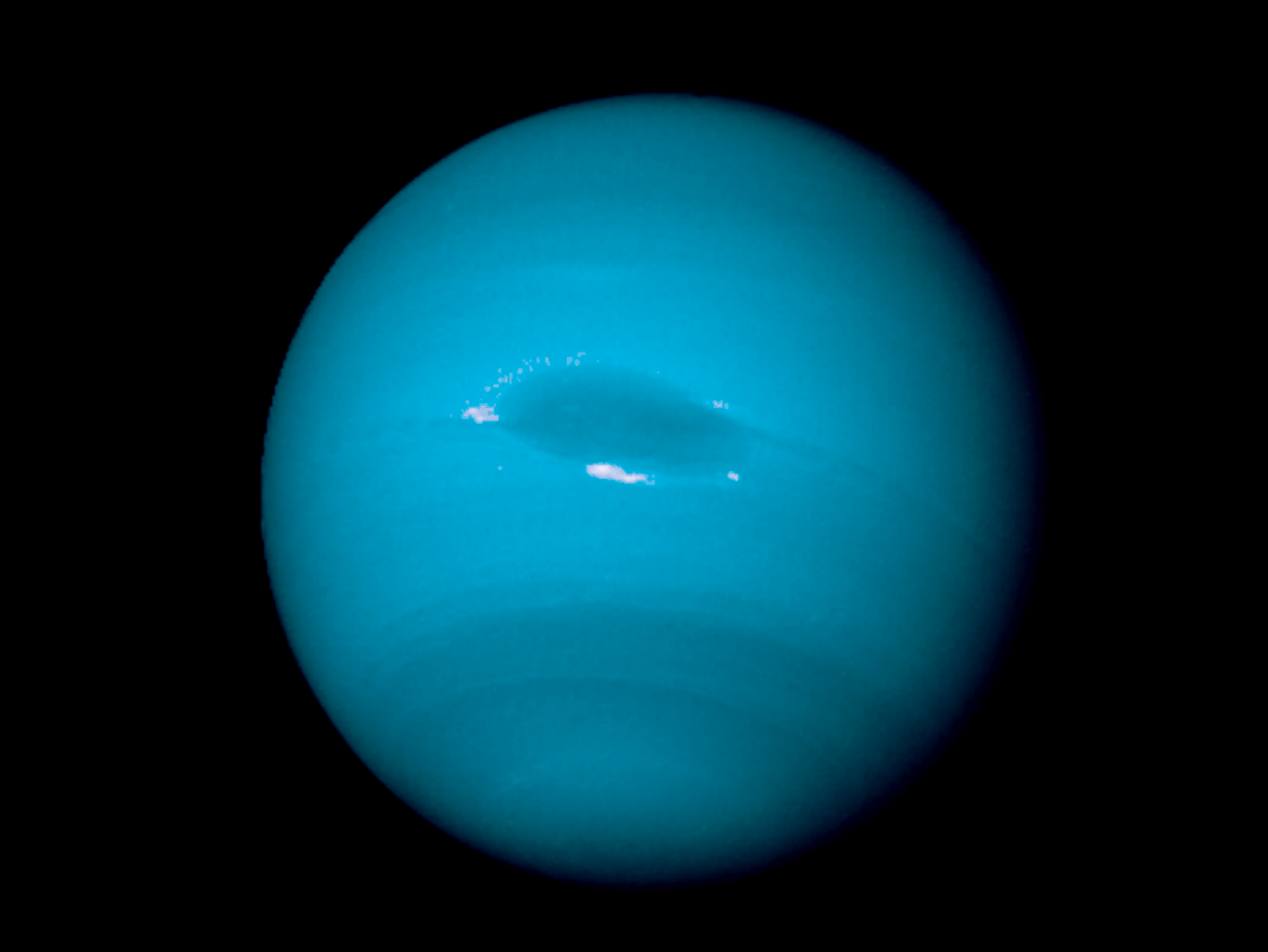
HIFI Uranus H_2O lines w/o and with filling factor



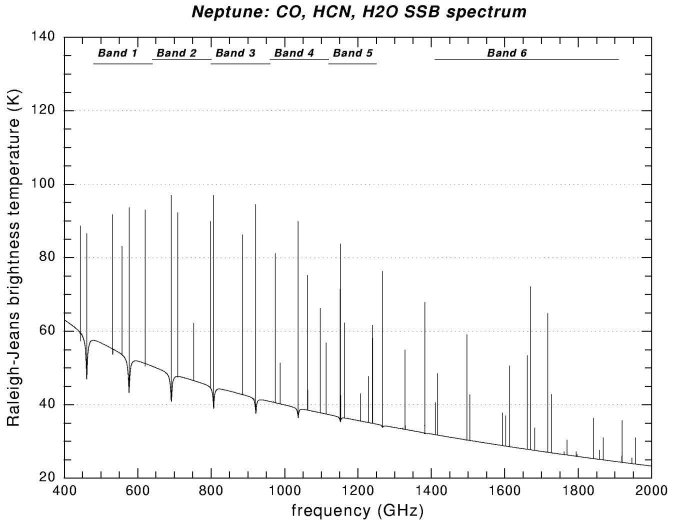


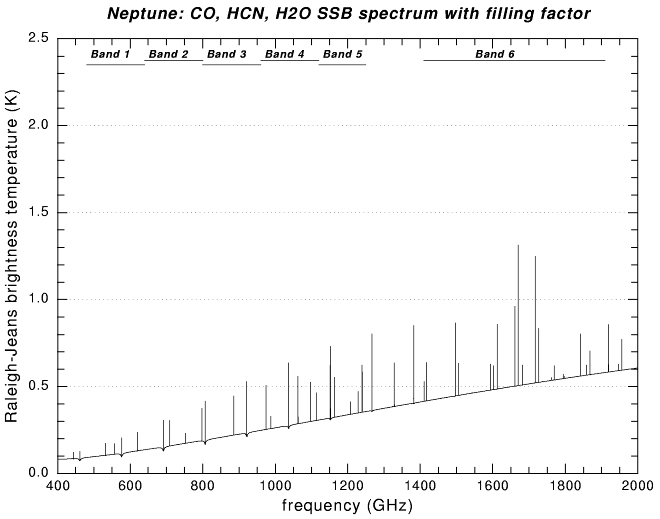


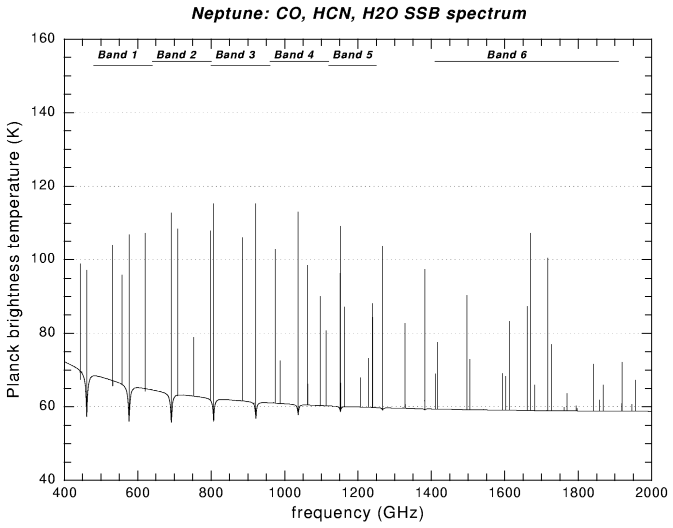


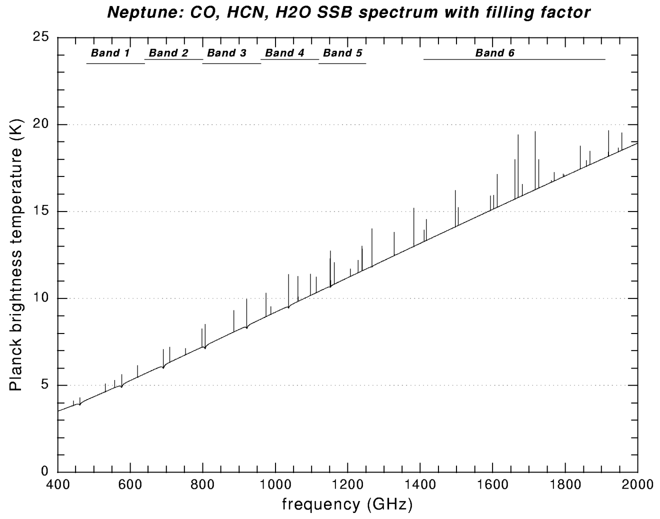


HIFI Neptune CO, HCN and H_2O lines w/o and with filling factor





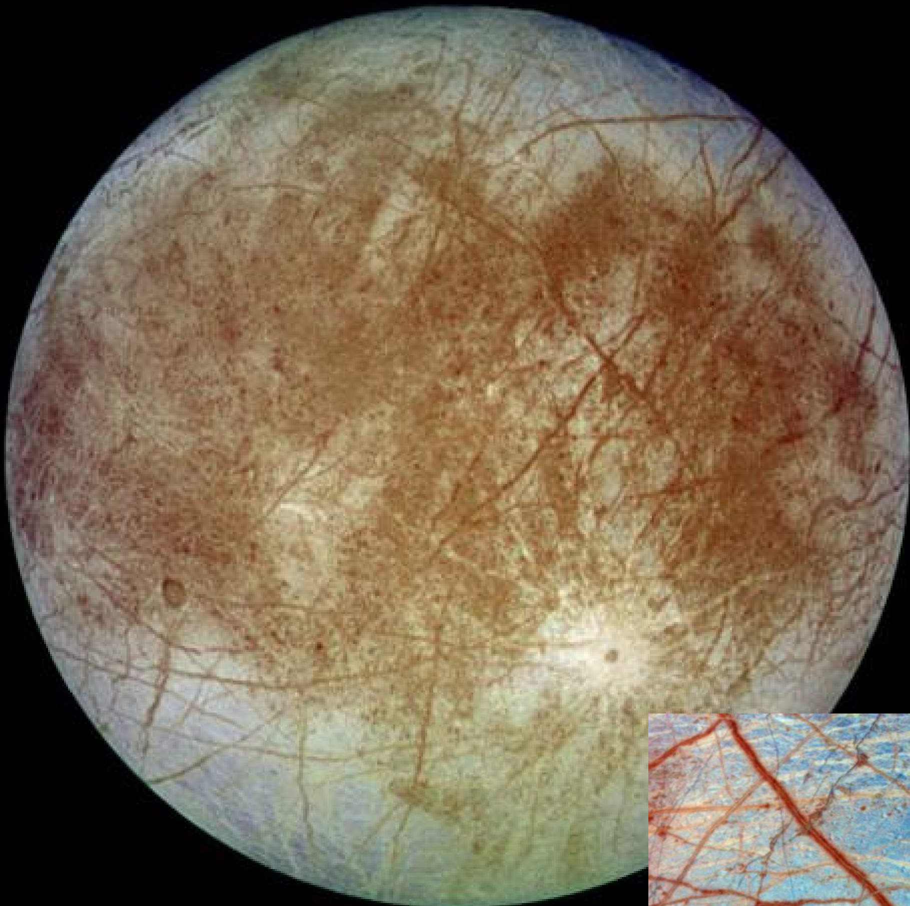


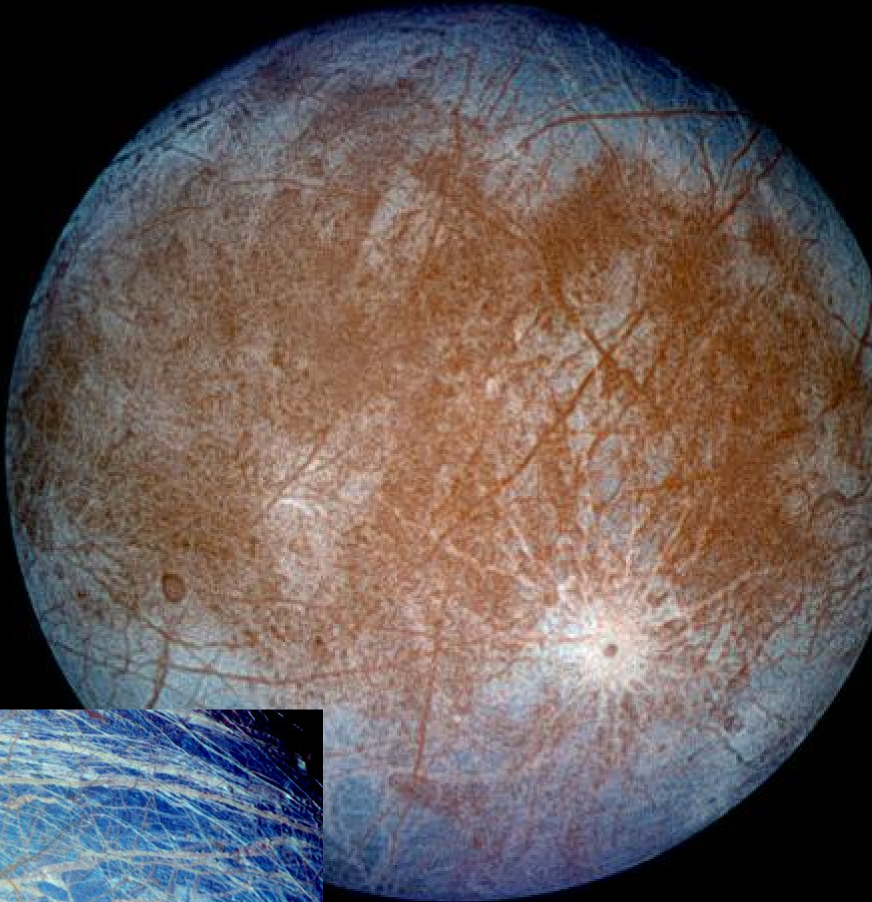


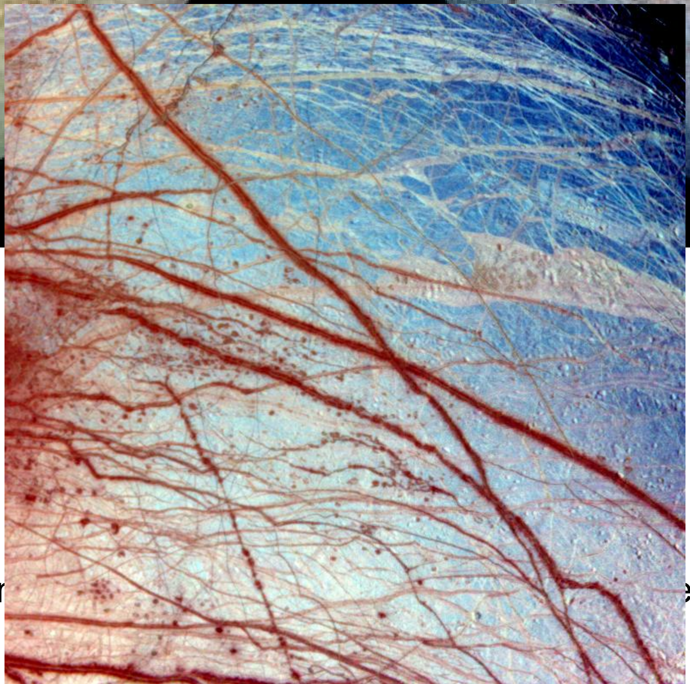
Galilean Satellites: Europa

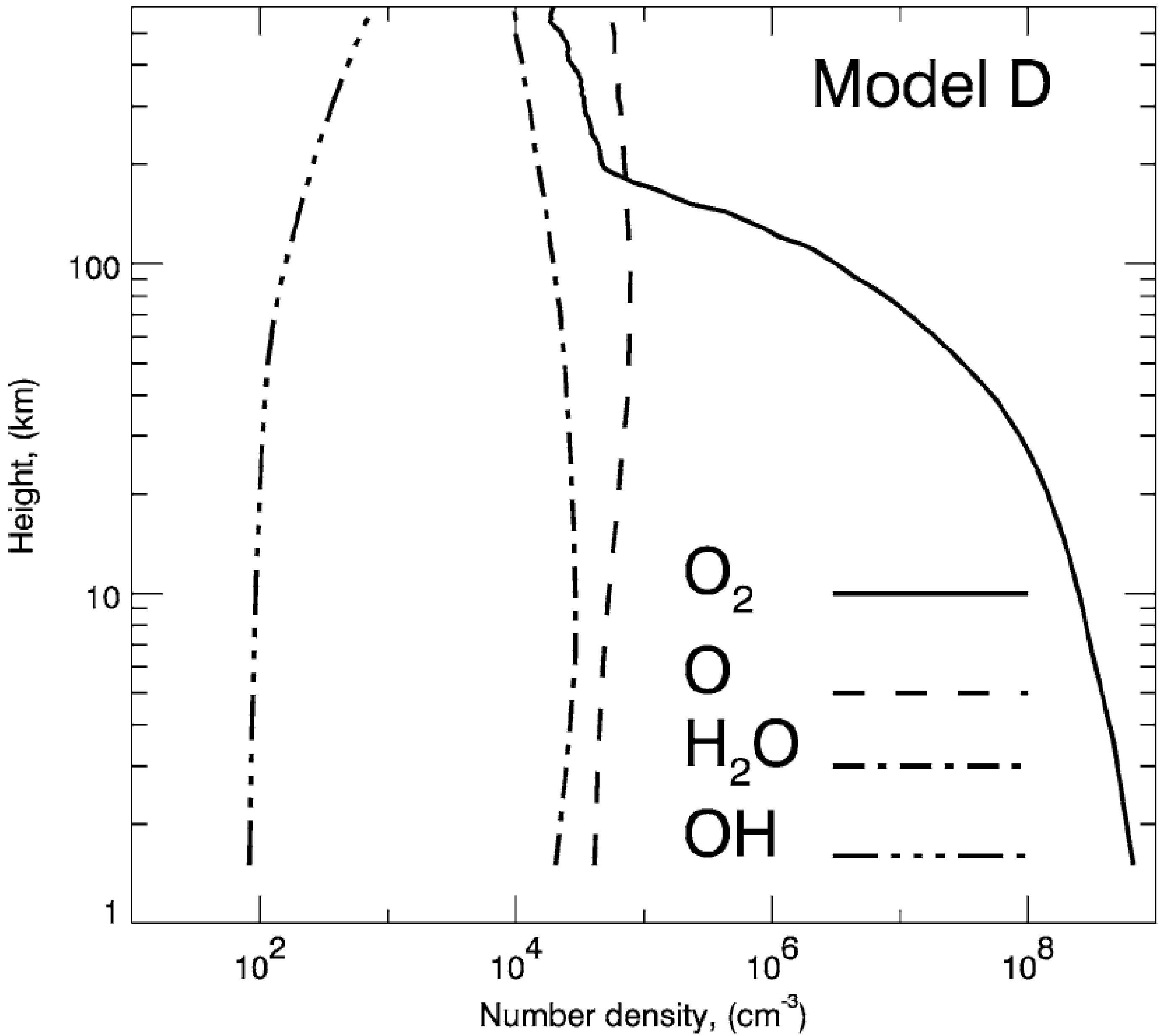
- Water density profiles according to Shematovic et al., 2005
- T-profile: const. 103 K (mean surface temperature)
- Signal comes from limb
- Collisional line excitation (LTE)
- Europa`s disk diameter: 0.75 arcsec

- *Water is produced by sputtering processes and sublimation near the equator during noon.*

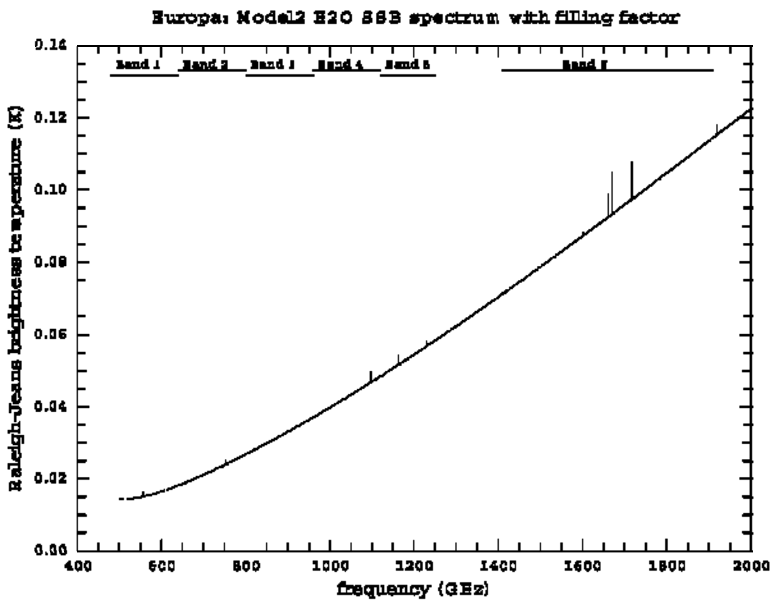


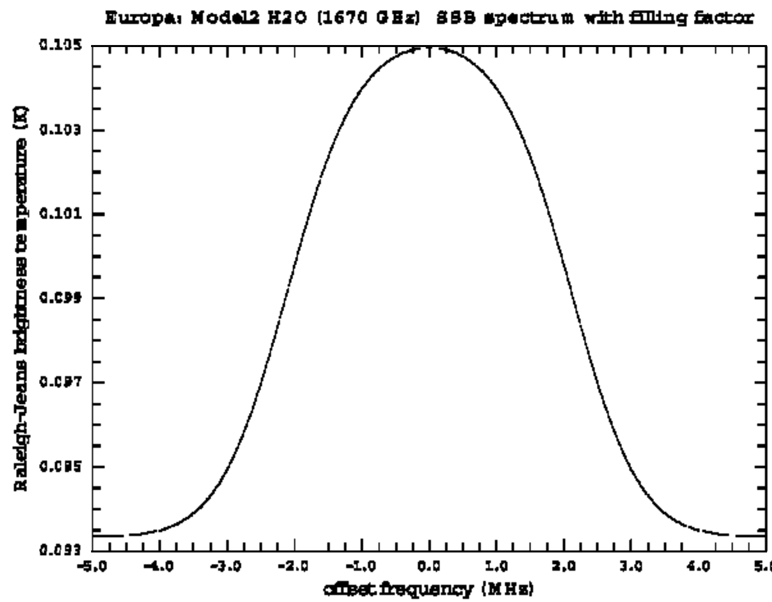


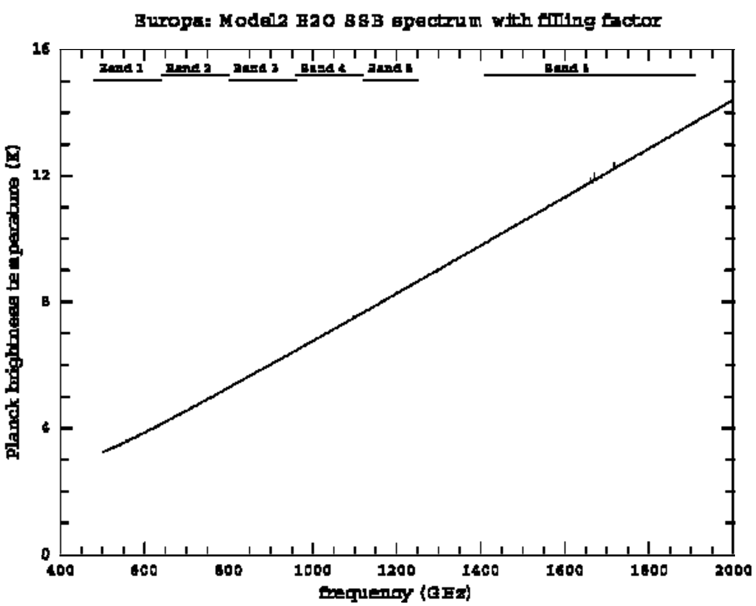


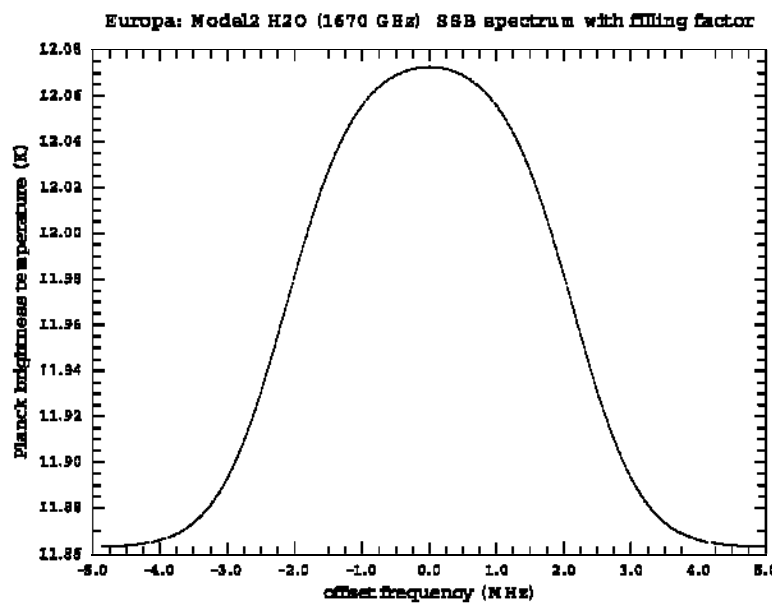


Model D
Height, (km)
100
10
1
10^2
10^4
10^6
10^8
Number density, (cm^{-3})
O_2
O
H_2O
OH


Europa: Model2 H2O SSB spectrum with filling factor
Band 1
Band 2
Band 3
Band 4
Band 5
Raleigh-Jeans brightness temperature (K)
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
400
600
800
1000
1200
1400
1600
1800
2000
frequency (GHz)

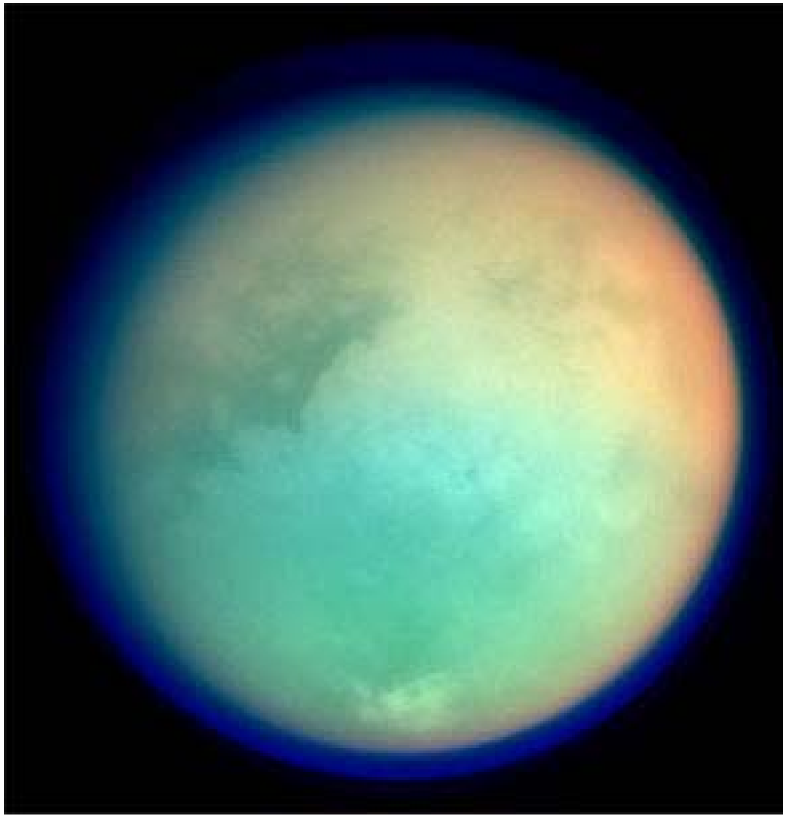

Europa: Model2 H2O (1670 GHz) SSB spectrum with filling factor
Raleigh-Jeans brightness temperature (K)
0.105
0.103
0.101
0.099
0.097
0.095
0.093
-5.0
-4.0
-3.0
-2.0
-1.0
0.0
1.0
2.0
3.0
4.0
5.0
offset frequency (MHz)

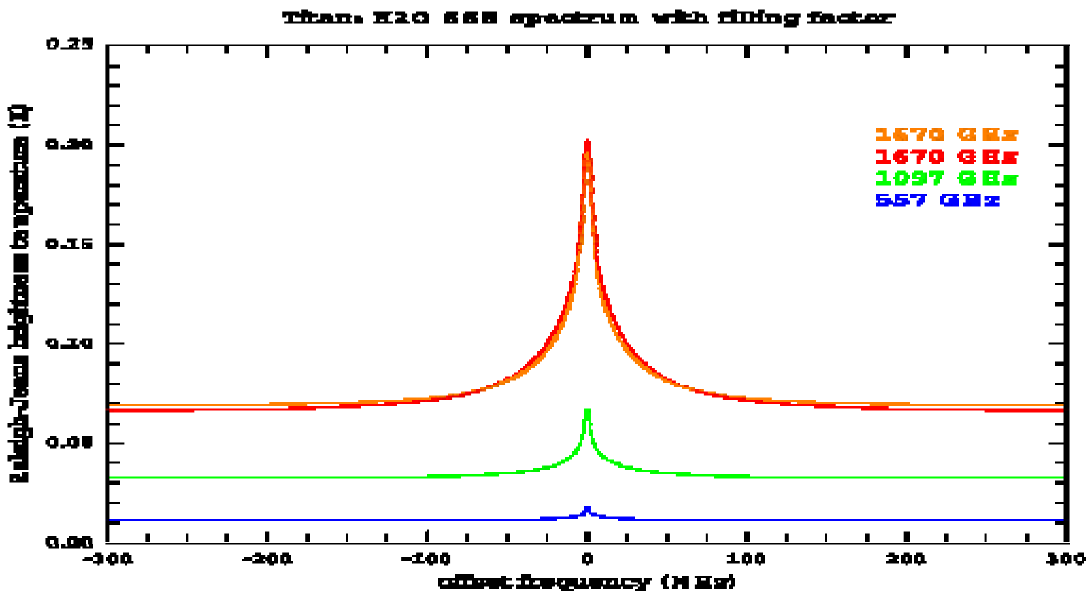

Europa: Model2 H2O SSB spectrum with filling factor
Band 1
Band 2
Band 3
Band 4
Band 5
Planck brightness temperature (K)
16
12
8
4
0
400
600
800
1000
1200
1400
1600
1800
2000
frequency (GHz)

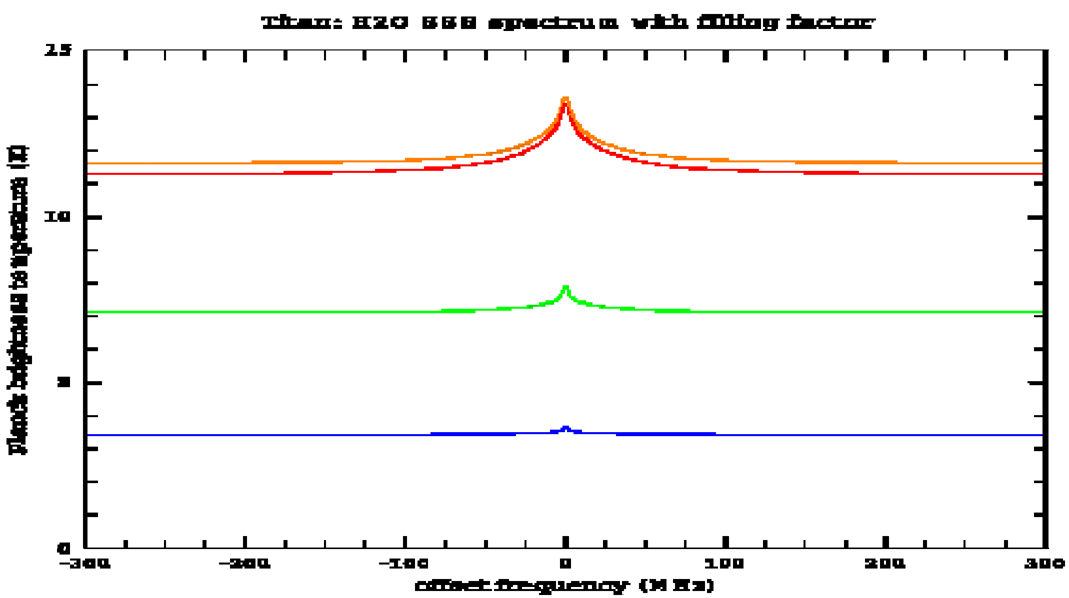

Europa: Model2 H2O (1670 GHz) SSB spectrum with filling factor
Planck brightness temperature (K)
12.08
12.06
12.04
12.02
12.00
11.98
11.96
11.94
11.92
11.90
11.88
11.86
-5.0
-4.0
-3.0
-2.0
-1.0
0.0
1.0
2.0
3.0
4.0
5.0
offset frequency (MHz)

Titan

- *Goal: determine vertical water vapor profile in order to constrain 2 different models*

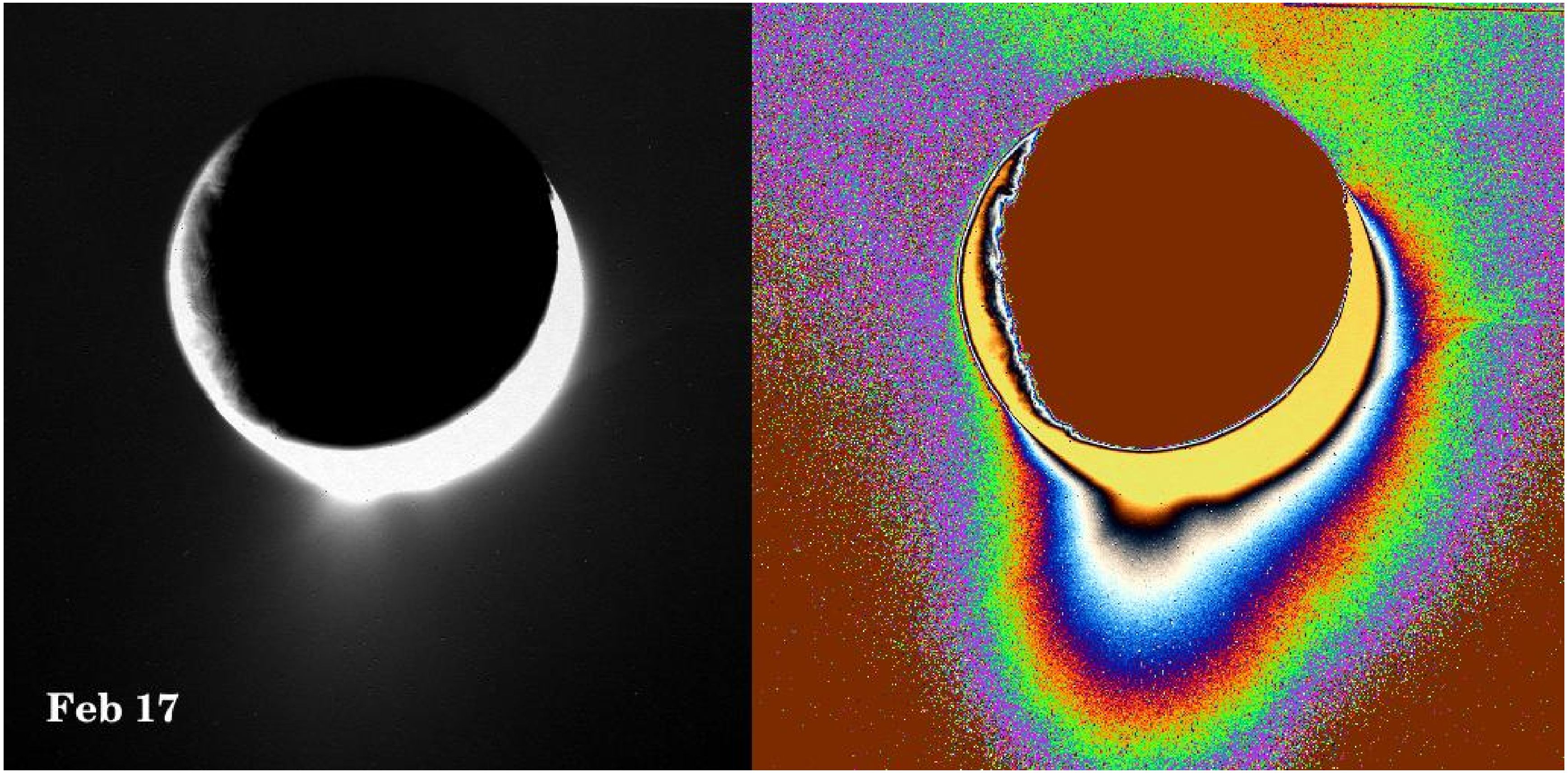



1670 GHz
1670 GHz
1097 GHz
557 GHz
0.25
0.20
0.15
0.10
0.05
0.00
-300
-200
-100
0
100
200
300
offset frequency (MHz)


15
10
5
0
-300
-200
-100
0
100
200
300
offset frequency (MHz)

Enceladus

Detection of water bearing material. Perhaps even near surface boiling water.
Evidence of third solar system object with volcanic activity, South polar hot spot.
Herschel will determine the amount of water vapor (vs water and other ices)



Search for water in weakly active objects

- *29P/Schwassman-Wachmann1: ice grains in extended source? -> 557 GHz water vapour*

- *Near Earth Objects (NEOs): extinct of dormant comets? Activity?*

Constrain water excitation and physical conditions of comets

- *HIFI, PACS and SPIRE: water simultaneously over whole spectral range*
- *Detect asymmetric outgassing, velocity offsets, self absorption and temperature profiles(r) observing lines of different excitation (τ – dep.),ortho-to-para ratio*

HDO: search for D/H in selected Comets

- *Get "Jupiter-family" D/H for the first time for $Q[H_2O]$ > 5x1-e27/s at r_h = 1 AU*

- *Search for minor species together with H_2O: NH_3, or H_2O-18 and HNC*

Microwave Brightness Temperature I

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

Planck's law for blackbody radiation:

$$I_\nu = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/kT(x)} - 1}$$

Radiometer formula and Calibration

- *Microwave heterodyne spectrometers need to be calibrated in order to get the absolute brightness temperature of the source and to get rid of systematic errors (band pass characteristics, 1/f- noise, etc.). Take into account that in general the received signal intensities are only a small fraction of the noise the system produces itself. In order to get a sufficient signal-to-noise ratio, the spectrometer has to integrate long times. The radiometer formula describes how the rms of noise on measured signals depends on the noise – or system temperature* T_{sys}*, the resolution bandwidth of a spectrometer channel, B and the integration time* τ*.*

$$\Delta T = \frac{T_{sys}}{\sqrt{B \cdot \tau}}$$

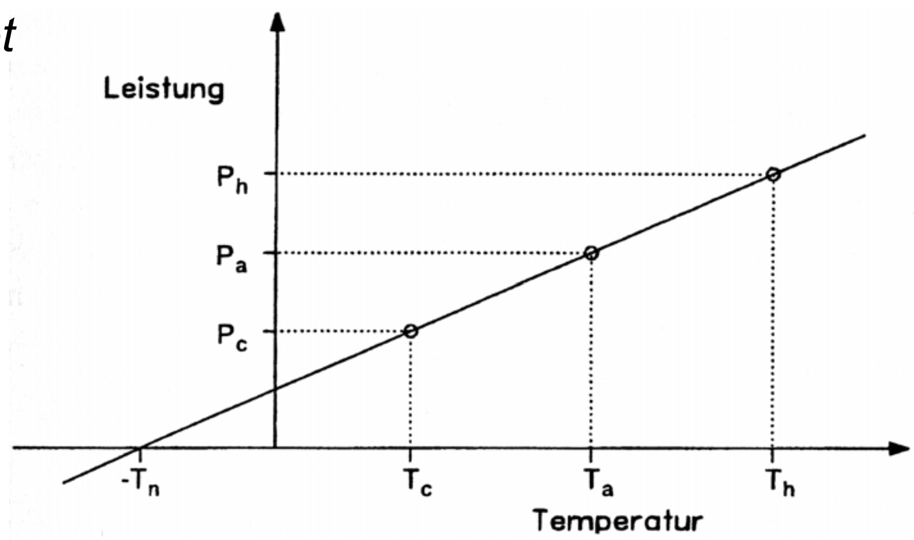
Calibration: Antenna – and Receiver Noise Temperature

- *The radiation received by the antenna (P_A) of the microwave receiver creates an antenna temperature T_A. Its absolute calibration is done by measuring the power (P_A, P_c) radiated by black bodies of known temperature (T_A, T_C) , here denoted as cold load and hot load. Due to the linear relationship between radiated power and temperature according the Rayleigh – Jeans formula we have to solve a linear equation (see picture) and get:*

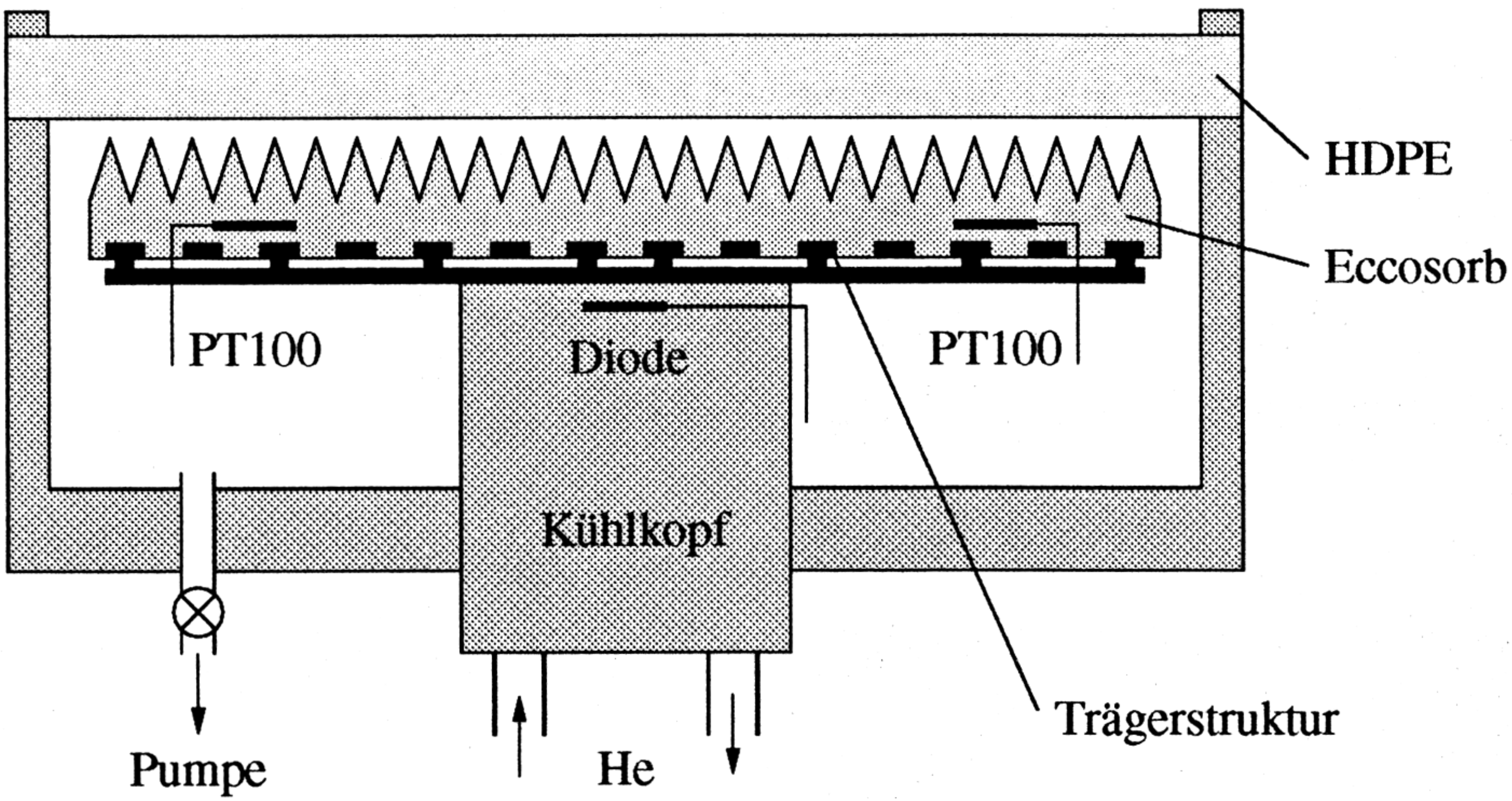
$$T_A = \frac{P_A - P_C}{P_H - P_C}(T_H - T_C) + T_C \quad [K]$$

Replacing P_A by P_n with P_n = 0, we get for the receiver noise temperature T_n:

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



Example: Cold Load



Microwave Radiative Transfer: Basic Formulas

$$I_\nu(x) = I_\nu(x_0)\, e^{-\int_{x_0}^{x} \mu_\nu(x')\, dx'} + \int_{x_0}^{x} \mu_\nu(x')\, J_\nu(x')\, e^{-\int_{x'}^{x} \mu_\nu(x'')\, dx''}\, dx'$$

I_ν = *Intensity of radiation*

ν = *Index of frequency*

x = *Local coordinate*

μ_ν = *Absorption coefficient*

$$J_\nu(x) = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/kT(x)} - 1}$$

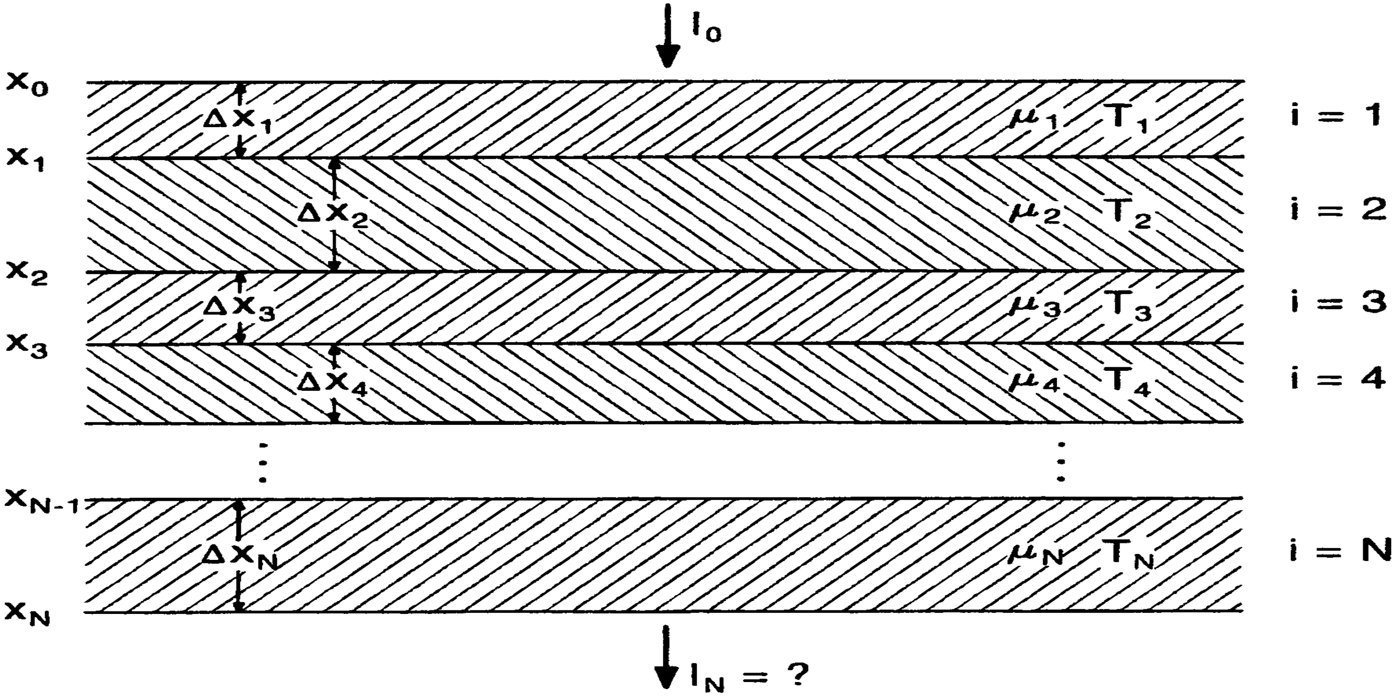
= *Source function (Planck)*

First term of equation: absorption of radiation on its way from x_0 to x

Second term: radiated and transmitted intensity (from gas molecules) along the line of sight to location x

Microwave radiative transfer equation: discretization

$$I(x_N) = I(x_0)\, e^{-\sum_{i=1}^{N} \mu_i \Delta x_i} + \sum_{i=1}^{N} J_i\, \mu_i\, e^{-\sum_{j>i}^{N} \mu_j \Delta x_j} \Delta x_i$$



Absorption coefficient

$$\mu_\nu = N\left(\frac{1}{4\pi\,\epsilon_0}\right)\frac{8\pi^3\mu_{lu}^2}{3hc}g_l g_u \frac{e^{-E_l/kT} - e^{-E_u/kT}}{Q(T)}\,\nu\, f(\nu,\nu_{ul})$$

N	=	*Number of emitting and absorbing molecules per volume*
ϵ_0	=	*Dielectric constant*
μ_{lu}	=	*Matrix element of electrical dipol moment*
g_l, g_u	=	*Degeneracy factor of upper and lower level*
E_l, E_u	=	*Energy of lower and upper level*
$Q(T)$	=	*Partition function*
$b(\nu,\nu_{ul})$	=	*Line shape function*
ν_{ul}	=	*Frequency of line center*

Line Shape Functions: collisional (pressure) broadening

Lorentz shape function

$$f_L(\nu, \nu_{ul}) = \frac{1}{\pi} \frac{\Delta\nu_C}{(\nu - \nu_{ul})^2 + \Delta\nu_C^2}$$

Pressure broadening parameter (HWHM)

$$\Delta\nu_C = \Delta\nu_0 \cdot \frac{p}{p_0} \left(\frac{T}{T_0}\right)^{-x}$$

Line Shape Functions: Doppler broadening

Doppler shape function (Gaussian velocity distribution of molecules)

$$f_D(\nu, \nu_{ul}) = \frac{1}{\Delta\nu_D}\sqrt{\frac{\ln 2}{\pi}}\, e^{-\ln 2\left(\frac{\nu - \nu_{ul}}{\Delta\nu_D}\right)^2}$$

Doppler broadening parameter

$$\Delta\nu_D = \nu_{ul}\sqrt{2\,\ln 2}\sqrt{\frac{kT}{mc^2}}$$

Line Shape Functions: Voigt function

Transition region: convolution between pressure and Doppler broadening

$$f_V(\nu, \nu_{ul}) = \int_{-\infty}^{\infty} f_L(\nu', \nu_{ul}) \cdot f_D(\nu', \nu)\, d\nu'$$