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A Study of the Astroclimate in the Dagestan Mountains Agul Region and at the Ali Observatory in Tibet as Possible Locations for the Eurasian SubMM Telescopes (ESMT)

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Using the ECMWF Reanalysis v5 (ERA5) and the GNSS method as well as meteorological and observational data, the statistics of the PWV, TCC, SD, and other astroclimate indicators were obtained for a number of possible ESMT locations in the Russian Federation. These sites are compared with the Ali observatory in Tibet and the BTA location area. The first results of the GNSS PWV measurements on Mt. Kurapdag convincingly confirm the choice made earlier using the ERA5 data.

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1. Introduction

Scientific tasks for a large 20-m-class mm/submm telescope include: the study of star formation in the Universe, the search for new chemical compounds, including organic molecules in space, the search for primary (cosmological) molecules in the early Universe, the study of the Sunyaev–Zeldovich effect in clusters of galaxies, the polarization of the and spectral distortions of the cosmic microwave background radiation after recombination and before the epoch of reionization ("Dark Ages") [1]. New single mm/submm telescopes are in high demand in Eurasia today, as is their inclusion in the VLBI Event Horizon Telescope (EHT) network to study supermassive black holes located at the centers of our and nearby galaxies.

The concept of the ESMT project [1] provides for the construction of three new high-performance mm/submm radio telescopes of the 15–21 m class on the Suffa plateau 2400 m above sea level or higher, 3282 m, on Mt Aktashtau, in Russia (above 3000 m above sea level), and on the Tibetan plateau in China (above 5000 m above sea level). The concept of the ESMT project was developed by specialists from SAO RAS and IAP RAS together with EIE Group Srl. (Italy) and NAOC (PRC) at the end of 2019. Possible ranges of ESMT operation in the best places of the Russian Federation and Uzbekistan (Aktashtau) are 100–350 GHz, in Tibet 100–1500 GHz.

The ESMT design is based on the 12-m antenna of the ALMA telescope. Mechanical and thermal modeling performed by the EIE Group showed that it is possible to increase the antenna diameter to 15 m using design scaling, but to increase the antenna diameter to 21 m, an optimization of the optical design and the telescope truss frame is required [2]. To implement a wide field of view, it is proposed to use multiwavelength (multicolor) 10^4–10^5-px KID matrices of limiting sensitivity [3].

Due to the high interest to the appearance of submm telescopes in Eurasia, it is relevant to study the astroclimate of their placements [4–8]. This paper continues the search for locations of the submm telescopes in Eurasia, started in [6], using the data from the European Center for Medium-Range Weather Forecast ReAnalysis (ERA5) and the geodetic stations of the Global Navigation Satellite Systems (GNSS). The PWV (Precipitable Water Vapor) estimate by the GNSS method is obtained by calculating the propagation delay of the GNSS signal from the satellite to the receiver due to tropospheric refraction For a more accurate estimate of the PWV, the measured values of the tropospheric signal delay are corrected according to the model [11].

The concept of astroclimate includes the statistics of atmospheric transparency, cloudiness, moisture content of the atmosphere, wind speed, turbulence indicators, including astronomical seeing conditions. In addition, for the successful operation of the telescope in the submm range and the achievement of high sensitivity on it, the choice of a suitable site is aimed at minimizing the radio brightness temperature of the atmosphere and its variations. To estimate the content of water vapor in the vertical column of the atmosphere (from the earth surface to a given height), the amount of deposited water vapor, denoted PWV, is often used. Due to the fact that the spatial resolution of ERA5 is limited and also poorly takes into account the conditions of rugged terrain, in calculations of the PWV on mountain tops the following formula is used [8]:

$$\mathrm{PWV} = k\,\mathrm{PWV}_0\,\exp\left(\frac{C_{\mathrm{PWV}}\,\delta z}{1000}\right) \tag{1}$$

where δz is the height difference for the site under consideration, C_{PWV} is the proportionality factor. The parameter k is estimated from comparing the ERA5 data and the measurement data at the site of interest. In the general case, C_{PWV} changes during the year, but as a first approximation we can assume that it takes the year-averaged value of 0.439. An important astroclimatic characteristic of the site is the number of clear (cloudless) days/nights during the year. To estimate it, the mean annual sunshine duration (SD) is often used, which for mountain astronomical observatories is usually at least 2500 hours, close to the concept of cloud intensity, determined from the ground visually or using a full-sky camera. One of the universal characteristics of atmospheric transparency is the optical depth. Ultimately, it is this that determines the quality of the astroclimate in terms of the transmission of the atmosphere at the frequency of interest and the amount of observational time achievable in a given frequency range at a given location. The optical depth is usually represented as an additive quantity [5]:

$$\tau(f, h, \mathrm{PWV}, Q) = \alpha(f)\ \exp\left(-h/h_0\right) + \beta(f)\,\mathrm{PWV} + \gamma(f)Q \tag{2}$$

where τ is the optical depth in Nepers, h is the height above sea level in km, h_0 is the characteristic height in the atmosphere, equal to 5.3 km, PWV is the precipitable water vapor in mm, Q is the cloud water content in kg/m^2. The specific absorption coefficients depend on the frequency and determine the absorption in dry air (α), water vapor (β), and due to the water content of clouds(γ). The coefficients depend on the season, climatic conditions, and altitude of the place, the values of both coefficients decrease with altitude [5, 9].

The astronomical seeing conditions are usually characterized by the Fried radius r_0 or by a parameter proportional to (λ/r_0) and measured in arcseconds, where λ is the wavelength of the detected radiation. The Fried radius, determined from observations of astronomical light sources, most often vary within 3–20 cm for the visible range. Having some value of r_0 in the visible range, it is possible to recalculate its value for the submm range [8]. Finally, a practically significant characteristic of the telescope location astroclimate is the statistics of the speed of wind gusts. In addition to imposing requirements on the stability and rigidity of the telescope structure, it, like other indicators of the astroclimate, determines the possible time of operation or idle time of the telescope. Thus, the loss of observational time on the BTA due to the wind gusts, which are unacceptable for BTA observations, is only 30% less than due to the cloudiness [10].

2. Results of studying the astroclimate of possible sites for the ESMT

Using ERA5, we plotted the PWV and TCC maps of the North Caucasus, which show that the arc of the PWV minimum passes in all seasons along the Main Caucasian Ridge from Gara-Bashi in the west to Mt Shalbuzdag in the east. The minimum TCC is in all seasons in the Rutulsky and Agulsky Districts of Dagestan. The technique that we used for obtaining the PWV values from the ERA5 data taking into account the terrain features is given in [12]. The median PWV and TCC values for the sites of practical interest in the North Caucasus (NC), Sayan, Suffa, and Tibet according to the ERA5 data are shown in Table 1. For comparison, the median PWV and TCC values are also given at the ALMA site and Muztag-Ata in the Chinese Pamirs.

An analysis of the PWV and TCC values shows that not only the Chinese but also the Sayan sites significantly exceed the Suffa Plateau, the site of the unfinished construction of RT-70, in terms of their capabilities. Suffa is generally very average and not a promising ESMT location. Cloudless weather here is observed only in summer and autumn during the period of positive temperatures and high atmospheric moisture content, which is unproductive for our tasks. Mt. Aktashtau has the best indicators of the astroclimate in this region.

The sustained low temperatures in the Sayan Mountains lead to air "freezing" and very low PWV values during the long winter period, which brings them very close to the significantly higher by altitude but also warmer sites of Tibet and Pamir.

Table 1: The median PWV and TCC values for the observed sites, 2018, nights

Site	Height, m	PWV, mm		TCC	
		Winter	Summer	Winter	Summer
Suffa, Uzbekistan	2400	2.7	8.7	0.60	0.32
Maidanak, Uzbekistan	2650	3.4	8.7	0.54	0.13
ALMA, Chili	5058	0.51	1.7	0.1	0.39
Aktashtau, Uzbekistan	3383	1.8	5.9	0.57	0.31
Ali 1, China	5100	0.4	4.4	0.35	0.57
Muztagh Ata, China	4536	0.7	3.7	0.42	0.62
Mondy, Sayan, Russia	2006	0.9	10.0	0.45	0.61
Khulugaisha, Russia	3015	0.6	6.8	0.44	0.60
Tashanta, Altai, Russia	2200	1.2	11.9	0.37	0.51
Arkarsara, Russia	2839	2.6	8.2	0.71	0.53
Peak Terskol, Russia	3150	1.8	5.8	0.69	0.54
Gara-Bashi, Russia	3847	1.2	4.9	0.68	0.55
Priut 11, Russia	4100	1.1	4.8	0.68	0.55
Abishira-Ahuba, Russia	3016	2.1	6.7	0.71	0.53
Horai, Russia	3521	1.4	6.6	0.45	0.34
Kurapdag, Russia	3724	1.4	6.5	0.44	0.35
Shatshatmaz, Russia	2096	3.6	9.0	0.59	0.56
RATAN-600, Russia	970	6.2	21.8	0.63	0.54
BTA, Russia	2070	3.9	12.9	0.67	0.55
Gruzinskii holm	2340	3.8	12.8	0.64	0.53
The top of Mt Pastuhova	2732	3.7	12.2	0.62	0.52

Let us pay special attention to the Khulugaisha peak in the Sayan Mountains (Fig. 1), which has rather low PWV and TCC values simultaneously. Since the Soviet times, the ISTP cosmic ray station has been located on the Khulugaisha peak, there are flat areas, and communications have been connected. The maximum average daily temperatures in winter are not higher than -18°C, the average annual temperature is -8.5°C, the annual rainfall is not more than 750 mm, the SD is 2500 hours. As can be seen from Table 1, the Khulugaisha peak, in terms of its characteristics, comes close to the sites of Tibet and the Pamirs.

Another promising astroclimatic region of the Russian Federation is the Chya basin in Gornyi Altai, where rather low PWV values, low temperatures, and low precipitation are combined with a high SD. The Kosh-Agach region, located on the border with Mongolia, is equated with the regions of the Far North, temperatures below -55°C are observed here in winter, the amount of precipitation in winter can be less than 5 mm per month. This area is a desert plateau with drought-resistant vegetation in the form of thorny bushes. Tashanta (2200 m), an automobile border checkpoint with Mongolia, 50 km from the regional center Kosh-Agach (Fig. 1), is of the greatest interest for placing the ESMT in this area. Winter here lasts 8–9 months, the average annual temperature is -6°C. The SD in the Kosh-Agach region is one of the highest in the Russian Federation: more than 2800 hours, and the rainfall rate is one of the lowest in Russia: less than 200 mm, and often does not exceed 125 mm.

The greatest astroclimatic interest in the NC is its eastern part [5, 6], in particular two neighboring regions of Dagestan Mountains: Rutul and Agul. The areas of Mts Khoray (3521 m) and Katalnats (3780 m) in the Rutul region and Mts Kurapdag (3724 m), Alakhundag (3842 m), and Kuradag (3837 m) in the Agul region have rather low values of PWV and TCC at the same time. On the slope of Mt Khorai at an altitude of 2200 m, there is the historical village of Tsakhur. Mt Khoray has flat areas on its top, it is easy to climb up the mountainside on foot or ride bypass trails on horseback. The slopes of Mt Katalnats are quite easily accessible from the highland village of Arakul (2100 m). The Khorai and Kurapdag mountains are of the greatest practical interest for the ESMT tasks. As observations have shown, more than 70% of the nights in the region of Mt Kurapdag are meteorologically clear. An important advantage of this option for ESMT deployment in the Russian Federation is its proximity to the largest Russian astrophysical observatory, SAO RAS, 860 km in winter and 760 km in summer and autumn through the Kukmadag pass as well as convenient railway communication along the route Mineralnye Vody–Makhachkala–Derbent, from where you can reach the village of Chirag by car or a shuttle bus in 2–3 hours (128 km).

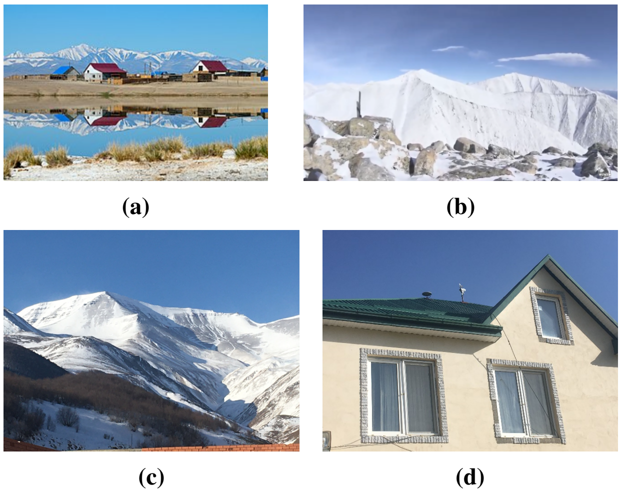

Figure 1: (a) the view of Kosh-Agach Village (1750 m); (b) Mt Munku-Sardyk (3500 m) from Khulugaysha Peak; (c) the view of Mt Kurapdag from Chirag Village; (d) the GNSS and weather stations installed on the roof of a guest house in the village of Chirag

3. First GNSS data of atmospheric moisture content on mountain Kurapdag

Figure 1c shows a view of Mt Kurapdag from the village of Chirag in Agulsky District of Dagestan. The distance of direct visibility of the peak of Mt Kurapdag from the village does not exceed 5 km, the peak and slopes of Mt Kurapdag are convenient for installing a telescope and connecting communications to it: a road for vehicles or a cable car. The top of the mountain is an almost flat field with a length of at least 1 km and a width of hundreds of meters. The snow cover of Mt Kurapdag is moderate, the accessibility of the peak from June to October is high, and the avalanche risk during the snowy period is low.

Table 2: The median and mean PWV values (mm) calculated from the GNSS observations in March–April 2022

Site	Height,	PWV, mm	
	m	median	mean
Observatory Peak Terskol	3150	3.68	4.22
Chirag (Dagestan, Agul region)	2200	5.09	5.47
Kislovodsk	2096	6.88	7.14
Zelenchuk Observatory	1166	7.63	8.04
CRAO, Crimea	652	9.69	9.83

Table 3: Coordinates and statistical estimates (median and mean) for the magnitude of the deposited water level for the GNSS sites, calculated from the measurements of 2022, July 2–6

Site	Code	Coordinates			Median,	Mean,
		Longitude, °E	Latitude, °N	Height, m	mm	mm
Chirag	CHRG	47.4391996	41.8197199	2204	13.04	13.24
Lake Debrisharo	SMOZ	47.4096807	41.7999113	2843	6.97	7.27
Samur Ridge	SMXB	47.3830239	41.7908446	3552	2.48	2.21

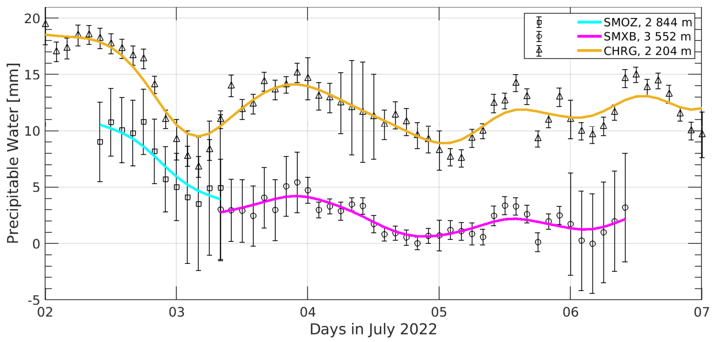

Figure 2: The smoothed PWV with determination errors for the GNSS sites CHRG, SMOZ and SMXB in the observations on July 2–6, 2022

The first results of PWV measurement by the GNSS method in the village of Chirag are shown in Table 2 in comparison with other astronomical sites. As can be seen from Table 2, despite the rather warm season at the beginning of the measurements: the end of March, the obtained PWV values in the village of Chirag (2200 m) are second only to Terskol Peak (3150 m). The Zelenchuk and CRAO observatories have quite expected high PWV values.

On July 2–6, 2022, an expedition was carried out to Mt Kurapdag in order to study its astroclimate using the GNSS equipment. In the highlands, continuous GNSS measurements were taken at two points. The first point, assigned the code SMOZ, is located near Lake Debrisharo (July 2–3). The second site, coded SMXB, is located on the ridge of Samur Range 200 m below Mt Kurapdag (Table 3). High-precision coordinate determinations of the location of points have been obtained, and the PWV values for them have been calculated. The results are shown in Fig. 2 and Table 3. The obtained PWV convincingly demonstrate the advantages of Mt Kurapdag and the prospects for further study of its astroclimate for the tasks of the ESMT project.

At present, we study the wind statistics in the region of Mt Kurapdag. According to preliminary data, the area of Mt Kurapdag looks better by the wind than the area where the BTA is located,

Table 4: Statistics of the main astroclimatic indicators in the most promising sites for the ESMT

Site	Median PWV, mm		Median TCC		Seeing, arc sec		Sunshine
	summer	winter	summer	winter	calc.	median of meas.	duration, hour
Kurapdag	6.9	1.4	0.33	0.43	—	—	2590
Khulugaisha	6.8	0.6	0.61	0.45	1.0	—	2500
Ali-1	4.4	0.4	0.57	0.37	0.6	1.08	3500
BTA	12.8	3.9	0.55	0.73	0.9	1.2	2220
Tashanta	11.9	1.2	0.51	0.37	—	—	2800
Aktashtau	5.9	1.8	0.31	0.57	—	—	3000

which, however, requires local confirmation. Therefore, in the high-land village of Chirag, closest to Mt. Kurapdag, an automatic weather station with an anemometer has been installed, which already provides weather data (Fig.1). The meteorological station is also equipped with a solar photometer (pyranometer), which will make it possible to locally determine the SD.

4. Statistics of the main astroclimate indicators of promising sites for ESMT

Table 4 contains statistical estimates for the main indicators of the astroclimate in the most promising ESMT sites in comparison with the BTA. To calculate the astronomical seeing conditions at Khulugaisha Peak, the Ali NAOC seeing model was applied [12]. In [12], a detailed analysis of optical turbulence in the atmospheric surface layer (ASL) at the Ali Observatory is presented. It also presents the statistics on the contribution of the ASL to the overall seeing conditions in the entire atmosphere at Ali. The median astronomical seeing at Ali is 0.86 arcseconds above 6 m with seeings less than 1.2 arcseconds during nearly 98 % of the time.

5. Conclusion

The best indicators of the astroclimate among the 15 places that we have considered in the Russian Federation have Mt Kurapdag in the Agulsky District of Dagestan, Khulugaisha Peak in the Sayan Mountains, and Tashanta in the Chya basin. The main advantage of the ESMT deployment at Khulugaisha Peak is the extremely low PWV during the long winter period, at Tashanta it is the availability of all necessary communications with fairly low PWV and TCC and high SD values, and at Mt Kurapdag the advantage is a high number of meteorologically clear nights (more than 70%) along with the fairly low moisture content of the atmosphere.

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