

5th Sweden EME Meeting 2017 by SM4IVE, Örebro

Calibrations of mm-wave antennas and RX systems using Moon radiation

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Radiometric sources in the sky

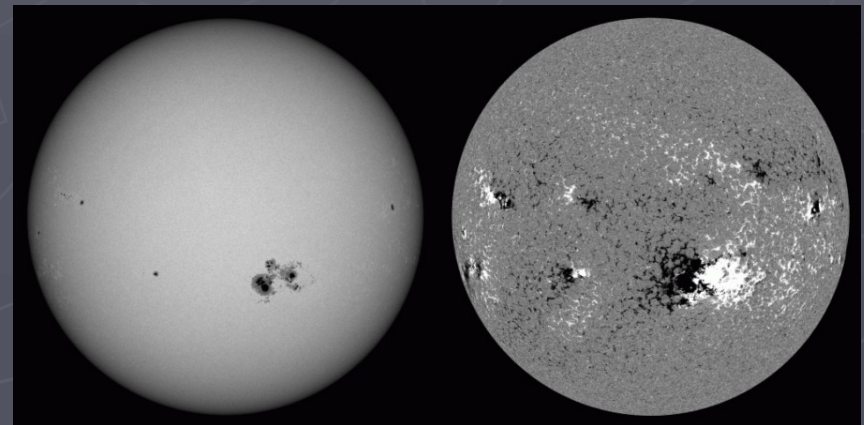
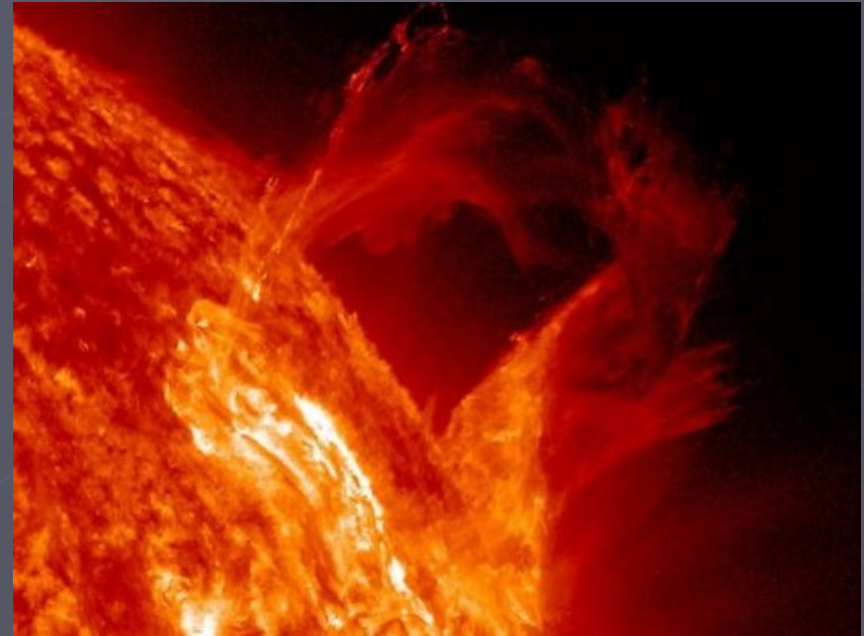
- ▶ Radiometry at mm-waves. The sensitivity of RX+antenna system can be estimated or measured by comparing the output response to signals from different points of the sky. Therefore, space radio sources with a well known power at the RX input (in antenna aperture) are needed for tests.

Looking up:

- ▶ The Sun – the brightest source, but may be not convenient for testing of RX because of the sunspots radiation, *see next slides ...*
- ▶ The Moon – emits the thermal radiation only, looks as a good source
- ▶ Galaxies noise, maser lines (emission from molecular clouds) – too weak at mm-waves with moderate size antennas (dishes up to 2 m).
- ▶ RW3BP tried to use the Jovian thermal radiation at 77 GHz, but flux is also faint, the RX response is about thousandths of dB with antenna $D = 2.4$ m, see <http://www.vhfdx.ru/apparatura/eme-antenna-and-jupiter-noise-on-77-ghz>.

The Sun: some details about this radiometric source

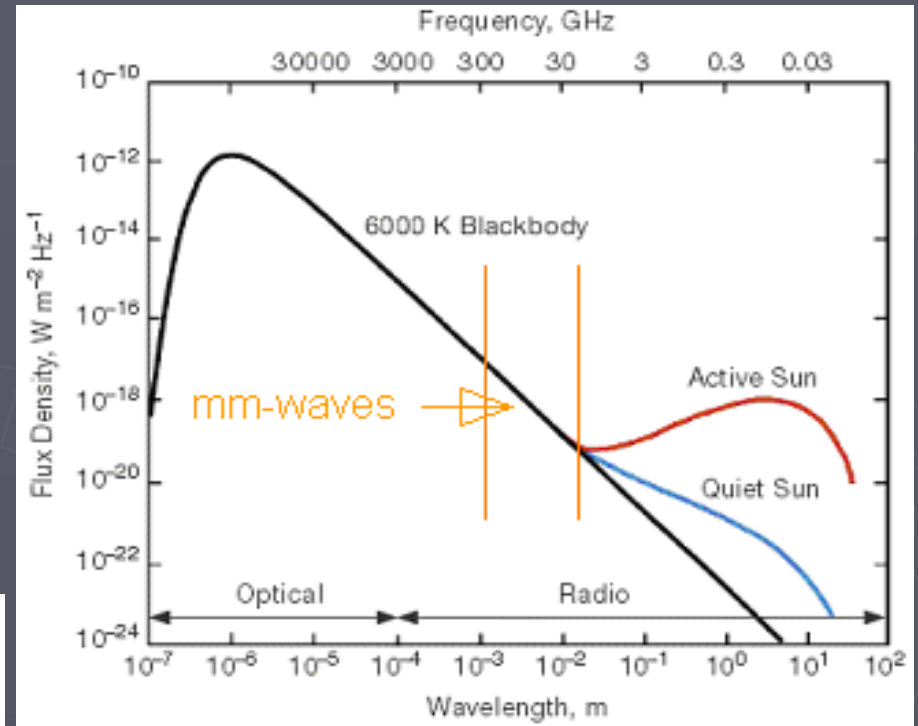
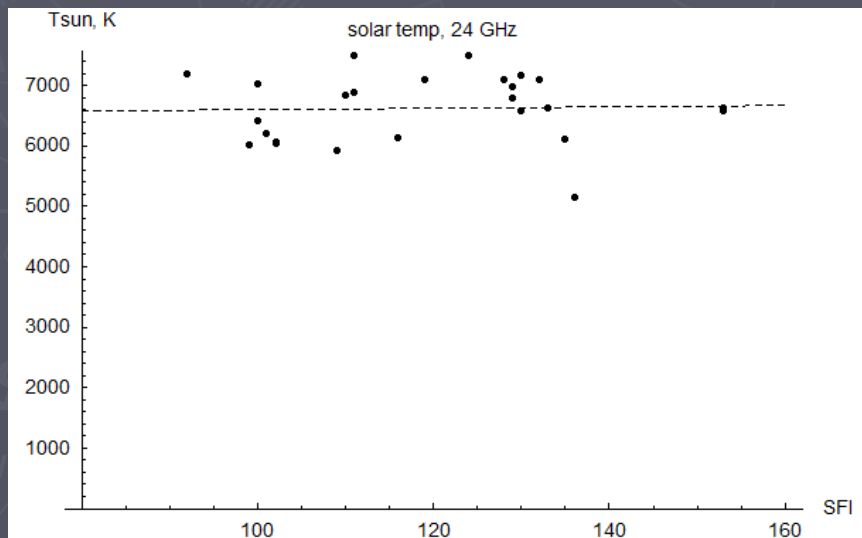
- ▶ High flux level (solar thermal component is characterized by $T_{\text{sun}} \sim 6000\text{-}7000\text{ K}$) and good RX response using antennas with diameter $D \sim \text{meters}$ and even $< 1\text{ m}$
- ▶ Beamwidth is usually narrow at millimeters, $\delta_{\text{HPBW}} \sim \delta_{\text{SUN}} = 0.5\text{ deg}$ and lower, antenna main beam may point to individual sunspots (2.4 m dish $\rightarrow \delta_{\text{HPBW}} = 0.12\text{ deg}$ at 77 GHz). Unfortunately, the level of sunspot radiation is not quite predictable, see also DUBUS 3/2016 p. 34 "Solar Flux and Temperature at Millimeter Waves".



Sunspots (visual picture – photosphere and magnetic map), late October 2014, Lebedev Physics institute, Moscow, http://www.tesis.lebedev.ru/sun_pictures.html?m=10&d=24&y=2014

Solar temperature at millimeters *versus* activity

- ▶ MM-wave band lays close to transition zone from GHz range (with fair dependence on activity) to blackbody with $T_{\text{sun}} \sim 6000\text{-}7000$ K. Thermal component is main but surprises are expected also. Solar Flux Index – SFI is usually measured at 2.7-2.8 GHz.
- ▶ 24 GHz without surprises for now, data were collected while testing my new transverter in 2013 (ant. 0.6 m, RX NF=1.7 dB) ...



Above plot from: Christian Ho, Stephen Slobin, Anil Kantak, and Sami Asmar, Solar Brightness Temperature and Corresponding Antenna Noise Temperature at Microwave Frequencies, Interplanetary Network (IPN) Progress Report 42-175, pp. 1-21, November 15, 2008, http://tmo.jpl.nasa.gov/progress_report/42-175/175E.pdf.

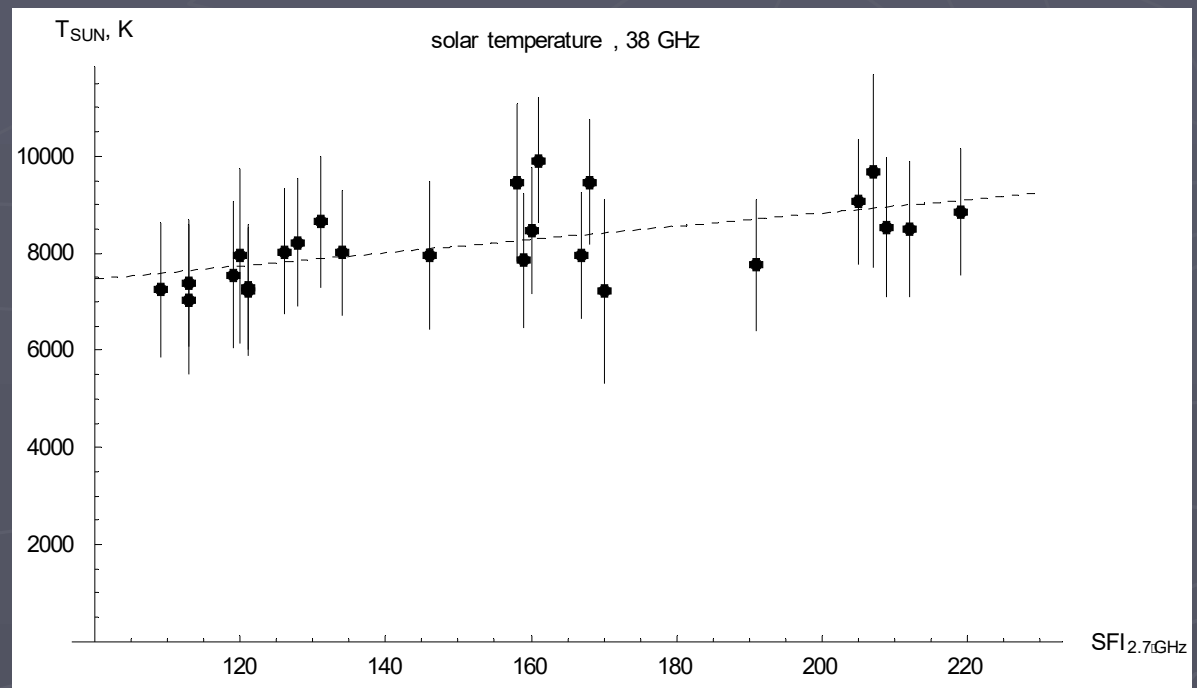
... but no regular experiments were made and 24 GHz researches are still needed

Higher frequencies ...

- ▶ At 38 GHz (lays close to 47 GHz band): the dependence on activity is seen using offset dish 0.9 m.
- ▶ Quiet Sun temperature ~ 7000 K at 38 GHz. The radiation of individual sunspots at 38 GHz was seen by Salomonovich et al using 22 mm radio telescope (Astr. J. U.S.S.R. 39, p. 260, 1962, russian).

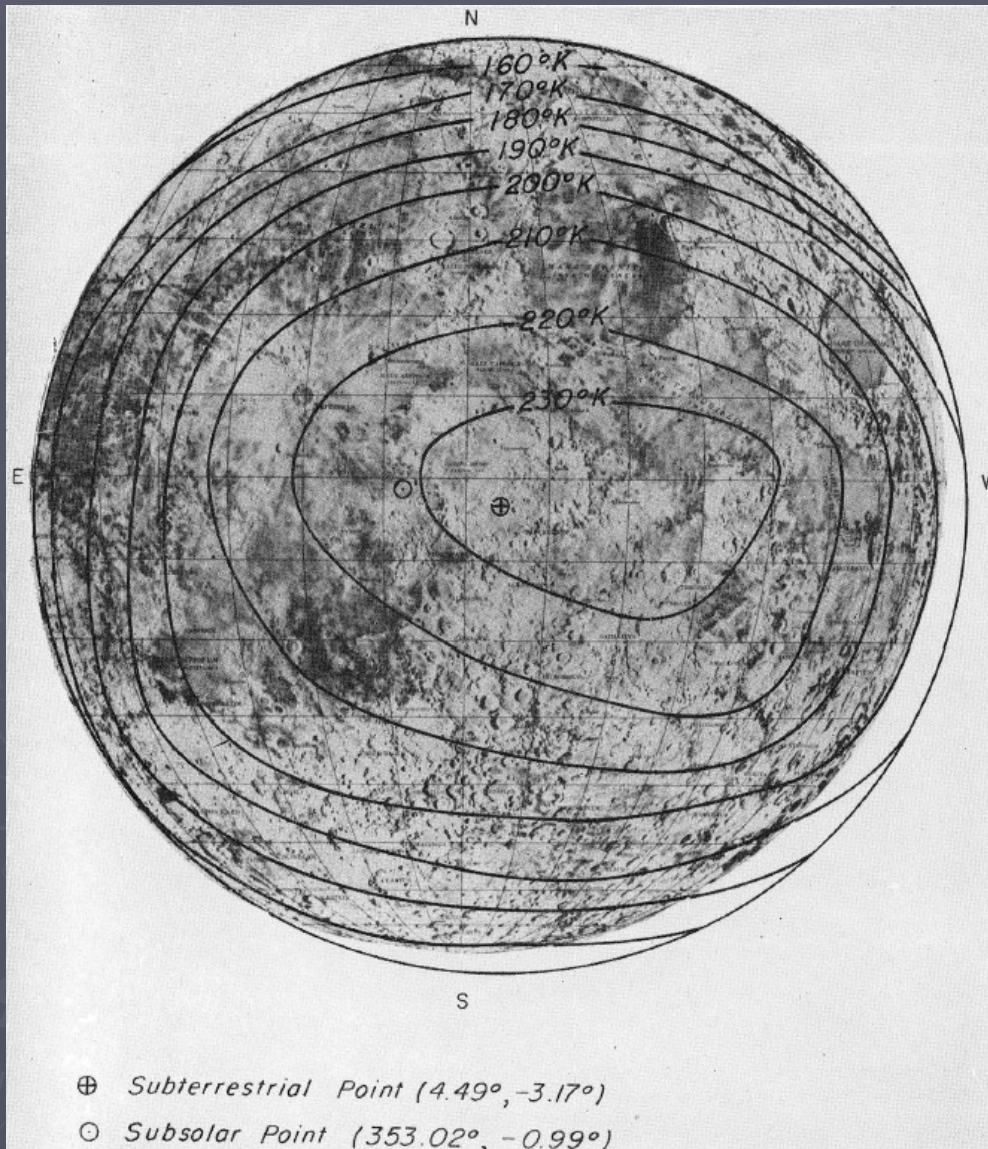
My measurements of the solar temperature at 38 GHz →→→

see DUBUS 3/2016 p. 34 "Solar Flux and Temperature at Millimeter Waves" by UA3AVR



- ▶ 76-77 GHz band is still a subject for investigations!

The Moon ...



- ... is just a spherical body up in the sky heated by the Sun. Lunar radiation is thermal, no peculiar spots on the surface, strong magnetic fields, sporadic bursts etc.
- Lunar temperature is well investigated, the Moon may be considered as a blackbody radiator at millimeter waves, but temperature changes with the lunar phase cycle, and there are temperature changes across lunar disc, the distribution of temperature is descending from center to edges, and form of distribution itself also varies during phase cycle.

$\lambda=8.6$ mm, moon phase 11.7 deg, waning gibbous, 0 deg is a full moon, by D.E. Clardy and A.W. Straiton, Radiometric Measurements of the Moon at 8.6- and 3.2-Millimeter Wavelengths, The Astrophysical Journal, v. 154, p. 775 (1968)

Lunar temperature distribution

$$T_{moon} = T_0 + T_1 \cos(\Phi_M - \varphi) ,$$

$$T_0 = 213 \pm 6 \text{ K}, \quad T_1 = (30 \pm 5) \lambda^{-0.67} \text{ K},$$

$$\varphi = \left(\frac{\pi}{5} \pm \frac{\pi}{25} \right) \lambda^{0.275} \text{ radians}, \quad \lambda = 0.1 \div 3 \text{ cm}$$

Patricia R. Foster, *Radio Observations in the Short Microwave Region*, Quarterly Journal of the Royal Astronomical Society, v. 10, p.206 (1969)

$$T_M(\rho) = T_{moon} e^{-\frac{4 \ln 2 \rho^2}{\delta_{moon}^2} \sigma^2} ,$$

$$\delta_{moon} \approx \delta_{sun} \approx 0.5 \text{ deg},$$

$$\sigma \approx 0.72$$

The blackbody model is accepted for the Moon, the noise temperature = thermodynamic temperature.

- T_{moon} – temperature at the center of lunar disc, depends on the Phase Φ_M ($\Phi_M = 0$ – corresponds to Full Moon).
- The distribution for phases near Full Moon described by Gaussian function: ρ – angular distance from the center, δ_{moon} – angular size of the Moon, σ – the distribution's parameter (taken according the picture by Clardy&Straiton from previous slide).

Next: Antenna beamwidth and $\eta_M \rightarrow \rightarrow \rightarrow$

Antenna beamwidth

- ▶ So, if source in the sky is chosen, let's handle the next problem – antenna beamwidth is about angular size of the source disk.

$$T_{ant} \approx \eta_M T_{src}, \quad \delta_{HPBW} \ll \delta_{src}$$

Possible at mm-waves

- ▶ If beamwidth is very narrow (like on background pic, $src=moon, sun, \dots$) antenna should see a point at the source with temperature T_{src} . T_{ant} – is a part of antenna temperature due to radiation of the source, η_M – **the Main beam efficiency, <1** .

averaged

$$T_{ant} \approx \frac{\Omega_{src}}{4\pi} D_{max} \bar{T}_{src}, \quad \delta_{HPBW} \gg \delta_{src}$$

Usual for low frequency bands

- ▶ If beamwidth is very wide it should see a mean (averaged) temperature of the source over the seen disc. Ω_{src} – the solid angle of the source $\ll 4\pi$, D_{max} – main lobe gain (directivity) of antenna.

For low- and medium-size mm-wave antennas ... (intermediate case, some formulas)

- Assuming a Gaussian form of the main lobe ... (ρ – angle from the max)

Antenna should see a mean temp of the source (weighted by main lobe form factor)

$$T_{ant} = \eta_M \left(1 - 2 \frac{\delta_{src}^2}{\delta_{HPBW}^2} \right) \bar{T}_{src}$$

- For dish with diameter d ... (η_A – Aperture efficiency)

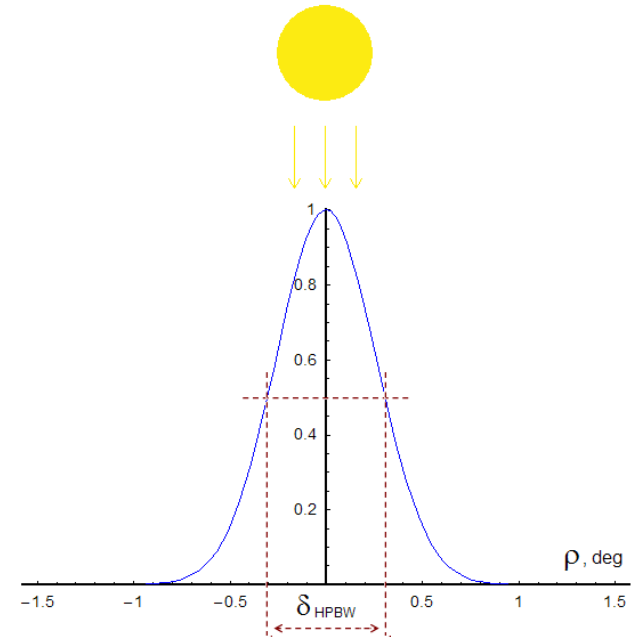
$$D_{max} = \frac{4\pi A_{geom} \eta_A}{\lambda^2}, \quad A_{geom} = \pi \frac{d^2}{4}$$

- For typical dishes ...

$$\delta_{HPBW} = 1.22 \frac{\lambda}{d}, \text{ radians}$$

See for reference: Daniel Minoli, *Satellite Systems Engineering in an IPv6 Environment*, CRC Press, 2009, pages 78-80

$$D(\rho) = D_{max} e^{-\frac{4 \ln 2 \rho^2}{\delta_{HPBW}^2}}, \quad D_{max} = \eta_M \frac{16 \ln 2}{\delta_{HPBW}^2}$$



- Aperture efficiency *versus* efficiency ... (calculated)

Main beam

$$\eta_A = k \eta_M, \quad k = \frac{16 \ln 2}{1.22^2 \pi^2} \approx 0.75$$

Next: Y-factor method →→→

The Y-factor method ...

- ▶ ... is known to be applied for RX Noise Figure measurements, but may be used in radiometry, antenna calibration etc.
- ▶ One should compare RX output when antenna looks to the Moon and on the cold sky.
- ▶ Antenna should see on the sky:
 - T_{hot} – from the source (the Moon) radiation
 - T_{cold} – from the Cosmic Microwave Background (CMB)
- ▶ The Atmospheric attenuation and noise should be taken into account. To do that I followed to ITU recommendations "Attenuation by atmospheric gases" (P.676-10, Sep 2013) and "Radio noise" (P.372-9, Sep 2013).
- ▶ Clear weather is needed, attenuation and additional noise from clouds and rain&snow is hardly predictable.
- ▶ "Hot" (at the lunar max) and "Cold" RX output should be measured at the same elevation.
- ▶ Full Moon or Phases nearby is essential.

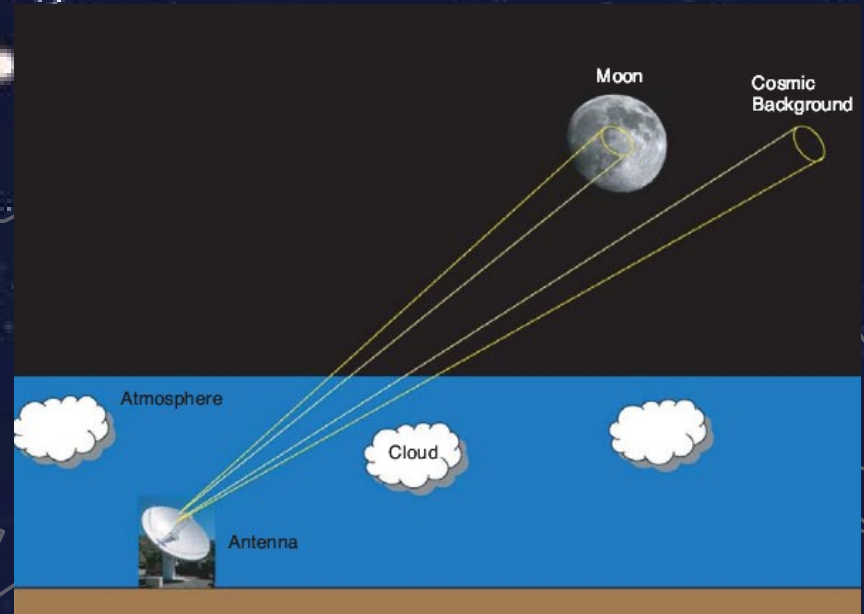


Image extracted from: D. Morabito, M. Gatti, and H. Miyatake, *The Moon as a Calibration Load for the Breadboard Array*, Interplanetary Network (IPN) Progress Report 42-172, pp. 1-21, February 15, 2008

$$Y_{measured} = \frac{P_{hot\ source}}{P_{cold\ sky}} = \frac{V_{hot\ source}^2}{V_{cold\ sky}^2}$$

Interesting facts and notes:

- ▶ The CMB is shadowed by the lunar body
- ▶ The quantum correction to CMB noise temperature $T_{CMB}=2.73$ K may be up to 1 K (as it follows from the Planck's law) for mm-waves.

If all parameters of RX system are known antenna should see ...

$$T_{moon} = \frac{\left(Y - 2^{-\delta_{moon}^2 / \delta_{HPBW}^2} \right) \eta_M T_{CMB} + (Y - 1) \left(\eta_M T_{atm} (L_{atm} - 1) + T_{sys} L_{atm} \right)}{\eta_M (1 - 2^{-\delta_{moon}^2 / \delta_{HPBW}^2} - \sigma^2)} \left(\frac{\delta_{HPBW}^2 \sigma^2}{\delta_{moon}^2} + 1 \right)$$

... temperature at the center of lunar disc.

- ▶ Actual temperature T_{moon} may be calculated using formulas by P. Foster, see slide 7.
- ▶ **Main beam efficiency** η_M was used as antenna performance characteristic.
- ▶ If η_M is not quite known one may use a typical value ~ 0.7 , and then correct it up to the actual lunar temperature with above formula.
- ▶ I used specially written calculator (for Excel spreadsheet), all big cumbersome formulas have been coded there.
- ▶ Y – is the measured Y-factor
- ▶ T_{CMB} – the CMB temperature, $\sim 2K$
- ▶ L_{atm} – atmospheric attenuation factor, $L_{atm} > 1$, should be calculated *a priori* for actual weather.
- ▶ T_{atm} – noise temperature of atmosphere (may be taken according ITU P.372, $\sim 275 K$)
- ▶ $T_{sys} = T_{RX} + T_{spill}$ – RX system temperature (at the antenna aperture), T_{RX} – is defined by RX Noise Figure, T_{spill} – the *spillover* temperature of antenna, could be estimated about 50-70 K (I used $T_{spill} = 70 \pm 30 K$)

See screenshots at the next slide...→→→

Calculate the lunar noise at millimeters quickly ...

	A	B	C	D	E	F	G	H
1	Freq=	38	GHz	Antenna:				
2	Lambda=	0.00789	m	Dant=	0.9	m (Reflector Diam)		
3				Eps_main=	0.67	Main beam efficiency		
4	Receiver:			k=	0.75	Eps_app=k*Eps_main		
5	NF(rcvr)=	5.5	dB	Eps_app=	0.50	Aperture efficiency		
6	Trcvr=	738.96	K	Dmax=	48.10	dBi (Antenna Gain)		
7				HPBW=	0.61	deg (Half Power Beam Width)		
8	Moon:			Tspill=	70	K (antenna spillover Temp)		
9	Moon size=	0.5	deg					
10	Moon temp distribution parameter:			Space and atmosphere:				
11	Sigma=	0.72		Tspace=	3.4	K (CMB)		
12	Moon phase	200	deg	Tatm=	275	K		
13	Full Moon 0/180 deg switch			Atm. att=	0.84	dB		
14				Latm=	1.21			
15	Full Moon	180	deg	Enter data in -> cells like me				
16								
17								
18	Yfact	Moon:		Yfact	Ground:			
19	measured=	0.23	dB	measured=	0.72	dB		
20								
21	Results							
22	Moon temperature (seen):			Ground temperature (seen):				
23	Tmoon=	268.17	K	Tground=	277.92	K		
24	Moon temperature (data):							
25	Tmoon_data=	247.16	K					
26		±	8.33	K				

Weather & elevation data:

	A	B	C	D
1	Atmospheric attenuation (<54 GHz):			
2	Frequency	38	GHz	
3	Air pressure	1018	hPa	<--enter
4	Temperature	-20.5	C	<--enter
5	Humidity (rel)	82.5	%	<--enter
6	Elevation	23	deg	<--enter
7	Clouds not accounted			
8	Attenuation	0.8368	dB	

Actual lunar temperature

If more of parameters is not well known ...

- ▶ For example, if RX Noise Figure is known estimately or with high uncertainty,
- ▶ Antenna should be turned to ground outside (after Cold Sky measurement), and test RX system by the Ground thermal radiation. Formula for corresponding temperature → → →

- ▶ ... an additional verification procedure can be applied.

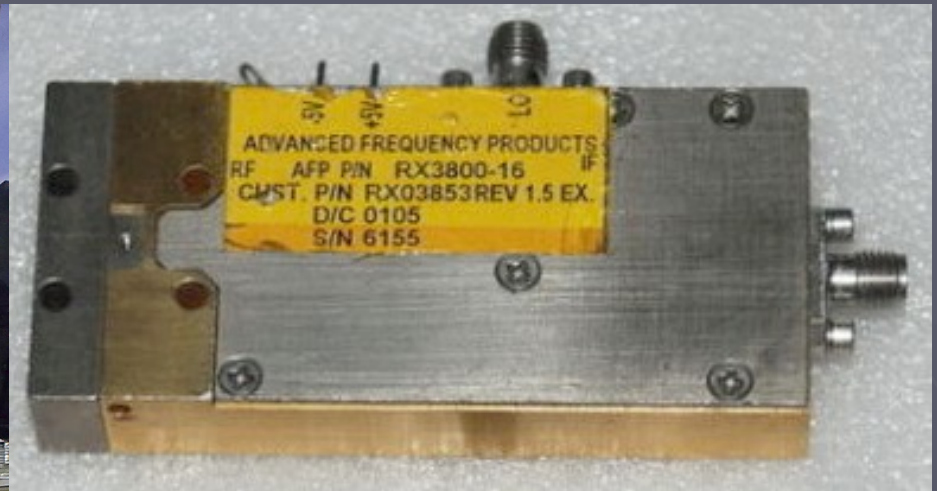
The Ground temperature, as it seen by RX:

$$T_{ground} = Y \left(\frac{T_{CMB}}{L_{atm}} + \left(1 - \frac{1}{L_{atm}} \right) T_{atm} \right) + \frac{(Y-1)}{\eta_M} T_{sys}$$

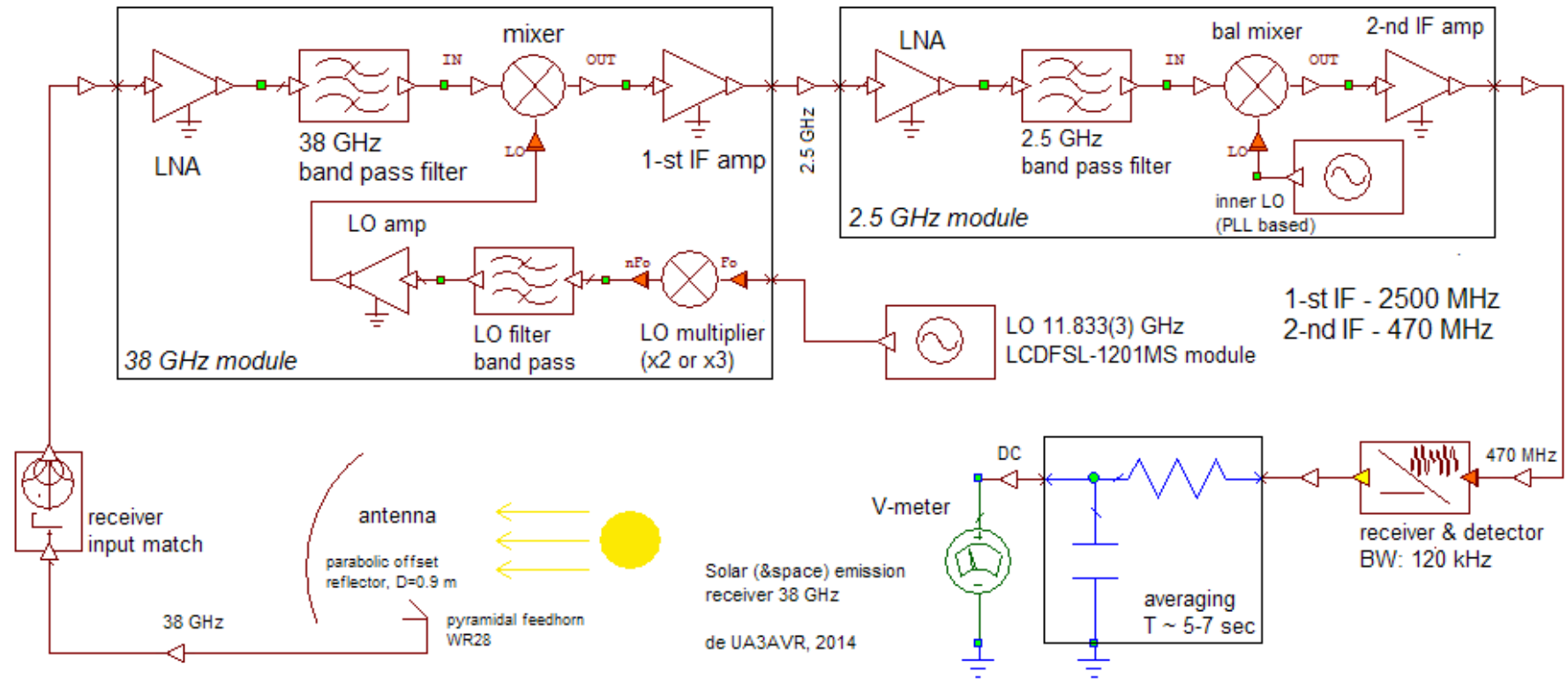
- ▶ The Ground noise temperature should be about the same with indications of thermometer outside, ~ 280-290 K. As I guess, its uncertainty gap is also expected high, up to several tens of K. But poorly known NF of receiver could be verified (and, if needed, η_M slightly corrected too).

NEXT: about receiver (radiometer) 38 GHz →

Radiometer (antenna+RX system) 38 GHz,
built for solar measurements 2014-2015



Schematic (block diagram):



- ▶ Feed for dish – is pyramidal horn, matched to RX module using screws in the input waveguide.
- ▶ 38 GHz module RX3800-16 and LO module LCDFSL-1201MS – from eBay
- ▶ 1-st IF=2500 MHz is handled with MMDS-converter Gospell MDF-10T
- ▶ Calibrated using the thermal radiation of the Moon, and was built for solar radio astronomy initially.
- ▶ Averaging with $\tau \sim 5-7$ sec gives the opportunity to measure with detection accuracy <0.02 dB (for weak signals).

Parameters of 38 GHz radiometer after calibration ...

Parameter	Comment	Value
d	Diameter of the antenna reflector	0.9 m
$D_{\max}$	Directivity (max gain)	48.1 dBi
η_M	Main beam efficiency	0.67
η_A	Aperture efficiency $= k \eta_M$	0.50
δ_{HPBW}	Half Power Beam Width (HPBW)	0.6 deg
NF	Receiver Noise Figure (at the feedhorn aperture)	5.5 dB
T_{spill}	Spillover and other background noise temperature besides the main beam	70 K
T_{sys}	Overall system temperature $= T_{spill} + T_{rcvr}$ (at the antenna aperture)	809 K

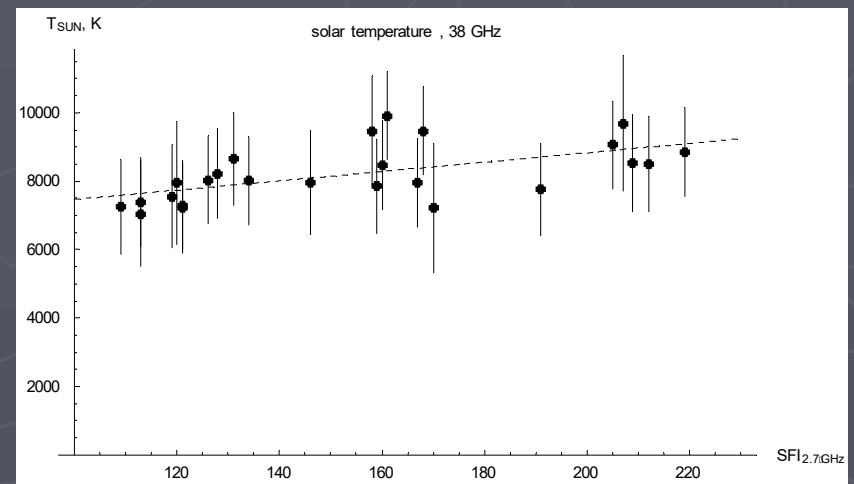
Results ...

- Solar temperature versus activity
- Quiet Sun value ~ 7000 K (meets the results of other researchers)

$$T_{sun}(SFI) = 6099 + 13.7 SFI, \text{ K}$$

$$T_{quiet} = 7328 \pm 604 \text{ K} \quad (SFI_{quiet} = 90)$$

$$T_{quiet} = 6973 \pm 802 \text{ K} \quad (SFI_{quiet} = 64)$$



Conclusion and notes ...

- ▶ The Moon appears as a good radiometric source for calibration of mm-wave RX with moderate size antennas (dishes up to 2 m).
- ▶ Note: large size antennas require a higher profile accuracy of reflector for mm-waves. Phase errors (due to errors in shape) rise with frequency and lead to worsening of antenna performance. The gain degradation can be estimated with Ruse's Equation, ε – means here the RMS-error (or the fabrication tolerance) over reflector surface →
$$G = G_0 - 685.8 \left(\frac{\varepsilon}{\lambda} \right)^2, dB$$
- ▶ Main beam efficiency η_M appears to be a suitable characteristic for mm-wave antennas with narrow lobes. Objects in the sky (the Moon and the Sun) may be noticeably wider. Described calibration procedure takes into account uneven heating of the Moon's surface.

Some more works about using the Moon as a source for radiometry:

- [1] Jeffry Linsky, *A Recalibration of the Quiet Sun Millimeter Spectrum Based on the Moon as an Absolute Radiometric Standard*, Solar Physics, v.28, pp.409-418, 1973, SpringerLink: <http://link.springer.com/article/10.1007%2FBF00152312>, see also <http://adsabs.harvard.edu/full/1973SoPh...28..409L>
- [2] D. Morabito, M. Gatti, and H. Miyatake, *The Moon as a Calibration Load for the Breadboard Array*, Interplanetary Network (IPN) Progress Report 42-172, pp. 1-21, February 15, 2008, http://ipnpr.jpl.nasa.gov/progress_report/42-172/172G.pdf.

Thanks!

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73 & good luck in GHz EME!
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