STATUS OF THE RELICT-2 MISSION AND OUR FUTURE PLANS

STRUKOV I., SKULACHEV D., BUDILOVICH N., BRJUKHANOV A., NEMLIKHER YU., KOROGOD V. , KOSOV A. , RUKAVICIN A. , BOROVSKY R. AND NECHAEV V.
Space Research Institute of Russian Academy of Sciences
Profsojuznaja ul., 84/32, Moscow, 117810, Russia

Abstract. We review the main results obtained in the first cosmic experiment for study of the large scale anisotropy of CBR at 8 mm RELICT-1 and compare them with data of COBE mission.

1. Introduction

Investigation of the anisotropy of the cosmic background radiation is one of the most important directions for the more precise determination of such fundamental parameters as H, Ω, h.

In this paper we will discuss main results obtained in the first cosmic experiment for study of the large scale anisotropy of CBR at 8 mm RELICT-1.

Results of comparison of the experimental data of RELICT-1 and first year COBE data and low-frequency surveys are presented. The performed analyze showed that the accuracy of the COBE data is not enough for separation background anisotropy caused by galaxy emission from the CBR anisotropy. For such separation one need of many-frequency survey with more accuracy. Such accuracy may be achieved in the RELICT-2 project that has an unique radiometric equipment in the frequency band from 22 to 90 GHz with sensitivity more than 10 times better than COBE.

The experimental procedure of RELICT-2, its orbit and results of the engineering testing of the RELICT-2 equipment are discussed in the paper.

For more precise determination of the spectral index n it is useful to investigate CBR anisotropy with angular resolution about 3° .

M. Kafatos and Y. Kondo (eds.), Examining the Big Bang and Diffuse Background Radiations, 45–58.

2. Comparison of the RELICT-1 and COBE Data

RELICT-1 was our first space-borne experiment, Strukov and Skulachev (1984, 1987). It was performed by means of small satellite Prognoz-9 that was launched in 1983 to a high altitude orbit with apogee about 700 000 km as shown in Fig.1.

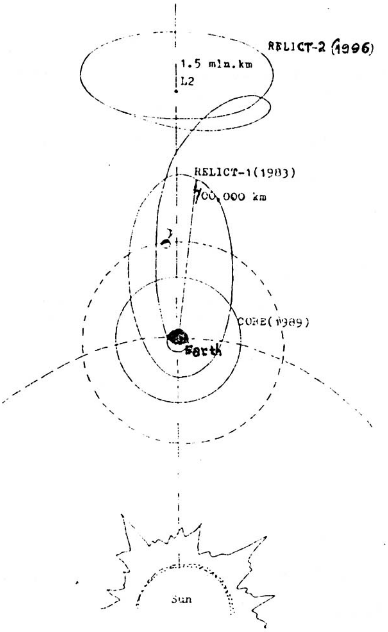

Figure 1. Orbits

RELICT-1 was our first attempt to investigate the large-scale CMB anisotropy. We understood that one need of more sensitive receiver for such investigation which can be used at the frequency band from 22 to 100 GHz. So the next most important goal of the experiment was study of environment conditions during long term space experiment and choice of the type of receiver for such investigation.

The detectors of the receivers can be cooled to 80 K by means of radiative loss of heat into space. Degenerated paramp and Schottky mixers showed promise as sensitive devices for the conditions mentioned above. Degenerated paramp is the most sensitive type of detectors, but it is regenerative device and investigation of the stability of such devices under long-term use in deep space in terms of optimizing the parameters of the next generation of instrumentation was one of the most fundamental goals of the RELICT-1 mission.

The main goal of all investigations of the large scale anisotropy of CMB performed before the RELICT-1 mission was determination of the model independent magnitude of the quadrupole component, Cheng et al.(1979), Fabbri et al.(1980).

Choice of the strategy of data reduction was based on the next assumptions, Strukov and Skulachev (1987), Strukov (1991):

1) after averaging we have only one sample of noise;
2) we have only one Universe;
3) in theoretical models the population variance is used, but not sample one;
4) quadrupole has only 5 degrees of freedom:
5) in any case in comparison of experimental and theoretical data always the concrete model is used;
6) observational sample is not uniform: different sample units have different statistical weight. Weighting process causes the transformation of signal and noise response

$$S_{output}(l,m) = ||T(l,m)|| \cdot S_{input}(l,m)$$

$$||T(l,m)||^{-1} \quad \text{– is not exist}$$

Of course after some regularization matrix $||T(l,m)||$ is transformed to the form of square matrix.

In this case inversed transformation exist but regularization process brings additional uncertainies if signal/noise ratio is small.

7) The mapping strategy in experiment RELICT-1 allows to determine population variance of the instrumental noise.
8) The instrumental transform function and the statistical weight can be determined with high accuracy.
9) The number of degrees of freedom for sum of spherical harmonics is more than for the quadrupole one.

The mentioned above assumption gave us a possibility to abandon model independent estimate of quadrupole component and using Monte Carlo simulation we can determine the constraints on the power spectrum for any cosmological model and after that to receive the constraints on the quadrupole magnitude or on magnitude of an arbitrary spherical harmonic, Strukov et al.(1988).

After careful data reduction we have discovered anisotropy in the background radiation, Strukov et al.(1992, 1992, 1993).

Parameters of the instrumental noise and measured values for the different smoothing parameters are tabulated in Table 1.

Smoothing parameter φ_0, degree	Measured variance on the map μK^2	Variance of the noise μK^2	Degrees of freedom of noise	Sky variance
6	127^2	124^2	106	27.4^2
12	67^2	56^2	19	36.8^2
24	34.5^2	23.7^2	9	25.1^2

TABLE 1. *Parameters of noise and measured values*

It should be stress that the main part of the observed by RELICT-1 mission anisotropy is caused by decreasing of background temperature. We proposed that the discovered signal has cosmological nature, Strukov et al (1992).

It is necessary to stress that the direct comparison of massives of the RELICT-1 and COBE data is impossible. Poor signal/noise ratio in RELICT-1 data causes a necessity to use weighting, that dramatically changes a form of output signal. In this case the spherical harmonics lose their orthogonality and power of some input harmonics transfer in different output harmonics, moreover the transform functions are different for COBE and RELICT-1 radio maps.

We can correctly compare the results of two experiments only after receiving constraints for one or other type of cosmological model.

In case of Harrison-Zeldovich spectrum we have received constraints on the quadrupole component and on the amplitude of the metric fluctuations, Strukov et al. (1992)

$$17\,\mu\mathrm{K} < \langle Q_2 \rangle < 95\,\mu\mathrm{K}$$

and

$$5.2 \cdot 10^{-6} < \varepsilon_{\mathrm{H}} < 2.9 \cdot 10^{-5}$$

The first results of COBE mission gave the next constraint on that parameters, Smoot et al.(1992)

$$2.6 \cdot 10^{-6} < \varepsilon_{\mathrm{H}} < 1.1 \cdot 10^{-5}$$

and Tenerife experiment gave, Hancock et al. (1994)

$$5.8 \cdot 10^{-6} < \varepsilon_{\mathrm{H}} < 9.7 \cdot 10^{-5}$$

Thus for Harrison-Zeldovich spectrum we have rather good agreement between estimates of RELICT-1 and Tenerife experiments. COBE experiment gave the less level two times more.

But after 2 years of COBE data reduction for Harrison-Zeldovich spectrum was obtained the next estimate for the quadrupole component, Gorski et al.(1994)

$$18.3 < \langle Q_2 \rangle < 21.5 mK$$

$$6 \cdot 10^{-6} < \varepsilon_{\mathrm{H}} < 7 \cdot 10^{-6}$$

that supports our data.

Additional constraints on the ε_{H} for different values of Hubble parameter one can receive from the magnitude of the dipole component, Abbott and Schaefer (1986). The mentioned above constraints on ε_{H} together with the constraints on ε_{H} caused by measured dipole component give us constraints on the density, Strukov et al.(1994), Strukov (1994).

You can see from Fig.2 that we can receive constraints on the density

$$0.16 < \Omega < 0.5.$$

If we don't tolerate a nonzero cosmological constant $\Omega = 1$ and the dipole gives more stringent constraints on the magnitude of ε_{H}. This magnitude is less than low limit of the mentioned above experiments.

In this case we can conclude that the part of anisotropy is caused by anisotropy of the galaxy background. It is interesting to make rough comparison of the RELICT-1 and COBE maps and comparison of COBE and low-frequency maps, Haslam et al. (1982). At comparison we used an information about transform and weighting function RELICT-1 mission.

We propose that cross-correlation between the maps is

$$\rho_{31}{}^\frown{}_{37} \approx 1; \quad \rho_{31}{}^\frown{}_{37} \approx 0.7; \quad \rho_{31}{}^\frown{}_{37} \approx 0.3.$$

Than we can compare proposed (for measured signal/noise ratio) and measured cross-correlation between the different channels of COBE data and RELICT-1 data for the different smoothing parameters. Results of comparison (at smoothing function $\exp(-\varphi/2\varphi_0)$ and $b > 20°$) are tabulated, see Table 2.

In the Table 3 cross-correlation between COBE, 408 MHz and 19 GHz maps for $b > 20°$ and for different smoothing parameters is represented.

You can see a rather strong correlation between COBE and mentioned above maps, especially for $\varphi_0 = 24°$. This shows that galaxy emission is strong enough and one need a precise methodic for the separation of the galaxy and cosmic background anisotropies.

There are two ways to separate galactic and cosmic emission. COBE team method based on the recount synchrotron emission from 408 MHz to 31.5, 53 and 90 GHz by using of measured electron energy distribution and determination of variation of magnetic field strength received from

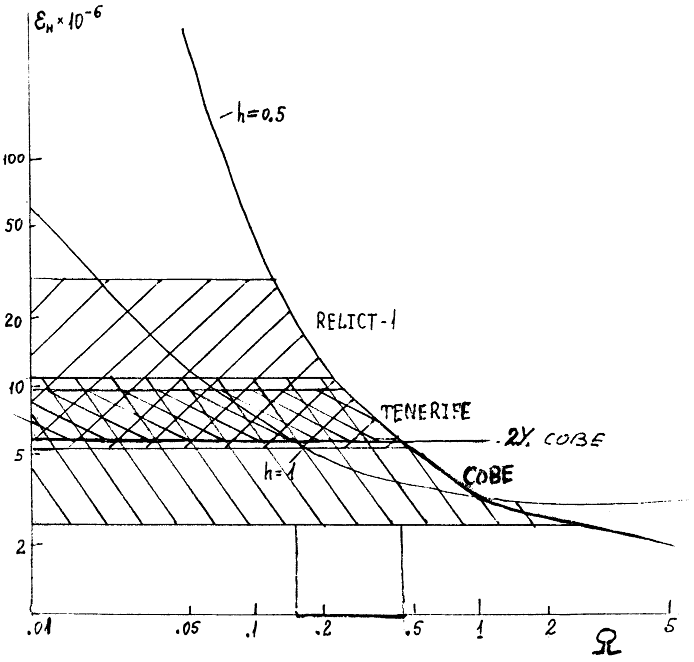

Figure 2. Constrains on the density

$\varphi_0 = 12°$	$\nu = 19$					
		31A	31B	31Σ	53Σ	90Σ
RELICT-1	prop. meas.	0.27 ± 0.2 0.29	0.27 ± 0.2 -0.06	0.33 ± 0.2 0.11	0.3 ± 0.19 0.24	0.12 ± 0.23 -0.29
$\varphi_0 = 24°$	$\nu = 9$					
RELICT-1	prop. meas.	0.30 ± 0.3 0.30	0.35 ± 0.3 -0.01	0.42 ± 0.27 0.12	0.4 ± 0.28 0.34	0.18 ± 0.3 -0.35
$\varphi_0 = 12°$	$\nu = 50$					
COBE 31B	prop. meas.	0.36 ± 0.12 0.28	1.00 1.00		0.37 ± 0.12 0.54	0.17 ± 0.12 0.42
$\varphi_0 = 24°$	$\nu = 12$					
COBE 31B	prop. meas.	0.2 ± 0.27 0.22	1.00 1.00		0.34 ± 0.22 0.47	0.13 ± 0.28 0.43

TABLE 2. *Comparison results*

spatial variation in β_{synch} (408, 1420 MHz), Bennett et al. (1992) or taking $\beta_{synch} = 2.75$. Accuracy of such methodic may be not very good, because of

	$\varphi_0 = 3°$		$\varphi_0 = 12°$		$\varphi_0 = 24°$	
	408 MHz	19 GHz	408 MHz	19 GHz	408 MHz	19 GHz
31Σ	0.45	0.65	0.56	0.68	0.92	0.90
53Σ	0.18	0.25	0.38	0.35	0.65	0.65
90Σ	0.20	0.15	0.24	0.21	0.48	0.48

TABLE 3. *Cross-correlation between COBE, 408 MHz and 19 GHz maps*

very high frequency difference and instrumental and systematic noise of 408 and 1420 MHz maps and difference of angular resolution at low frequency and COBE maps.

Separation of the galactic and cosmological background is complicated because of similarity of their spatial frequencies spectra. Our analysis showed that spectral index $n = 1.27$ for total 408 MHz map and $n = 1.33$ for 20° cutting.

Our method is based on the possibility to do very precise measurements of the large scale anisotropy in background emission at different frequencies . But we must improve the equipment sensitivity at least by factor 10. So one of the main goals in time of preparation of the RELICT-2 mission was an essential improvement of the radiometers sensitivity.

In case of cosmic nature of the anisotropy of the background radiation that has been discovered by RELICT-1 and COBE teams and if its spectrum is the Harrison-Zeldovich spectrum a minimal magnitude of the rms per 10° field of view would be about 30 μK, Strukov et al.(1992, 1992), Smoot et al.(1992).

The quadrupole components of the dust emission are rather small (at 53 GHz rms$\approx$ 2 μK), Bennett et al.(1992). So we can not take into account the dust emission in the frequency band below 60 GHz. That gives the possibility to use very precise measurements of the background radiation anisotropy at 22, 34.5 and 60 GHz for separation of the cosmic and galactic emission. But that calls for the use of much more sensitive radiometers than were employed in RELICT-1 and COBE experiments.

Only after such separation we can determine magnitude of spectral index n with accuracy about 10% . We can receive 6% accuracy by improving angular resolution to 3°, Sazhin et al.(1994?).

In spite of the high apogee of the RELICT-1 experiment orbit and rather low level of its antennas sidelobes we observed an existence of a large contribution of the Moon's and Earth's thermal emission to antenna temperature. Thus the RELICT-2 experiment can not have an orbit such as the orbit of the RELICT-1.

3. Status of the RELICT-2 Mission

3.1. WAYS OF A SENSITIVITY IMPROVING

The main goals of the preparation of the RELICT-2 mission till now were:

1. Determination of essential improvement of the radiometers sensitivity to reach a signal/noise ratio $\sigma_s/\sigma_n > 1$.
2. Investigation of the possibility to decrease the size of the halo-orbit about Sun-Earth L2 libration center.
3. Adjustment and test of the radiometers of the RELICT-2 engineering module.

In order to design and build extremely sensitive radiometers working at 80 K we have made the investigation in the following directions: i) finding methods for improving of quality of solid- state devices; ii) investigation of the possibility to decrease the losses in input devices; design of the low-losses switches; iii) choice of the optimal scheme of the radiometer; iiii) finding methods to provide a normal operation of the radiometers at ambient (300 K) and cryogenic (80 K) temperature. This is important especially for radiometers with a degenerated parametric amplifier.

First of all it was necessary to choose the type of receiver for each frequency band. In order to simplify the engineering testing before the launch the cooled radiometers must work at the room and cryogenic temperature without tuning. This makes additional difficulties in design and adjustment of the radiometers. The degenerated paramp testing during the PROGNOZ-9 flight and our comprehensive investigation of its behaviour have shown its excellent noise and operating performances.

We have proposed a such paramp-doubler configuration that provides an extremely high stability. It provides 10 times less gain sensitivity to the changing of power and frequency of the paramp's pump in comparison with RELICT-1. In order to realize this configuration we are needed to improve varactors' quality by a factor 2. Besides that we have designed and built and tested room and cryogenic temperature frequency doublers for 22-150 GHz frequency band with efficiency more than 50%.

Degenerated paramps are the most sensitive mm wavelengths devices today. Fig.3 shows as a function of the input frequency, noise measure of the degenerated paramps at different ambient temperatures.

Fig.4 shows that recent degenerated paramps have significantly better noise measure that futuristic MODFET.

3.2. SPACECRAFT AND ORBIT

The RELICT-2 configuration is shown in Fig.5. The LIBRIS spacecraft is a cylindrical structure (1). House keeping systems and electronic units

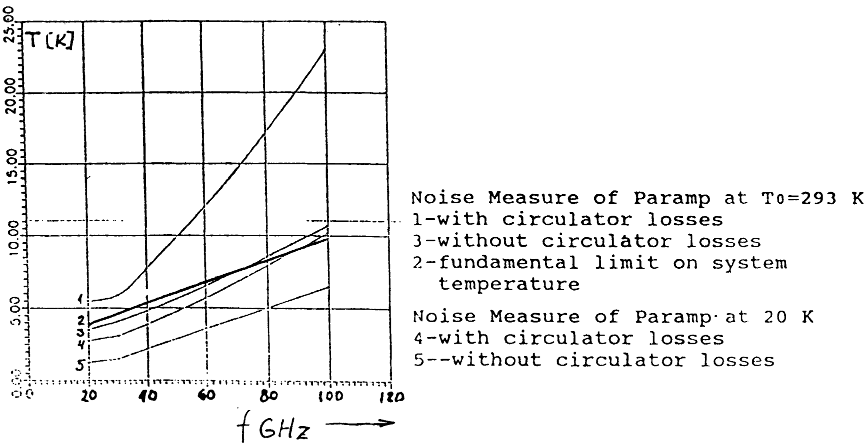

Figure 3. Noise measure

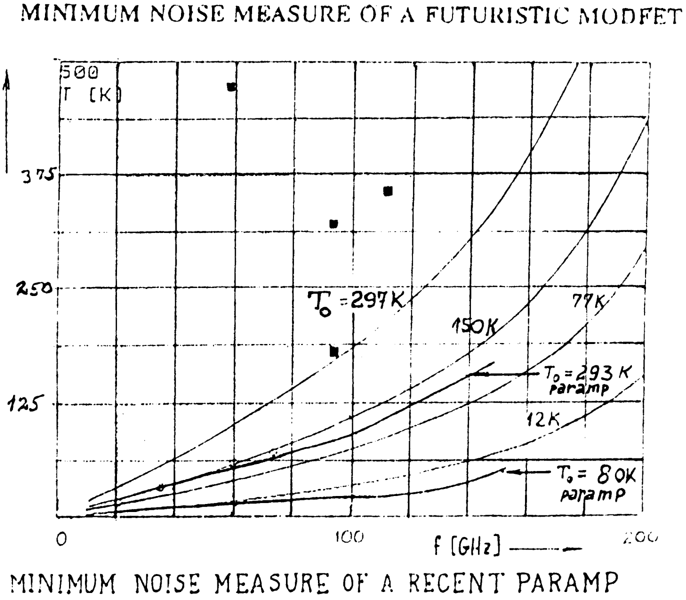

Figure 4. Comparison of the recent degenerated paramp and futuristic MODEFET

of the scientific payload are installed inside the spacecraft in a hermetic volume on two frames. Most of the scientific instruments, sunsensors of the orientation system (3), spherical gas containers of the orientation system (4), the propulsion system (5), and the antenna for communication (6) are located on a cylindrical structure with four solar array panels (2) extended like petals of a flower to provide power.

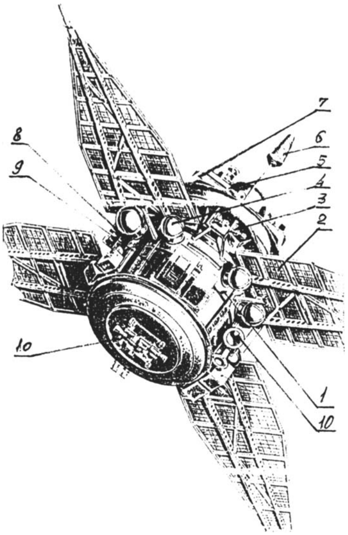

Figure 5. LIBRIS spacecraft with the installed radiometers

The passive cooling system with the radiometers is located on the shadow side of the spacecraft (10). The 22 GHz radiometer is installed on the cylindrical side of the spacecraft (11). The spacecraft is spin stabilized with the spin-axis pointed toward the Sun. The LIBRIS spacecraft will be built by Babakin Space Center in Moscow in collaboration with other industrial enterprises.

Two orbits: a large-amplitude Lissajous orbit and small-amplitude orbit with a lunar-gravity assist maneuver has been investigated, Strukov et al. (1993).

The results of analysis that had been made by a joint US/Russia flight dynamic team show a possibility to put RELICT-2 into a small-amplitude orbit about the Sun-Earth L2 libration point utilizing a lunar swingby, Eismont et al. (1991), Durbeck et al. (1991), Farquhar (1991), Relict-2 ... (1992), Fig.6. Multiple revolutions should be made in the transfer orbit from the parking orbit to the lunar swingby to reduce the size of maneuvers needed to correct TTI errors, as explained in Dunham et al. (1990). The multiple lunar-swingby on the trajectory would provide an extremely small signal from the Moon, Earth and Sun (less than 1 mK). The possibility of the realization of such an orbit, taking spacecraft maneuver execution errors into account, is proved now.

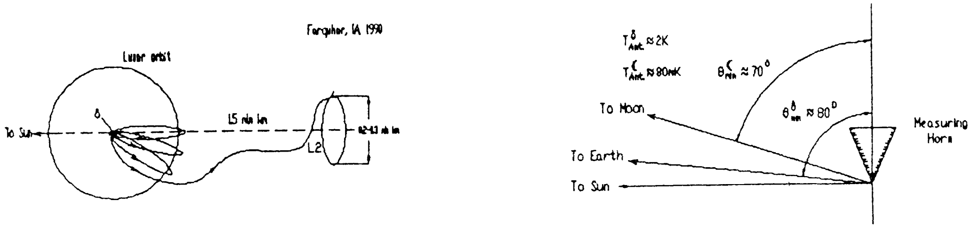

Figure 6. Scheme of the RELICT-2 transfer trajectory with lunar swingby maneuver

3.3. INVESTIGATION OF THE PARAMETERS OF THE ENGINEERING COMPLEX

The entire engineering instrument consists of four radiometers, an electronic subsystem and star detector OREOL-3 for the definition of three-axial orientation of spacecraft with accuracy 4 s. Three radiometers are passively cooled ($T_0 = 80$ K) for 34.5, 60 and 83 GHz, Strukov et al.(1993). 22 GHz radiometer is an ambient temperature radiometer ($T_0 = 300$ K). Each of the radiometers has an antenna system with the corrugated horns. Their nominal beamwidth is 7 deg full width at half maximum power.

We have chosen the schematic of the 22 GHz and 34 GHz radiometers with the degenerated paramp at the input, Strukov et al. (1993). The output of the Faraday-rotation-switch is alternate between the inputs from the corrugated horn antenna and the ambient temperature load. The nominal output signal is compensated by means of the IF-amplifier gain modulation. The Table 4 represents the results of testing of the engineering complex.

f (GHz)	22	34.5	60	72	83
σ_{real} mK·s$^{-1/2}$	5.5	3	8	-	8
σ_{progn} mK·s$^{-1/2}$	2.4	0.8	< 1	1	-

TABLE 4. *Bench testing and future performances*

3.4. THE RELICT-2 FUNDAMENTAL INSTRUMENT

The entire fundamental instrument for investigation of the large scale anisotropy of cosmic background radiation will consist of four radiometers, electronic subsystem and the star detector, Strukov et al. (1993). We have chosen an ambient temperature (300 K) radiometer with a degenerated paramp for 22 GHz system and three passively cooled radiometers (80 K): one of them for 34.5 GHz and other two for 60 GHz. All configurations of the radiometers have a waveguide switch. In the 22 GHz radiometer output of the waveguide switch will be alternate between the inputs from corrugated horn antenna and the temperature stable load. We hope to receive the radiometers sensitivity 2.4 μK·$s^{1/2}$.

In 34.5 and 60 GHz radiometers with degenerated paramp at the input an output of the waveguide switch will be alternate between two inputs from the corrugated horns antennas. The receiving signal has an orthogonal polarization for these radiometers and the same polarization for their reference horns. That provides the additional possibility for investigation of the cosmic background radiation.

The recent launch date of the RELICT-2 is the end 1996. We hope that the RELICT-2 mission put the last point into an experimental investigation of the large scale anisotropy of microwave background radiation.

4. Future Plans

Now we look for a possibility of collaboration in the field of cosmological and solar-terrestrial investigation. One of possible examples of such collaboration is shown in Fig.7. For such investigation we propose to use two additional LIBRIS-type spacecrafts. One of them will be put in the neighbourhood L2 point and two others - in the vicinity L1 point. The instrumental complex for the anisotropy CMB investigation will be installed on the shadow side of spacecraft and solar-terrestrial equipment - on the Sun-side of the spacecraft. On the first spacecraft will be installed two radiometers at 60 and 72 GHz with angular resolution 1.5 deg and sensitivity 1 μK·$s^{1/2}$. On the second spacecraft will be installed three radiometers at 34, 60 and 72 GHz with angular resolution 3 deg and with the same sensitivity.

If we can receive foreign support then these investigations would be incorporated into RELICT-2 program.

In a future plan of Russian Academy of Sciences was included RELICT-3 mission (Phase A). Main goal of the RELICT-3 mission is investigation of the intermediate scale anisotropy of the CMB. We plan to perform investigations at frequencies from 34 to 90 GHz with an angular resolution near 1 deg and sensitivity 0.5 μK·$s^{1/2}$.

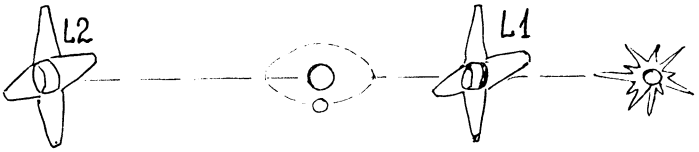

Figure 7. Scheme of cosmological and solar-terrestial investigations

Acknowledgements: We are grateful to all collective of Department 61 of the Space Research Institute of the Russian Academy of Sciences. We acknowledge the support of the RFFI (Grants 93-02-2930 and 93-02-2931), Cosmion and Soros Foundation (Grant M06-000).

References

Abbott, L.F., Schaefer, R,K.: 1986, Ap.J. **308**, p.546.

Bennett, C.L., Smoot, G.F., Hinshaw, G., Wright, E.L., Kogut, A., De Amisi, G.: 1992, Ap.J.Lett. **396**, L7.

Cheng, E.S., Saulson, P.R., Wilkinson, D.T., Corey, B.E.: 1979, Ap.J.Lett. **232**, L139.

Durbeck, M., Hung, J., Regardie, M.: 1991, GMAS User's Guide, Revision 3, Goddard Space Flight Center document 552-FDD-91/020/CSC, Feb. 1991.

Dunham, D.W. et al.: 1990, IAF Paper 90-309, Dresden, Germany, Oct. 1990.

Eismont, N. et al.: 1991, Paper at the 3rd Intern. Symp. on Spacecraft Flight Dynamics, Darmstadt, Germany, Oct. 1991.

Fabbri, R., Guidi, I., Melchiorri, F., Natale, V.: 1980, Phys.Rev.Lett. **44**, p.156.

Farquhar, R.W.: 1991, Acta Astronautica **24**, p.227.

Gorski, K.M., Hinshaw, G., Banday, A.J., Bennett, C.L., Wright, E.L., Kogut, A., Smoot, G.F., Lubin, P.: 1994, COBE Preprint No.94-08.

Gush, H.B., Halpern, M., Wisshnow, E.H.: 1990, Phys.Rev.Lett. **65**, p.537.

Hancock, S. et al.: 1994, Nature **367**, p.333.

Haslam, C.G.T., Salter, C.J., Stoffer, C.J., Wilson, W.E., Thomasson, P.T.: 1982, Astro. and Astrophys. Suppl. Ser. **47**, p.1.

Mather, J.C. et al.: 1990, Ap.J.Lett. **354**, L37.

Reich, P., Reich, W.: 1988, Astron. and Astrophys. **196**, p.211.

Relict-2 Mission Trajectory Design, Goddard Space Flight Center document 554-FDD-92/027/CSC: 1992.

Reynolds R.J.: 1984, Ap.J. **282**, p.191.

Sazhin, M.V. et al.: 1994?, Sov.Astron.Lett. (in prepare)

Smoot, G.F. et al.: 1990, Ap.J. **360**, p.685.

Smoot, G.F. et al.: 1992, Ap.J. Lett. **396**, L1.

Smoot, G.F., Tenorio, L., Banday, A.J., Kogut, A., Wright, E.L., Hinshaw, G., Bennett, C.L.: 1994, COBE Preprint No.94-03.

Strukov, I.A., Skulachev, D.P.: 1984, Pis'ma Astron. Zh. **10**, 3, p.3

Strukov, I.A. et al.: 1984, Abstracts of 25 COSPAR, Graz, Austria, 1984.

Strukov, I.A., Skulachev, D.P.: 1987, SSR/Astrophys. and Space Phys., **vol.6**, ser.E, p.145.

Strukov, I.A., Skulachev, D.P.: 1987, Sov.Astron.Lett. **13(3)**, p.191.

Strukov, I.A., Skulachev, D.P., Klypin A.A.: 1988, Acta Astronautica **17**, No.8, p.903.

Strukov, I.: 1991, Thesis on Phys. and Mathem. Dr. Degree.

Strukov, I.A., Brjukhanov A.A., Skulachev, D.P., Sazhin, M.V.: 1992, Pis'ma Astron. Zh. **18**, 5, p.387.

Strukov, I.A., Brjukhanov, A.A., Skulachev, D.P., Sazhin, M.V.: 1992, M.N.R.A.S. **258**, p.37.

Strukov, I.A. et al.: 1993, Adv. Space Res. **13**, No.12, p.(12)425.

Strukov, I., Brjukhanov. A., Skulachev, D., Sazhin, M.: 1993, Phys.Lett.B **315**, p.198.

Strukov, I.: 1994, Proc.Conf. "Astrophysics and Cosmology after Gamov", Odessa, 1994 (in prepare).