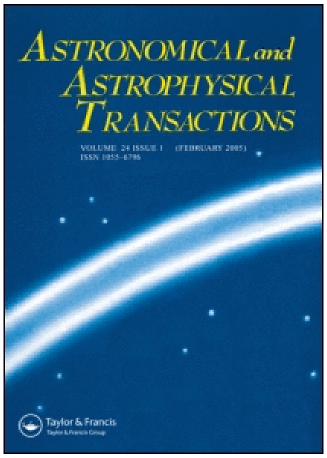

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Limit on ground-based CMBA experiments

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LIMIT ON GROUND-BASED CMBA EXPERIMENTS

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We demonstrate that the 'super-aperture' method developed by the Pulkovo group (Esepkina *et al.*, 1973, earlier papers cited there) can be used efficiently in ground-based CMBA (Cosmic Microwave Background Anisotropy) experiments. With big enough reflectors, simple beam-switching and two-frequency observations suppress the atmosphere (and ground) radiation down to the noise level of the best receivers for angular scales smaller than some critical value. New generation RATAN-600 experiment ('Cosmological Gene' project: see Parijskij *et al.*, 1998; Parijskij, 1999; http://brown.nord/nw.ru/CG/project.htm; http://www.sao.ru) will be based on this idea, and we hope to observe all acoustic modes with l (multipole number) > 200–500 with the same receivers as accurately as in space.

KEY WORDS CMB anisotropy, cosmology

1 INTRODUCTION

The atmospheric thermal emission increases the system noise of ground-based experiments by nearly a factor of two even in the clearest frequency range. The strongly non-Gaussian statistics of the fluctuation of this emission, with a powerful low-frequency tail, prevents the averaging in the frequency- and time-domains we use for the white component of the receiver noise. That is why, under standard atmospheric conditions, the atmospheric noise at the radio telescope output dominates the white component of the receiver noise by several orders (e.g., 100–1000 in the transit mode of observation with a PLANCK-class mirror and receivers, but at sea level). This means that to get the same results as expected in the PLANCK SURVEYOR mission, a 10^4–10^6 year long ground-based experiment has to be done.

There are several well-known methods of suppression of the atmospheric noise. The most radical one is to put the radio telescope above the atmosphere (satellites or balloons) or to put it at dry or cold place. Very strong suppression can be achieved at any observing site using interferometers. All these methods are based on simple but different physics:

(a) there are no emitting particles (or only a small number) in the field of view;

(b) there are no common particles in the field of view of interferometer elements and zero correlation function of the atmosphere noise at the output is observed;

(c) the nature of the atmospheric noise is non-Gaussian (Jorgensen *et al.*, 1999).

The beam-sweeping mode can be used in some cases, and, with a very high speed, receiver noise will dominate. One can come back to the same place of the sky when the atmospheric noise is fully independent. Any $1/f$ noise can be suppressed by this method.

Atmosphere filtration algorithms for the far-field zone case have been recently considered (Lay and Halverson, 1999). However, as has been noted by the Pulkovo group (Esepkina *et al.*, 1973), with very big reflectors several new effects appear and new methods of atmosphere suppression can be used. We call all of them the 'near-field zone' approach and collect them in the next section.

2 NEAR-FIELD ZONE EFFECTS

(a) Averaging over the aperture. Using the Big Pulkovo Radio Telescope (BPR) with antenna size 130 m × 3 m, which is the prototype of the RATAN-600, it was realized in the 1960s that with the telescope size $D \gg \sqrt{H\lambda}$, were H is the atmosphere effective scale, all small-scale variations of the atmospheric emission will be suppressed by the aperture size even in the single-beam mode of observation.

(b) Simple beam-switching mode in the near-field case. The efficiency of this very old method strongly depends on the aperture size and for an angular scale comparable to the beam size it approaches the D/λ suppression factor. This case is opposite to the interferometry case, because all emitting particles in the near-field zone are practically the same in both beams. Also, comparison of this method with the beam-switching mode in the far-field zone shows a very small filtration factor of the last one (Lay and Halverson, 1999).

(c) For the same reason the double- (multi-)frequency mode is very effective in the near-field zone and may be used if the atmospheric noise spectrum is much different from the CMBA one (just the case!). Again, at all frequencies the same volume (a slab with a geometrical aperture at the base) with the same emitting particles is visible with all receivers. For $30 < l < 10000$, the cross-correlation coefficient between 3.9 cm and 2.1 cm has the value 0.99 about 50% of the time at RATAN-600 (Kaidanovski *et al.*, 1982).

(d) We can add a new effect to these. It is possible to separate the atmospheric component in the double-beam mode of observations due to the great difference in relative velocities of the atmospheric screen across the aperture (wind

Table 1. Atmospheric noise suppression methods.

N	*Method*	*Source size* $\Theta_s = 1/l$	*Residual atmospheric fluctuations*
1.	Single-beam, software filter	$\theta_s \le \tau_h \Omega_s$	$\frac{V_c \tau_h}{2\sqrt{3}L}\sqrt{D\left(\frac{L}{V_c}\right)}, \quad \tau_f \ll \frac{L}{V_c}$
			$\frac{\tau_h}{2\sqrt{3}\tau_f}\sqrt{D(\tau_f)}, \quad \tau_f \gg \frac{L}{V_c}$
2.	Double-beam	$\theta_s \le \Delta\theta$	$\frac{\Delta}{L}\sqrt{D\left(\frac{L}{V_c}\right)}, \quad \tau_f \ll \frac{L}{V_c}$
			$\frac{\Delta}{V_c \tau_f}\sqrt{D(\tau_f)}, \quad \tau_f \gg \frac{L}{V_c}$
3.	Double-beam with image restoration	$\Delta\theta < \theta_s < 5\Delta\theta$	$\frac{\Delta}{L}\sqrt{D\left(\frac{L}{V_c}\right)}, \quad \tau_f \ll \frac{L}{V_c}$
			$\frac{\Delta}{V_c \tau_f}\sqrt{D(\tau_f)}, \quad \tau_f \gg \frac{L}{V_c}$
4.	Two frequencies, software cleaning	$\theta_s \gg \theta_a$	$\sqrt{2(1 - M_{12})D_1}$

Note: We use Kaidanovski *et al.* (1982) notation: L – aperture size, D – structure function, V_c – wind velocity, Δ – linear difference of the positions of the aperture projection on to the atmospheric emitting layer for two different beams, $\Delta\theta$ – angular separation of the two beams, θ_s – size of the field to be observed ($\theta_s = 1/l$ for CMBA experiments), θ_a – antenna beam, τ_h, τ_f – parameters of the output filter, ones depends, on the beam size and source size and velocity relative to the beam ($\tau_f = \theta_s/\Omega_s$, where Ω_s is the source angular velocity relative to the antenna beam, τ_h – optimal parameter of the low-frequency cutoff filter, see Kaidanovski *et al.* (1982) for details).

velocity) and CMBA across the beam (Earth rotation for transit mode) even with the same spectra and with the same structural functions of the atmospheric and CMBA (or any other distant screens) noises. This method is effective in the case when the angular correlation function of the CMBA drops significantly on a scale comparable to the beam-throw in the beam-switching mode. Scalar type polarization may belong to this class of CMBA.

We see that in all domains – space-frequency, time-lag and time-frequency – there are specific near-field effects which can be used in the CMBA experiments.

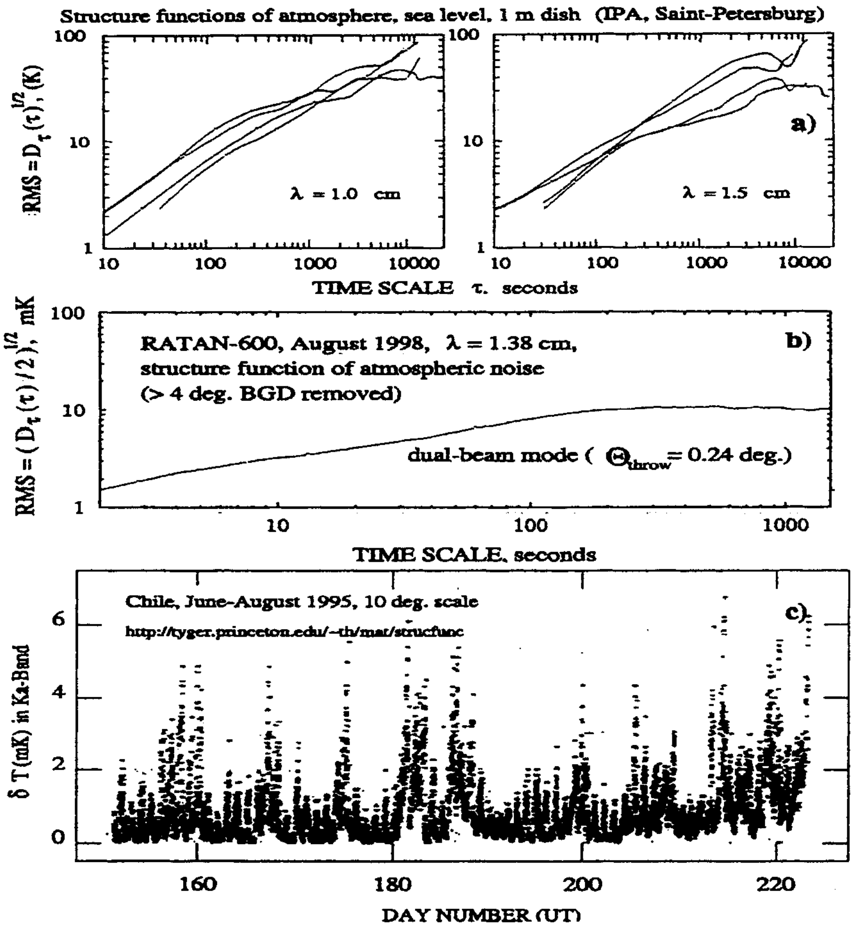

Figure 1 Compilation of published atmospheric noise at 30GHz for very different sites and telescopes: (a) Sea level with 1 m dish (Saint-Petersburg); (b) RATAN-600 site with 450 m aperture at elevation about 1000 m; (c) Chile, 4200 m, small dish. In all cases the atmospheric noise may strongly dominate over the receiver noise. The RATAN-600 site, as expected, lies between the Sea and Chile cases.

3 EXPECTATIONS AND REAL LIFE: THE RATAN-600 CASE

Several tables and figures below demonstrate the experimental results we have so far obtained using the world's biggest reflector-type radio telescope RATAN-600 (Parijskij, 1993).

Formal solutions for the near-field case can be found in the monograph 'Radio Telescopes And Radiometers' (Esepkina *et al.*, 1973, in Russian) and also in Kaidanovski *et al.* (1982, in English). We select below a few most important statements (Table 1).

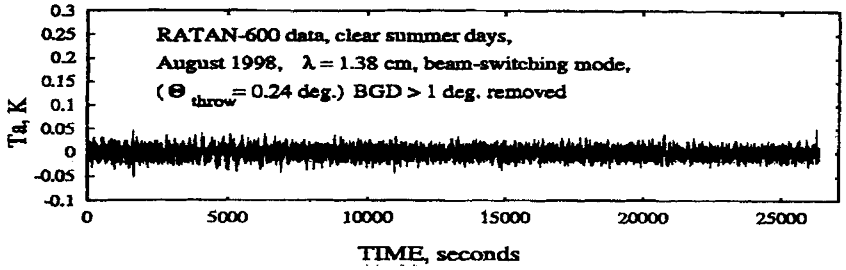

Figure 2 RATAN-600, 1.38 cm, clear summer day, July 1998, very wide (0°.24) beam-switching mode, $l < 100$ scales are removed as background.

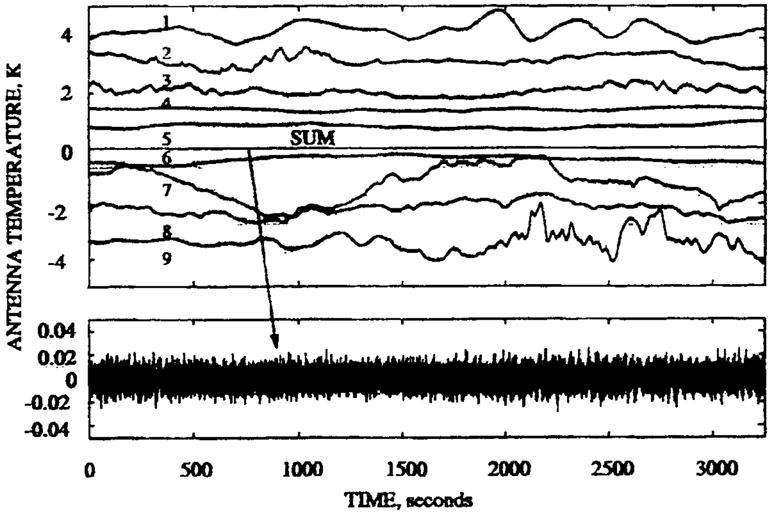

Figure 3 RATAN-600, $\lambda = 1.38$ cm, transit scans of the same part of the sky on nine bad-weather days are shown with the standard single-horn mode and reference horn directed to the Pole. Software filtration of $l < 900$ harmonics only results in SUM record, shown in the middle, which looks like white noise (see below) with the RMS of a few mK $s^{1/2}$.

With the double-beam switching strategy we may expect a suppression factor of up to 1000; another factor, 10, can be released provided that a reflector as big as RATAN-600 is used with the double-frequency strategy. Below we show some new results of the atmospheric noise measurements at RATAN-600 (see Figures 1–8).

From the figures it can be seen that there is qualitative agreement between the experimental data of RATAN-600 and the theory developed for the special 'near-field zone' case, and in all cases the factor D/λ really works in the filtration process. But this agreement has a statistical meaning. A single realization may be very different from the mean. All expectations can be related to the median values only. At the same time, even with much better receivers than those used

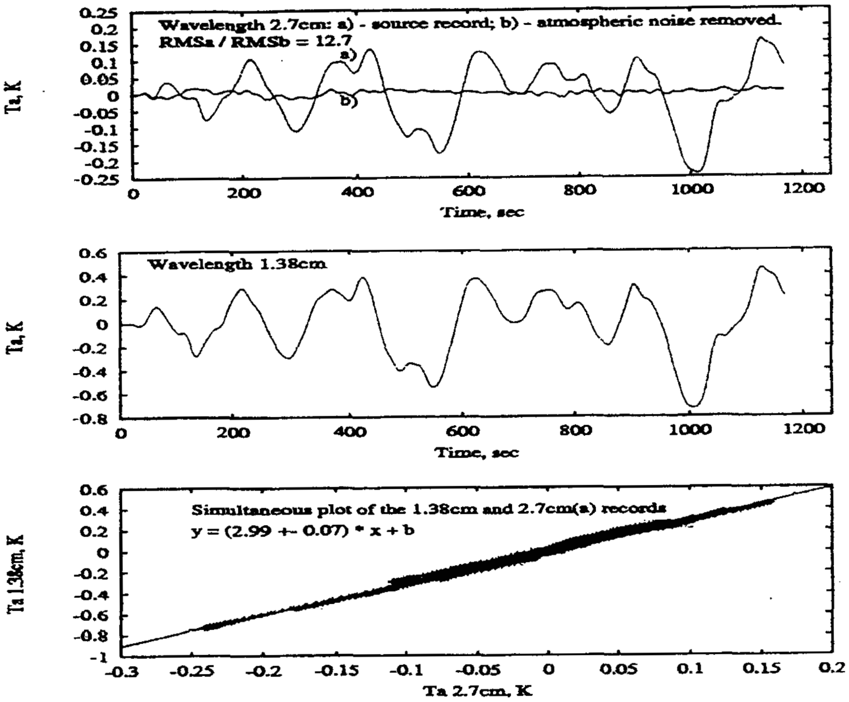

Figure 4 RATAN-600, near-field zone effect (bad weather case) results in a high (0.99) correlation between 1.38 cm and 2.7 cm receiver output. Correlated noise is removed. As a result, 2.7 cm output has RMS by a factor of more than 10 less than original signal (curve *b* on the upper graph).

by Korolkov's group in the 1970s, we cannot trace short-term atmospheric noise (shorter than 10 sec, $l > 3000$) in the transit mode. Also we cannot separate the instrumental $1/f$ noise from atmospheric noise at $l < 100$, and all data here should be used as an upper limit of the atmospheric contribution. The large dispersion in amplitude of the atmospheric noise renders the median values of percentage of the 'quiet' realization (atmospheric noise is less than receiver noise) not very sensitive to the receiver noise. It does not mean that much better receivers do not help: sensitivity will be realized (only a bit!) for smaller numbers of individual records.

4 CONCLUSIONS

1. For atmosphere noise statistics of the given site, it is possible to find the part in the D–l plane which is free from atmospheric noise limitation. Both higher l and smaller D can be used in the ground-based experiments, but in either case one must have a 'super-aperture', when $D \gg \lambda(1/l)$. There is

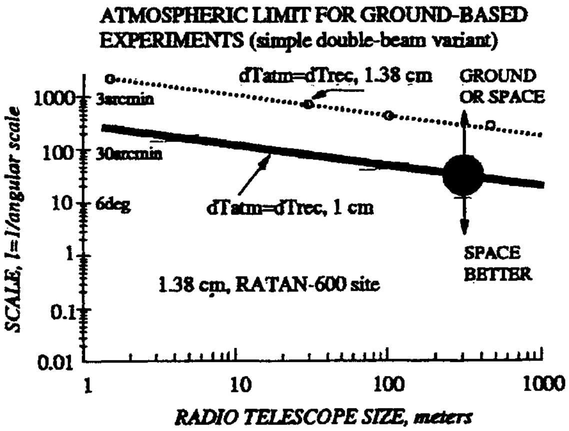

Figure 5 Ground–Space CMBA experiment boundary in the D–l plane; beam-switching and two-frequency cleaning was used (see Kaidanovski *et al.*, 1982; Parijskij, 1993). Dots – real experiment at the RATAN-600 site at frequency close to the water vapour line (1.38 cm). Solid line – expected boundary at 30 GHz, 'Cosmological Gene" project central frequency. We can see that sub-degree scales can be studied from the ground as deep as from space with an aperture greater than a few hundred metres. Scales greater than 1° should be studied from space only with beams much smaller than 1°.

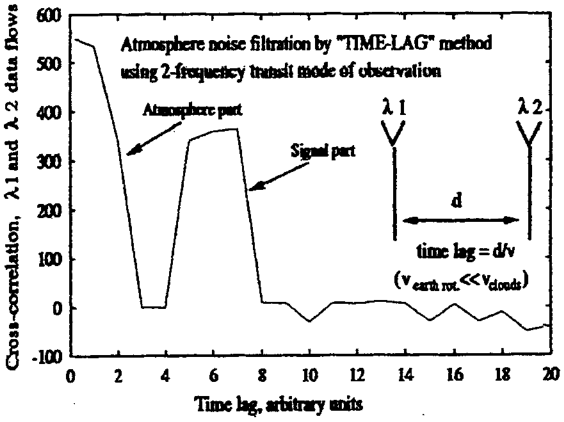

Figure 6 'Time-Lag' method uses the difference between the wind velocity across the aperture and sky velocity across the beam. In the case shown, the beam-switching mode was used with the 'beam throw' greater than the correlation angle of the small-scale CMBA. Atmospheric noise gives a correlated signal with a nearly zero lag, but CMBA gives a correlated signal at much greater time lag. Noise can be separated even in the single-horn but different frequency-mode, normally used at RATAN-600.

some boundary in the D–l plane which divides experiments into two groups: experiments that can be done in space only (small l), and those that can be done in space as well as on the ground (large l).

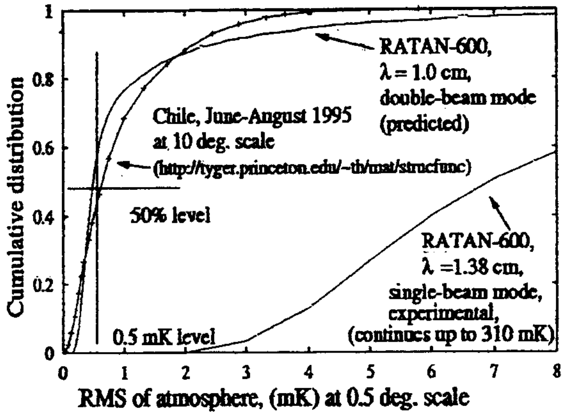

Figure 7 Cumulative distributions of the atmospheric part of the noise component at 2000 patches on the sky 0°.5 long ($l > 200$) each in the simple single-beam transit mode of observations at the wavelength 1.38 cm (right bottom curve). Up to 310 mK RMS was observed, but with beam-switching mode at 1 cm in 50% of cases the noise will be less than 0.5 mK.

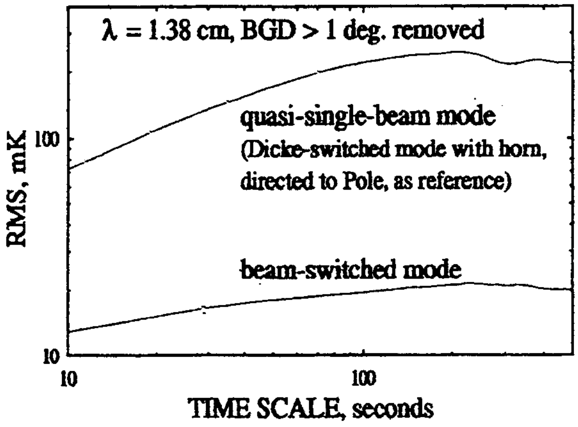

Figure 8 RATAN-600, 1.38 cm, 1998; Cloudy atmosphere case. Single-beam versus beam-switching ($\theta_{\rm throw} = 0°.24$ mode.

2. RATAN-600 size can be efficiently used for CMBA experiments for $l > 200$, 500 and even for much smaller l in C_{lQ}, C_{lU} measurements. The same near-field methods can be used to suppress the variation of the ground radiation in I, Q, U Stokes parameters. First results can be found in SAO WEB sites (http://brown.nord/nw.ru/CG/project.htm; http://www.sao.ru).

3. Even for a well-studied site, one can be free to use only 'median' values. The real dispersion of the atmospheric noise may be much greater or much

lower than the median value of the dispersion. This means that the 'median' boundary in the D–l plane is not very sensitive to receiver noise.

All methods have their own difficulties. The 'space' solution is most expensive and the resolution is limited. The interferometry solution has problems with the small spacing and small dishes for the case of small l in CMBA (common atmosphere is visible by different elements) plus the brightness temperature sensitivity degradation due to the 'aperture filling factor' effect. The 'super-aperture' method may be used only at big enough reflectors, and even for very high-priority experiments like CMBA investigation, it is not easy to get observation time from aJew month to a few years.

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