Millimeter astronomy in Russia: what, where and when?

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There are obvious questions, namely:

A what? Where is? And when?

Of course, we have to add more, what for?

In the last few years there have been various discussions about the development of millimeter and sub-millimeter astronomy in Russia.

The report will address:

- Today's state in Russia;
- Overview of leading foreign (international) observatories;
- Offers to choose an antenna;
- Proposals for choosing the location of the radio telescope installation.

The program of the meeting will discuss all these issues in detail. I will try to describe the general vision from the point of view of a person who **has observed** the evolution of

«questions-and-answers»

to these problems over the last 40 years in the USSR and the Russia from within.

The answers to these questions can be obtained by solving the problem of linear programming, i.e. optimizing the parameters that are not optimized at the same time.

Naturally, to answer these questions it is necessary to start with the main thing, namely - whether we are talking about single antennas or antenna array.

Early stage of millimeter astronomy in the USSR

Then I will present on the basis of the book

A Brief History of Radio Astronomy in the USSR. 2012. (chapter «Radio Astronomy Studies in Gorkii»)

almost verbatim

Early stage of millimeter astronomy in the USSR

Radio astronomy studies at short millimeter wavelengths (*λ<4 mm)* were begun at Gorkii (Radio Physical Research Institute, NIRFI-НИРФИ} by Kislyakov in 1954. By 1960, a modulation radiometer at 4.1 mm had been devised at NIRFI, as well as a broadband (3–7 mm) detector radiometer. Kislyakov and his colleagues used these radiometers to investigation of the Moon (phase dependence of the Lunar radio emission) and the Sun, as well as detailed studies of the dependence of the atmospheric absorption at 4 mm on the meteorological parameters (Kislyakov, Nikonov, Strezhneva and et al.).

Early stage of millimeter astronomy in the USSR

Further, a unique series of detector radiometers operating at 1.8, 1.3, 0.87 and 0.74 mm (Naumov, Yu. A. Dryagin, Fedoseev) were developed at NIRFI, which were used for observations of the Moon and the Sun, as well as studies of the atmospheric absorption of radio waves (L. M. Kukin, L. V. Lubyako, Fedoseev).

Studies of the radio emission of the Sun and studies of the radio emission of the Sun and Moon at 4 mm were then continued in collaboration with LPI (Lebedev Physical Institute), using the LPI 22-m radio telescope and radiometers provided by NIRFI. In this same period, Kislyakov, A. D. Kuz'min and Salomonovich conducted the first investigations of the radio emission of Venus at 4.1 mm.

Early stage of millimeter astronomy in the USSR

The new RT-25×2 radio telescope due to is good resolving power was used to study at millimetar wavelengths (4.1, 6, 8 mm):

- the brightness distribution over the disk of the quiet Sun, including limb effects;
- chromospheric granulation;
- a survey dark nebulae.

Kislyakov, Chernyshev, Fedoseev, S. A. Pelyushenko, Zinchenko, Shvetsov et al.

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Early stage of millimeter astronomy in the USSR

Further studies of the Sun and planets (Venus, Mars, Mercury, Jupiter) were continued in Crimea on the 22 m radio telescope of the Crimean Astrophysical Observatory

(Kislyakov, Efanov, Moiseev, Naumov, V. N. Voronov, I. I. Zinchenko and others).

Project “POLYGAMY”

The decision on the need to create the VLBI Network in the USSR, united by a specialized communications satellite, which in its scientific capabilities goes far beyond the radio astronomy itself, was taken at the general Session of the Council "Radio Astronomy" at the Presidency of the USSR Academy of Sciences. *(December 11-13, 1978, Svenigorod).*

In 1980, a project called POLYGAMY was announced.

(Bulletin of the Special Astrophysical Observatory

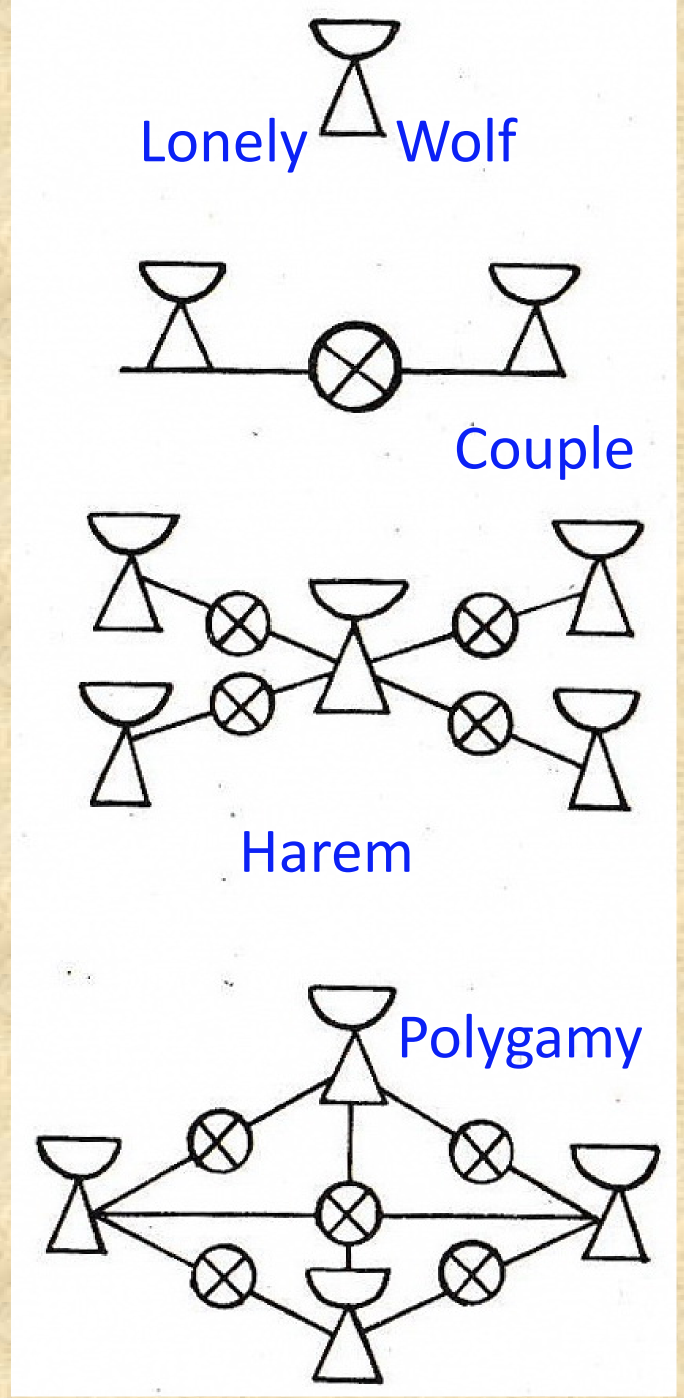
Сообщения Специальной Астрофизической Обсерватории, No 27, 1980)

Project “POLYGAMY”

In the community of radio telescopes, the following variants of "family happiness" are imaginable (*folklore of IAU Commission No. 40*)

This community has already gone through three phases.

This project envisages a transition to the fourth phase.



А К А Д Е М И Я Н А У К

СОЮЗА СОВЕТСКИХ СОЦИАЛИСТИЧЕСКИХ РЕСПУБЛИК

П Р О Е К Т

"ПОЛИГАМ"

Project "POLYGAMY"

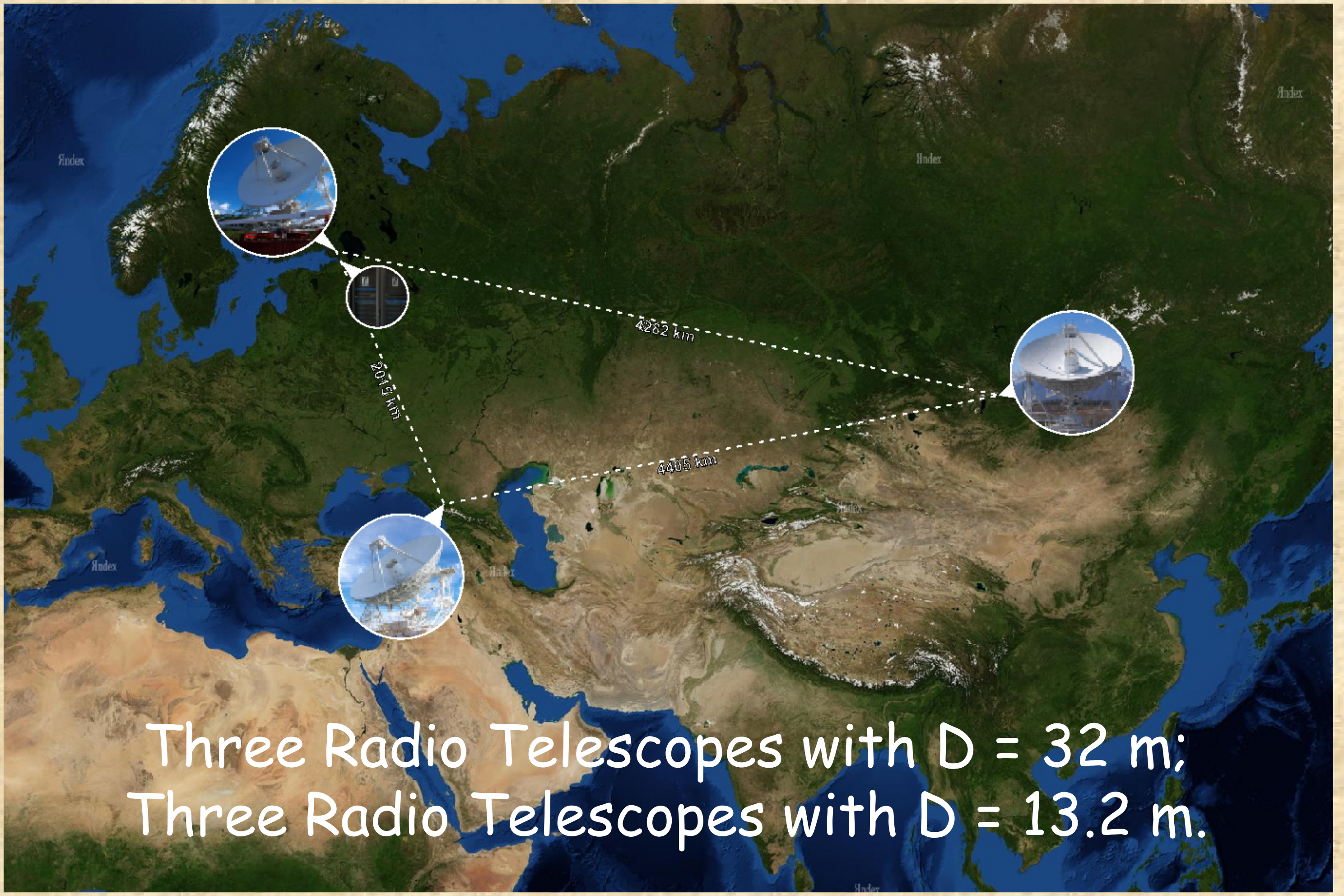
Project “POLYGAMY”

First stage – antennae, D = 64-70 m, $\lambda \geq 1.35$ cm

Further expansion of POLYGAMY into the millimeter and decameter range can be carried out by joining the system of mirrors already existing in the USSR. The development of the millimeter range is of particular interest, so it is necessary to consider the possibility of improving the surfaces of large elements of the system, as well as to include in the system, as one of their dominant elements, a millimeter range antenna with a diameter of D ≈ 36 m.

However, as they say in sport, there was a loss of pace. It ended with the creation of a national VLBI network with only three antennas with a diameter of 32 m – IAA RAS

The "Quasar" VLBI network



RT-13 (Badary, IAA RAS)

The following table is followed by a list of antennas and networks operating in the millimeter range

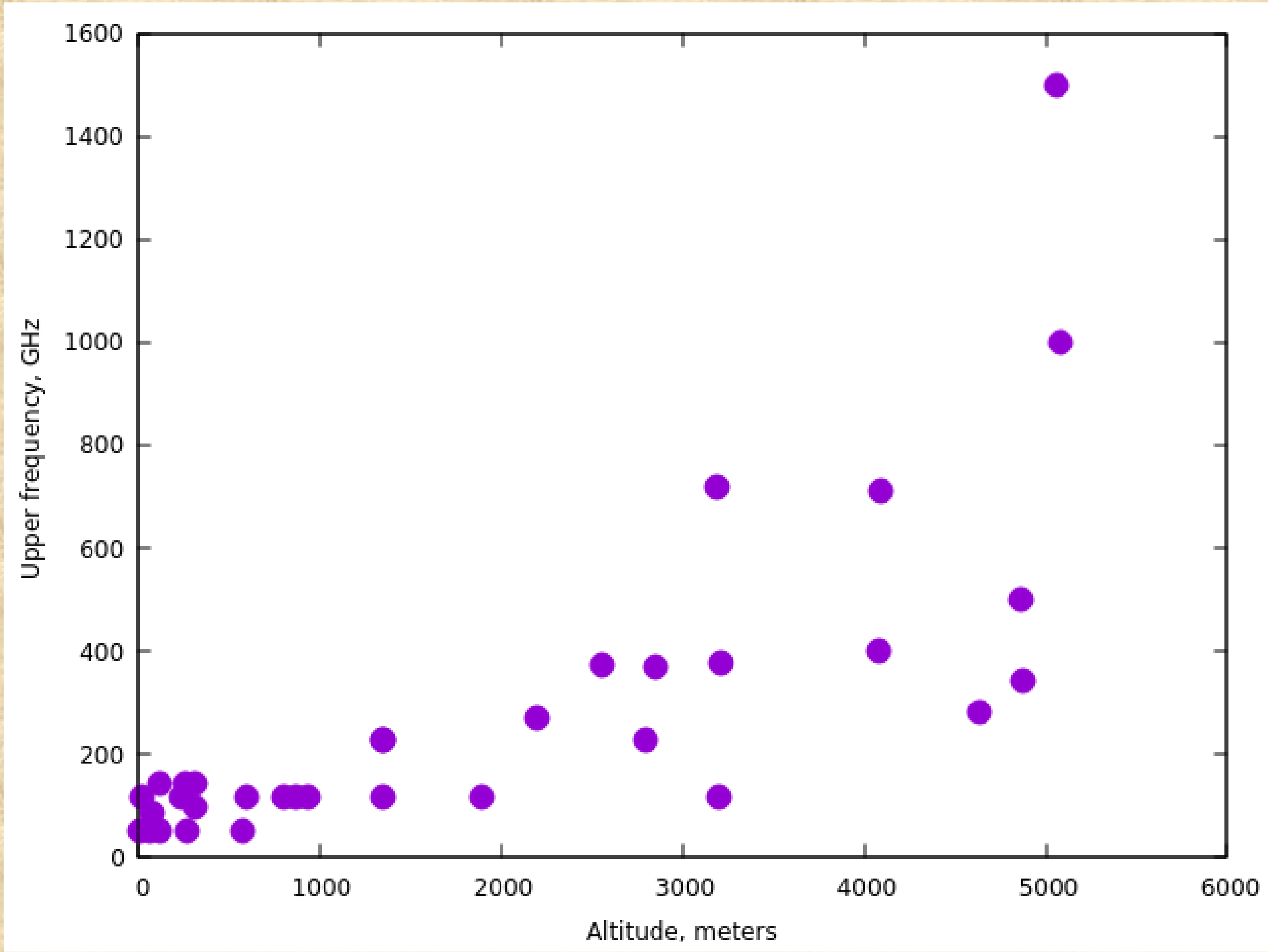
Frequency Range $\geq$ ***50 GHz***

Radio Telescope (Abbreviation)	D (m)	Nation	Altitude (m)	Frequency Range (GHz)
Green Bank (GBT)	100	USA	807	0.3–116
Effelsberg (EFF)	100	Germany	319	0.3–96
Tianma (TMRT)	65	China	7	1.25–50
Sardinia (SRT)	64	Italy	600	0.3–116
Large Millimeter Telescope (LMT)	50	Mexico	4640	75–280
Nobeyama (NOB)	45	Japan	1349	20–116
Yebes (YEBES)	40	Spain	931	2–116
Noto (NOTO)	32	Italy	78	1.4–86
Pico Veleta (IRAM30)	30	Spain	2850	70–370
Mopra (MOPRA) ; ATCA, 6 dishes	22	Australia	860; 236	1.2–117
Korean VLBI Network (KVN)	21	Korea	120; 260; 320	21–129
VLBI Exploration of Radio Astrometry (VERA)	20	Japan	116; 574; 273; 65	2.2–50
20 m Onsala (ONS20)	20	Sweden	20	2.2–116

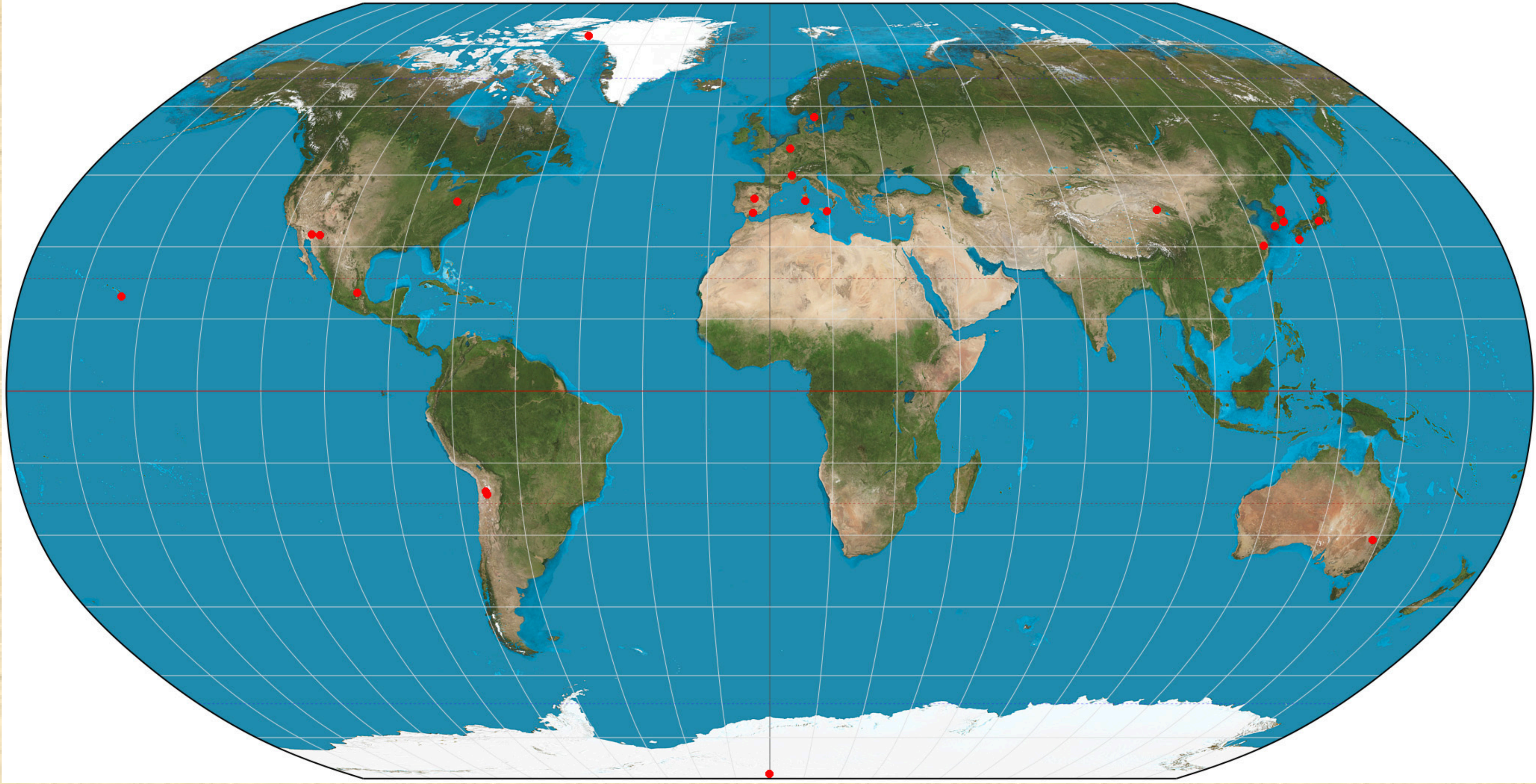
James Clerk Maxwell Telescope (JCMT)	15	USA/Hawaii	4092	211-710
NOrthern Extended Millimeter Array (NOEMA, 12 dishes)	15	France	2552	72-373
Quinghai Observational Station	13.7	China	3200	85-115
Metsahovi Radio Observatory	13.7	Finland	79	2-150
Atacama Large Millimeter Array (ALMA, 54 + 12 dishes)	12 and 7	Chile	5058	31-1000
Greenland Telescope (GLT)	12	Denmark	3210	84-377
Atacama Pathfinder Experiment (APEX)	12	Chile	5064	200-1500
Arizona Radio Observatory Telescope (ARO 12m)	12	USA	1894	84-116
ARO Submillimeter Telescope (SMT)	10	USA	3185	205-720
Solar Planetary Atmosphere Research Telescope (SPART)	10	Japan	1350	100-230
South Pole Telescope (SPT)	10	USA/Antarctica	2800	90-230
Atacama Submillimeter Telescope Experiment (ASTE)	10	Chile	4860	270-500
Submillimeter Array (SMA, 8 dishes)	6	USA/Hawaii	4080	200-400

Decommissioned Radio Telescope (Abbreviation)	D (m)	Nation	Altitude (m)	Frequency Range (GHz)
Combined Array for Research in Millimeter-wave Astronomy (CARMA), 6 + 9 + 8 dishes	10.4, 6.1, 3.5	USA	2196	80-270
Nobeyama Millimeter Array (NMA), 6 dishes	10	Japan	1350	80-230
Swedish-ESO Submillimetre Telescope (SEST, will be installed in Namibia as Africa Millimeter Telescope, AMT)	15	Chile	4875	85-345

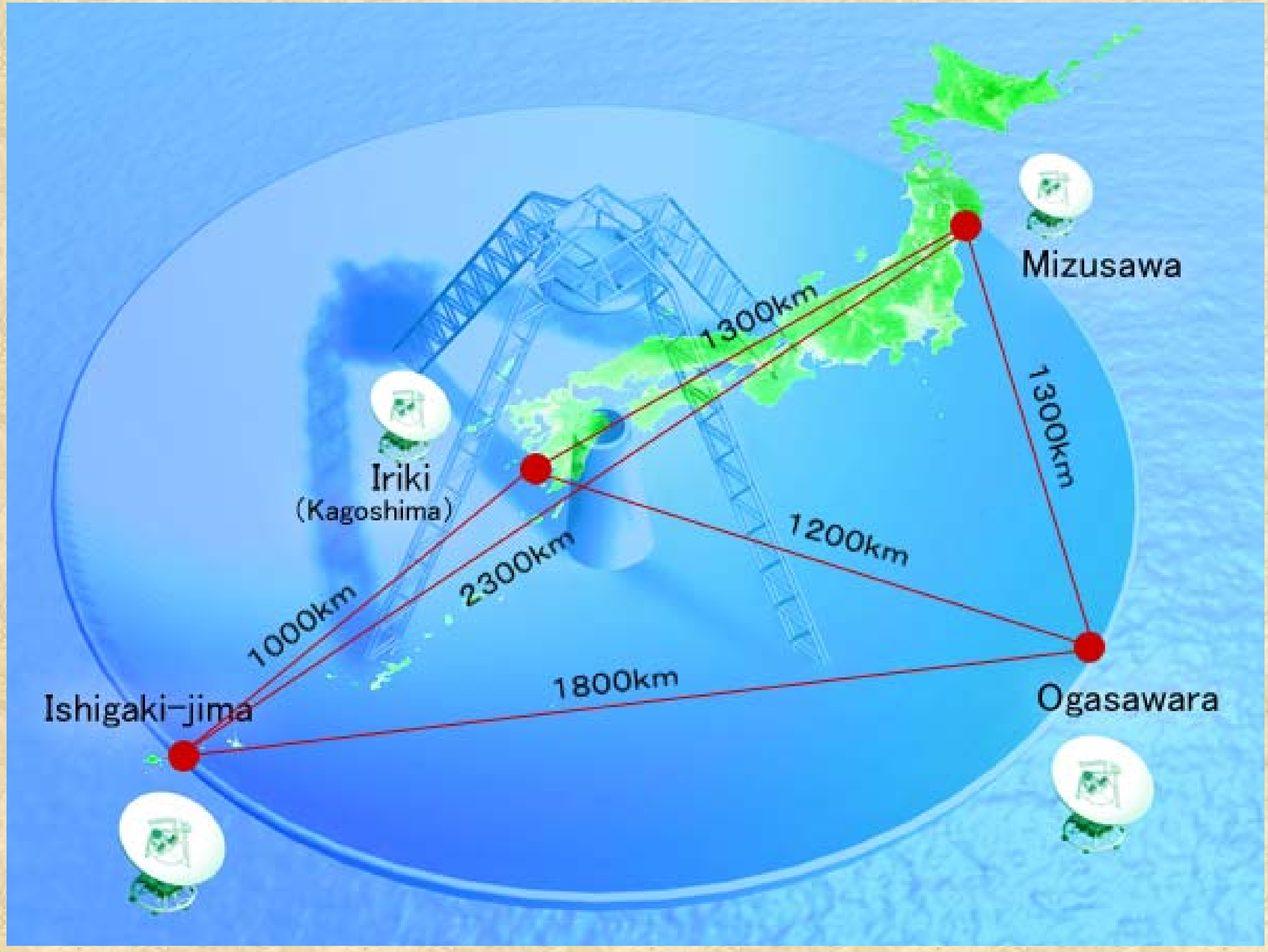
Higher frequency requires high altitude



Geographical distribution of the mm radio telescopes

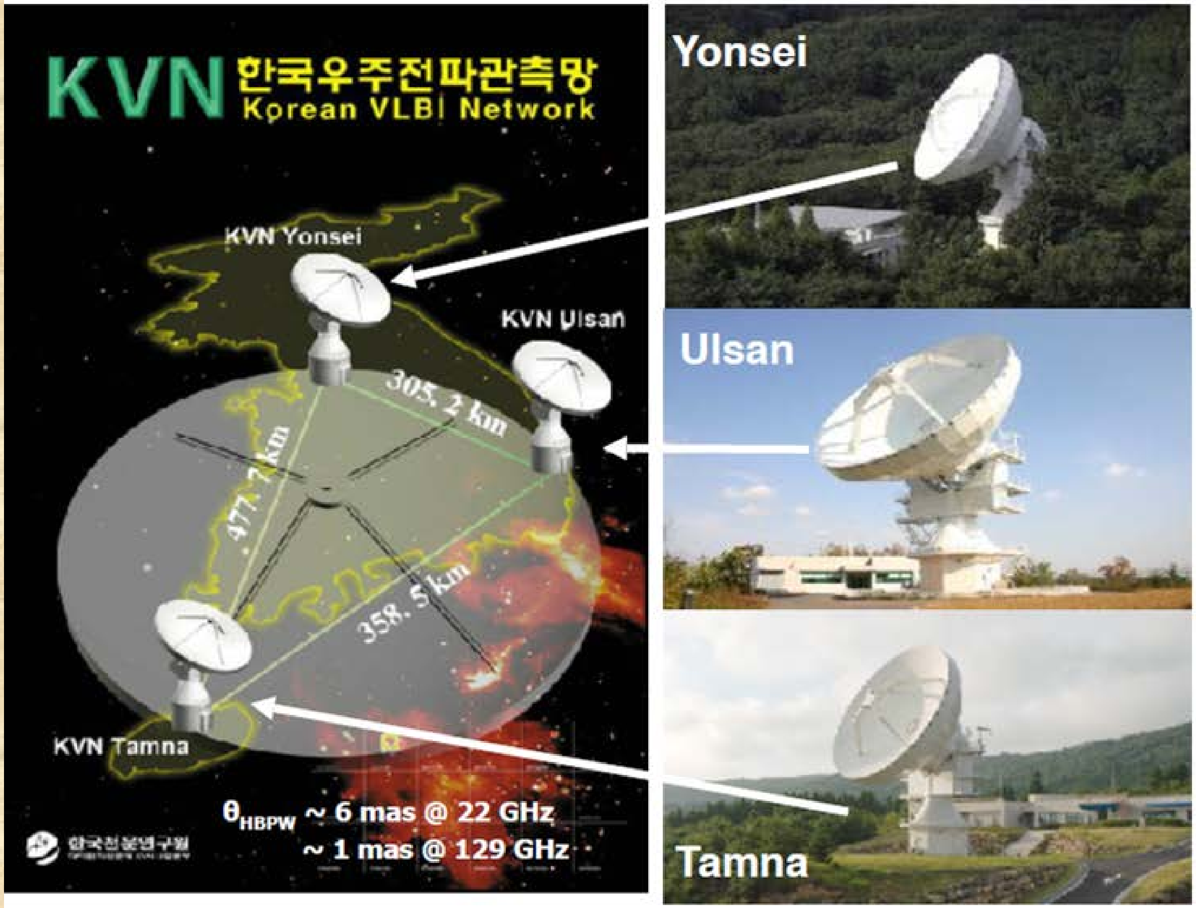


VERA (VLBI Exploration of Radio Astrometry) Japan



Altitude 116; 574; 273; 65 m; D = 20 m; 2.2–50 GHz

KVN (Korean VLBI Network)

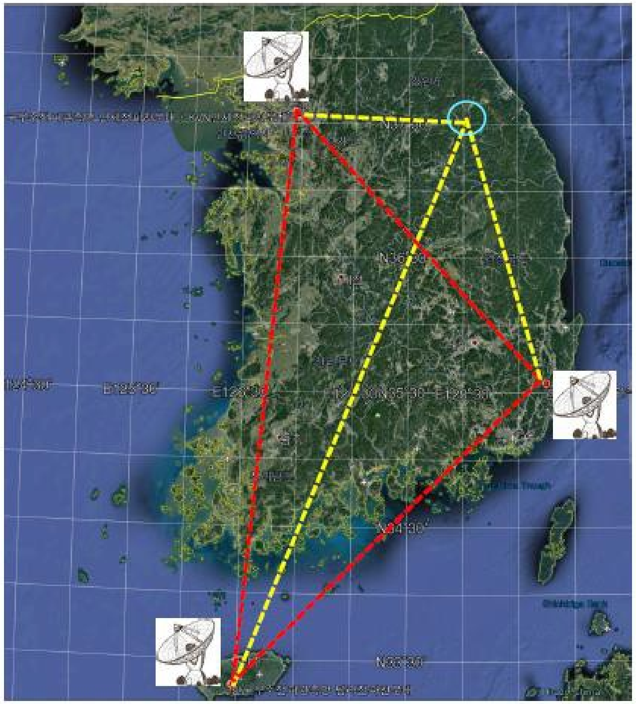


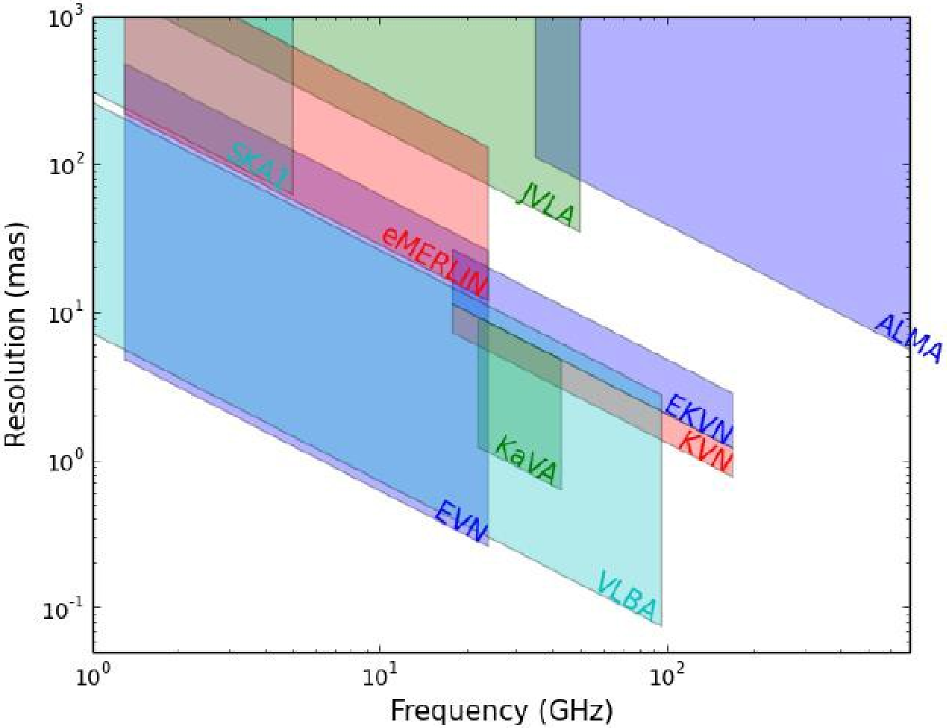
- 3 Telescopes (D = 21m)
- 22/43/86/129GHz
- 300 - 500 km
- Θ = 1 - 6 mas

- Science Targets
  AGN/SF/Evolved Star
  + microquasar

E-KVN Project: Construction of A New Telescope

❖ Almost same Telescope (D = 21m)
- Kangwon Province (~130 km E-W baseline)
- better surface accuracy (~80 um) for 230GHz operation





Tianma Telescope and Observation Station

- 65-m in diameter, fully steerable radio telescope;
- Active surface system installed;
- General-purpose (radio astronomy, single-dish, VLBI, geodynamics)

- Covering 1 – 50 GHz with 8 bands
  - L(1.6GHz),
  - S/X(2.3/8.4GHz)
  - C(5GHz),
  - Ku(15GHz),
  - K(22GHz)
  - Ka(30GHz),
  - Q(43GHz)

Qinghai observation station (Purple Mountain Observatory of CAS)

- Located in Qinghai Province (Delinha) on Tibetan Plateau at approximately 3200 m elevation (latitude φ = 37°22'.4N and longitude λ = 97°33'. 6E).
- The primary facility of Qinghai observation station is the 13.7m radio telescope equipped with a SIS superconductor receiver working in the band of 85-115 GHz.

The quote for mm dish from CETC54 (China)

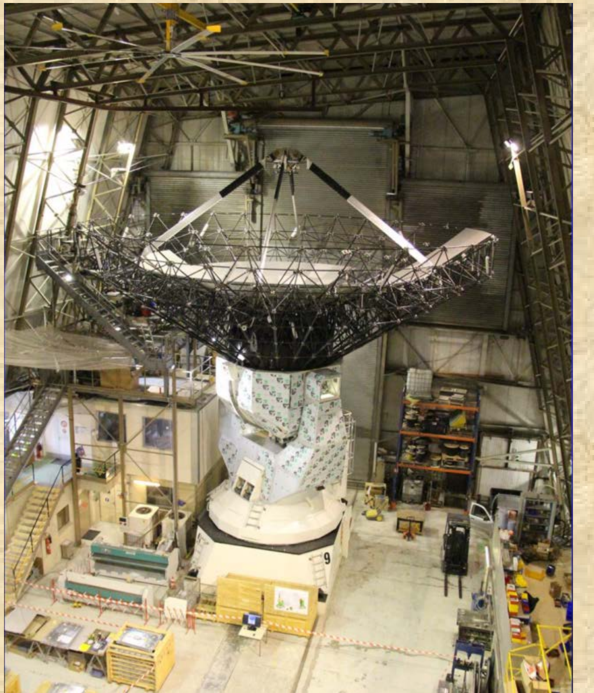
Our current design is for:

- D **15 m**
- ν **300 GHz**
- surface accuracy ***40 micrometer***
- pointing accuracy ***5"***
- travel speed ***2.0 degree/s***
- El speed ***1.0 degree/s***

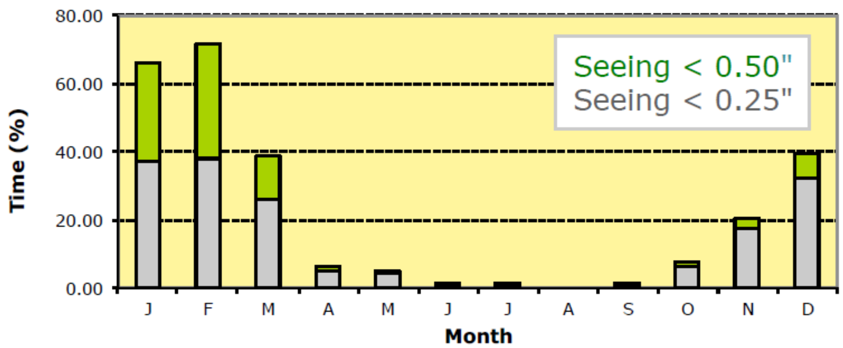
The estimated budget will be EURO 5.3m

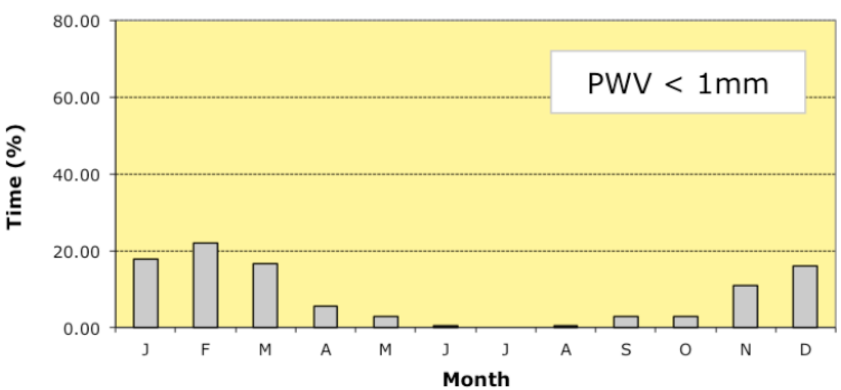
NOrthern Extended Millimeter Array (NOEMA)

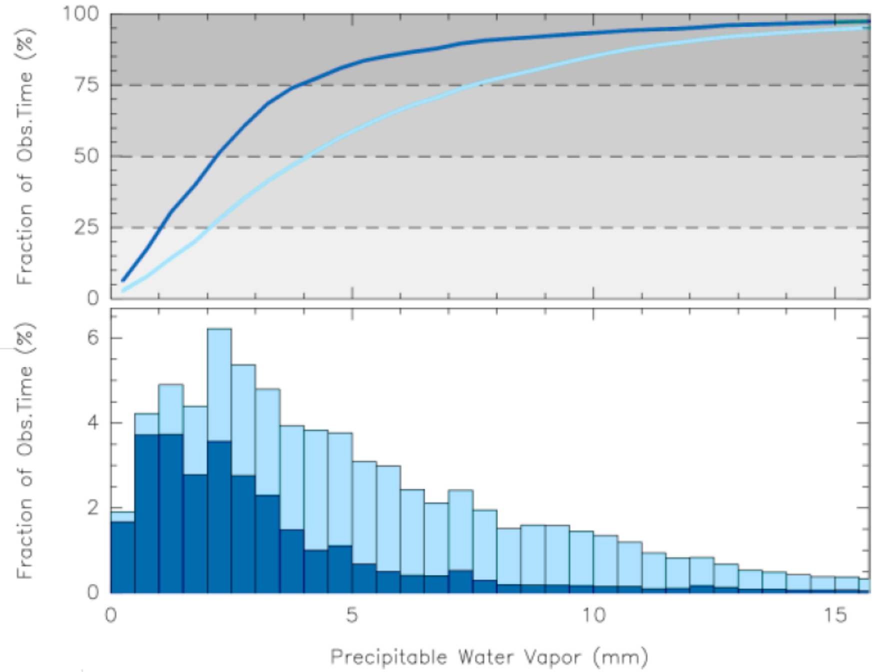
- Located on Plateau de Bure, French Alps, 2550m
- 11 antennas (09-2020), up to 12
- 15 meter dishes
- 70-373GHz frequency coverage
- 1.5 km maximum baseline
- About 0.1 arcsec resolution at 350 GHz



NOEMA weather statistics



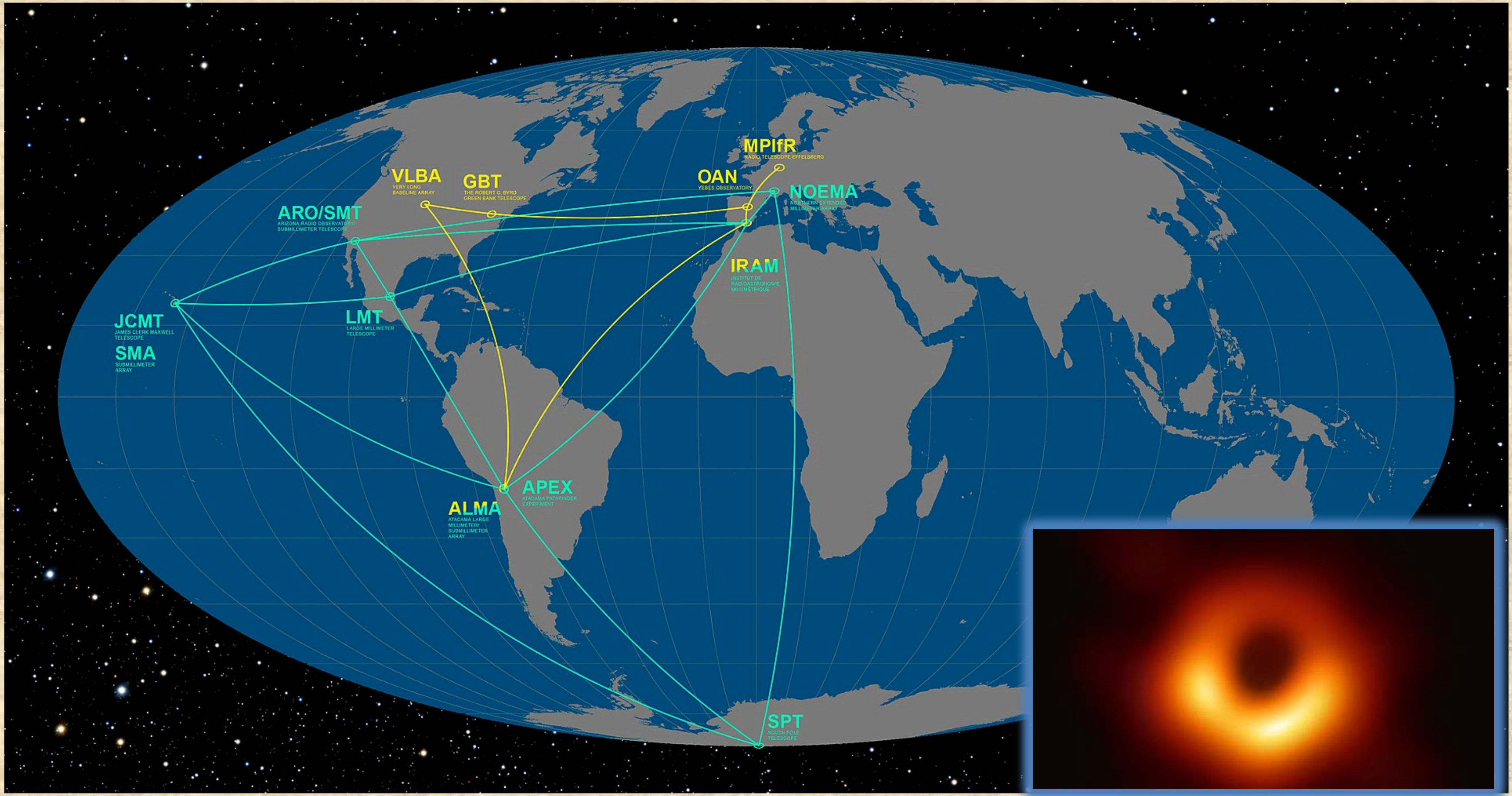




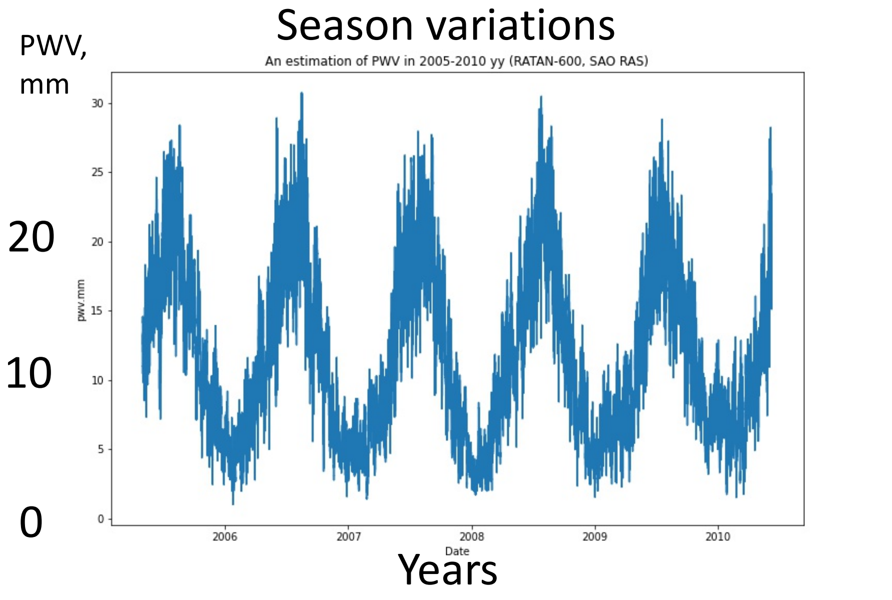
⇒ 2017: 80% of the observing time invested @ 3mm and 2mm

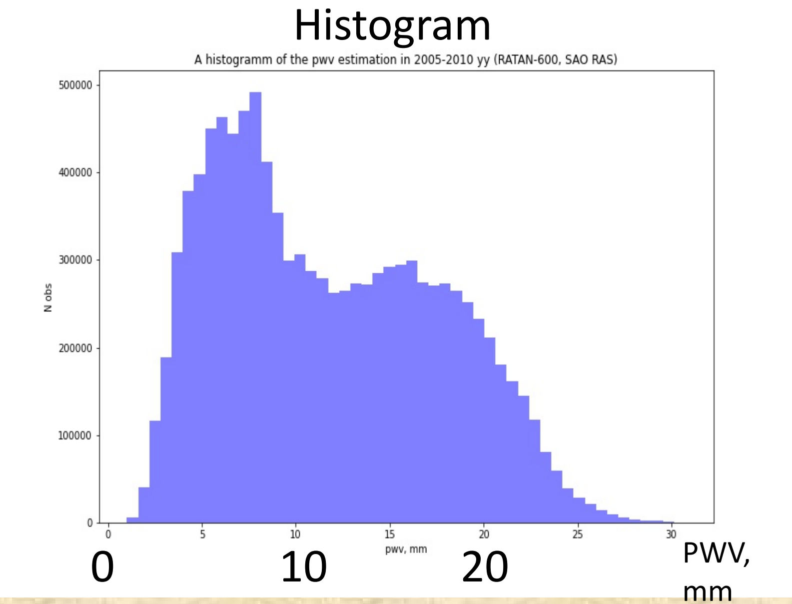
Neri R., The NOthern Extended Millimeter Array NOEMA, Xth Interferometry School (IRAM, 1-5.10.2018), p. 16

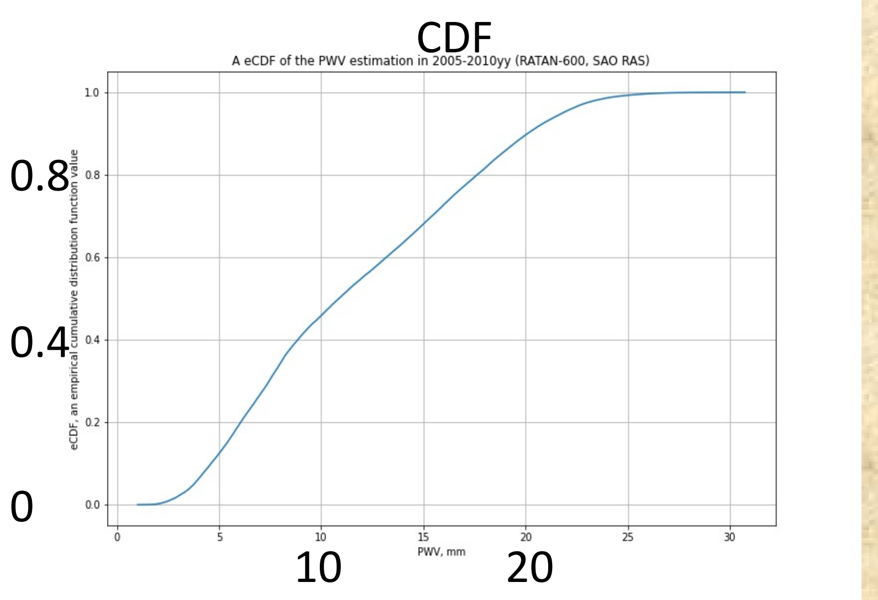
Some of the listed 230 GHz - capable instruments are in the EHT collaboration

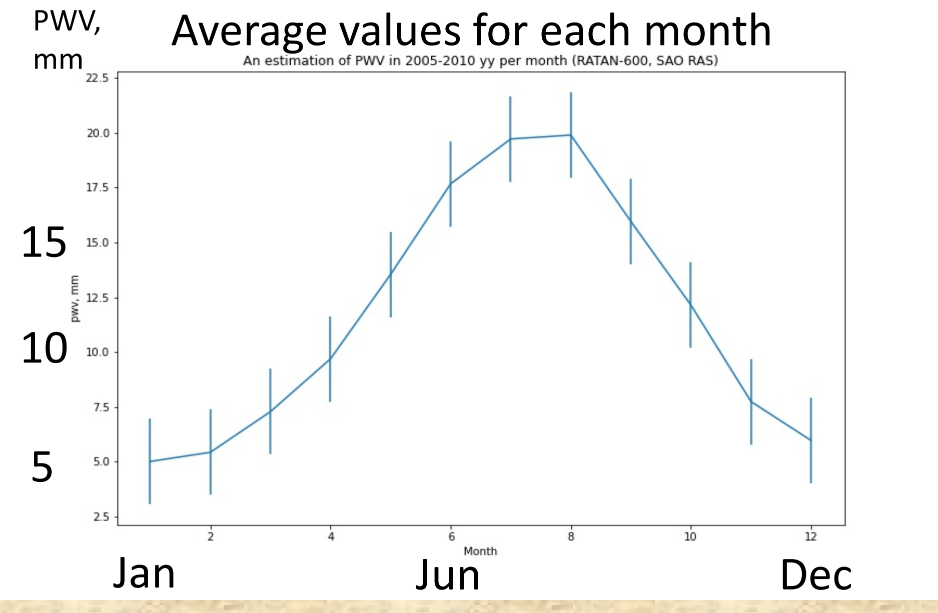


PWV statistics for the RATAN-600 site, 974 m, 2005-2010yy



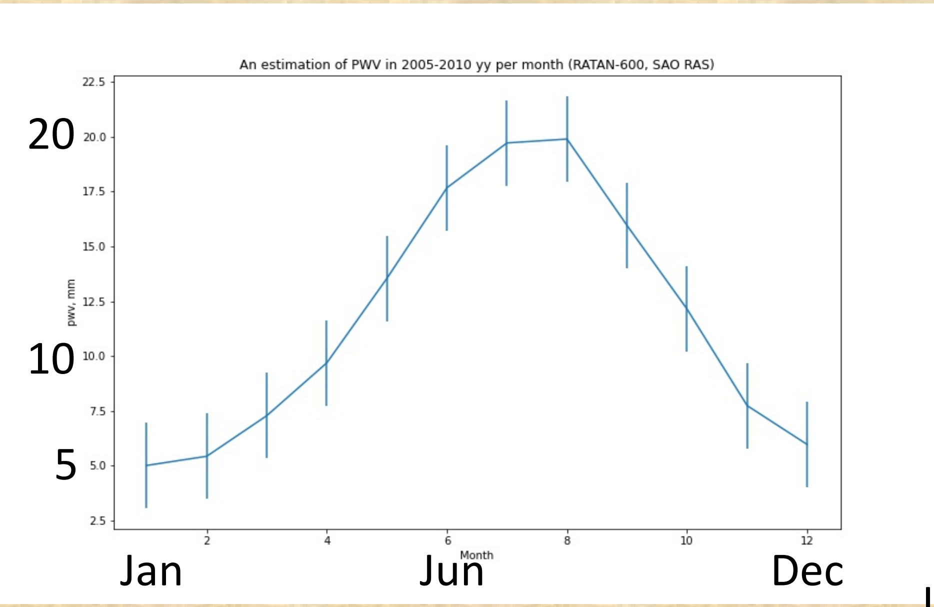


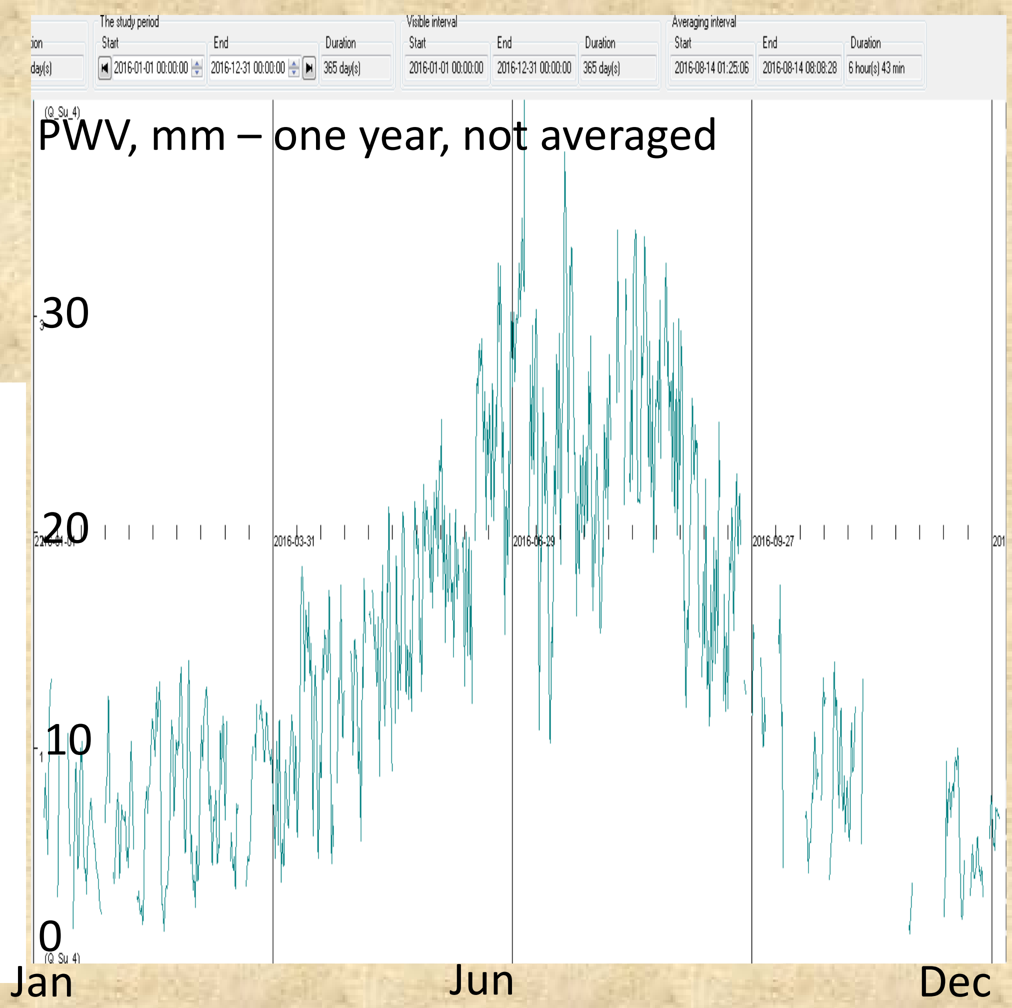




PWV statistics for the RATAN-600 site compared with the nearby Zelenchukskaya Observatory (IAA RAS) satellite data for 2016 year

PWV, mm – averaged in the one month bins for 5 years

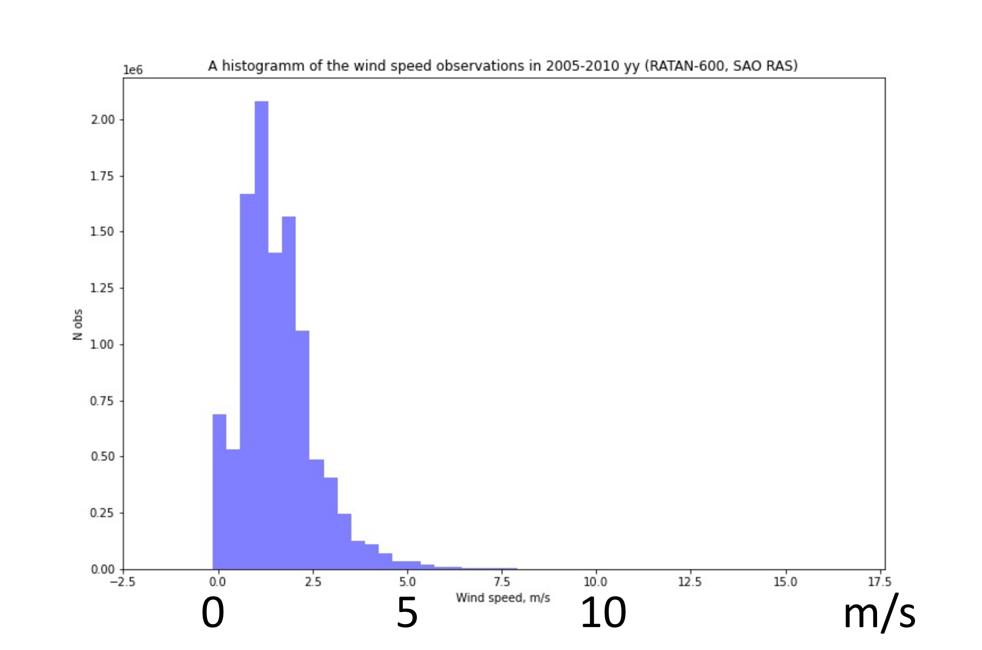




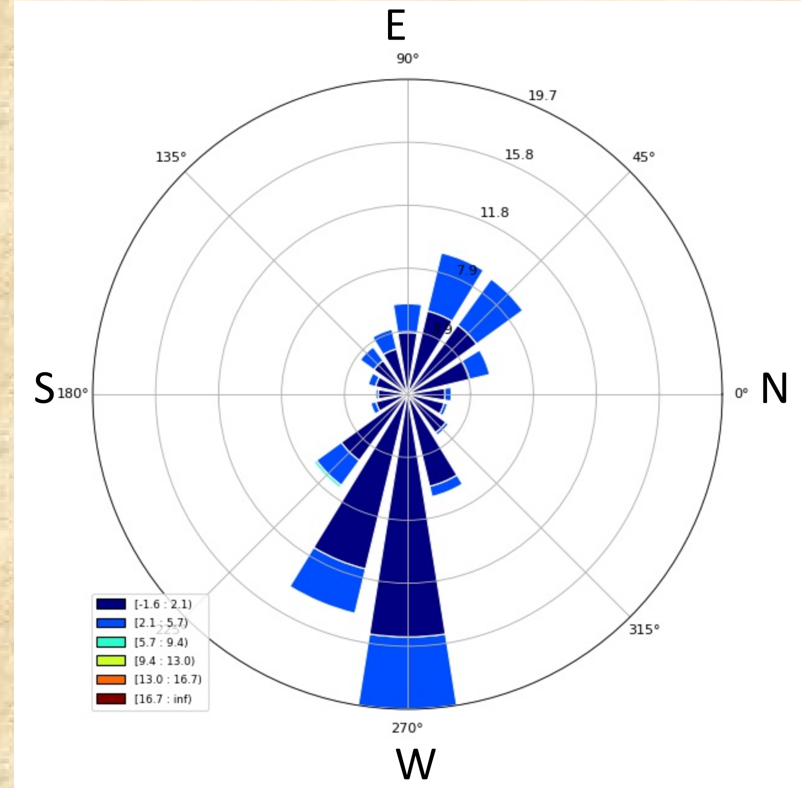
The plots are deliberately distorted to align the y-axis

Wind statistics for the RATAN-600 site, 974 m, 2005-2010yy

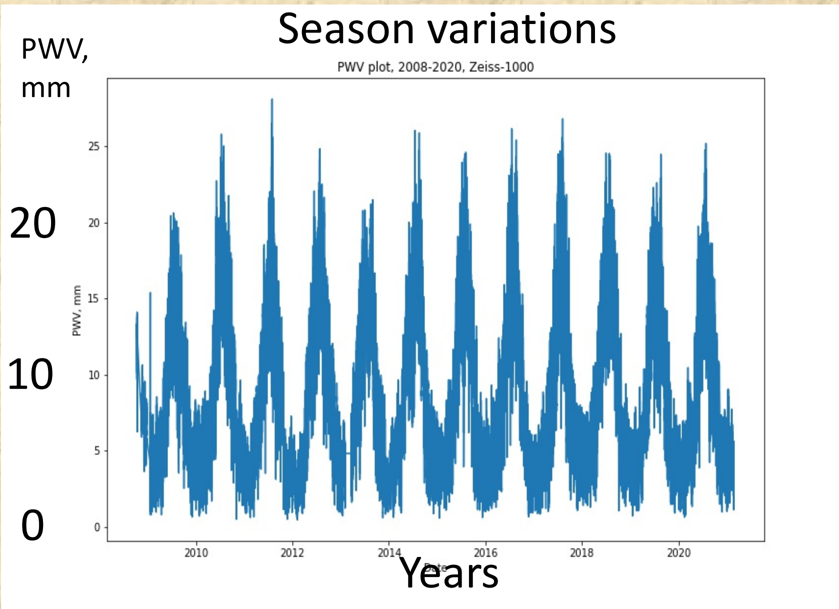
Wind speed histogram

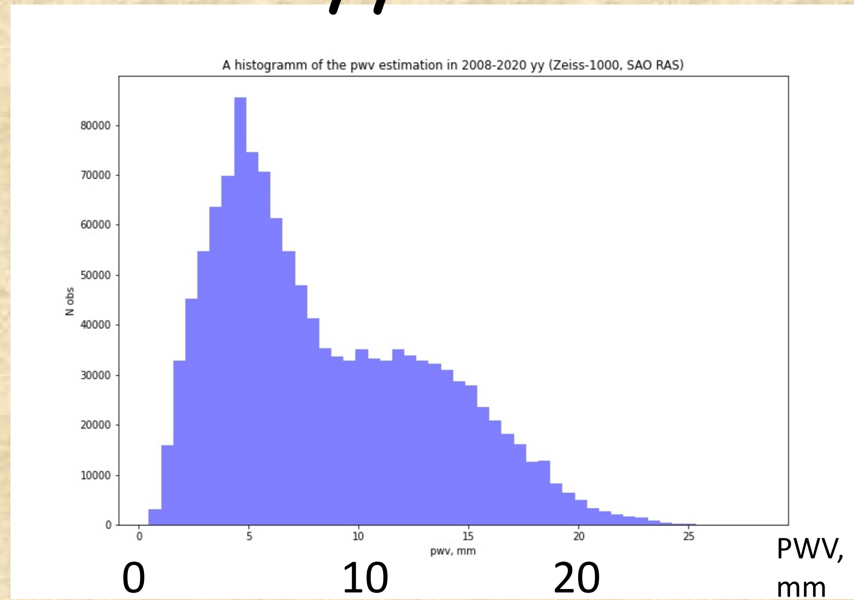


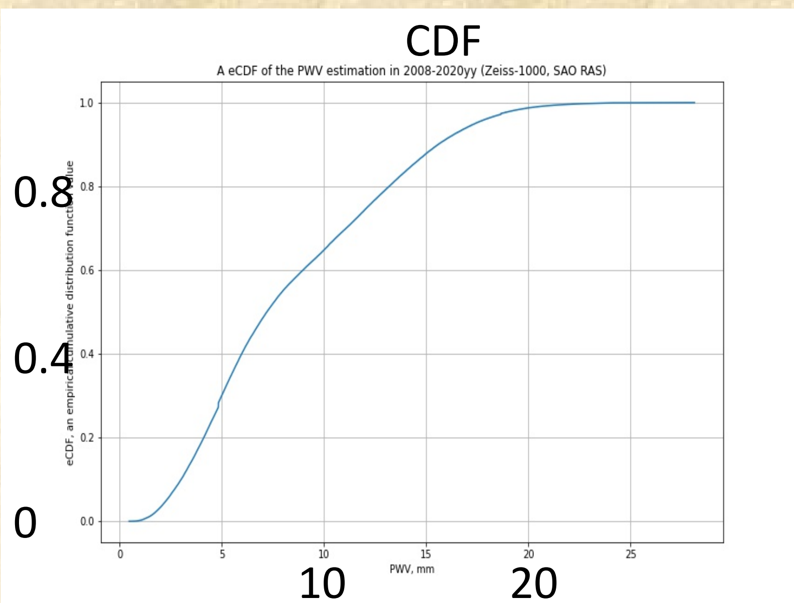
Wind rose

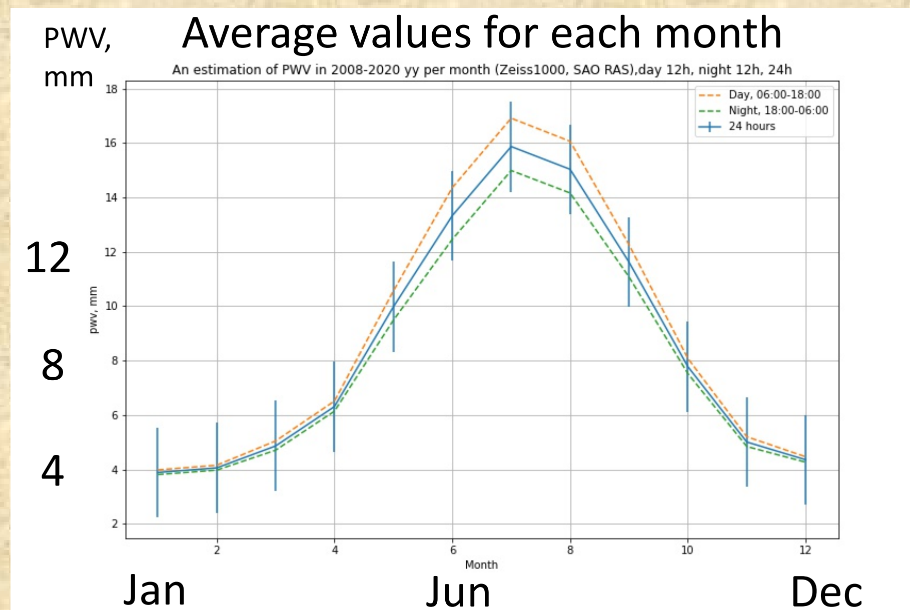


PWV statistics for the Zeiss-1000 site, 2100 m, 2008-2020yy



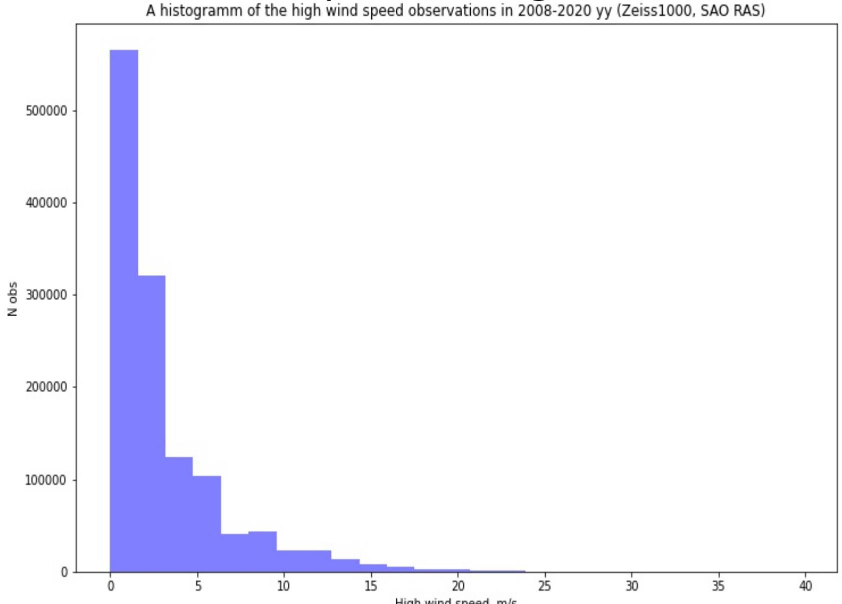






Wind statistics for the Zeiss-1000 site, 2100 m, 2005-2010yy

Wind speed histogram



0 5 10 20 m/s

Wind rose

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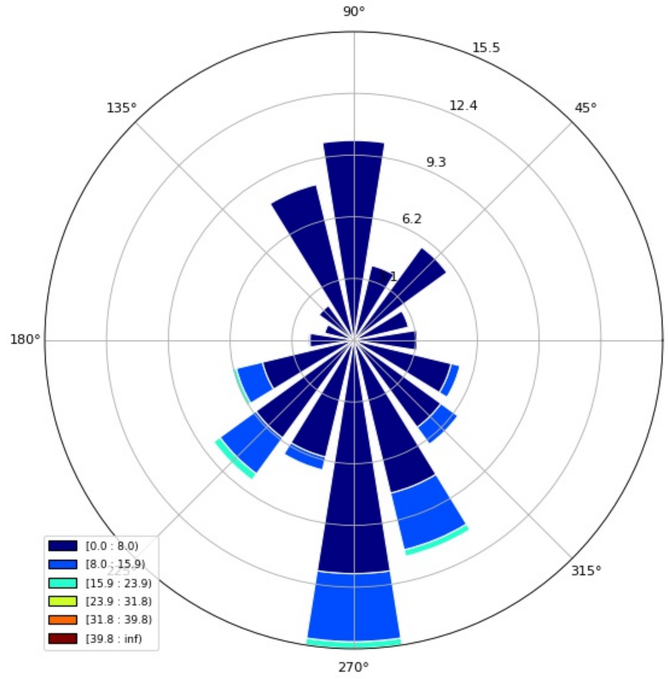

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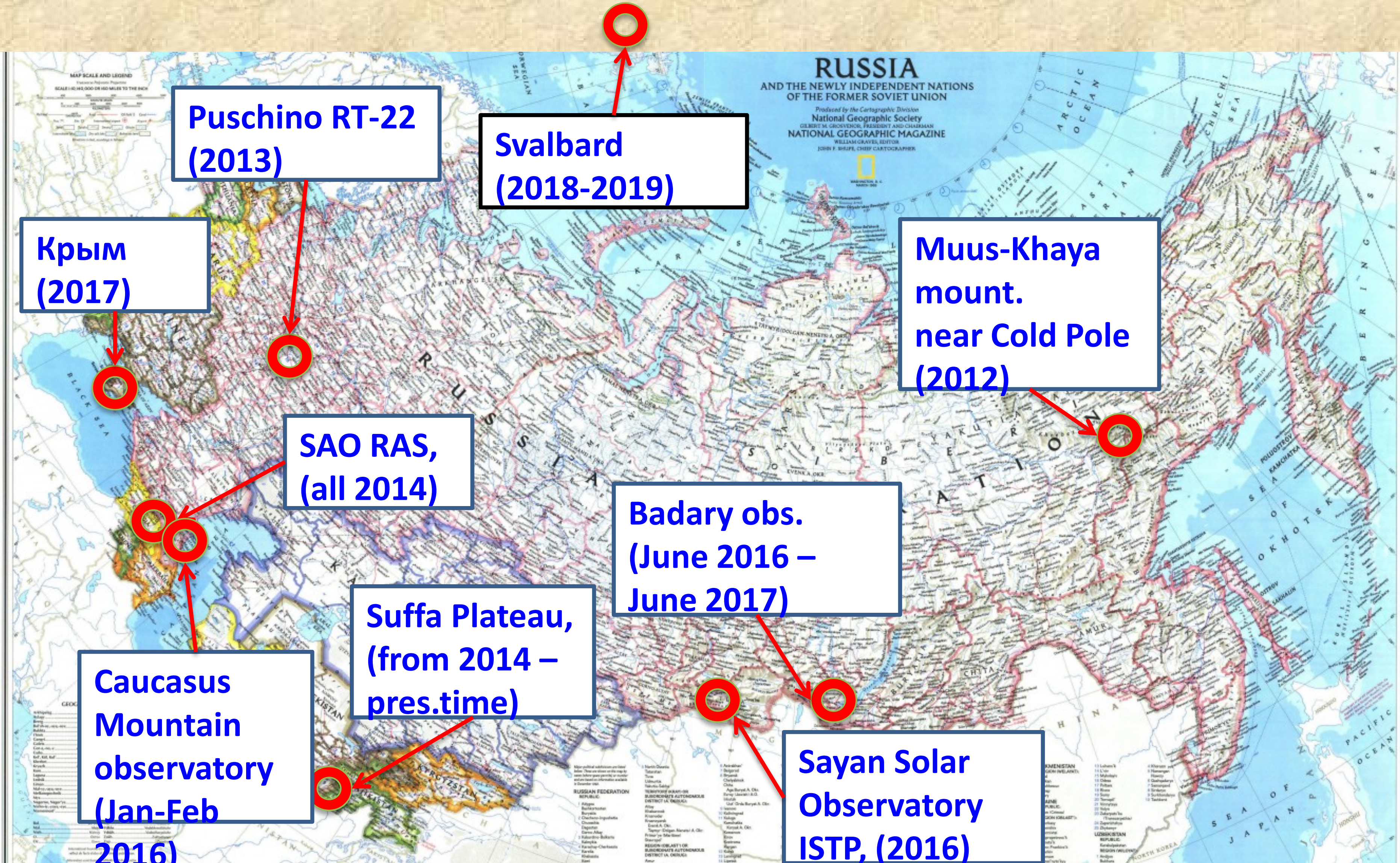
Comparing PWV at low-altitude telescope sites

Percent of time	NOEMA (2550m) Estimated PWV, mm, winter	NOEMA (2550m) Estimated PWV, mm, total	CARMA (2196m) Estimated PWV, mm	BTA (2100m) Estimated PWV, mm	RATAN-600 (974m) Estimated PWV, mm
90%	7	11	12	16	20
50%	2.1	4	5	7	11.5
25%	1	2	4.5	4.5	7.5
10%	0.3	1	3	3	4.5
5%	0.2	0.4	2	2	3.5

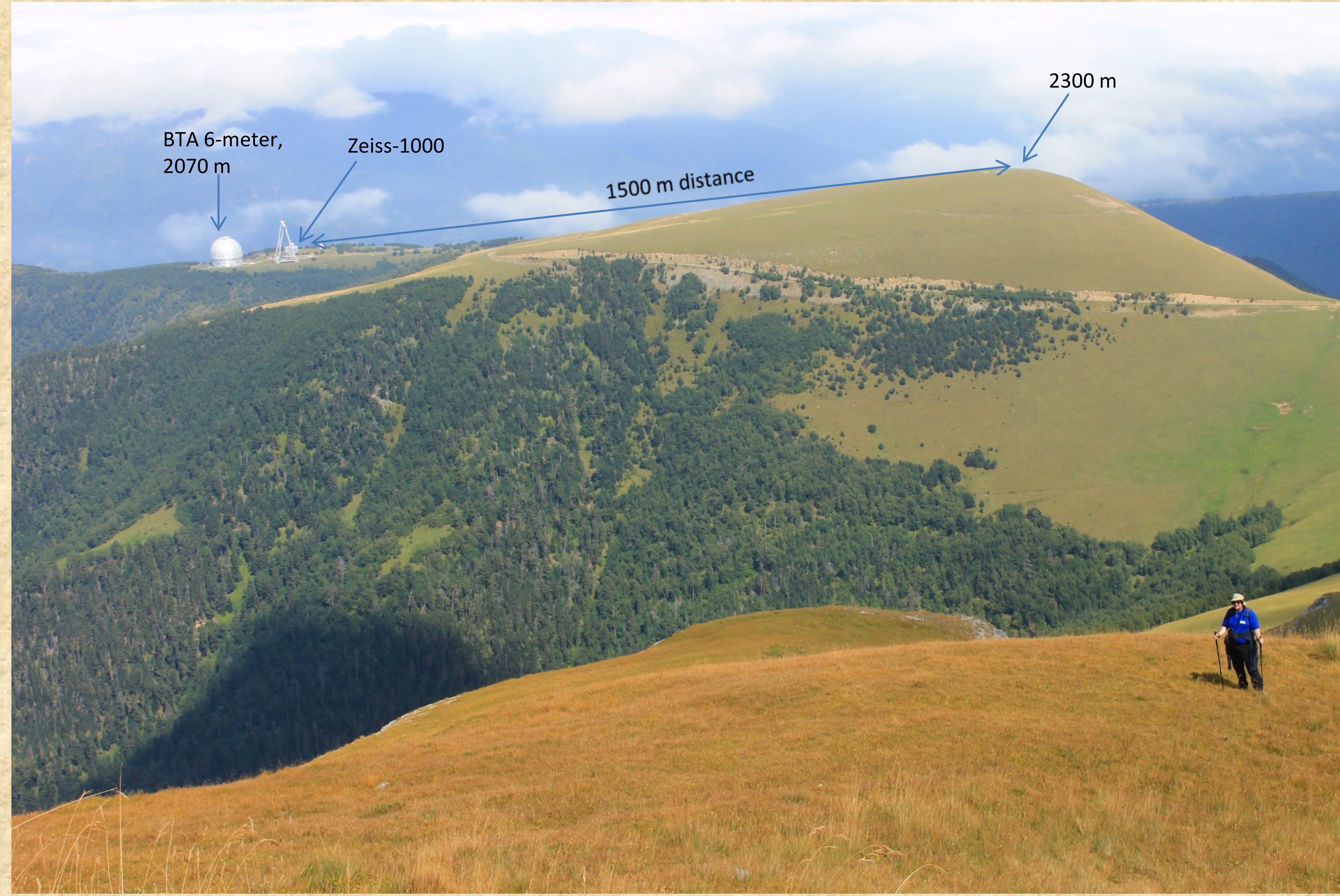
CARMA: Shiao et al, Water vapor in the atmosphere: an examination for CARMA phase correction, Proc of SPIE, v. 6275 (2006)
NOEMA: Neri R., The NOthern Extended Millimeter Array NOEMA, Xth Interferometry School (IRAM, 1-5.10.2018), p. 16

Potential site locations (2012-2019)



From Astroclimate Research talk by Bubnov et al, SAO RAS, October 24, 2019

Proposed mm dish location on the back of BTA/Zeiss telescopes



Thanks for your attention!

PWV estimation based on the temperature/humidity data

PUBLICATIONS OF THE ASTRONOMICAL SOCIETY OF THE PACIFIC, 122:470–484, 2010 April

Thirty Meter Telescope Site Testing X: Precipitable Water Vapor

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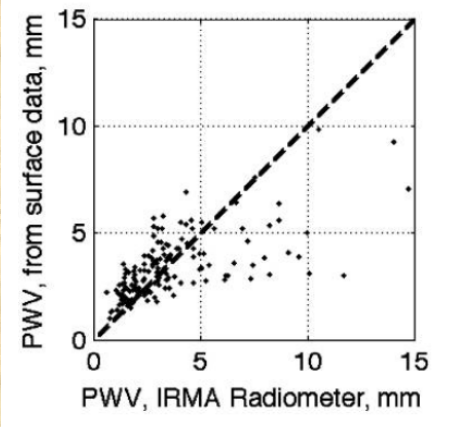
ABSTRACT. The results of the characterization of precipitable water vapor in the atmospheric column carried out in the context of identifying potential sites for the deployment of the Thirty Meter Telescope (TMT) are presented. Prior to starting the dedicated field campaign to look for a suitable site for the TMT, candidate sites were selected based on a climatology report utilizing satellite data that considered water vapor as one of the study variables. These candidate sites are all of tropical or subtropical location at geographic areas dominated by high-pressure systems. The results of the detailed on-site study, spanning a period of 4 yr, from early 2004 until the end of 2007, confirmed the global mean statistics provided in the previous reports based on satellite data, and also confirmed that all the candidate sites are exceptionally good for astronomy research. At the locations of these sites, the atmospheric conditions are such that the higher the elevation of the site, the drier it gets. However, the data analysis shows that during winter, San Pedro Mártir, a site about 230 m lower in elevation than Armazones, is drier than the Armazones site. This finding is attributed to the fact that Earth's atmosphere is largely unsaturated, leaving room for regional variability; it is useful in illustrating the relevance of in situ atmospheric studies for understanding the global and seasonal variability of potential sites for astronomy research. The results also show that winter and spring are the driest seasons at all of the tested sites, with Mauna Kea (in the northern hemisphere) and Tolonchar (in the southern hemisphere) being the tested sites with the lowest precipitable water vapor in the atmospheric column and the highest atmospheric transmission in the near and mid-infrared bands. This is the tenth article in a series discussing the TMT site-testing project.

$$
\begin{aligned}
&e_0 = e_s \frac{\mathrm{RH}}{100} \qquad e_s = 611.21 \cdot e^{\left(18.678 - \frac{T(^\circ C)}{234.5}\right)\left(\frac{T(^\circ C)}{257.14 + T(^\circ C)}\right)} \\
&\rho_{V_0} = \frac{e_0}{R_V \cdot T} \qquad \rho_{V_z} = \rho_{V_0} \cdot e^{-\frac{(z-z_0)}{H}} \\
&\mathrm{PWV} = \int_{z_0}^{z_{\max}} \rho_{V_0} \cdot e^{-\frac{(z-z_0)}{H}} \cdot dz \\
&\mathrm{PWV} = \rho_{V_0} \cdot H \cdot 1000 \cdot (1 - e^{\frac{z_0 - z_{\max}}{H}}).
\end{aligned} \tag{3}
$$

Here, the variables are: e_0, the surface level partial pressure of water vapor (Pa); e_s, the partial pressure of water vapor (Pa) at saturation as a function of the surface air temperature T (used in degrees Celsius where indicated, otherwise in Kelvin); RH, the surface relative humidity (in percent); ρ_{V_0}, the surface water vapor density (kg m^{-3}); ρ_{V_z}, the water vapor density at the altitude z above sea level (kg m^{-3}) $R_V = 461.9$, the water vapor gas constant (J kg^{-1} K^{-1}); H, the water vapor scale height (km); z_0, the geographic elevation of the site (km); and $z_{\max}$, the maximum altitude in the atmosphere considered for the integration of the water vapor density profile, in this analysis $z_{\max} = 12$ km. The equation for the determination of the water vapor at saturation is from the Buck Research CR4 Hygrometer Manual (2009).



PWV estimation based on the temperature/humidity data - II

ISSN 1063-7737, Astronomy Letters, 2012, Vol. 38, No. 4, pp. 271–279. © Pleiades Publishing, Inc., 2012.
Original Russian Text © O.V. Voziakova, 2012, published in Pis'ma v Astronomicheskiĭ Zhurnal, 2012, Vol. 38, No. 4, pp. 307–615.

Atmospheric Transparency over Mount Shatdzhatmaz in the Optical and Near-Infrared Ranges

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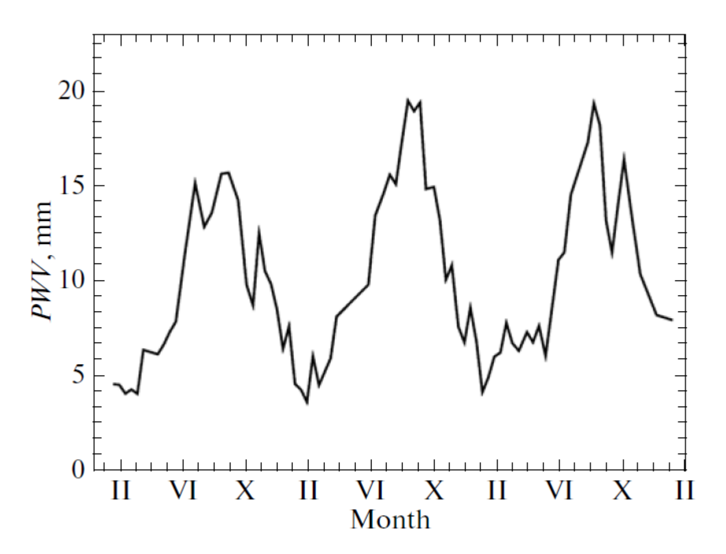
Received October 23, 2011

Abstract—We present the results of a three-year-long monitoring of atmospheric extinction over Mount Shatdzhatmaz (2112 m) in Northern Caucasus in a photometric band with $\lambda_{\text{eff}} = 480$ nm and the results of measurements of precipitable water vapor (*PWV*), which characterizes the atmospheric transparency in the near infrared. The yearly mean fraction of photometric weather is estimated to be 50% of the clear night time. The yearly median extinction is $0^{m}.21$; the median *PWV* on clear nights is 7.7 mm.

extinction, PWV.



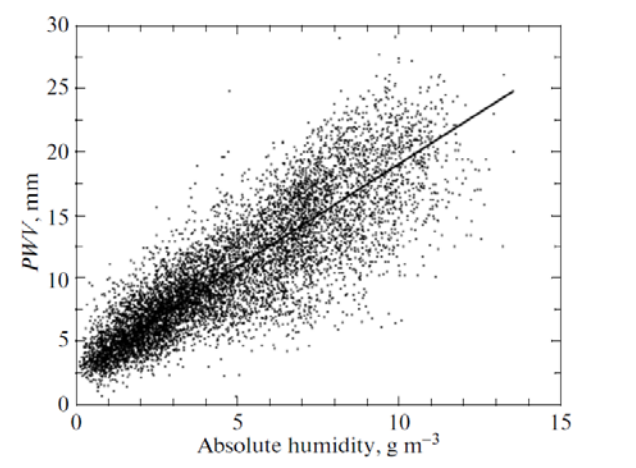


Fig. 5. *PWV* versus surface air humidity.

Some literature data on PWV for the proposed locations

30th International Symposium on Space THz Technology (ISSTT2019), Gothenburg, Sweden, April 15-17, 2019

Astroclimatic studies of the sites for forthcoming radio astronomical observatories

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Millimeter-wave astroclimate studies in the North Caucasus: expedition and first results

Grigoriy M. Bubnov, Andrey S. Marukhno, Marat G. Mingaliev, Anastasia P. Markova, Nikolay I. Shatsky, Olga V. Voziakova, Vyacheslav F. Vdovin, Peter M. Zemlyanukha, Igor I. Zinchenko, "Millimeter-wave astroclimate studies in the North Caucasus: expedition and first results," Proc. SPIE 11582, Fourth International Conference on Terahertz and Microwave Radiation: Generation, Detection, and Applications, 115821W (17 November 2020); doi: 10.1117/12.2583605

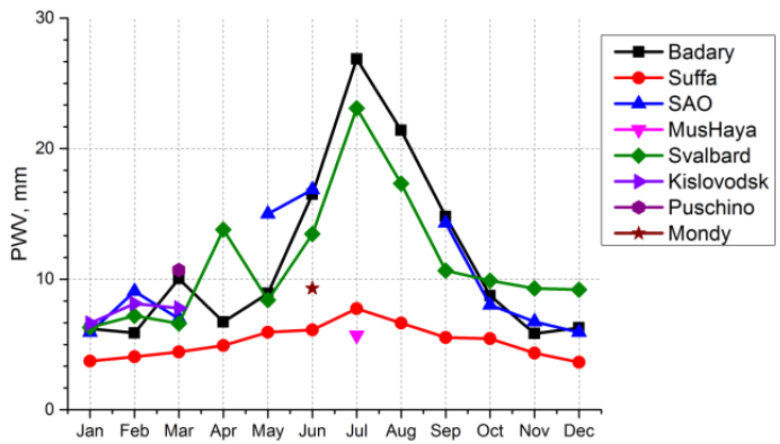


Fig. 10. Monthly median values of the PWV data obtained by our group on different sites starting from 2012.

Table 1. Results of 2020 astroclimate studies in the North Caucasus' sites

Site, Month	PWV by MIAP-2, mm	Opacity, 3 mm, Nep	Opacity, 2 mm, Nep	Data loss
RATAN-600 (2 days)	6.5	0.1	0.18	0 %
CMO of GAISh (1 day)	4.2	0.08	0.11	0%
Terskol, February	10	0.11	0.18	13%
Terskol, March	9.1	0.1	0.14	44%
Terskol, April	8.4	0.1	0.15	24%
Terskol, May	10.1	0.11	0.18	45%
Terskol, June	13.6	0.14	0.18	48%
Terskol, July	14.6	0.15	0.19	57%

RATAN, CMO - February

Some literature data on PWV for the proposed locations II

64 IEEE TRANSACTIONS ON TERAHERTZ SCIENCE AND TECHNOLOGY, VOL. 5, NO. 1, JANUARY 2015

Searching for New Sites for THz Observations in Eurasia

Grigoriy M. Bubnov, Evgeniy B. Abashin, Yuriy Yu. Balega, Oleg S. Bolshakov, Stepan Yu. Dryagin, Victor K. Dubrovich, Andrey S. Marukhno, Vladimir I. Nosov, Vyacheslav F. Vdovin, *Member, IEEE*, and Igor I. Zinchenko

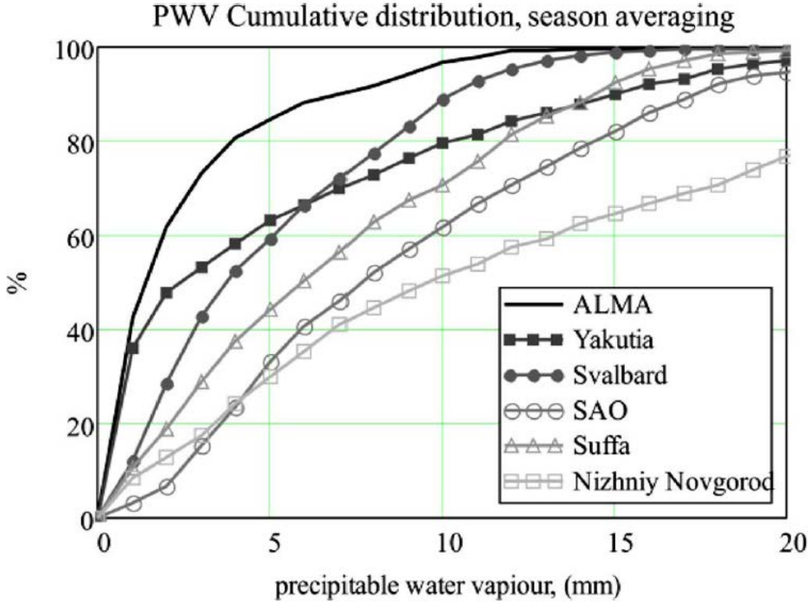


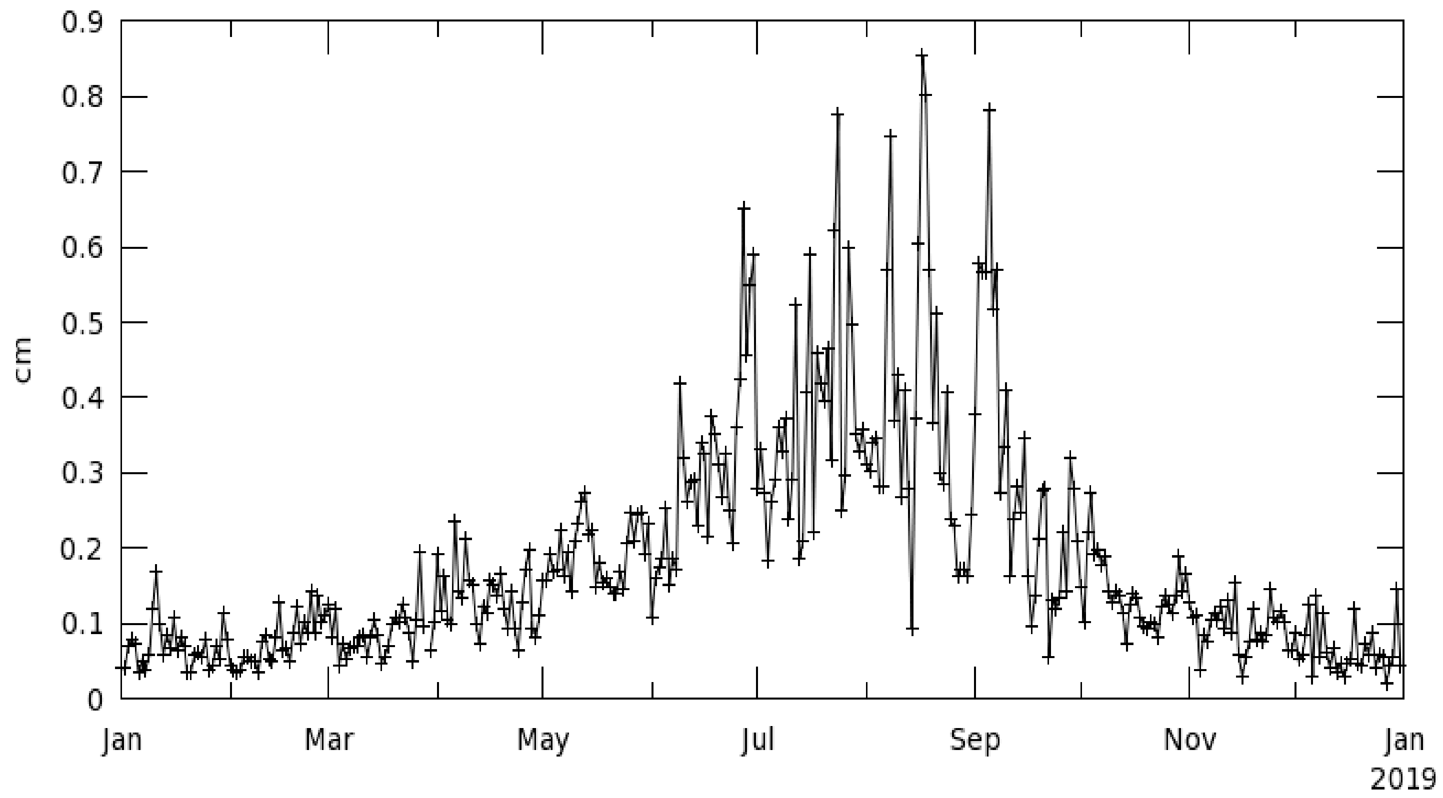
Fig. 2. Cumulative distribution of PWV by AIRS satellite.

TABLE II
CLEAR SKY PERCENTAGE BY SITE

wave length (mm)	SAO (AIRS)	SAO (Radiom.)	Central Russia	Suffa plateau	Yakutia
0.87	1.8	0.37	3.8	6.32	19
1.3	7.8	3.1	11.1	21	48
2	29	17	21	43	61
3	52	41	41	63	74
8	97	98	95	99	99

Tibet. PWV seasonal variations

Time Series, Area-Averaged of Precipitable Water Vapor (IR Retrieval) Total Column: Mean of Level-3 QA Weighted Mean daily 1 deg. [MODIS-Aqua MYD08_D3 v6.1] cm over 2018-01-01 - 2018-12-31, Region 79.5465E, 34.541N, 80.4639E, 35.4913N

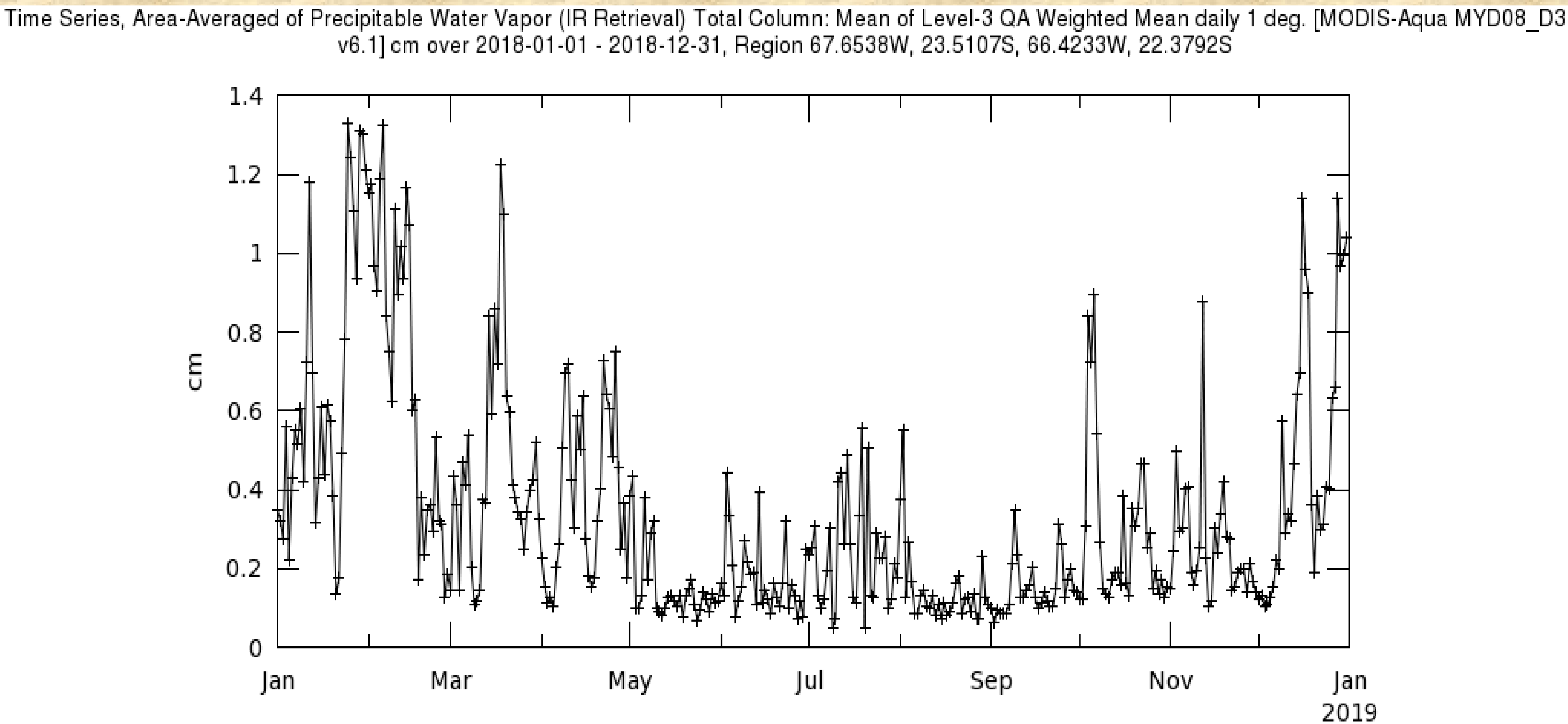


- The user-selected region was defined by 79.5465E, 34.541N, 80.4639E, 35.4913N. The data grid also limits the analyzable region to the this point: 80.5E, 35.5N. This analyzable region indicates the spatial limits of the subsetted granules that went into making this visualization result.

https://giovanni.gsfc.nasa.gov/giovanni

From Astroclimate Research talk by Bubnov et al, SAO RAS, October 24, 2019

Atacama (Chile) PWV seasonal variations



- The user-selected region was defined by 67.6538W, 23.5107S, 66.4233W, 22.3792S. The data grid also limits the analyzable region to the following bounding points: 67.5W, 23.5S, 66.5W, 22.5S. This analyzable region indicates the spatial limits of the subsetted granules that went into making this visualization result.

https://giovanni.gsfc.nasa.gov/giovanni

From Astroclimate Research talk by Bubnov et al, *SAO RAS, October 24, 2019*