Development of a Miniaturized Microwave Radiometer for Satellite Remote Sensing of Water Vapor

by Willow Toso

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Department of Electrical and Computer Engineering

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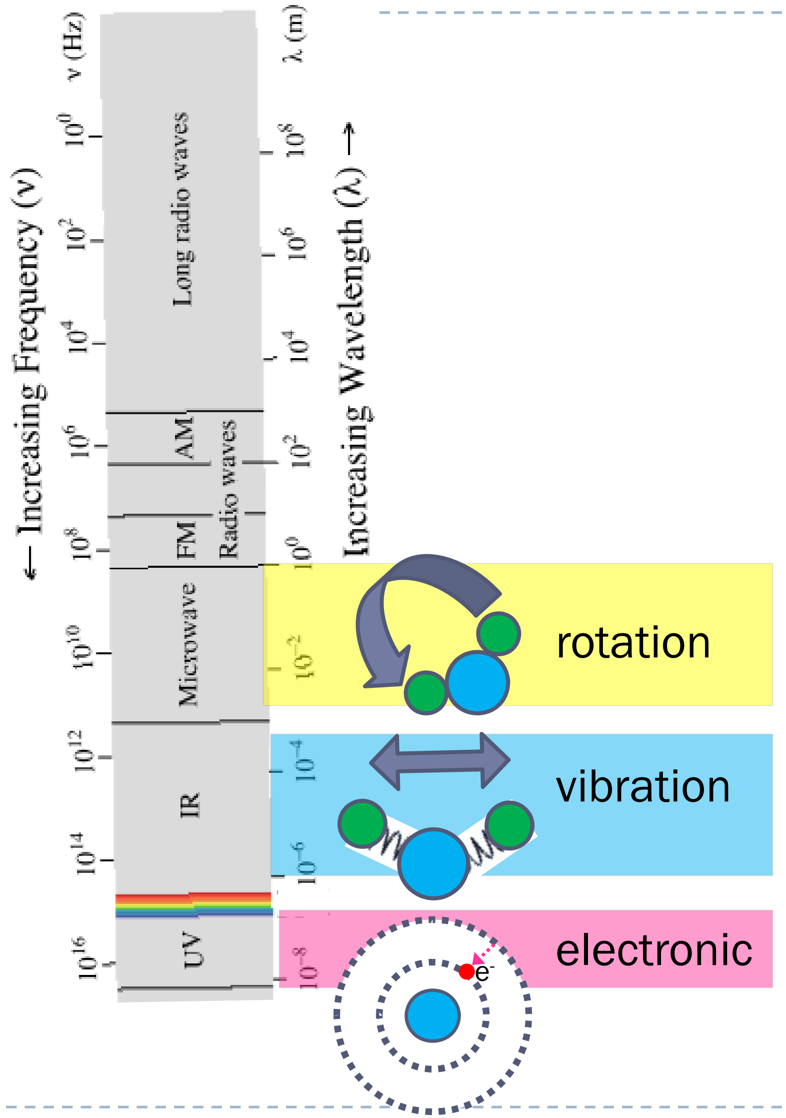
Scientific Background

Electromagnetic Radiation & Radiometry

The Dicke Radiometer

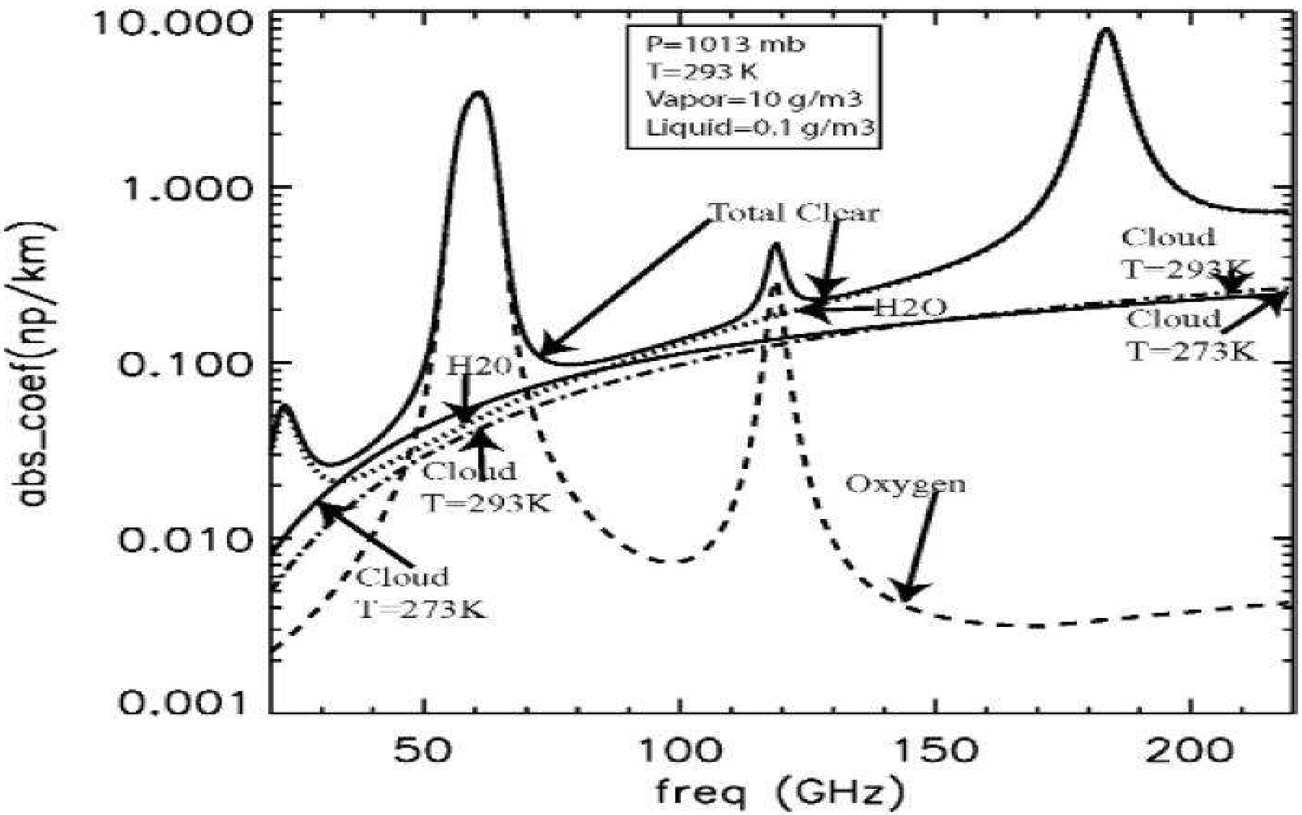
Water Vapor Monitoring

Electromagnetic Radiation



- All matter absorbs and emits electromagnetic radiation
- In addition to electronic transitions in their constituent atoms, molecules rotate and atoms vibrate (state transitions) at temperatures above absolute zero.
- The absorption of electromagnetic radiation is dependent on the type of state transition, i.e., rotational, vibrational or electronic.
- The specific state transition determines the absorption frequency.

Absorption of the atmosphere at 20-220 GHz

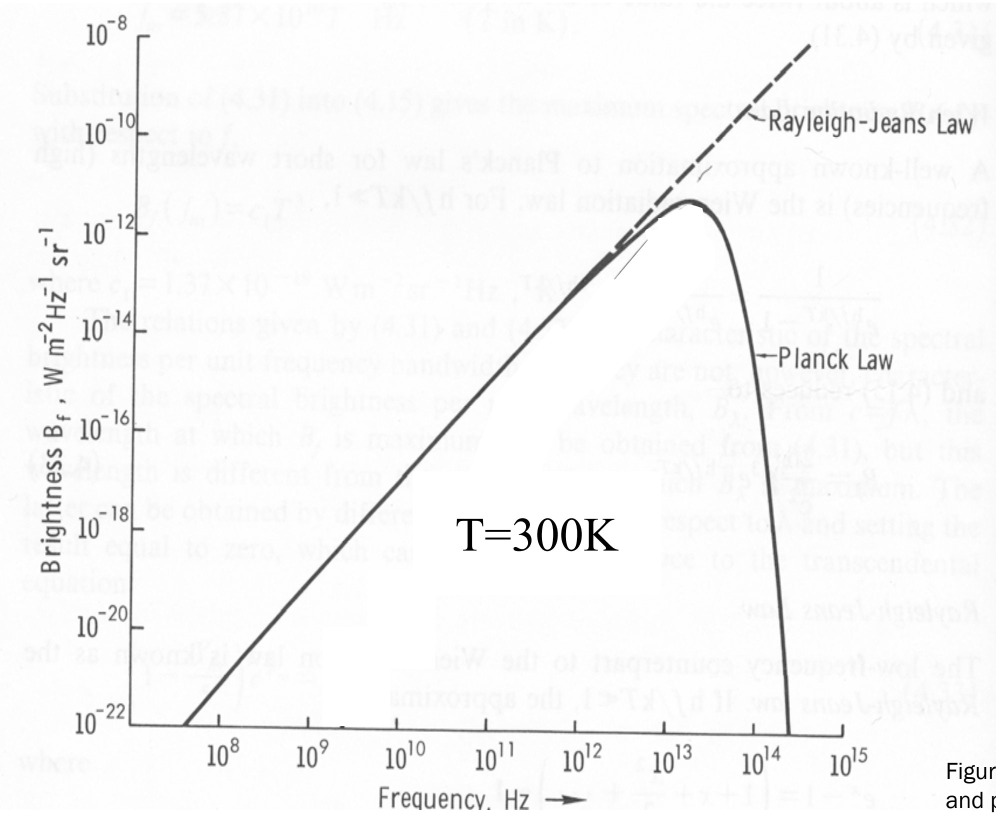


Contributions to atmospheric absorption by oxygen, water vapor and liquid water.[1]

[1] E.R. Westwater, S. Crewell, and C. Mätzler. "Surface-based microwave and millimeter wave radiometric remote sensing of the troposphere: a tutorial." *IEEE Geoscience and Remote Sensing Society Newsletter,* (134):16–33, March 2005.

Radiometry

- Radiometers measure radiation in the microwave and infrared regions
- The power measured is $P = kT_{ANT}\Delta f$ (W), where T_{ANT} is the apparent temperature measured by the radiometer.



$$B_f = \frac{2kT}{\lambda^2}$$

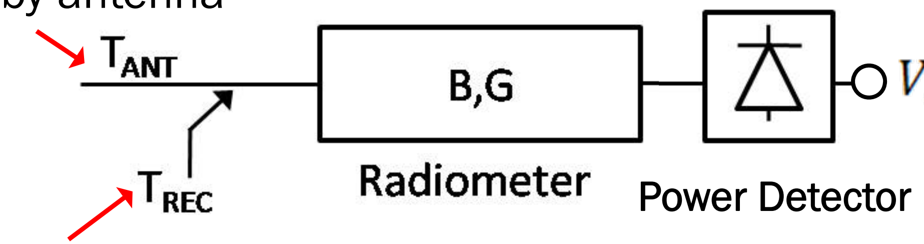
k = 1.38x10^{-23} J K^{-1}
T = absolute temperature (K)
λ = wavelength (m)

Figure from: F.T. Ulaby, R.K. Moore and A.K. Fung. “Microwave remote sensing: active and passive” Addison-Wesley Pub. Co., Reading, Mass., pp. 198, 1981

Total Power versus Dicke radiometer

Apparent temperature measured by antenna

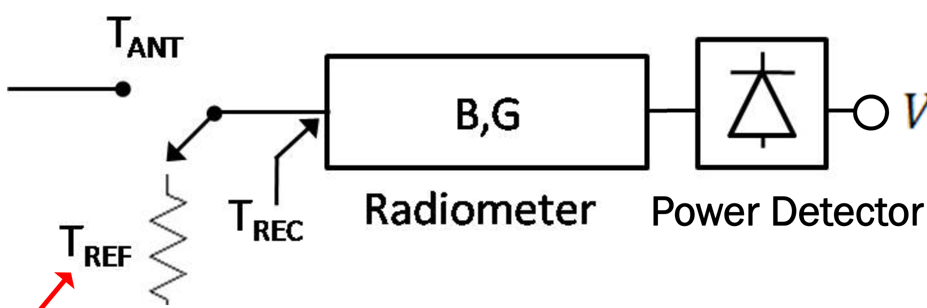
Total Power radiometer



$$V_{out} \propto P_{out} = kG\Delta f\,(T_{ANT} + T_{REC})$$

Equivalent noise temperature of receiver

Dicke radiometer



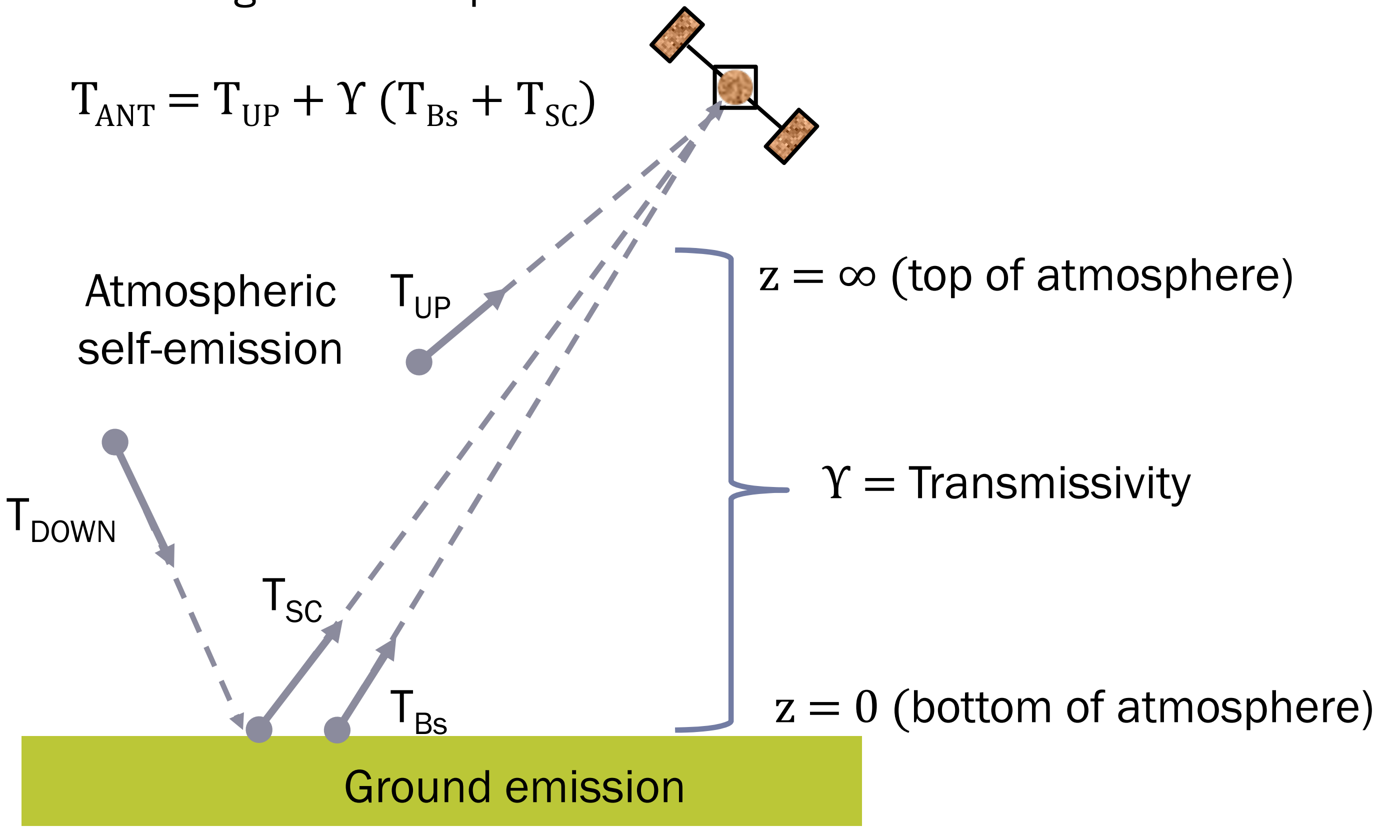
$$V_{out} \propto P_{out} = kG\Delta f\,(T_{ANT} - T_{REF})$$

Internal reference physical temperature

Apparent Brightness Temperature

- T_{ANT} is the apparent temperature measured by the radiometer
- T_{UP} is the upwelling radiation
- T_{SC} is the surface-scattered downwelling (T_{DOWN}) radiation
- T_{BS} is the surface brightness temperature

$$T_{ANT} = T_{UP} + \Upsilon\,(T_{Bs} + T_{SC})$$

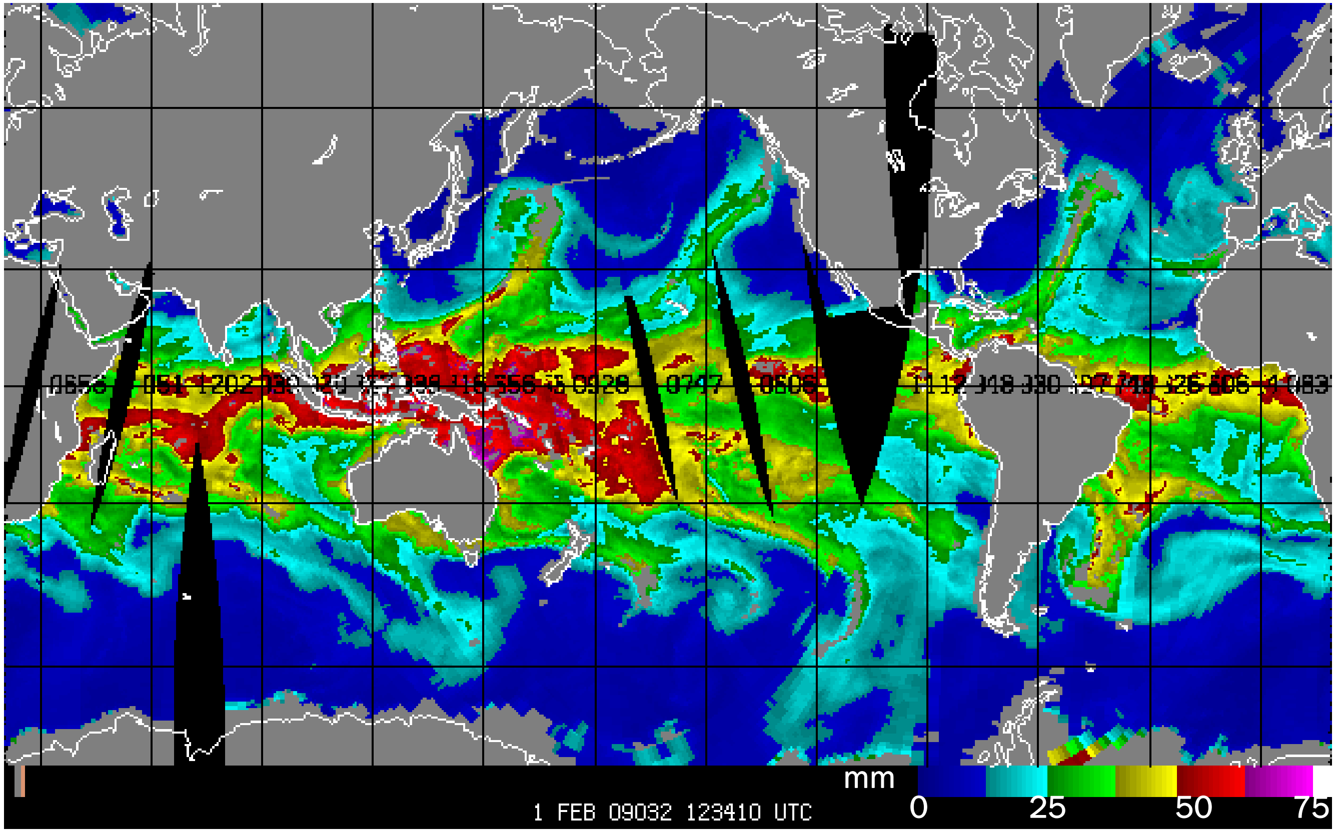


Why Water Vapor?

Observations of water vapor in the atmosphere are used in weather prediction and climate change models,

and water vapor plays an important role in climate change and atmospheric convection and precipitation.

Precipitable Water Vapor (PWV)



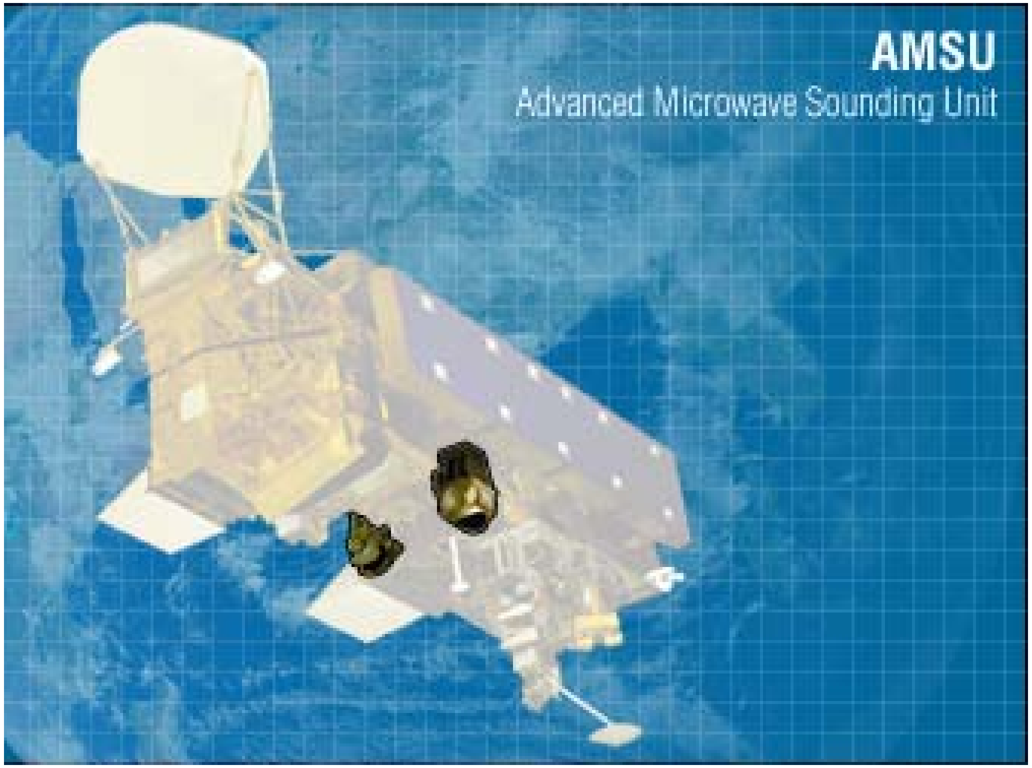
From http://amsu.cira.colostate.edu/

PWV was measured in Boulder, CO, on August 10, 2006 to be 21 mm*

*during Refractivity Experiment For H2O (water vapor) Research And Collaborative operational Technology Transfer (REFRACTT)

Advanced Microwave Sounding Unit (AMSU-A)

- AMSU-A is a microwave radiometer with 15 channels. Channel-1 measures water vapor and channel-2 measures liquid water.
- AMSU-A was launched on NOAA's Polar Orbiting Environmental Satellites 15-18. In addition, it is on-board NASA's Aqua satellite, launched on May 4, 2002, as shown below.



From http://aqua.nasa.gov/about/instrument_amsu.php

Table 1. AMSU-A CHANNEL CHARACTERISTICS

CH NO.	CENTER FREQUENCY (MHZ)	NO. OF PASS BANDS	BAND-WIDTH (MHz)
1	23800	1	270
2	31400	1	180
3	50300	1	180
4	52800	1	400
5	53596 ± 115	2	170
6	54400	1	400
7	54940	1	400
8	55500	1	330
9	57900.344 (f_{LO})	1	330
10	fLO ± 217	2	78
11	fLO ± 322.2 ± 48	4	36
12	fLO ± 322.2 ± 22	4	16
13	fLO ± 322.2 ± 10	4	8
14	fLO ± 322.2 ± 4.5	4	3
15	89.0 GHz	1	6000

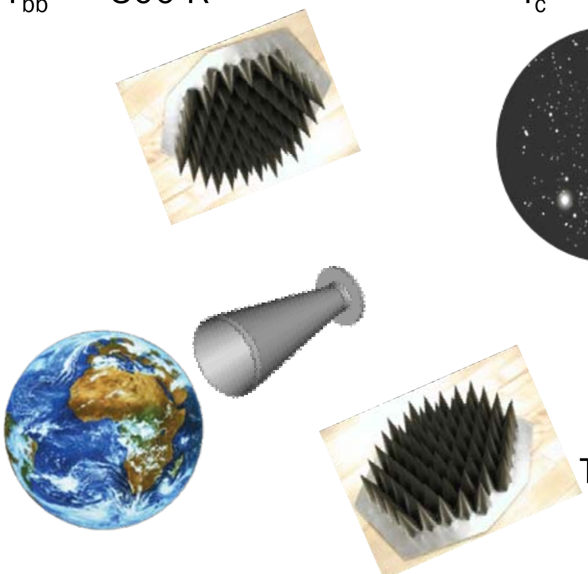
NOTE: Channels 1, 2, 3, 4, 7 and 15 are vertically polarized, other remaining channels are horizontally polarized.

P.K. Patel and J. Mentall, "The Advanced Microwave Sounding Unit-A (ASMU-A)", Proc. Of IEEE Topical Symposium on Combined Optical, Microwave, Earth and Atmospheric Sensing, pp. 159-164, 22-25 March 1993,

T_{ANT} from V_{out} by Calibration

Blackbody *
T_{bb} = ~300 K

Cosmic background
T_c = 2.73 K



Blackbody*
T_{bb} = ~300 K

$$V_{out,bb} = aT_{bb} + b$$

$$V_{out,c} = aT_c + b$$

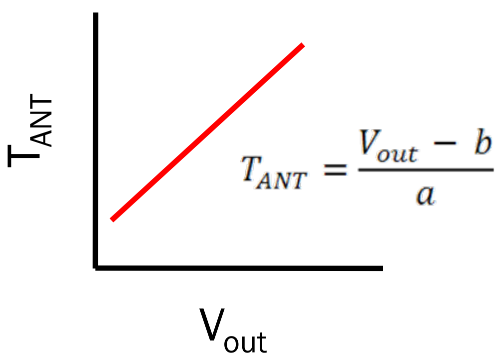
$$a = \frac{V_{out,bb} - V_{out,c}}{T_{bb} - T_c}$$

$$b = \frac{V_{out,c}T_{bb} - V_{out,bb}T_c}{T_{bb} - T_c}$$

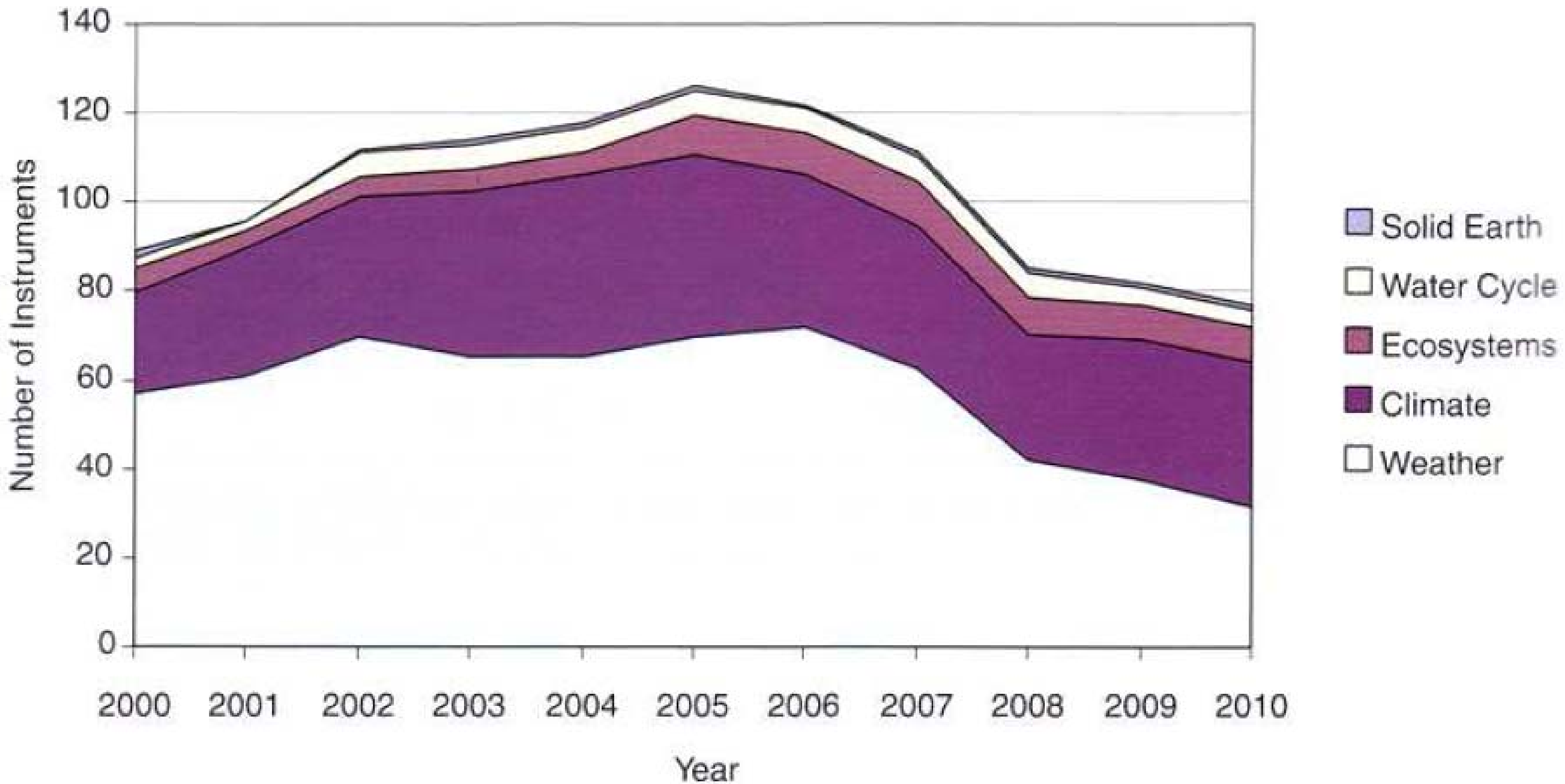
Example of calibration cycle on AMSU-A occuring every 8 s

T_{bb} is precisely known from PRTs embedded in the blackbody

* From http://arcade.gsfc.nasa.gov/instruments.html



Decline in Number of Climate Monitoring Instruments



- Number of U.S. space-based Earth observation instruments from 2000 - 2006, and projected from 2007 - 2010. Current instruments are projected to operate four years past their nominal lifetimes.*

* Committee on earth science, applications from space: A community assessment, and strategy for the future. “Earth science and applications from space: National imperatives for the next decade and beyond”. National Academies Press, Washington, DC, 2007

Venture Class Missions

- Seventeen missions were recommended to the National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA) by the National Research Council (NRC) decadal survey in 2007.
- These missions are recommended to be conducted by 2020 and are predicted to cost a total of US$ 7.5 B in FY2006 dollars.
- This is the same estimated cost of the National Polar-orbiting Operational Environmental Satellite System (NPOESS) before it breached the Nunn-McCurdy cost growth cap in 2005.
- It was recommended that NASA increase investment in cross-cutting technology development to decrease cost and create a new ”Venture Class” of low-cost research and application missions (US$100-200 M).
- The NASA “Venture Class” missions are for small, cost-effective spacecraft, which will carry light-weight, low-power instruments into orbit.

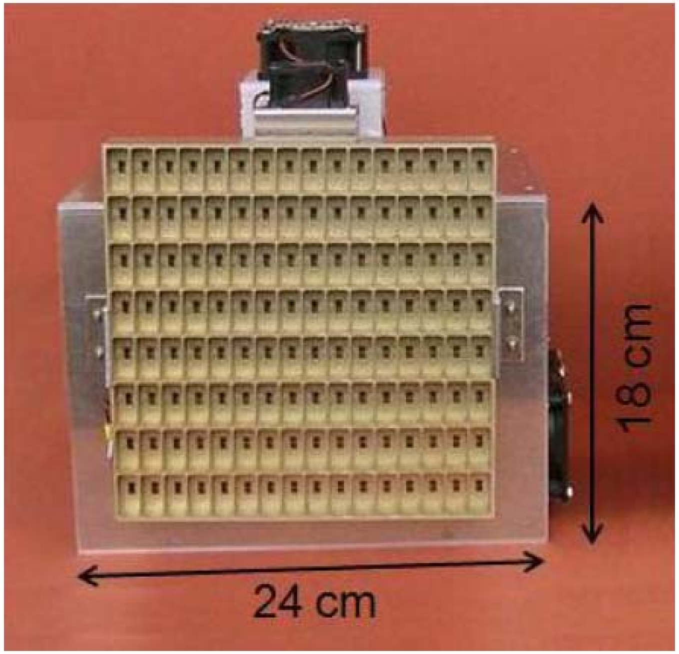
Miniaturized Radiometer for Remote Sensing of Water Vapor

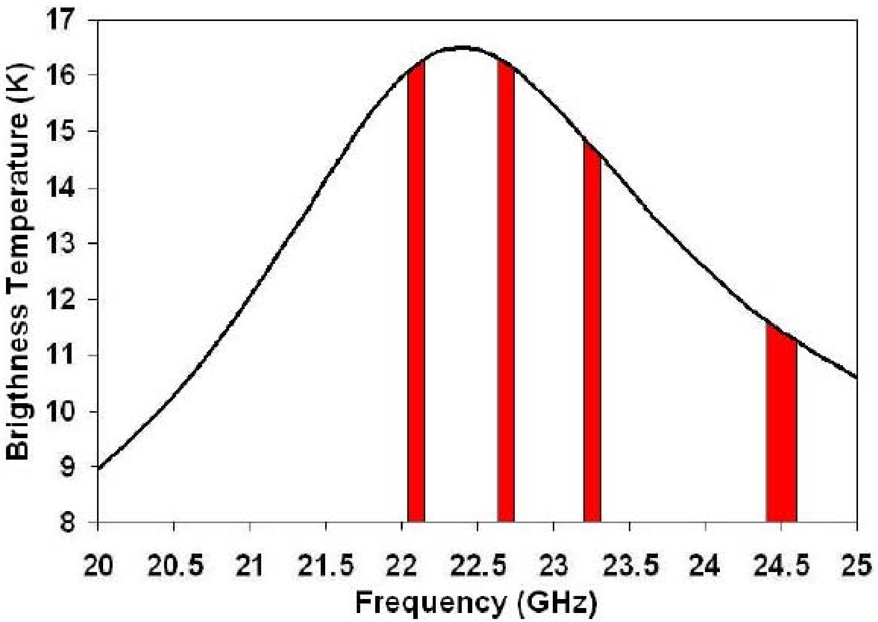
MMIC components

CMR-H

Microrad

Compact Microwave Radiometer for Humidity (CMR-H) Profiling





Mass (kg)	Dimensions (cm)	Power (W)	Beamwidth (deg)	Temp. Stability (°C)
6	24 x 18 x 16	50	3-4	0.1

Center Frequencies of the CMR-H: 22.12, 22.67, 23.25 and 24.5 GHz

- F. Iturbide-Sanchez, S. C. Reising and S. Padmanabhan, "A Miniaturized Spectrometer Radiometer Based on MMIC Technology for Tropospheric Water Vapor Profiling, *IEEE Trans. Geosci. Remote Sensing, vol. 44, no. 7, pp. 2181-2193, July 2007.*

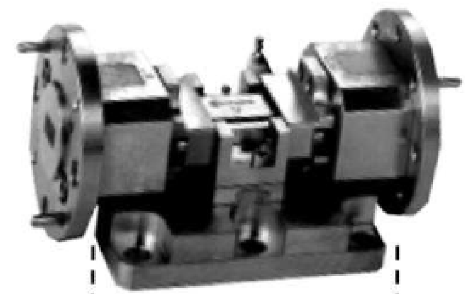
Monolithic Microwave Integrated Circuits (MMIC)

Connectorized and waveguide-based components

18-26 GHz LNA

10.94 mm

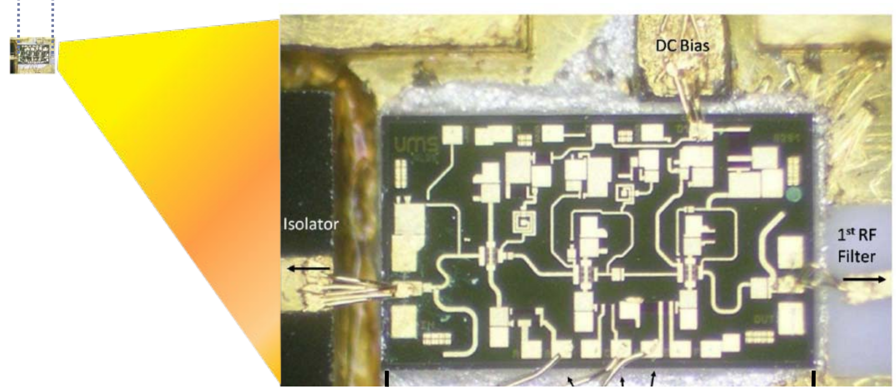
LNA with WR 22 or WR 19 waveguide inputs



40.78 mm

MMIC LNA scaled in comparison with the connectorized LNA and enlarged x25

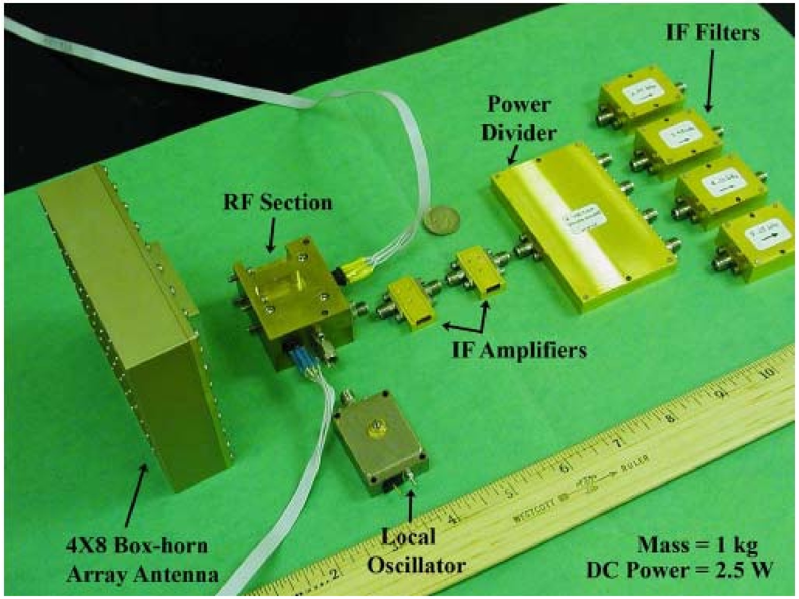
18-31 GHz GaAs MMIC LNA



2.17 mm

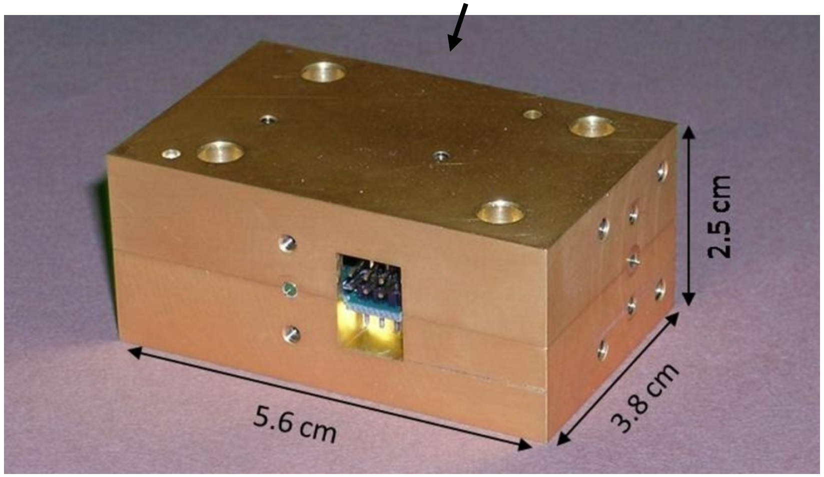
CMR-H and Microrad Multi-Chip Modules

CMR-H has 9 MCMs



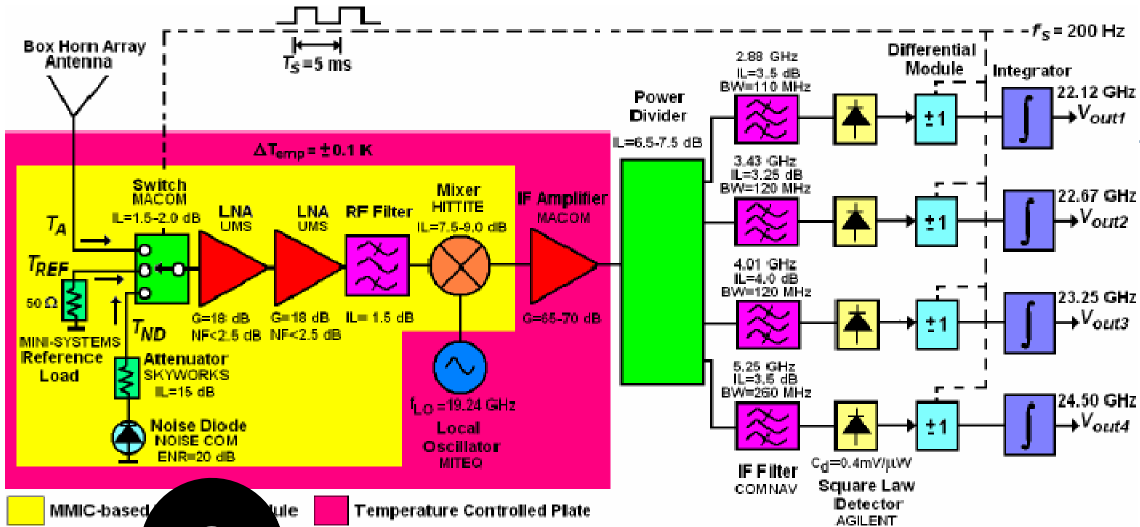
Microrad has 3 MCMs:
RF/IF MCM & VCO shown

RF/IF MCM

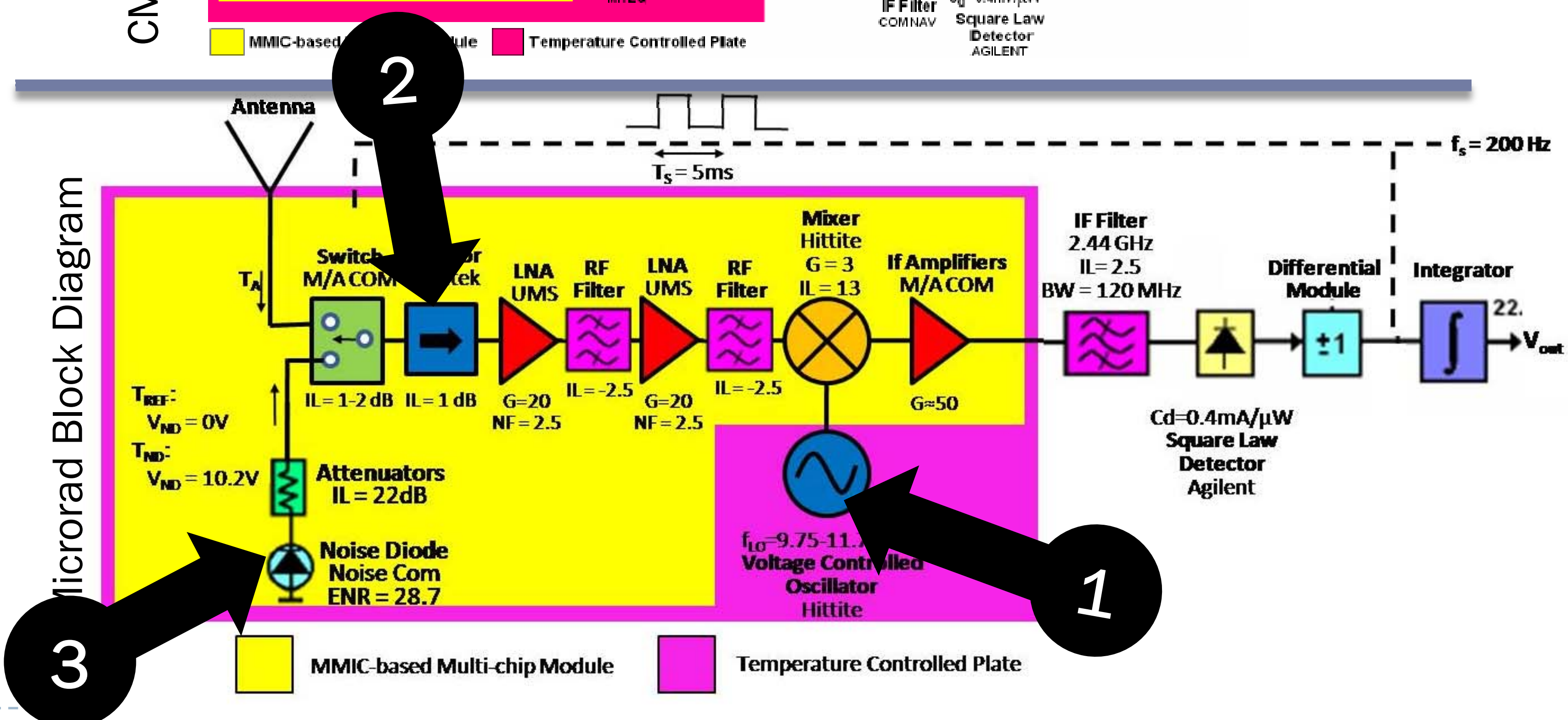


Hittite HMC-030

CMR-H Block Diagram

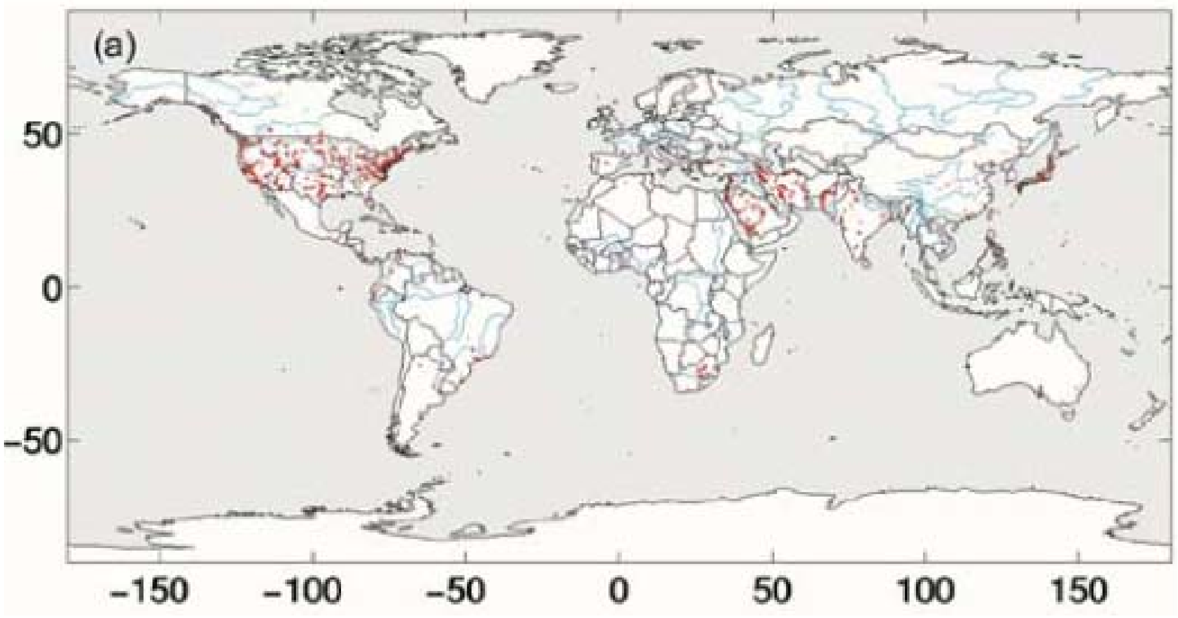


Microrad Block Diagram



Radio-Frequency Interference (RFI)

- Space-based passive microwave measurements of Earth must cope with RFI from other satellites and ground-based transmitters, principally radar and communications transmitters.
- Hotspots around the globe interfering with AMSR-E 6.9 GHz channel are shown*.



*E.G. Njoku, P. Ashcroft, R.K. Chan, and Li Li, "Global Survey and Statistics of Radio-Frequency Interference in AMSR-E and Observations", IEEE Trans. On GeoScience and Remote Sensing, vol. 43, no. 5, May 2005

Microrad RF/IF Multi-chip Module

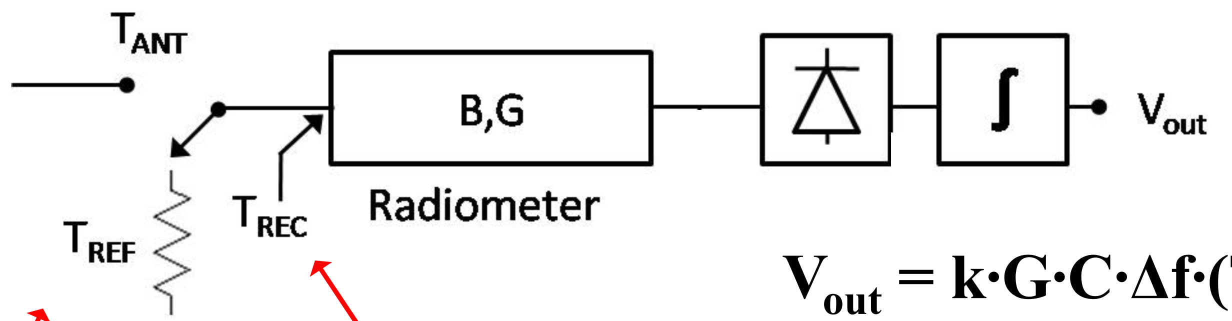
Radiometric Resolution

Receiver Noise Temperature

Internal Calibration

Effect of Gain Variation on Dicke Radiometer

Brightness temperature measured by antenna



$$V_{out} = k \cdot G \cdot C \cdot \Delta f \cdot (T_{ANT} - T_{REF}) + k \cdot \Delta G \cdot C \cdot \Delta f \cdot (T_{ANT} - T_{REF})$$

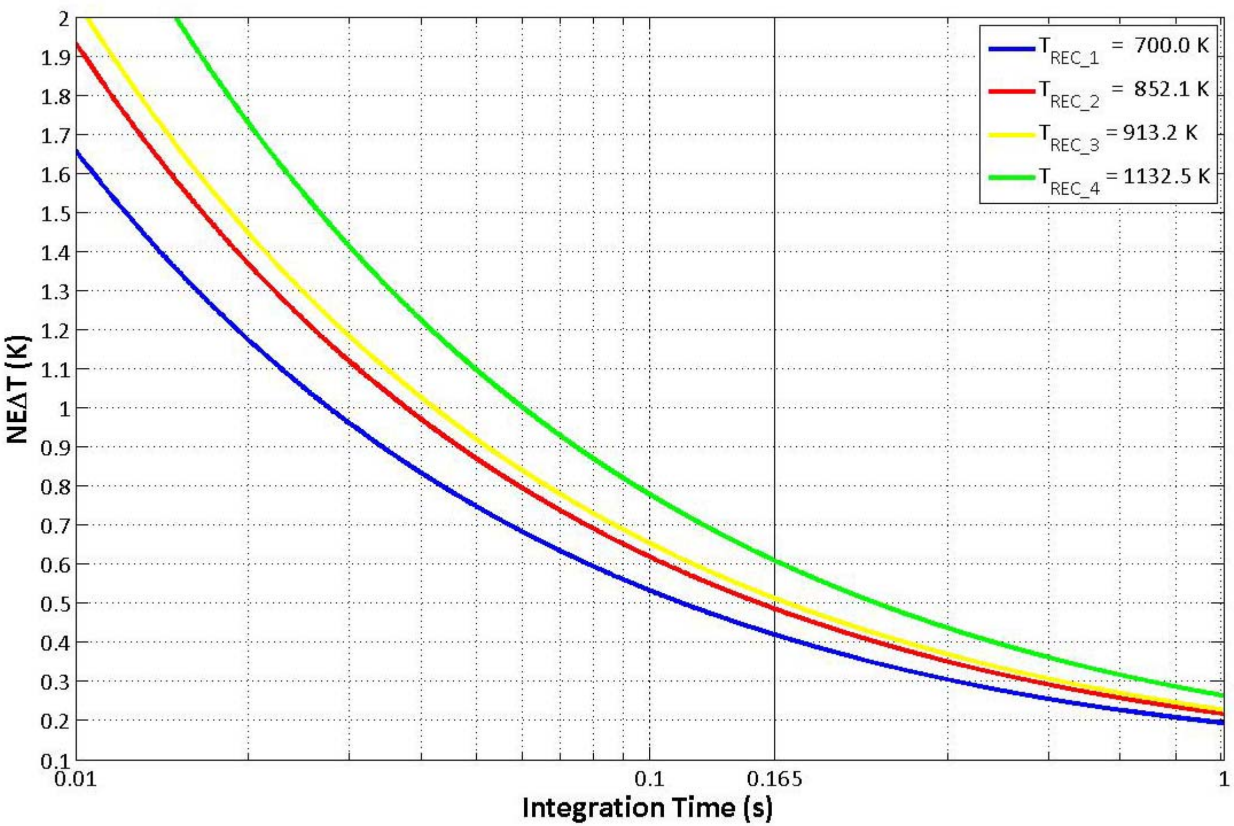
Internal reference physical temperature

Equivalent noise temperature of receiver

ΔG is gain variation
C is the sensitivity (V/W) of the power detector

Radiometric Resolution

$$NE\Delta T = \left[\frac{2(T_{ANT} + T_{REC})^2 + 2(T_{REF} + T_{REC})^2}{B\tau} + \left(\frac{\Delta G}{G}\right)^2 (T_{ANT} - T_{REF})^2 \right]^{\frac{1}{2}}$$



The smallest increment in brightness temperature, NEΔT, that can be detected is roughly proportional to T_{REC} and ΔG/G, the fractional gain variation.

B is the bandwidth and τ is the integration time.

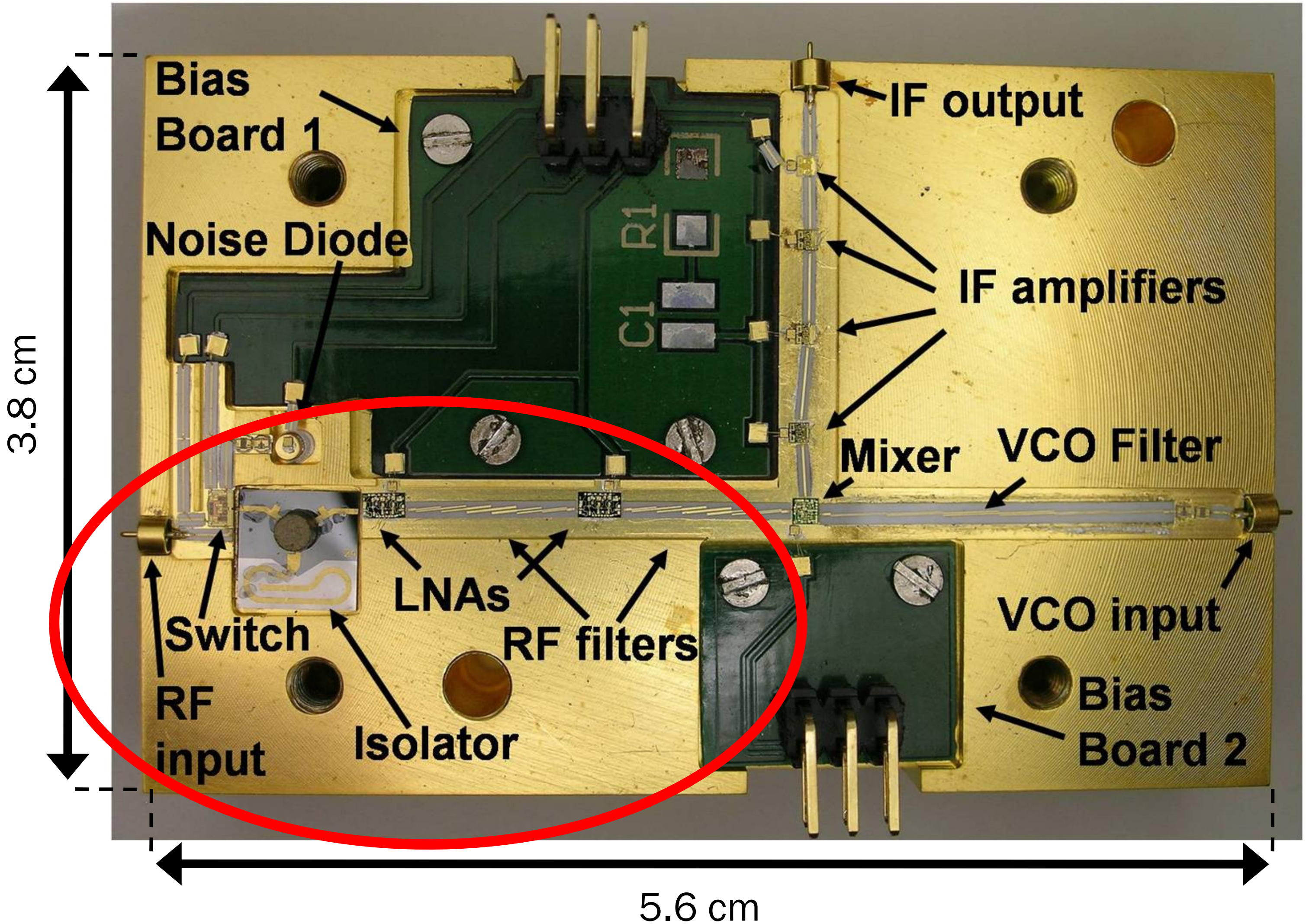
Calculating Receiver Noise Temperature

$$T_{REC} = (F_{REC} - 1)T_{o}, \quad T_o = 290 \text{ K}$$

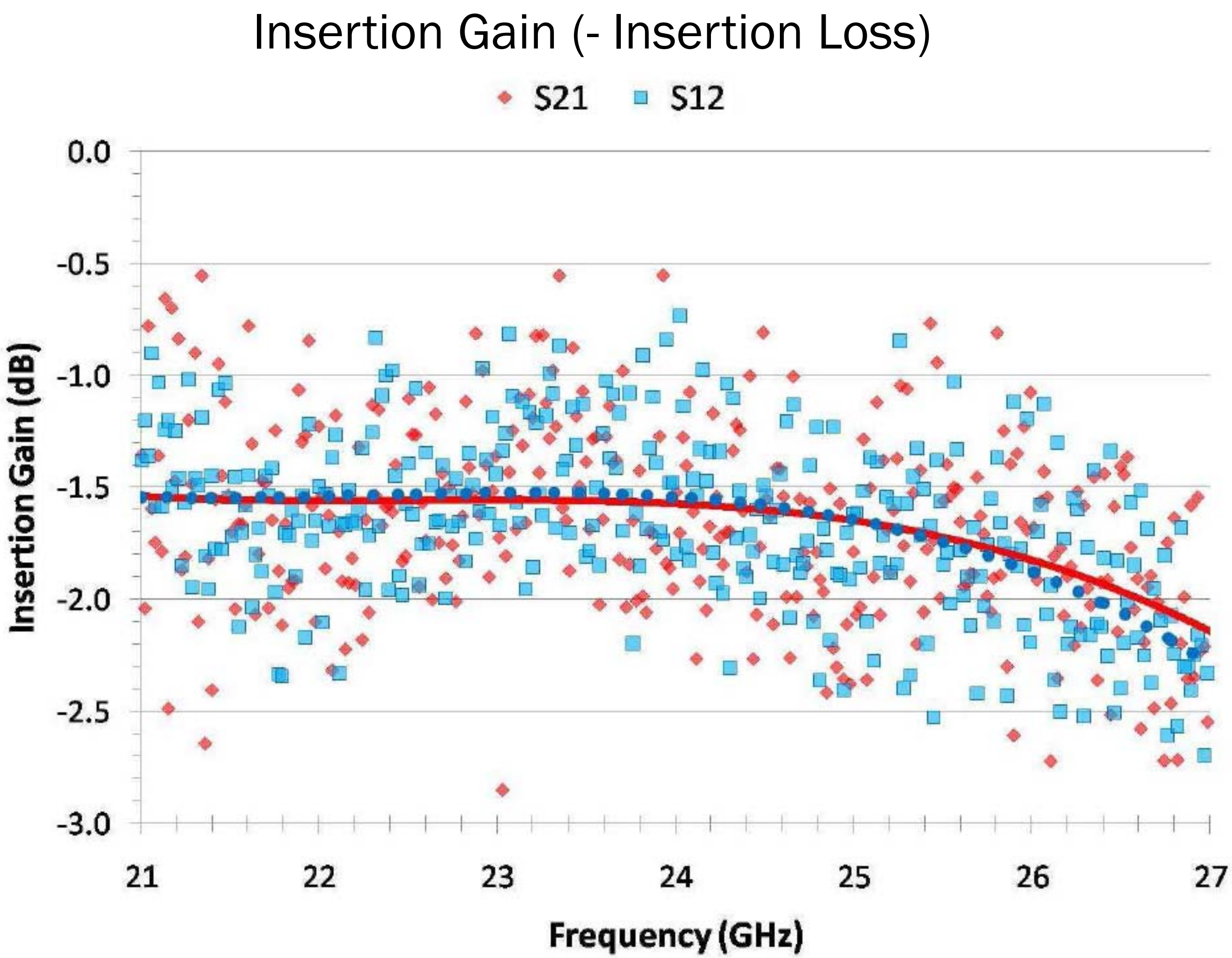
$$F_{REC} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 \cdot G_2} + \frac{F_4 - 1}{G_1 \cdot G_2 \cdot G_3} + \cdots$$

- F_1 is the noise figure of the first component
- G_1 is the gain of the first component
- F_2 is the noise figure of the second component
- G_2 is the gain of the second component, and so on...
- The noise figure (linear, not dB) of a lossy component is equal to its insertion loss at a physical temperature of T_o

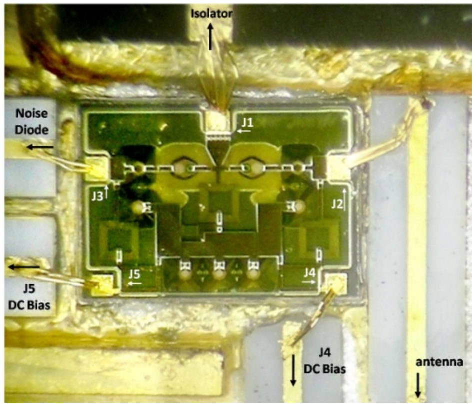
Microrad RF Section



Pin Diode Switch

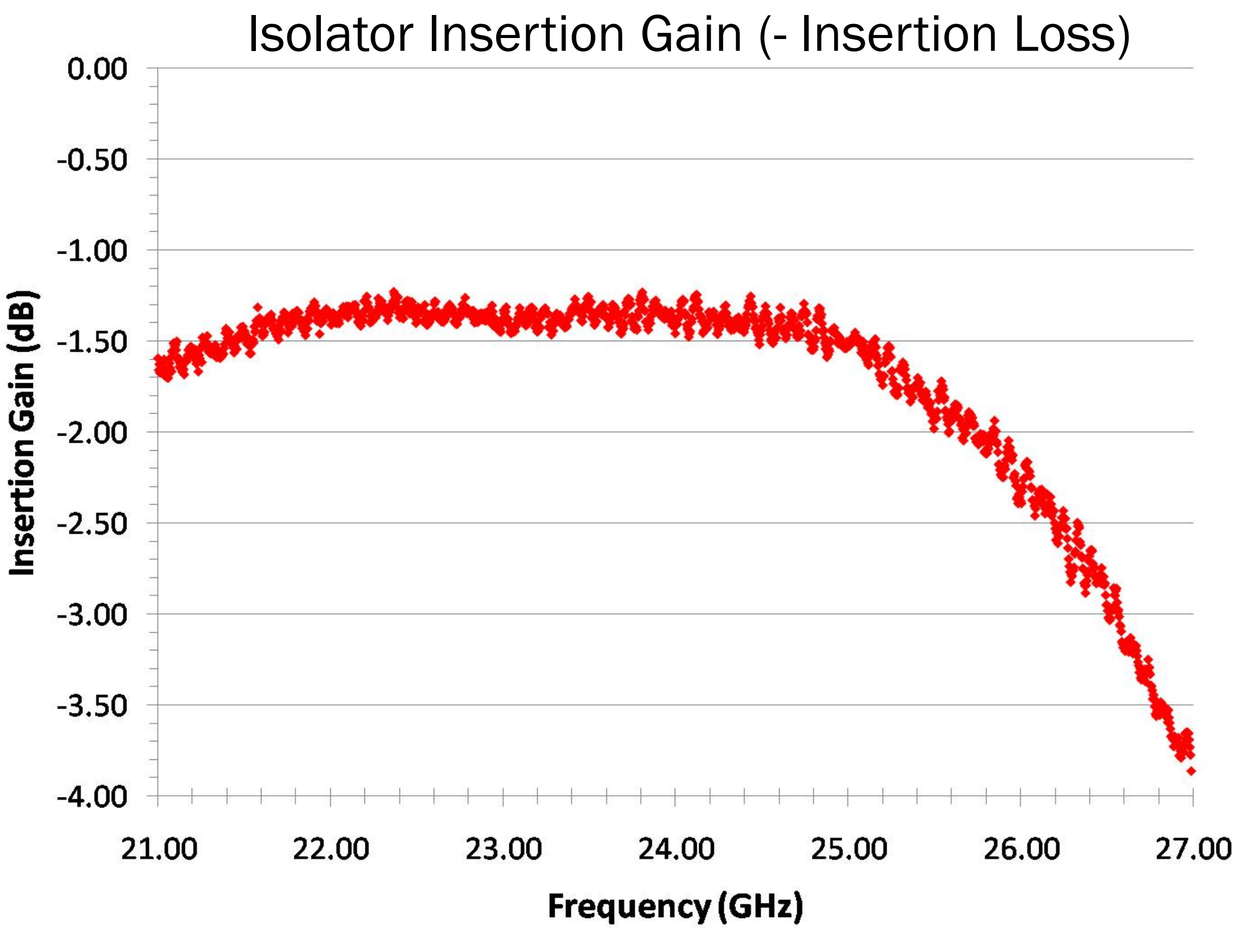


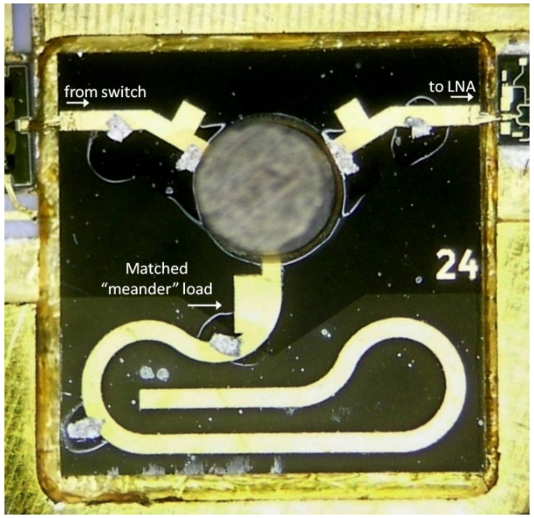
data courtesy of Eve Klopf



M/A-COM MA4SW210B-1

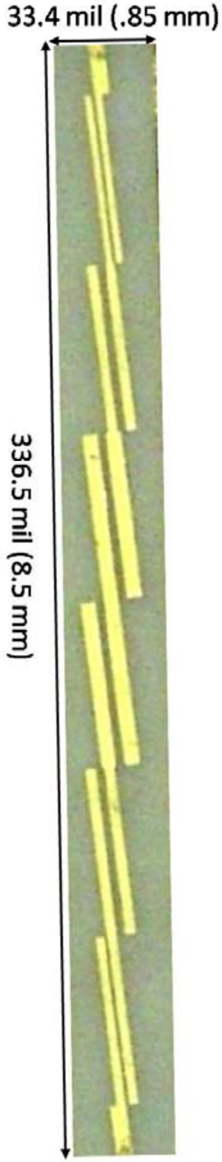
Isolator Insertion Gain

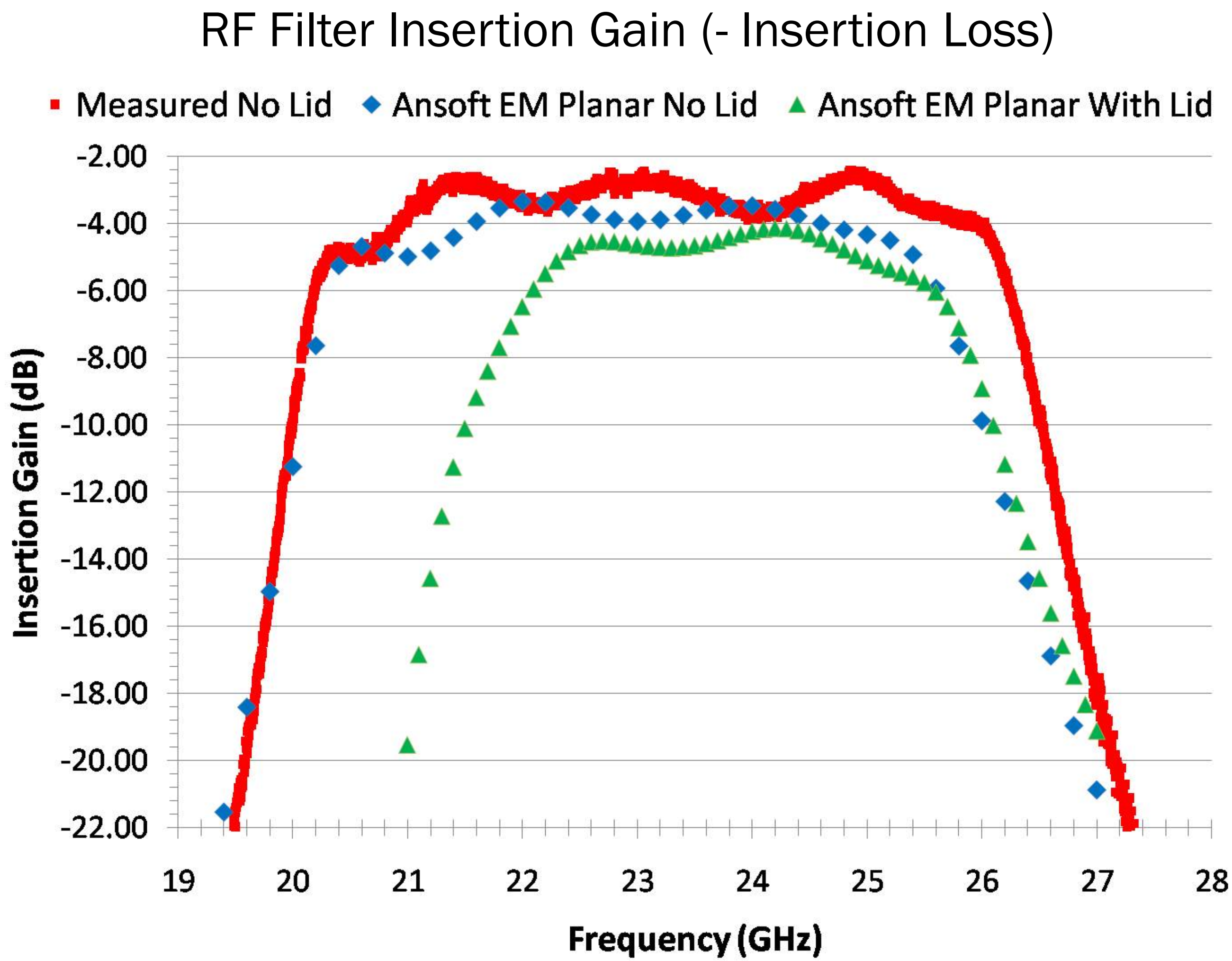




RADI-22-26-MSS-0.2WR-NM

RF Bandpass Filter





Noise Figure for 22 – 25.5 GHz

Components (in order)	Gain (dB)	Noise Figure (dB)
RF input*	-0.5	0.5
Switch	-1.51	1.51
Isolator	-1.4	1.4
LNA #1	21	2.5
BPF #1	-2.58	2.58
LNA#2	21	2.5
BPF#2	-2.58	2.58

Total Gain (dB)	32.53
Total Noise Figure (dB)	5.95
Equivalent Noise Temperature (K)	852.1

*RF input includes waveguide-to-K adapter, glass bead and first transmission line

NEΔT Varies with Frequency

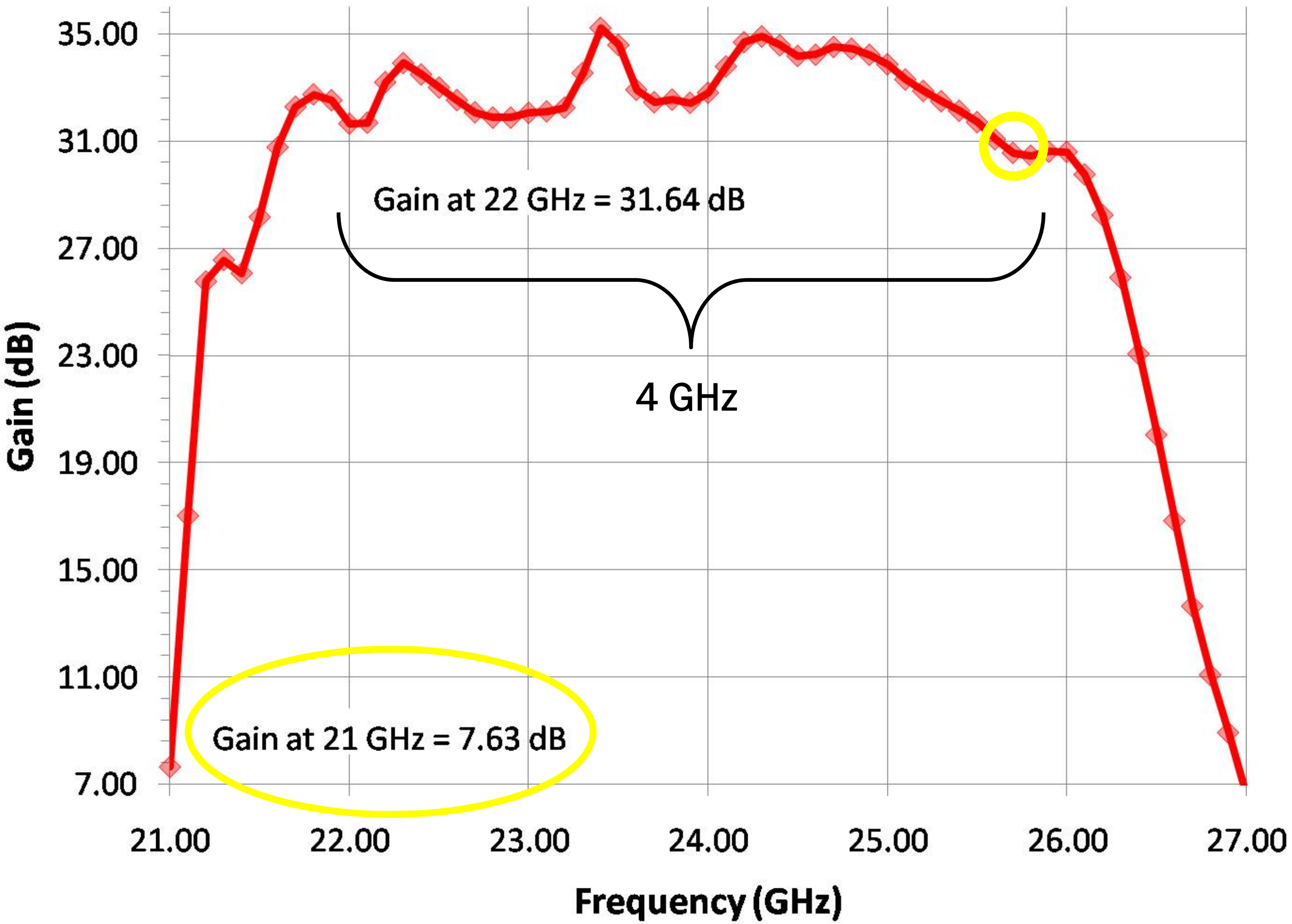
Frequency Range (GHz)	Equivalent Noise Temperature (K)	NEΔT for 0.165 second integration time (K)
22-25.5	852.1	0.50
25.5-26	1132.5	0.60

AMSU-A Channel-1 (GHz)	Equivalent Noise Temperature (K)	NEΔT for 0.165 second integration time (K)*
23.8	-	0.45

External calibration needs to be performed before the NEΔT can be accurately measured

*T.Mo. "Postlaunch calibration of the NOAA-18 Advanced Microwave Sounding Unit-A." *IEEE Trans. Geosci. Remote Sensing*, 45:1928–1937, Jul 2007.

Microrad RF Section Gain

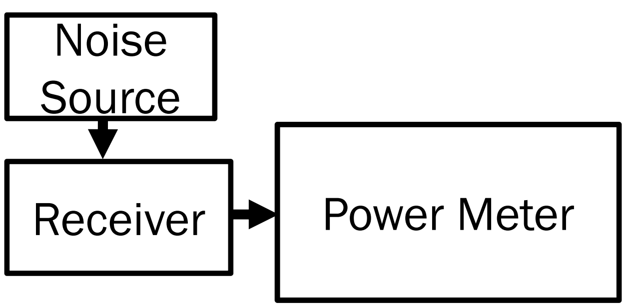


Measured Noise Figure Over 4 GHz RF Bandwidth

- Y- Factor Method uses the ratio of two known noise power levels to determine the noise of the receiver. An Agilent 346C Noise Source was used as the known source of noise.

$$Y = \frac{T_S^{on} + T_{REC}}{T_o + T_{REC}}$$

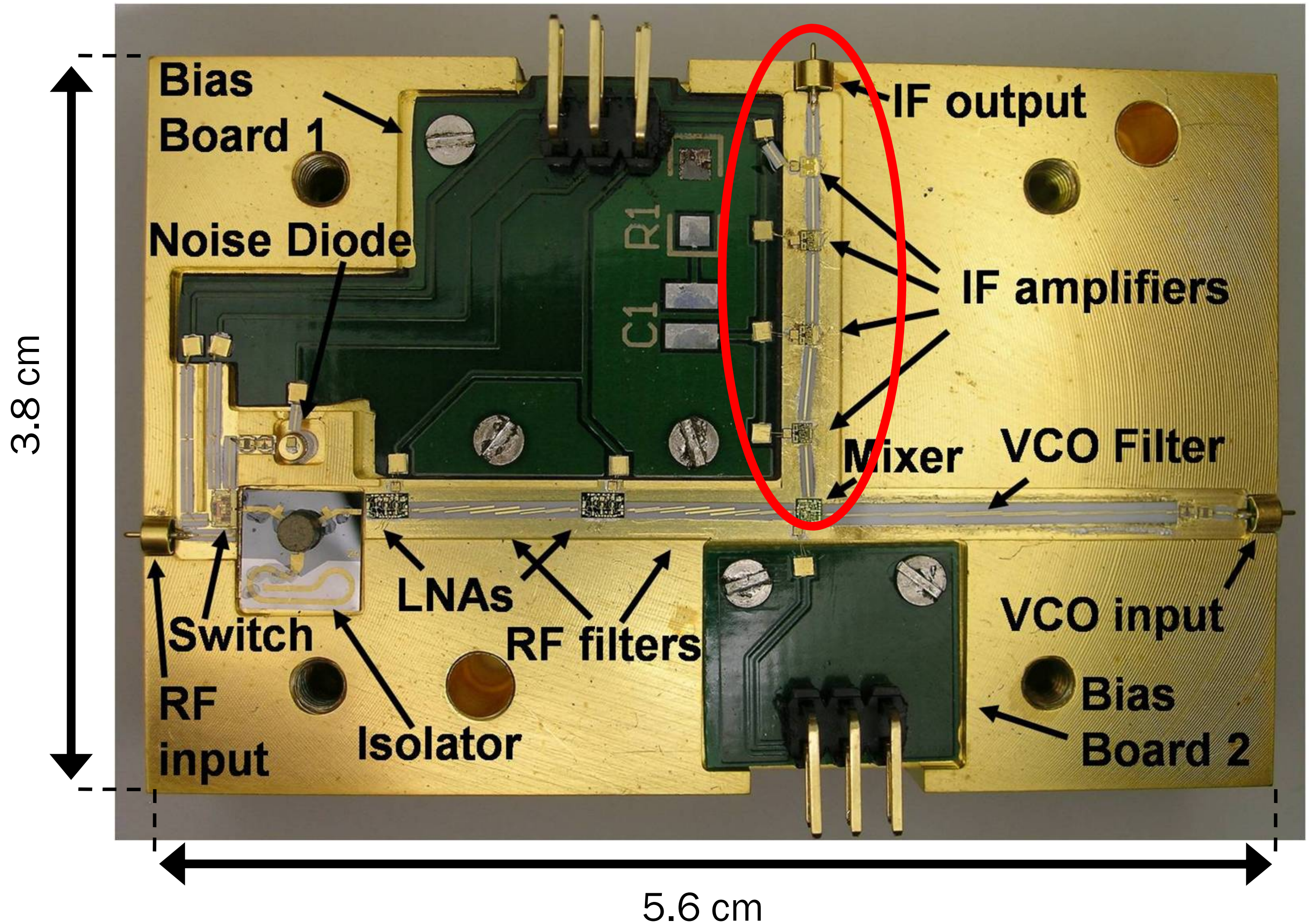
- The equivalent noise temperature of the noise source on is T_s^{on} = 9460.6 K, and off is equivalent to T_o = 290 K.



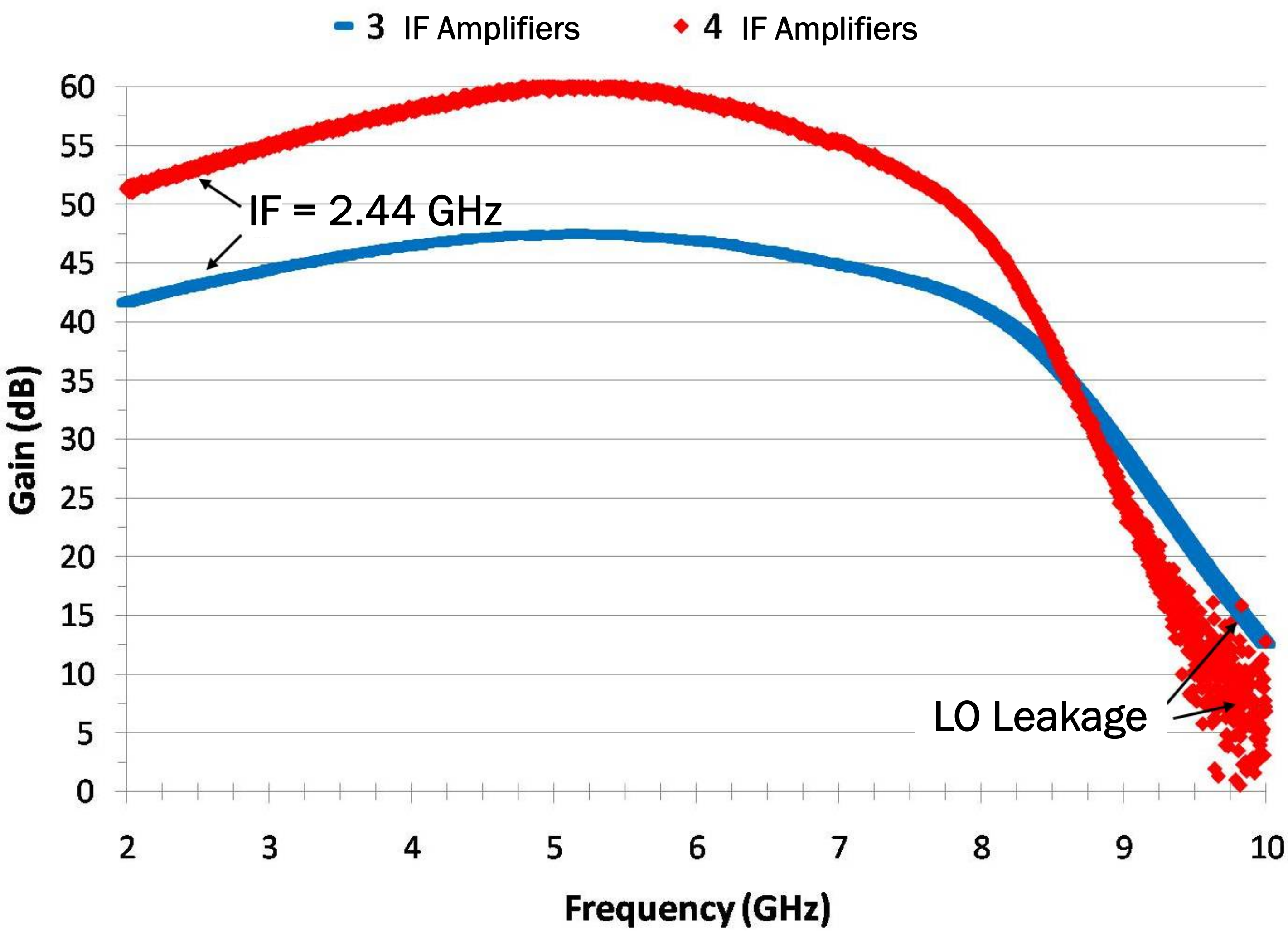
measured with Agilent E4419B power meter

$$T_{REC} = \frac{T_S^{on} - YT_o}{Y - 1} = 851.7\,K$$

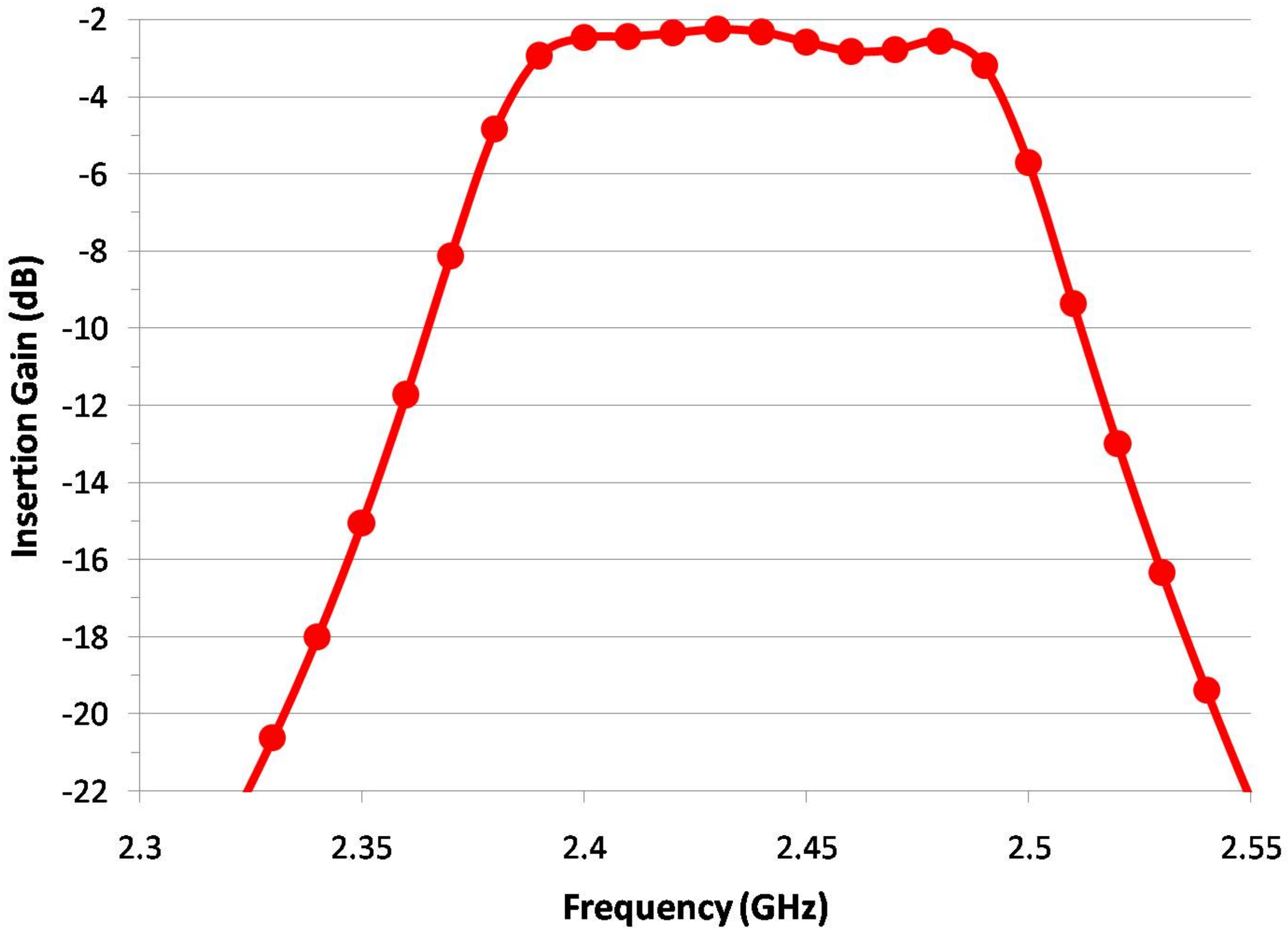
Microrad IF Section



Measured IF Amplifier Gain

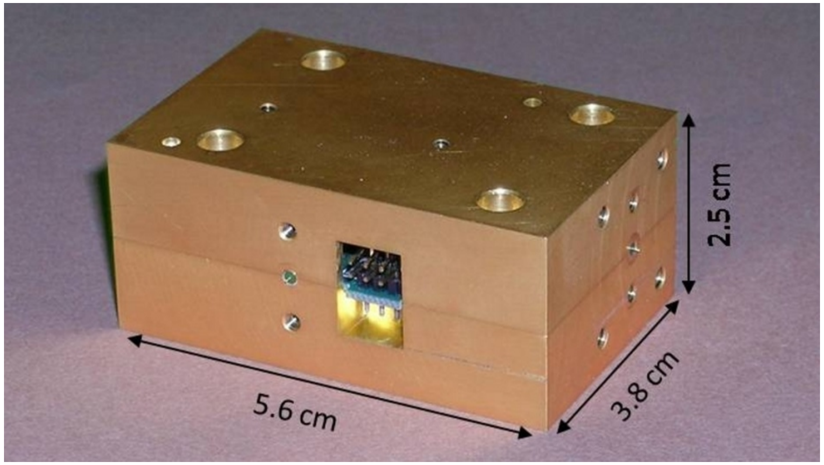


IF Filter Insertion Gain (-Insertion Loss)



Summary

Noise Figure	5.95 dB
Receiver Equivalent Noise Temperature	851.7 K
Total Gain	70 dB
Operation Bandwidth	22 – 26 GHz
Max Power Consumption	3.26 W
Mass	450 g
Size	5.8 x 3.7 x 2.5 cm



Comparison of Space-borne Microwave Radiometers for Observing Water Vapor with CMR-H

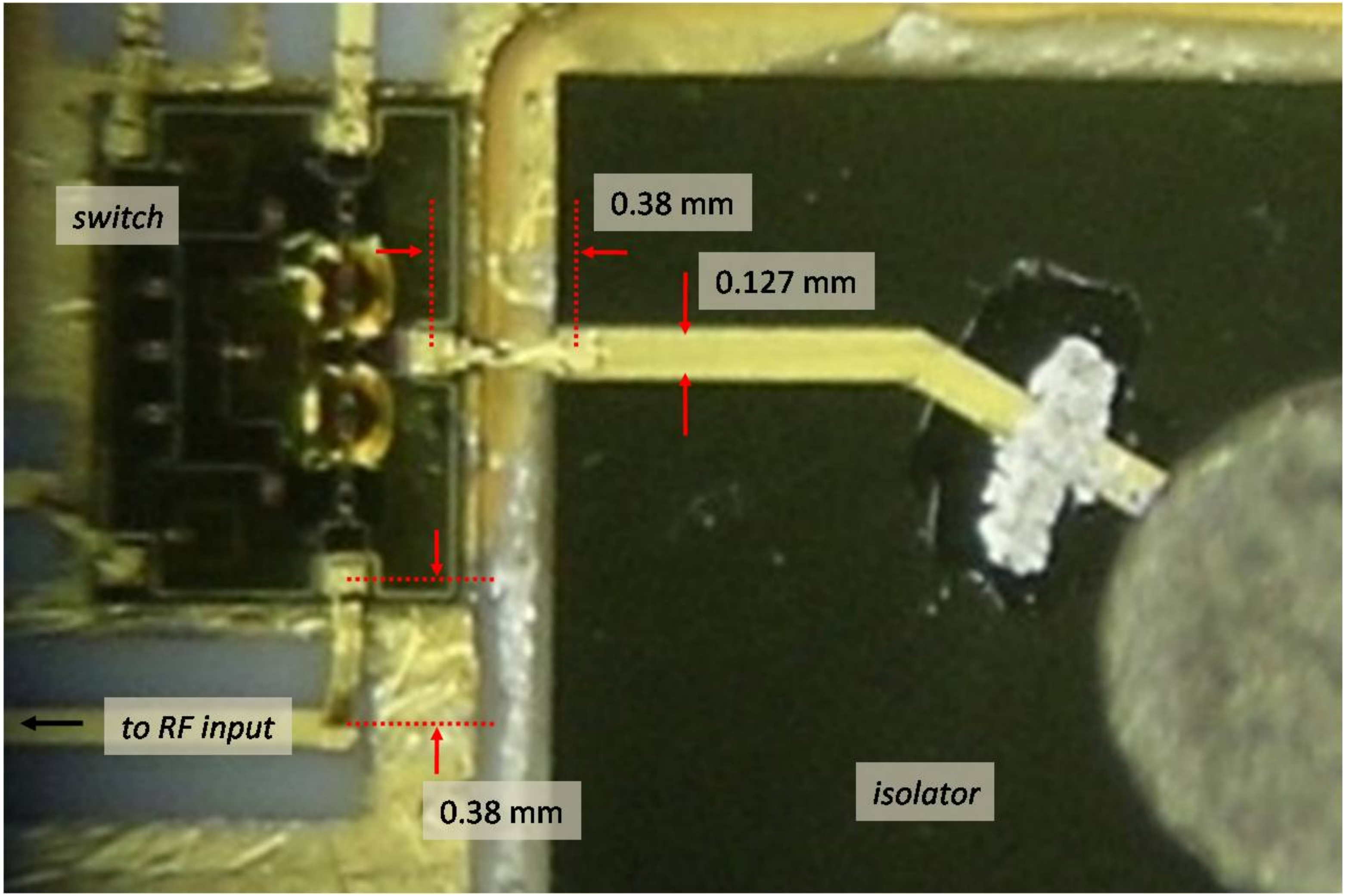
Instrument (on multiple satellites)	Number of Channels	Frequencies (GHz)	Power/Channel (W)	Mass (kg)	Nominal Operational Period
TMI	5	10.79-85.50	5.6	65	1997-2009
SSM/IS	24	19.35-85.50	5.6	96	2003-2016
SSM/I	7	19.30-85.50	6.4	49	1997-2009
AMSU-A	15	23.80-89.00	6.6	104	1998-2020
GMI	13	10.65-183.31	6.9	80	2013-2019
WindSat	22	6.93-89.00	15.9	342	2003-2009
AMSR-E	12	6.93-89.00	29.2	314	2002-2009
Microrad	-	**22.0-26.0**	**5.04**	**6**	N/A

Recommendations to Improve the Noise Figure

- Housing redesign so that shorter wire bonds between components before the first LNA can be achieved
- Raise lid height – Evidence that lid height lower than 1.1 mm negatively affects amplifier performance*, current lid height is 0.25 mm
- Changing the receiver pass band to 22-25.5 GHz, would relieve the requirements on the RF bandpass filter, this would decrease its insertion loss and ripple.

*J.-M. Lesage, R. Loison, R. Gillard, T. Barbier and T. Mancuso. Global EM analysis of packaging effects on MMIC amplifier isolation using the compression approach. Microwave and Optical Technology Letters, 46(4):372–375, 20 Aug 2005

Long Wire Bonds



Decreasing the Size of RF/IF MCM Housing

- Two RF bandpass filters are used to increase the rejection at 21 GHz, an image frequency. Not sampling above 25.5 GHz would relieve this requirement, and only one filter would be necessary. This would decrease length of the housing by 8.5 mm (14%).
- The VCO filter is not required, decreasing the length of the housing by 7.6 mm (13%).
- The transmission lines between IF amplifiers can be shorted, decreasing the width by 3.1 mm (8%).
- **Reduction in volume & mass = 34%**
- Anticipated dimensions: 4.2 x 3.4 x 2.5 cm
- Anticipated mass = 300 g

Conclusion

- Microrad is a prototype for a space-borne remote sensor for water vapor. The mass and volume are reduced compared to contemporary radiometers and Microrad would fit well NASA's new Venture Class missions.
- Microrad has an equivalent noise temperature of 850 K, compared to CMR-H, which has an equivalent noise temperature range of 650 to 900 K.
- Improvements in the MCM housing design have been recommended in order to lower the equivalent noise temperature, improving Microrad's radiometric resolution.
- The radiometer was delivered to Ball Aerospace & Technologies Corp. (BATC) on November 25, 2008.
- The next step in this BATC/CSU collaboration is to install the antenna, perform external calibrations and test for accuracy and precision.

Questions?