Astroclimatic studies of the sites for forthcoming radio astronomical observatories

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***Abstract*— We are presenting results of the observations our research group has been conducting for about 7 years. Over this time, we have gathered statistical data from a number of sites which can be used for radio astronomical observations in the millimetre and sub-millimetre bandwidths. We have just finished a year-long cycle of tests in Svalbard and are now able to compare its atmospheric transparency with other sites. The astroclimatic analysis is a prerequisite for selecting a site for radio astronomical observations in the millimetre bandwidth.**

***Index Terms*—Astroclimate, radio astronomy, millimeter wave propagation, atmospheric measurements.**

I. Introduction

THE ATMOSPHERIC propagation of terahertz waves strongly depends on the atmospheric conditions, and one of the topical problems of today is to investigate this dependence and develop techniques, instrumentation and mathematical modelling of the atmospheric transparency investigations. We have developed instrumentation [1] and improved the methods [2] for investigation of atmospheric propagation of terahertz waves. Since 2012 we have gone on 8 expeditions and explored atmospheric absorption at over 11 sites [3 and References]. Our goal is to find the most appropriate place for a radio telescope operating in the millimetre and sub-millimetre wavelength. For estimating the atmospheric absorption (also referred to as optical depth or tau, and measured in Nepers) we use the atmospheric-dip method in automatic remote measurements mode with the help of the radiometric system MIAP-2 operating in 84-99 GHz (3 mm) and 132-148 GHz (2 mm) bands.

Over the last 6 years we have collected a broad array of statistical data on atmospheric absorption, which allows us to compare different places in terms of suitability for radio astronomy. We ourselves believe that the Suffa plateau deserves being most promoted as a site of a prospective radio astronomy project. Therefore, we are presenting the Suffa plateau statistical data sets in comparison with Svalbard, Northern Caucasus, Badary and other locations.

II. Sites description

Among all sites where we have been collecting astroclimatic data, are only four where we were able to collect enough data to plot statistical diagrams and make conclusions as regards averaged seasonal variations of the atmospheric transparency. These sites (either functioning observatories or research stations), unlike the rest of them, are also equipped with service staff and supplied with electricity and the Internet connection.

A. Svalbard

Geographic coordinates: 78° 5'42.22“N 14°12'35.98“E;
Observation period: June 2018 – June 2019;
Elevation: 100 m;
Climatic conditions: Arctic, but weather often warm due to the impact of the Gulf Stream;

Svalbard is in the Arctic being the northernmost habitable land featuring permanent residents and provided with such utilities as electricity and the Internet. The archipelago has two residential towns and several seasonal settlements. The high latitudes of the location make it reasonable to suppose that the optical depth will not be large here. Its highest point is 1,713 m, but available sites of sufficient areas for mounting a telescope are at the elevation of about 1,500 m. Among drawbacks of Svalbard intended for an observational radioastronomy site we can mention the Gulf Stream flowing by the southern part of the archipelago bringing in warm and humid air.

We did our research at the research station of the Polar Geophysical Institute found 3 km north of Barentsburg. Since we set up our equipment on June 9, 2018 the automatic recording of the atmospheric depth has been carried on with 10-minute intervals. We have already quoted some of the results of these observations in our previous publications [3,4,5]. Below are statistical diagrams including histograms and cumulative distribution plots of the optical depth observed. All data are grouped according to similarity of weather conditions: December, January, February and March are considered the winter season; October, November, April and May the transitional period; and June, July, August and September the summer season.

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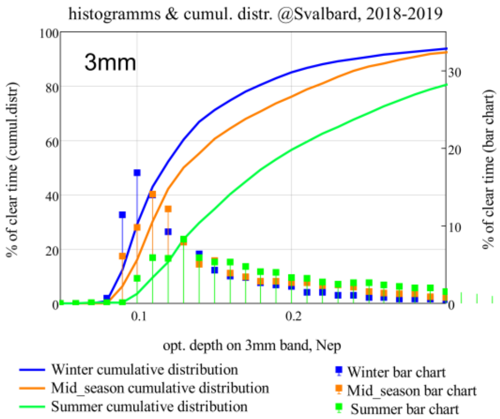

Fig. 1. Histograms and cumulative distribution plots of optical depth measured on Svalbard at 3 mm wavelength in 2018-2019.

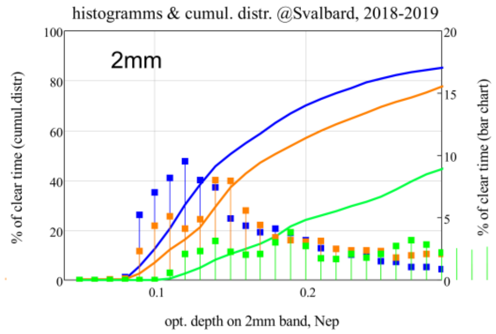

Fig. 2. Histograms and cumulative distribution plots of optical depth measured on Svalbard at 2 mm wavelength in 2018-2019.

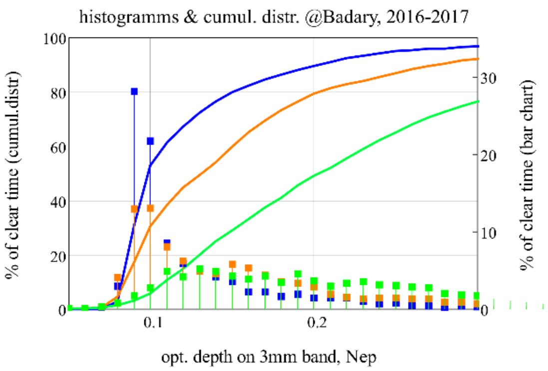

Fig. 3. Histograms and cumulative distribution plots of optical depth measured at the Badary observatory at 3 mm wavelength in 2016-2017.

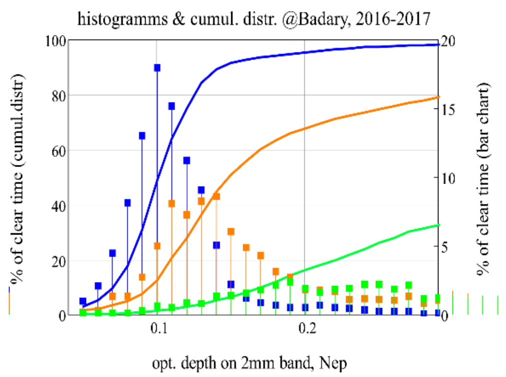

Fig. 4. Histograms and cumulative distribution plots of optical depth measured at the Badary observatory at 2 mm wavelength in 2016-2017.

B. *Badary observatory*

Geographic coordinates: 51°46'10.75“N 102°14'6.13“E;
Observation period: June 2016 – June 2017;
Elevation: 700 m;
Climate zone: Sharply continental, but it’s often humid due to the valley’s terrain;
Climatic conditions: Sharply continental, but often humid due to the peculiarities of the Tunkin Depression;

The Badary Observatory of the Institute of Applied Astronomy is a part of the Kvazar-KVO radiointerferometric network. It is located in the Tunkin Depression 300 km west of Lake Baikal. The extreme continental climate is characteristic of this entire region with its dry frosty winters and relatively short summers. The averaged precipitable water vapour (PWV) is relatively low, which is seen also by the weather satellites data (we are not quoting these data here). However, the Tunkin Depression facilitates collection and accumulation of water vapour thus nullifying the advantages of the sharply continental climate. To the west of the Badary observatory, the Observatory of the Institute for Solar and Terrestrial Physics is found near the village of Mondy; the elevation of this site is 2,100 m. Our observations have shown that the astroclimatic conditions in this latter place are far better than in the depression, but we were unable to conduct a full-scale year-long observation cycle. [6]

Below are histograms and cumulative distribution plots of the optical depth observed. All data are grouped by seasons similarly to the previous example.

C. *Special astrophysical observatory (N. Caucasus)*

Geographic coordinates: 43°38'51.45“N41°26'31.00“E;
Observation period: 2014 – 2015;
Elevation: 2100 m;
Climatic conditions: Predominantly temperate climate, but the site borders the subtropical climate zone;

The Special Astrophysical Observatory of the Russian Academy of Sciences (SAO RAS) is one of the largest optical observatories of the world. It is located at 2,100 m above the sea level near the village of Arkhyz in the Northern Caucasus. Among the reasons for the choice of the place for the observatory were its good astroclimatic conditions: the stability of atmosphere in the optical band, high percentage of occurrence of the clear sky, and relatively dark nights. Located at the height of more than 2 km above the sea level, the SAO RAS site enjoys low oxygen absorption; however, the Black Sea being only 90 km away enhances the absorption of non-condensed water vapor (the sky remains cloudless) up to quite high values.

We carried out our measurements through one of the windows of the BTA (Large Altazimuth Telescope) tower in different months from 2014 through 2015. The observation time covers about 10 months, which seems enough for reconstruction of statistics of the whole year. At the time the 2-millimetre channel of the radiometer was not operable, and that is why the statistics has been gathered for the 3-mm channel only. In detail, the results of these observations were presented in [7].

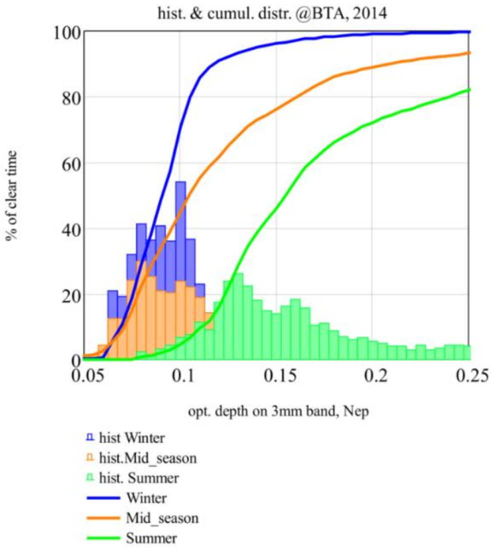

Fig. 5. Histograms and cumulative distribution plots of optical depth measured at the SAO RAS observatory at 3 mm wavelength in 2014-2015.

D. *Suffa plateau*

Geographic coordinates: 39°37'28.46“N 68°26'54.16“E;
Observation period: uninterrupted since 2012;
Elevation: 2400 m;
Climatic conditions: Dry sharply continental climate;

The Suffa plateau was chosen for the setup of the 70-metre radio telescope RT-70 similar to the Yevpatoria RT-70 telescope in the Soviet times. The construction started with the foundation of the telescope and some structures. Then, in the 1990's, the construction work stopped to be renewed only in 2018 and 2019 when some international intergovernmental contracts were drawn. Located at the height of 2,400 m above the sea level, the Suffa plateau enjoys a high percentage of occurrence of clear sky both in the optical and millimetre bandwidth. Observations on astroclimate started here as early as the end of the 1980's and included launches of weather balloons, standard meteorological records and research of the convectional stability of the atmosphere in the optical bandwidth. In 2012 first test measurements were taken, and since 2014 up to now full-scale regular observations have been carried out of the millimetre bandwidth astroclimate. Statistical data regarding the Suffa plateau itself is abundant; see the statistical diagrams on figures 6 and 7.

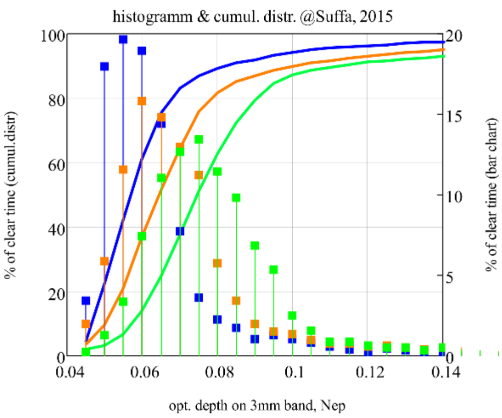

Fig. 6. Histograms and cumulative distribution plots of optical depth measured on the Suffa plateau at 3 mm wavelength in 2015.

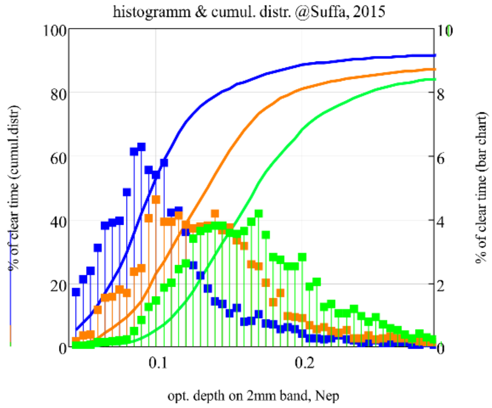

Fig. 7. Histograms and cumulative distribution plots of optical depth measured on the Suffa plateau at 2 mm wavelength in 2015.

In one of our expeditions we climbed a mountain 3,300 m high located in the vicinity of the plateau. We could see dense low clouds at the height of 100 to 200 m above the plateau, but at 3,300 m the sky was clear. The local staff told us, and their words are indirectly corroborated by the radiometer MIAP-2 data, this was a normal situation in that place (see Fig. 8).

It is difficult to evaluate quantitatively the advantages of the 3,300-m site in comparison with the 2,400-m site without taking direct measurements; however, at this stage of research we would describe this advantage as “substantial” for the millimetre and especially the sub-millimetre bandwidth. We are planning to carry out measurements in an expedition in 2019 or 2020.

Fig. 8. This photo was taken from the mountain 3,300 m high located near the plateau. The low-altitude clouds covering the Suffa plateau can be seen.

III. Sites Comparison

We have gathered enough data on the sites described in the previous section for statistical comparison. As for the remaining sites mentioned in this paper, we were able to dedicate to them only short-time observations from a couple of hours to several months. One should bear this in mind when studying the plots and diagrams with the median values of optical depth indicated because the averaging period is different for each particular site. The median values have been calculated for a month-long uninterrupted record or shorter, depending on a particular case. Initially one of the MIAP-2 tools was operating in the single-channel mode only, this is why we do not have 2-millimetre transparency window measurements for all sites.

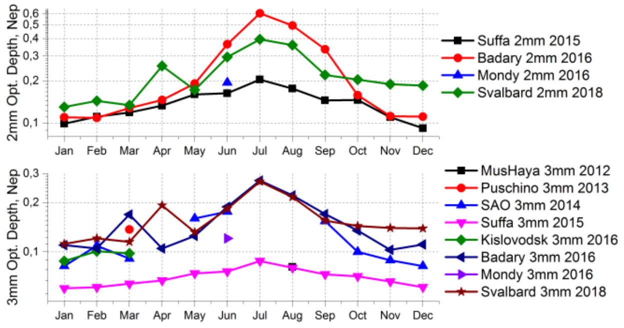

Fig. 9. Monthly median values of optical depth data obtained by our group on different sites starting from 2012.

Among all the sites described the Suffa plateau has most advantages. The median optical depth values are not higher than 0.2 Nepers for the 2-millimetre band and 0.1 Nepers for 3-millimetre. This is to be expected as the Suffa plateau is located high in the mountains in dry sharply continental climate. The site on Mus-Khaya Mountain in the south-east of Yakutia which is also located in conditions of sharply-continental climate near the Pole of Cold (Oymyakon) can rival with that on the Suffa plateau. However, the nearest habitation to Mus-Khaya Mountain is 100 km away, and one will have to pass the dense taiga on the way. On the Suffa plateau, on the other hand, there are basics of conveniences: there is a road, and electric power and running water supply.

The worst transparency values for the millimetre bandwidth are those sites that are closest to the sea: Kara-Dag (Crimea), Svalbard, and the SAO RAS. The Badary Observatory stands apart in this list as its climate is characterized by low atmospheric humidity, but the local impact of the Tunkin Depression collecting vapor cancels the climatic advantages of the location.

The optical depth in the millimetre bandwidth is defined by water vapor and oxygen absorption. The oxygen absorption depends mostly on the elevation of the site, while the water vapour part varies depending on the weather. Therefore, we can numerically describe the astroclimate of a site through precipitable water vapour. The method of calculation of PWV was discussed in our previously published papers [6,3]. The comparative analysis of sites' PWV is shown below.

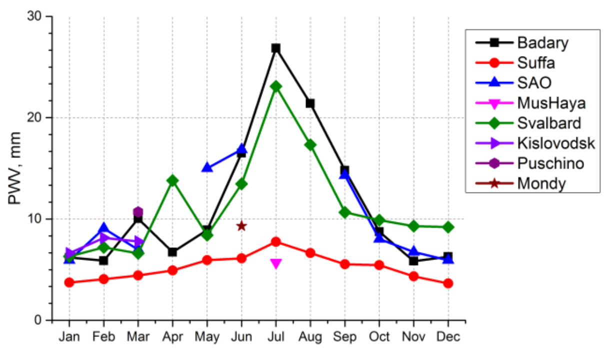

Fig. 10. Monthly median values of the PWV data obtained by our group on different sites starting from 2012.

The Suffa plateau and Mus-Khaya Mountain are also the best as far as PWV is concerned. The site of the Institute for Solar and Terrestrial Physics near the village of Mondy has also shown good results in PWV by the measurements taken over two days. At this stage of research, we can say that Mondy is the best place for the millimetre-bandwidth radioastronomy in Russia as it is equipped with all necessary utilities being a functioning optical observatory. Adding the millimetre bandwidth to its toolkit would be the most rational decision in view of both the astroclimate and the construction expenses.

For most sites our observations did not last longer than a year. Climatic conditions can change from year to year, and statistics of transparency may vary. The radiometric system MIAP-2 on the Suffa plateau is operating continuously, and its data can be used for tracking yearly changes (see Fig. 11).

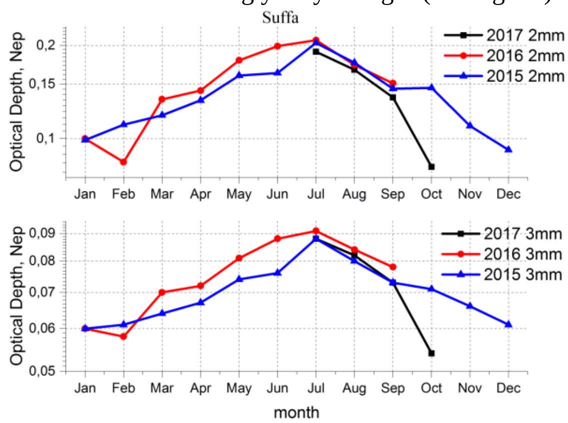

Fig. 11. Monthly median values of optical depth data obtained in different years on the Suffa plateau.

To draw the final line, we are offering this table of comparison of all the sites for which we have gathered enough data to present seasonal statistics. The table shows the share of the year when the optical depth observed is lower than 0.1 nepers. Two values are indicated for the Suffa plateau, the first value (2,400 m) is for the plateau itself following the immediate measurements, while the second one (3,300 m) is an extrapolation of the Suffa data for the 3,300-metre elevation made with the use of the standard atmospheric profile. In the observatory of the Institute for Solar and Terrestrial Physic near Mondy village we were not able to conduct long-term observations, but the results of our short-time measurements permit to extrapolate the Badary observatory data and complete the statistics for a year with some degree of accuracy.

TABLE I
CLEAR SKY TIME PERCENTAGE COVERING OPTICAL DEPTH BELOW 0.1 NEP

Site	Altitude, m	3mm	2mm
Svalbard	100	16%	7%
Badary	700	30%	21%
Mondy*	2100	47 %	45%
SAO	2100	14%	-
Suffa	2400	90%	27%
Suffa*	3300	94%	51%

* Extrapolation of the data obtained at the closest point.

Conclusion

In this paper we are presenting a comparison of different sites which can be suggested for construction of a radio astronomical observatory operating in the millimetre bandwidth. Among all sites having ever been studied with our radiometer MIAP-2, the Suffa plateau is the best choice for astroclimatic reasons. However, our observations have shown that the mountain peak close by might prove a better choice. We are planning to go on expedition to study that mountain in 2019. At present there are plans to cut some of the bandwidths of the RT-70 radio telescope in order to lower the expenses and accelerate the construction process. We, on the other hand, are proposing to add to the Suffa observatory another tool operating in the sub-millimetre bandwidth at the elevation of 3,300 m. Assembling a commercial compact instrument will be easier and faster than constructing the RT-70 which has not gone further than the designing stage so far. Our instrument will permit to collect data in the Suffa observatory in near future without waiting for the construction completion of the RT-70.

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