

A scenic landscape featuring a full moon in a clear blue sky, with dark, silhouetted mountains in the background and a calm body of water in the foreground. The overall tone is serene and natural.

Swedish EME Meeting 2019 by SM4IVE, Örebro

About using the Cosmic Microwave Background in Noise Figure measurement applications

Dimitry Fedorov UA3AVR

... plus a short message about Black Hole image 2019

24-26 May 2019

Radio Astronomy and noise measurement applications

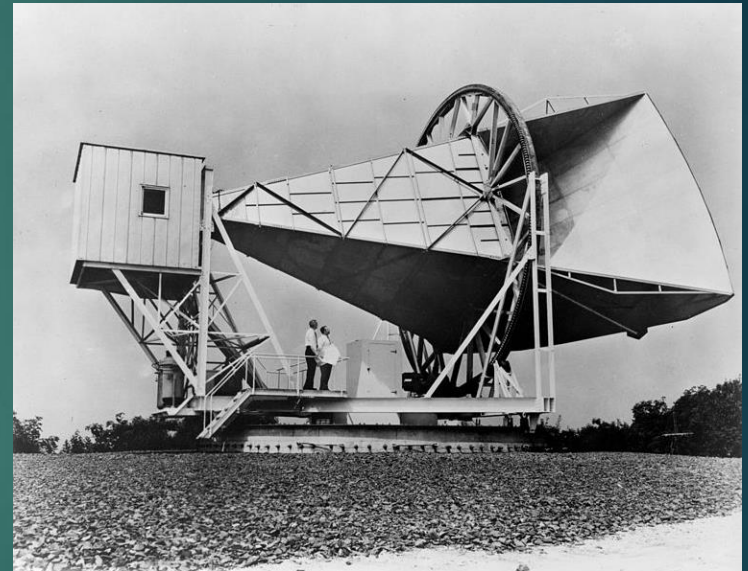
a range of issues and questions at the beginning of work

- ▶ How to use celestial sources as radiating standards for measurements? There are well investigated sources in the sky.
- ▶ What sources are acceptable for noise tests? Spread spectrum radiating objects in the space. Lunar and solar radiation.
- ▶ The Cosmic Microwave Background. Blackbody radiation from the sky.
- ▶ A problem of interfering radiation from objects on the Earth. Atmospheric radiation.
- ▶ What about an accuracy of results?

The Cosmic Microwave Background (CMB) radiation

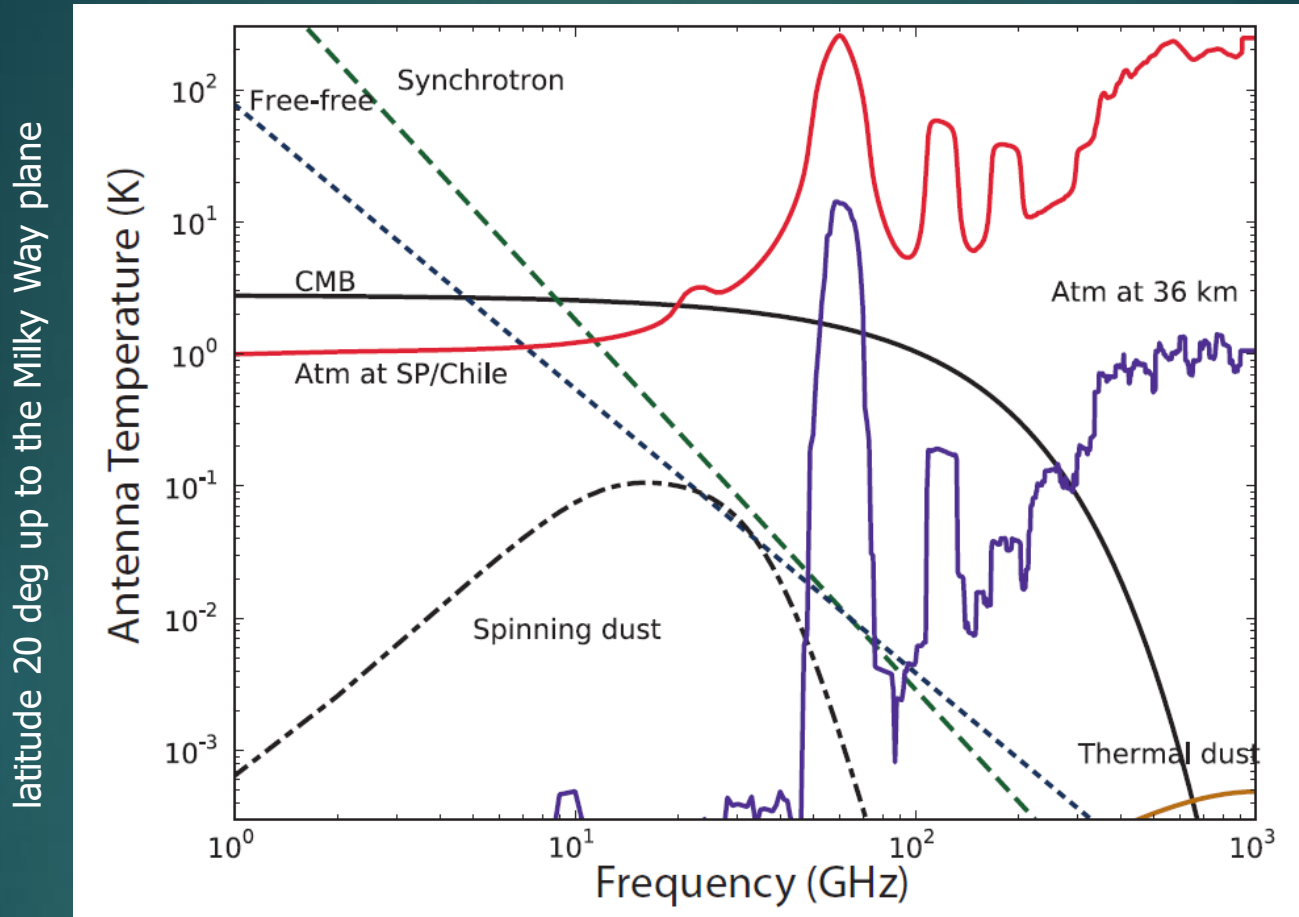
- ▶ Originated in the early Universe, when the matter in atoms was formed. The CMB fills the Universe now, almost isotropic, but can be shadowed by nearby cosmic objects like Sun, Moon.
- ▶ Is well investigated. The CMB has the spectrum of a blackbody. The temperature of CMB have been measured with a good accuracy, $T_{\text{CMB}}=2.7255 \text{ K}$.
- ▶ Can be used as a standard in radiometry. CMB is just a faint cosmic radio noise. An upward directed microwave feedhorn can see the CMB radiation and produce an output noise at temperatures of cryogenic range. CMB can be applied as a noise source with known temperature.
- ▶ Has inspired at least two Nobel Awards: Penzias and Wilson in 1978, and John C. Mather and George Smoot in 2006 for the "discovery of the black body form and anisotropy of the cosmic microwave background radiation".

Discovered unintentionally (by a good fortune) in 1964 by Arno Penzias and Robert Wilson with a big microwave horn in the Bell Labs in New Jersey. The horn was built to support the NASA project Echo for communication via passive satellite bouncing.



The CMB was predicted earlier in 1948-1955 by Ralph Alpher and Robert Herman, rediscovered by Yakov Zeldovich and Robert Dicke in 1960. Andrey Doroshkevich and Igor Novikov have described it as detectable phenomenon in the spring of 1964. The same year Dicke's coworkers in Princeton University, David Todd Wilkinson and Peter Roll have began constructing a radiometer especially for CMB detecting.

Anything besides CMB? Spectrum of the sky radiation

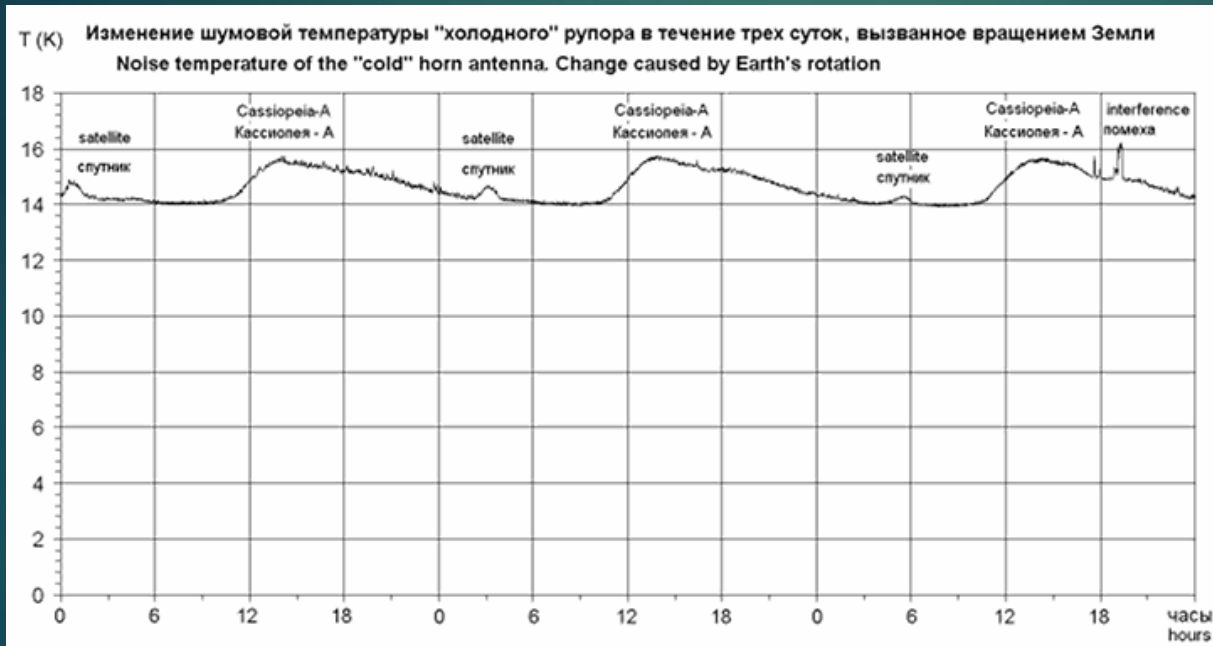


- ▶ Low frequencies – the galactic radiation (may be high, but depends on galactic latitude)
- ▶ High frequencies – the atmospheric noise
- ▶ The CMB temperature is falling with frequency due to quantum effects.

CMB Telescopes and Optical Systems, by Shaul Hanany, Michael Niemac, and Lyman Page, Princeton University, arXiv:1206.2402, 2012.

1296 MHz sky noise observations

- Daily plot for antenna temperature at 1296 by Sergey RW3BP



Reference: Sergei Zhutyaev RW3BP, *1296 MHz Small EME Station with Good Capability (Part 3), Accurate Noise Figure measurements on 1296 MHz*, 2010

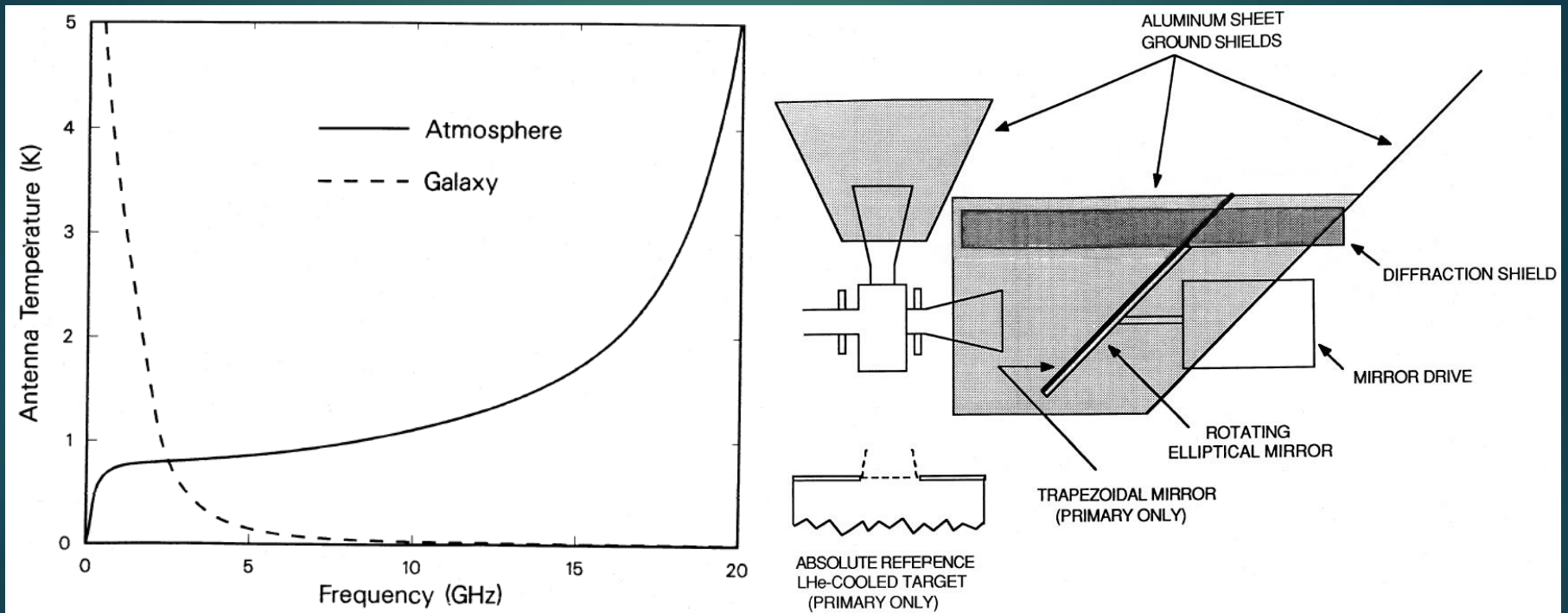
Zenith oriented horn with
HPBW \approx 20 deg

Other data ... 10 GHz

CMB temperature measurements using microwave horns;

80s project with a liquid Helium reference for instrument calibrations;

The result: $T_{\text{CMB}} = 2.61 \pm 0.06 \text{ K}$

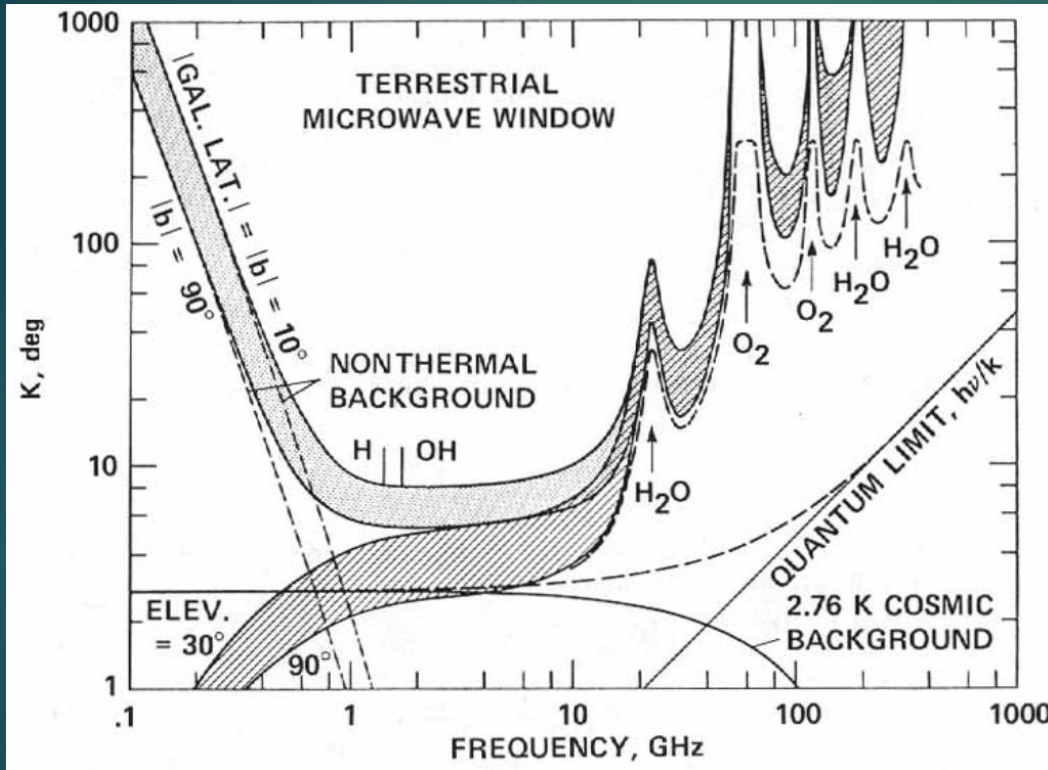


A Kogut et al, *The Temperature of the Cosmic Microwave Background Radiation at the Frequency of 10 GHz*, *The Astrophysical Journal*, 325, pp. 1-15 (1988 February 1)

Amateur measurements ... 10 GHz

The CMB temperature was measured with a liquid Nitrogen reference. The result: $T_{\text{CMB}}=3.9$ K. Quantum limit – is the lowest detectable noise level caused by the quantum nature of photons.

The sky radiation data taken with a reference to NASA



Jack J Gelfand PhD, *An Amateur Instrument for the Detection of the Cosmic Microwave Background*, Conference Paper, July 2017. The source – ResearchGate, <https://www.researchgate.net/publication/317275082>

About the quantum limit see: Luis Cupido CT1DMK, *How low can the NF go?*, DUBUS Technik XIV, 2015, p. 249

More amateur CMB measurements ... 10 GHz

Measurements using satellite dishes.

Examples of ambient noise protection (the spillover protection)



Timo Stein and Christopher Förster, 2008, the result - $T_{\text{CMB}} = 3.6\text{--}4.5\text{ K}$

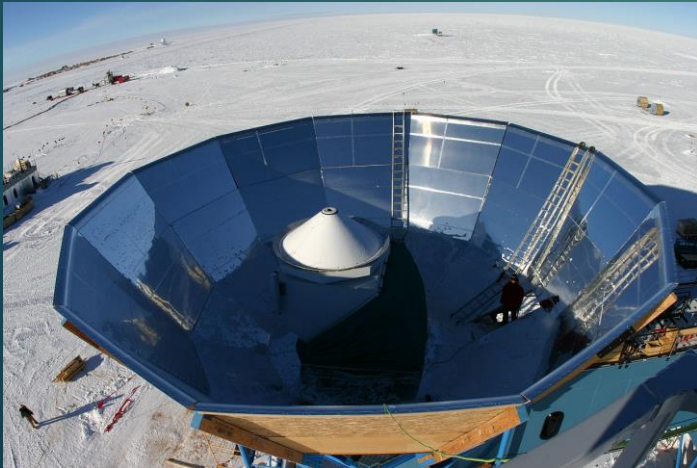


Michel Piat, the result - $T_{\text{CMB}} = 2.27 \pm 0.09\text{ K}$

The source of pictures, info and description of data processing: Joachim Köppen, DF3GJ, *How to Measure the Cosmic Microwave Background with TV Satellite Equipment*, Inst. Theoret. Physik u. Astrophysik, Univ. Kiel, October 2015, <http://portia.astrophysik.uni-kiel.de/~koeppen/CMB.pdf>

High precision experiments ...

- ▶ Practiced in the mm-wave frequency range where the CMB dominates, at 20 GHz and higher. Anisotropy and polarization measurements (very subtle matters!) are the main subject for experiments.
- ▶ Ground based CMB telescopes are located in mountains or in Antarctic to reduce an atmospheric influence. Balloon borne and satellite telescopes are in action too. Precision optics with multiply reflectors and lenses is a core of the modern CMB testing equipment.



The QUaD SMB telescope, South Pole



10m South Pole Telescope (SPT)

- ▶ The sensitivity of receivers can be close to the quantum limit. The noise from reflectors of optical systems itself can be significant for ambient temperatures, so cryogenic systems are used.

The most of info from: *CMB Telescopes and Optical Systems*, by Shaul Hanany, Michael Niemac, and Lyman Page, Princeton University, arXiv:1206.2402, 2012.

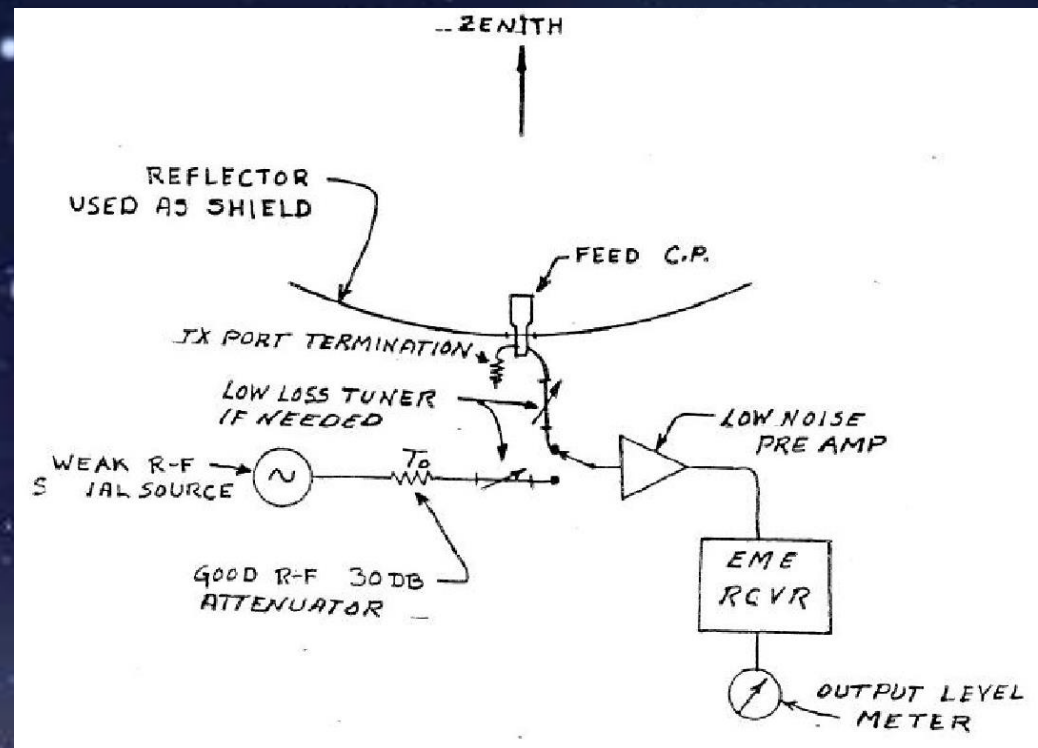
Testing an equipment on the Earth

- ▶ The CMB temperature is considered as known a priori, then the attention is focused on unknown receiver characterization including a Noise Figure

Testing a receiver temperature – NF for EME purposes (the first known to me) ...

Richard H. Turrin W2IMU, *Subjects Method for Estimating Receiver Noise Temperature*, Crawford Hill Tech Note #20, December 1986, digitizing by W1GHZ, March 2018.

- ▶ He used a reflector shield for interference protection from the warm ground.
- ▶ The Y-factor method was used to extract the RX system temperature.



Why the Y-factor? Accuracy issues and "Cold Horn"

- ▶ A kind of Y-factor method with noise temperatures is used. A receiver is tested by two reference temperatures, *Hot* and *Cold*.

$$T_{RX} = T_{hot} \frac{1}{Y-1} - T_{cold} \frac{Y}{Y-1}, \quad NF = 10 \cdot \log \left(1 + \frac{T_{RX}}{T_0} \right), \quad \delta NF = \frac{10}{\ln 10} \frac{\delta T_{RX}}{T_0 + T_{RX}}$$

- ▶ An uncertainty of receiver temperature and Noise Figure depends mainly on uncertainty of the Cold temperature rather than the Hot temperature.

$$\delta T_{RX} = \sqrt{\delta T_{hot}^2 \frac{1}{(Y-1)^2} + \delta T_{cold}^2 \left(\frac{Y}{Y-1} \right)^2}$$

- ▶ Y-factor – the relation of Hot and Cold powers at RX output.
- ▶ Its value >3 usually.
- ▶ When the Cold temperature is lower, its uncertainty would be lower too.
Such an opportunity can be provided with upward directed horn antennas.
The name "Cold Horn method" could emphasise this fact.

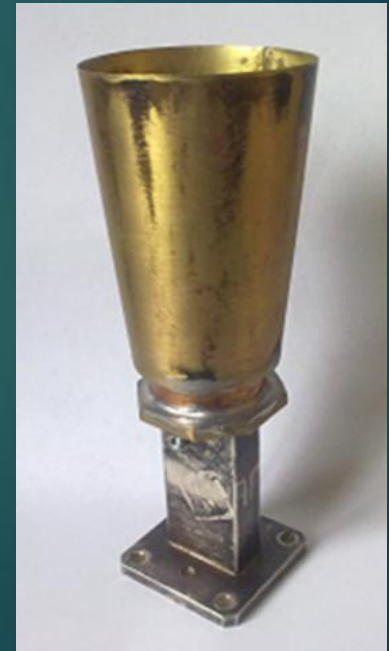
Choosing a horn and temperature calculations ...

- ▶ A horn with wider beam would be less prone to a space radiation besides the CMB, i.e. to localized space sources.
- ▶ The space contribution to the horn's temperature could be estimated as: $T_{space} \pm \delta T_{space} = 4.2 \pm 1.5 \text{ K}$

The lower edge of uncertainty gap is at the CMB temperature = 2.7 K.

- ▶ An unprotected (unshielded) horn collects a noise from warm surroundings. The best choice is dual mode horns with suppressed back- and side-lobes.
- ▶ An atmospheric noise depends on elevation angles and contributes more with rising frequency.

10GHz wide-beam Skobelev horn, HPBW \approx 40 deg --->



Atmospheric contribution

ITU recommendations P.372, Radio noise;
P.676 Attenuation by atmospheric gases.

- ▶ What temperature T_{cold} will the horn see at its aperture?

$$T_{sky} = T_{eff} \left(1 - 10^{-\frac{A}{10}} \right) + T_{space} 10^{-\frac{A}{10}}, \quad A = \frac{A_{90^\circ}}{\sin \psi}$$

$$T_{cold} = \frac{1}{4\pi} \left(T_{amb} \int_{gnd, wall} G(\theta, \varphi) d\Omega + \int_{sky} T_{sky}(\psi) \cdot G(\theta, \varphi) d\Omega \right), \quad d\Omega = \sin \theta d\theta d\varphi$$

ψ - elevation angle

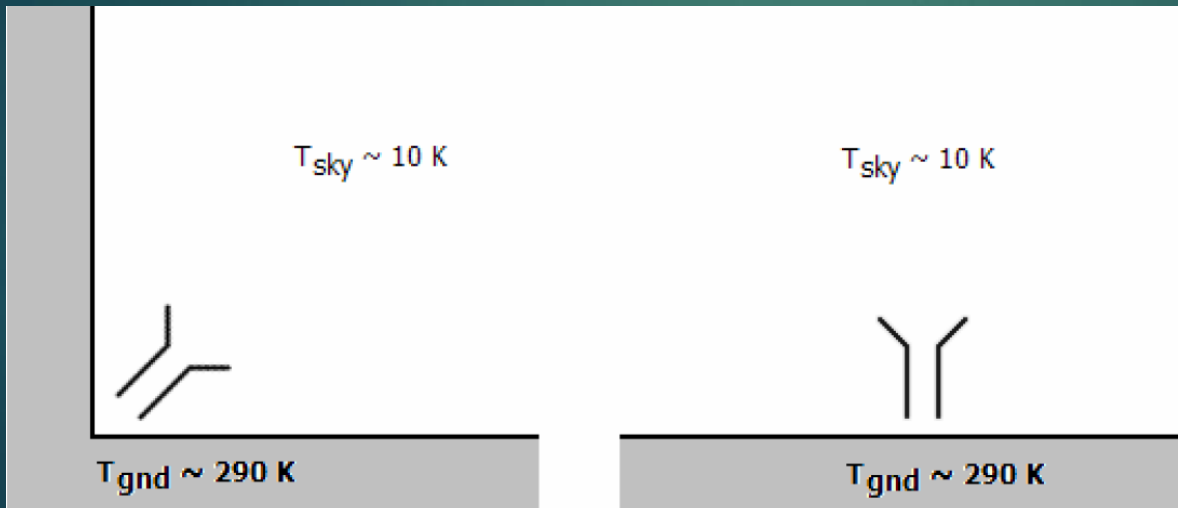
A_{90° - zenith absorption

T_{eff} - temperature of atmosphere, ≈ 275 K

T_{amb} - ambient temperature, ≈ 290 K

$G(\theta, \varphi)$ - far field directivity

- ▶ The most important for wide-beam unprotected horns



Possible positions of the measuring horn

T_{cold} uncertainty estimations, a 10 GHz example

Weather (current, dated April 2014):	20° C (293 K), humidity 29%, pressure 1023 hPa, clear, Moscow
Cosmic noise:	$T_{\text{space}} \pm \delta T_{\text{space}} = 4.2 \pm 1.5$ K
Atmospheric attenuation (zenith):	0.048 dB (by ITU methodic)
Sky noise (including atmosphere):	$T_{\text{sky}} = 9.41$ K (by integration using horn's directivity in sky direction)
- from uncertainty of attenuation:	$\delta T_{\text{atm1}} = 0.6$ K (taken as 10% from atmospheric noise)
- from uncertainty of atmospheric effective temperature T_{eff} :	$\delta T_{\text{atm2}} = 0.6$ K (taken as 10% from atmospheric noise)
- additional uncertainty from errors at small elevation angles:	$\delta T_{\text{atm3}} = 0.3$ K
Total noise of Cold Horn:	$T_{\text{cold}} = 11.91$ K (by integration using horn's directivity over full sphere)
- uncertainty for the noise added from ground and warm wall:	$\delta T_{\text{gnd}} = 0.8$ K (estimated as $\sim 1/3$ form ambient noise's contribution)
- possible error of numerical calculations:	$\delta T_{\text{num}} = 0.5$ K
Total for uncertainties:	$\sum_{\text{RSS}} \delta T \approx 2$ K (RSS summation)
Total result for Cold Horn:	$T_{\text{cold}} \pm \delta T_{\text{cold}} = 11.91 \pm 2$ K

Wide-beam unprotected Skobelev type horn

- RSS summation of errors: all components are considered as uncorrelated

$$\delta T_{\text{total}} = \sqrt{\delta T_1^2 + \delta T_2^2 + \dots + \delta T_n^2}$$

Hot source for 10 GHz ... WR-90 dummy load



- ▶ Applied at ambient temperature usually
- ▶ A good VSWR is needed.
- ▶ The problem is changes in VSWR when switching between Cold and Hot.

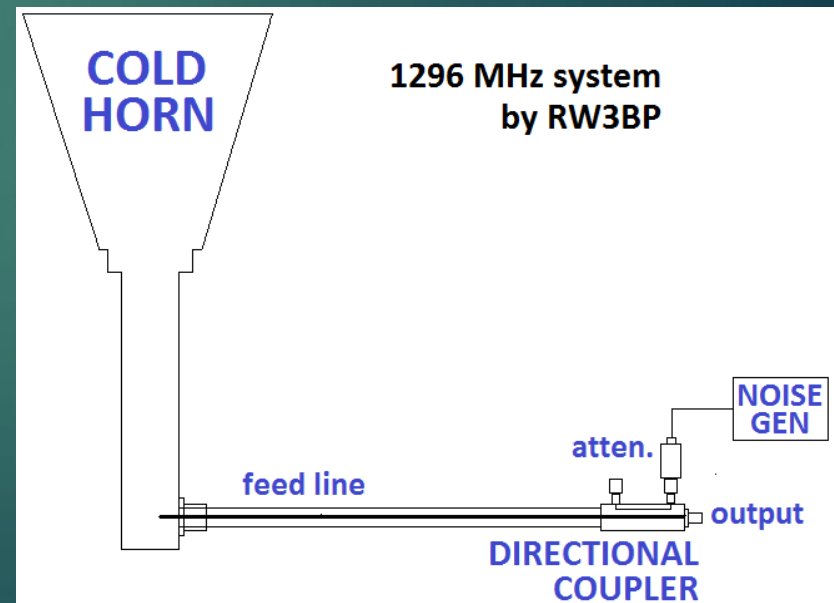
The mismatch issues & uncertainty:

$$T_{in} \pm \delta T_{in} \approx (1 - |\Gamma_{RX}|^2) \cdot (1 - |\Gamma_{source}|^2) \cdot (1 \pm 2 \cdot |\Gamma_{RX}| \cdot |\Gamma_{source}|) T_{source}$$

$T_{in} \pm \delta T_{in}$ - characterizes the delivered power;

$\Gamma_{RX}, \Gamma_{source}$ - reflection coefficients.

- ▶ The problem also is the RX Noise Figure itself can be changed by a source mismatch.
- ▶ A good matching of measuring horn is needed too to mitigate the problem of VSWR change. It is feasible for narrow frequency bands.
- ▶ RW3BP applied a directional coupler to mix a noise from the hot source --->



Cold Horn NF and uncertainty calculator ...

Excel spreadsheet with macros

Takes
into
account:

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1														
2														
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Cold horn RF receiver measurements

T cold, K: 12.67 T hot, K: 285.9 Y factor: 5.44 = 3.499 (ratio)

T cold uncertainty, K: 2.08 T hot uncertainty, K: 7.15 Mismatch (click) Y factor uncertainty: 0.05 dB

Trx = 96.65 K, receiver NF = 1.249 dB Attenuation & losses

RSS (stat) uncertainty = 4.45 K, 0.05 dB

Absolute (max) uncertainty = 7.55 K, 0.086 dB Write to list and Close

Cold horn RF receiver measurements

T cold, K: 13.11 T cold uncertainty, K: 2 Trx = 96.03 K, receiver NF = 1.242 dB

RSS (stat) uncertainty = 4.45 K, 0.05 dB

Absolute (max) uncertainty = 7.55 K, 0.086 dB

Mismatch uncertainties

VSWR source: 1.1 ± 0.1 VSWR receiver: 1.3 ± 0.3

Mismatch uncertainty: 1.242 %; Temp correction: -1.924 %

Correct Tcold & its uncertainty RSS Abs

Correct Thot & its uncertainty

Correct (if checked) & Close Write to list and Close

- ▶ Noise meter instrumental uncertainty (due to the limited time of noise averaging, errors from nonlinearity)
- ▶ Losses in the horn and interconnects
- ▶ Mismatch uncertainties and VSWR errors

Results ...

1296 MHz: 0.12 ± 0.03 dB



- ▶ Unprotected narrow-beam zenith directed horn were applied
- ▶ The result is achieved on a modified G4DDK LNA

10 GHz: $\delta NF = \pm 0.05$ dB



- ▶ Unprotected wide-beam horn were applied, elevation 45 deg
- ▶ The result is achieved on an intentionally matched test LNA

Notes, problems and references ...

- ▶ Contributions to the horn temperature for low band (1296 MHz) and high band (10 GHz): the space and ambient noise are approximately the same. The atmospheric contribution is low at 1296 MHz, $\sim 1.5\text{K}$, and significant at 10 GHz, $\sim 6\text{K}$ and more. A losses and noise in interconnects may contribute significantly at 1296 MHz.
- ▶ A high precision can be achieved, what is significant for low NF devices. Achieving a high accuracy at mm-waves is expected problematic due to high atmospheric influence at the ground.

- ▶ An accuracy for the conventional Y-factor with diode noise heads is estimated worse ---> (10 GHz example)

... but simpler in applications.

Rohde & Schwarz Noise Figure and Uncertainty Calculator 3.10

File Option Web Help

Noise Source

ENR: 11.95 dB
Output Match: VSWR 1.2, RL (dB) 1.2
Eff. ENR: 11.94 dB
Noise Source: User
Ambient Temp: 25 C
ENR Uncertainty: 0.1 dB
Toff: 298.2K (77.0F)
Ton: 4833.6K

DUT

Input Match: 1.3, VSWR, RL (dB)
Output Match: VSWR 1.8, RL (dB)
Freq: 10.36 GHz, Freq Conv.
NF: 0.9 dB
Gain: 12.8 dB

Analyzer

Ext PA Input Match: 1.5, VSWR, RL (dB)
SA Gain Unc: 1 dB
SA NF Unc: 0.2 dB
Ext PA:
PA Gain: 20 dB
PA NF: 2.6 dB
Analyzer Noise: 9 dB, NF (dB), DANL (dBm/Hz)
Net Analyzer NF: 2.76 dB

NF Measurement Uncertainty

$\pm 0.25\text{ dB}$

Measurement Guidelines

Goal

- >3dB: ENR - NF_{sa} = 9.18 dB
- >5dB: ENR - NF_{dut} = 11.04 dB
- >1dB: (NF+G)_{dut} - NF_{sa} = 10.94 dB

ROHDE & SCHWARZ

... notes & problems continued

- ▶ A temperature regime becomes significant in high precision measurements, especially for outdoor experiments.
- ▶ The ambient temperature should be noted carefully; a tested device should be switched on in advance for self-warming up. It may be a problem to provide a repeatability of NF results for the achieved uncertainty gaps.
- ▶ Precise VSWR measurements, especially at 10 GHz and higher may be a problem too. Using modern VNAs with computational error corrections inside is not a cheap solution.
- ▶ The Cold Horn is not too simple in applications but advanced in precision.

References:

1296 MHz: Sergei Zhutyaev RW3BP, *1296 MHz Small EME Station with Good Capability (Part 3), Accurate Noise Figure measurements on 1296 MHz*, 2010

10 GHz: Dimitry Fedorov UA3AVR, *The Cold Horn method for NF measurements – notes about 10 GHz applications*, DUBUS v. 47, 1.Quarter 1/2018, page 57

The Moon as a radiometry standard ...

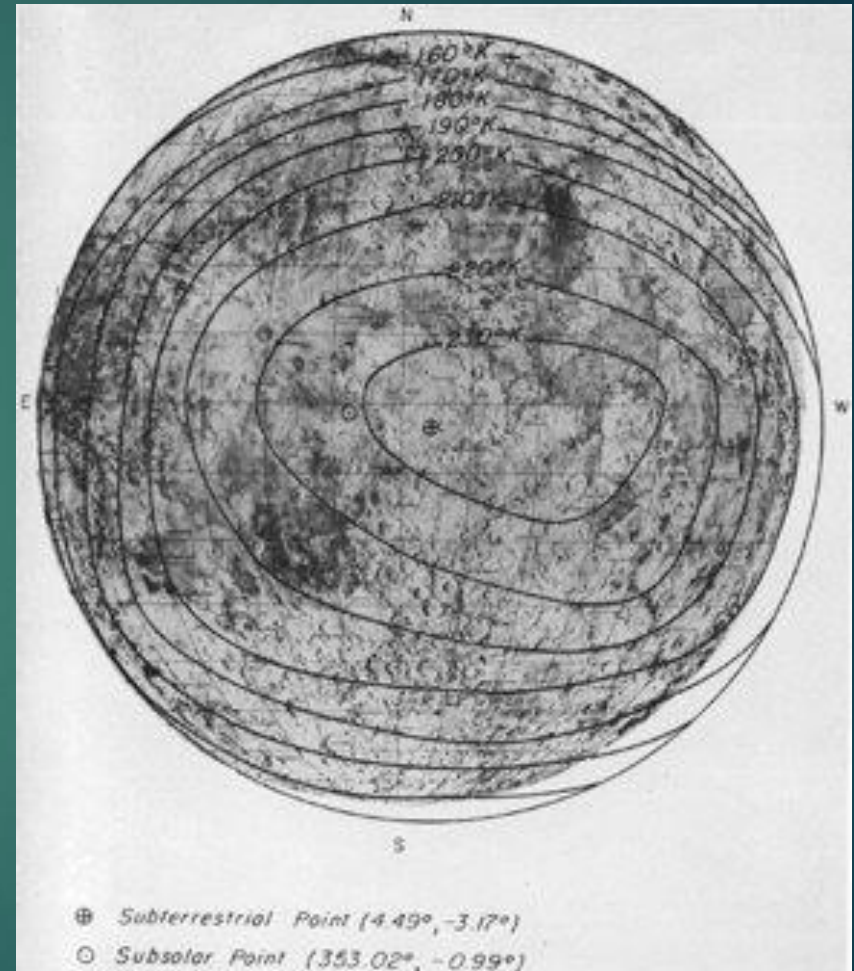
- ▶ ... is a thermal noise source, at least, in radio frequency bands.
- ▶ The lunar temperature was a subject of multiple investigations for different frequencies; a lot of info is available. There are changes of the temperature across the disk and during the phase cycle.
- ▶ There are temperature variations during the phase cycle; they are different for different frequencies. For the disk center [*]:

2.3 GHz – almost a constant, $T_{\text{center}} \approx 136 \text{ K}$;

8.4 GHz – $T_{\text{center}} = 189 \pm 6 \text{ K}$

32 GHz – $T_{\text{center}} = 166 \pm 20 \text{ K}$.

- ▶ Distribution data could be also found for some frequencies:



[*] D.D. Morabito, Lunar Noise-Temperature Increase Measurements at S-Band, X-Band, and Ka-Band Using a 34-Meter-Diameter Beam-Waveguide Antenna, IPN Progress Report 42-166, August 15 (2006)

$\lambda = 8.6 \text{ mm}$, moon phase 11.7 deg to 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)

The Y-factor implementation ...

- ▶ A cold source is still the CMB radiation ...
- ▶ ... therefore, a contribution of the Cold temperature errors to total measurement ones is reduced. The Hot temperature – a Moon noise

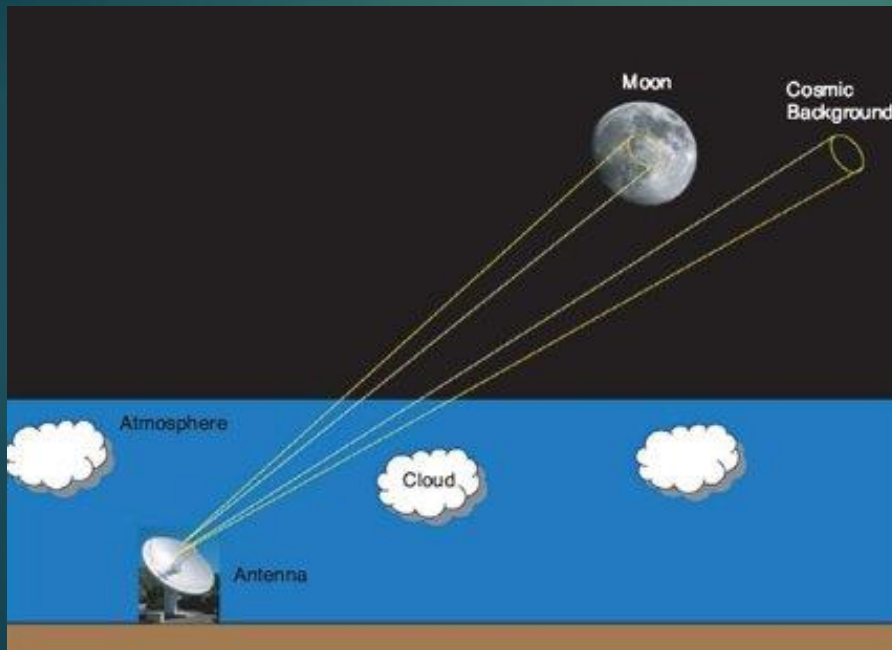


Image source: D. Morabito, M. Gatti, and H. Miyatake, *The Moon as a Calibration Load for the Breadboard Array, Interplanetary Network (IPN) Progress Report 42-172*, pp. 1-21, February 15, 2008

$$T_{hot} = T_{lunar}^{**} + T_{RX} + T_{atm} + T_{spill},$$
$$T_{cold} = T_{CMB}^* + T_{RX} + T_{atm} + T_{spill},$$
$$NF_{RX} = 10 \log_{10}(1 + T_{RX}/T_0).$$

* - corrected by atmospheric losses

** - corrected by a temperature distribution and atmospheric losses

Possible issues:

- ▶ High T_{spill} - a noise from antenna lobes besides the main beam,

$$T_{spill} \cong T_{amb} \frac{1-\eta_M}{2}$$

η_M - the Main Beam Efficiency as a parameter of antenna characterization.

- ▶ Atmospheric losses, uncertainties in absorption rate and atmospheric temperature, especially for mm-waves.
- ▶ Low Y-factor value, the result uncertainty rises, especially when $Y < 2$.

Mm-wave Y-factor tests



38 GHz, 2015*



76 GHz – recent attempts

- ▶ A sheet of absorber in front of the feed can be used as additional noise source – left picture

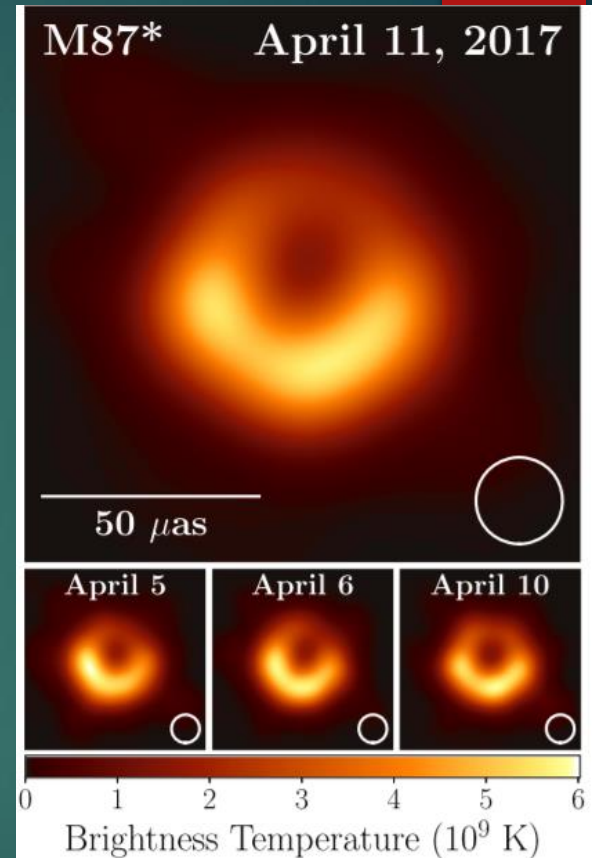
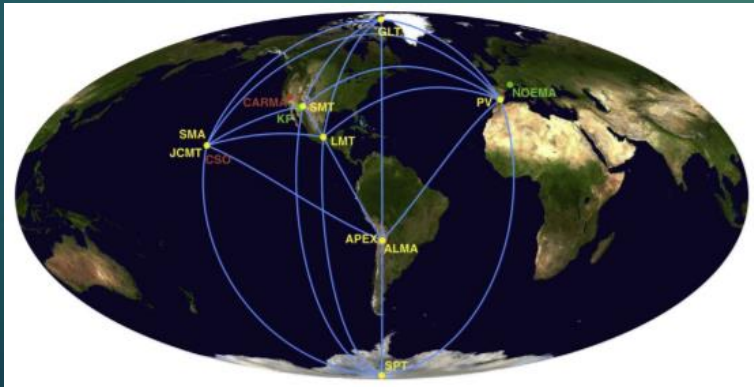
That's all for the main part of talk.
Questions?



Black Hole image 2019

this slide is just a remark about outstanding Radio Astronomy achievement recently

- ▶ A real black hole was never been caught on a snapshot previously.
- ▶ M87 – a giant galaxy with supermassive black hole in the center.
- ▶ Event Horizon Telescope – is the system of Millimeter Wave radio telescopes, $\lambda=1.3$ mm with an interferometry technique (VLBI).
- ▶ The signal receiving in two adjacent 2 GHz wide frequency bands centered at 227.1 and 229.1 GHz, heterodyne DSB system with a final baseband digitizing at 32 Gbps.
- ▶ Data had been collected in 2017. The data were being processed during 2 years.



References:

- The Astrophysical Journal Letters, 875:L1 (17pp), 2019 April 10
- The Astrophysical Journal Letters, 875:L2 (28pp), 2019 April 10
- The Astrophysical Journal Letters, 875:L3 (32pp), 2019 April 10
- The Astrophysical Journal Letters, 875:L4 (52pp), 2019 April 10
- The Astrophysical Journal Letters, 875:L5 (31pp), 2019 April 10
- The Astrophysical Journal Letters, 875:L6 (44pp), 2019 April 10

Thanks!

Swedish EME Meeting by SM4IVE
Örebro, 24-26 May 2019

73 & and good luck in GHz EME!
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A lot of references in above presentation are available
with open access, please, use Google or ask me

