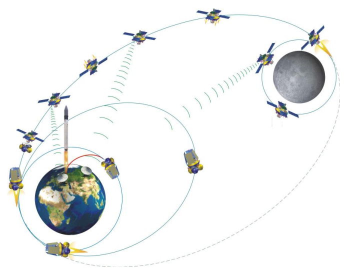
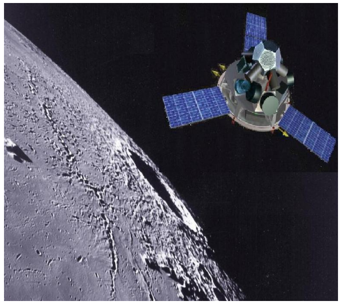




Lunar Space Missions for Ultrahigh-energy Cosmic Rays and Neutrinos Observation

G. A. Gusev, V. A. Chechin, and V. A. Ryabov.

P. N. Lebedev Physical Institute, Russian Academy of Sciences

ARENA2012, Erlangen 19-22 June

Two stages of a lunar experiment with the regolith as a target for the interaction of ultrahigh-energy cosmic rays and neutrinos are considered. The first stage deals with the LORD experiment within the framework of the Luna-Glob space mission scheduled for 2016. The current status of the LORD-instrumentation development is discussed. The aperture of the lunar orbital radio detector exceeds all existing ground-based arrays. Successful realization of the LORD experiment will make it possible to start the second stage of the program. Multi-satellite lunar orbital systems are proposed to increase the aperture and the measurement informativity and accuracy.

Outlook of Presentation

- **Problems of ultrahigh-energy cosmic rays and neutrinos observation.**
- **LORD space experiment and design of apparatus**
- **Multi-satellite circumlunar array, the results of Monte Carlo simulation**
- **Conclusion**

The Main Goal of the LORD Experiment

The primary goal of the LORD experiment is the detection of ultrahigh-energy cosmic rays and neutrinos.

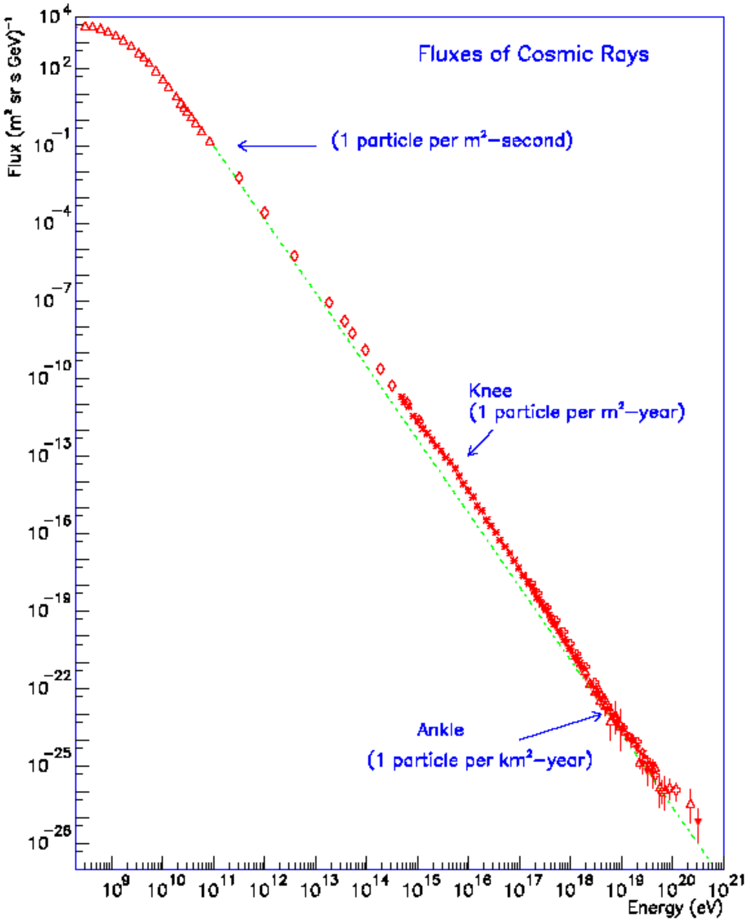
An investigation of the nature and spectra of cosmic particles with energies $E \geq 10^{20}$ eV (‟ultra-high energies”, UHE) is one of the most challenging problems of modern physics and astrophysics.

Information on these particles is important for solving fundamental problems of astrophysics and particle physics relating to cosmic ray sources and acceleration mechanisms.

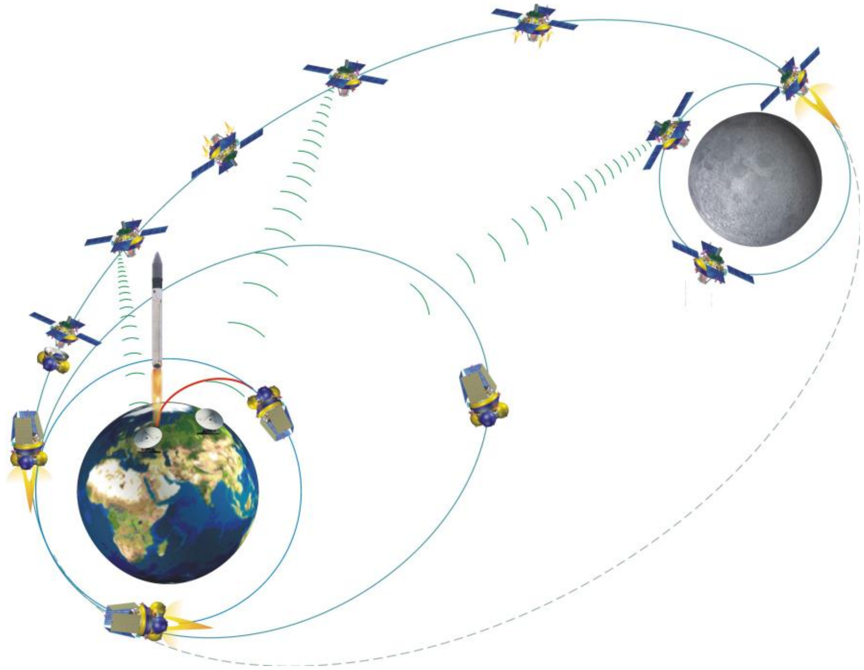
Currently we have a very controversial and paradoxical situation in UHE region. We know neither the nature of UHE particles, nor their sources or processes where they were accelerated to such extremely high energies.

The many facts of the experimental observations at different CR detectors contradicts to the current understanding of the Universe, because a flux of these energetic particles must be suppressed, owing to the GZK CR spectrum cutoff ($E_{GZK} \approx 7 \cdot 10^{19}$ eV, Pierre Auger Observatory (PAO) spectrum extrapolation $dN/dE \sim E^{-4.3}$) caused by the interaction with microwave cosmic background.

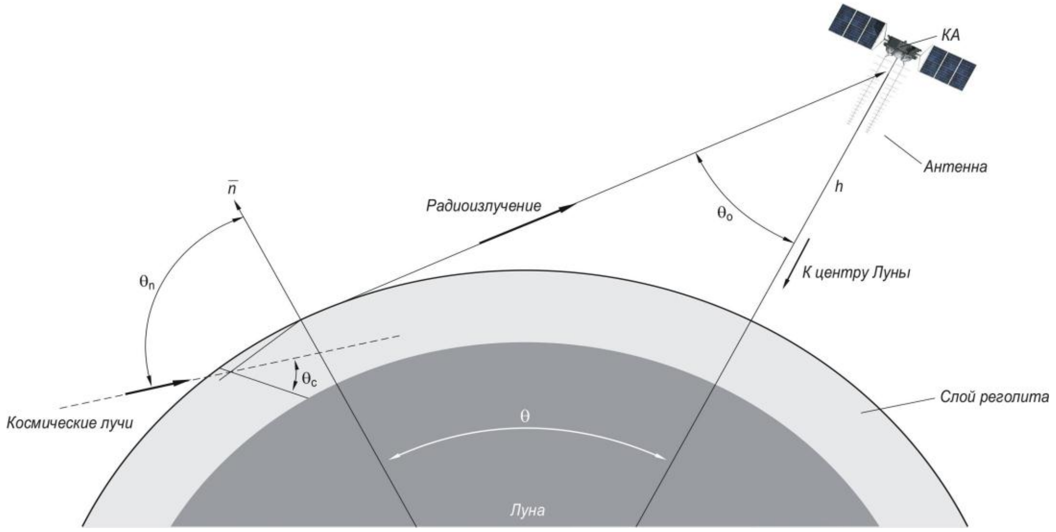
For resolving these contradictions, new independent measurements are necessary.

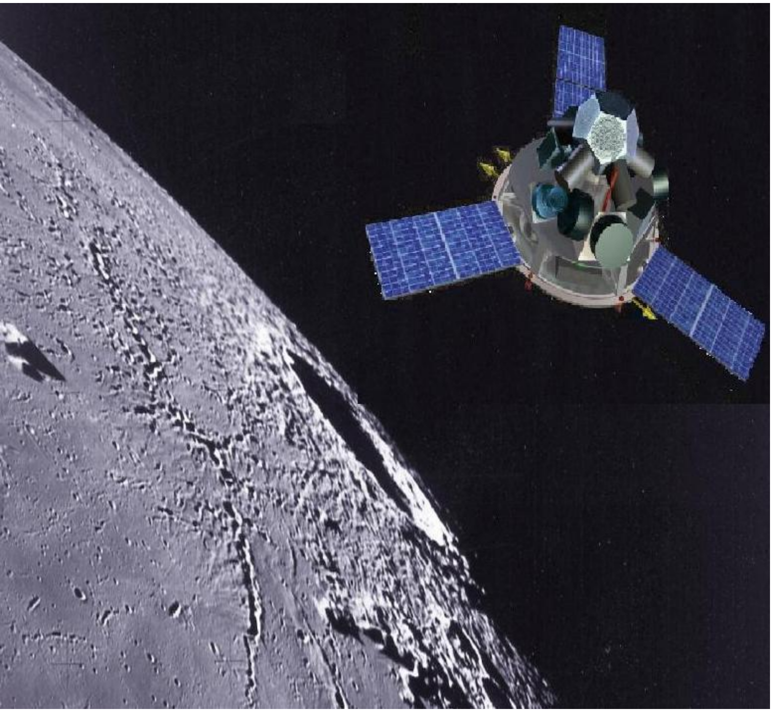


Currently radio method is used as the basis for a number of experiments and projects on the ultrahigh-energy particle detection in such radio-transparent media as the atmosphere, salt domes and ice sheets of Antarctic and Greenland.



LORD EXPERIMENT

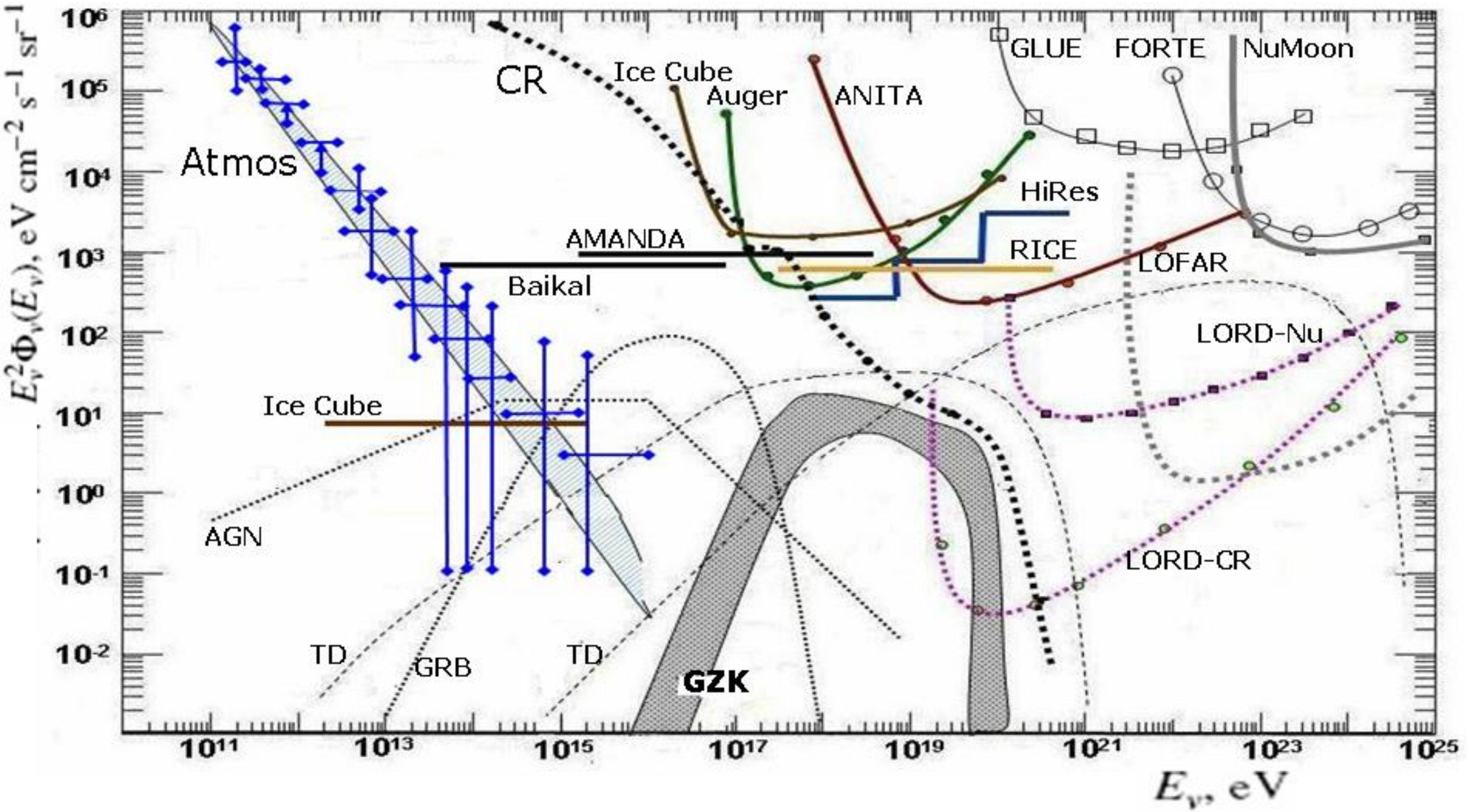




Cosmic rays, neutrino interact with regolith and produce coherent Cherenkov radiation pulse, which after refraction on the Moon surface goes out to vacuum. It can be observed by the LORD apparatus, amplitude, polarization, frequency spectrum being measured.

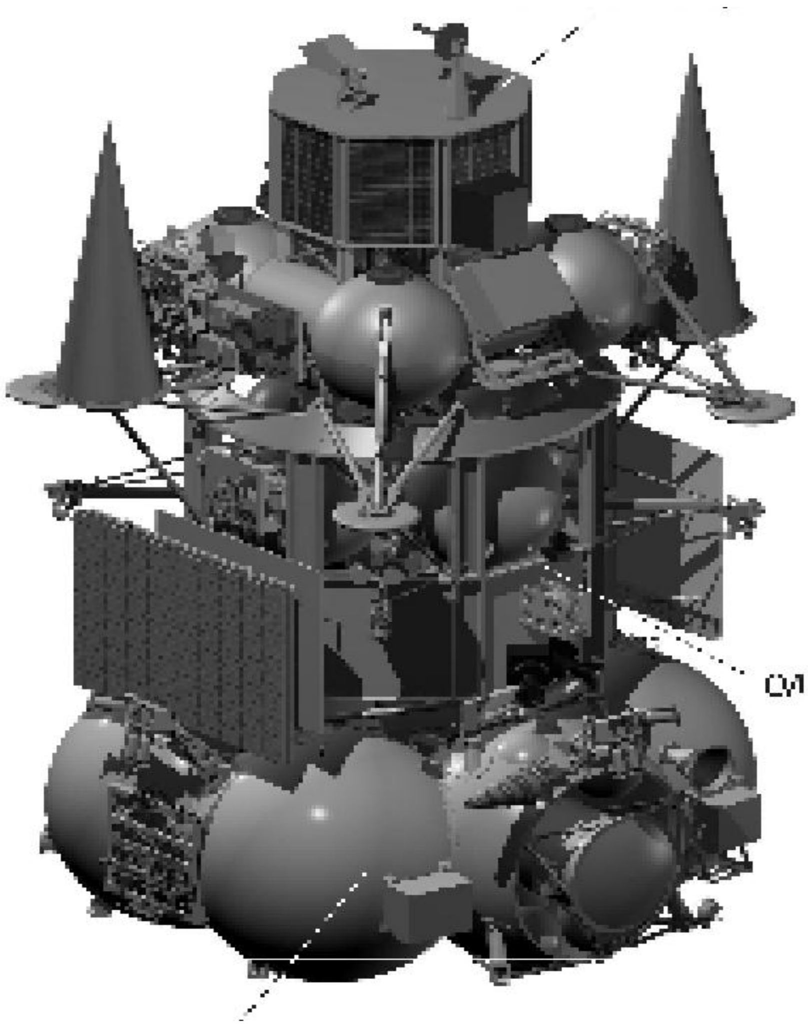
Its aperture is more than one order comparatively PAO one.

Limits for CR and Neutrino Fluxes and LORD Performance

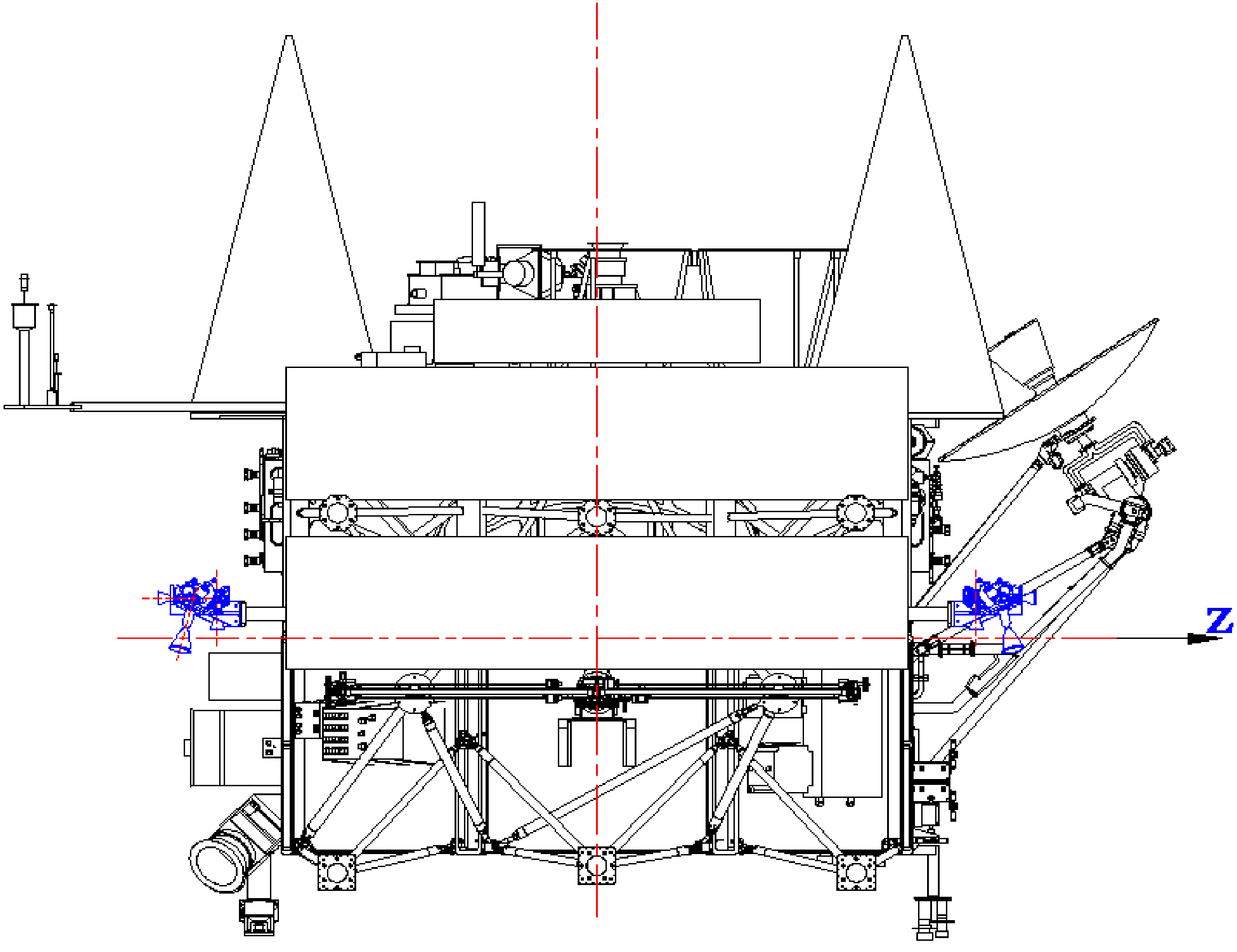


LORD apertures for UHECR & UHEN detection are higher than in all ongoing experiments (with one exception for neutrino detection by LOFAR in the energy range more, than 10^{22} eV) and for energy 10^{21} eV are about $3 \cdot 10^5$ km^2 sr for UHECR and $4 \cdot 10^3$ km^2 sr for UHEN (AUGER aperture for UHEN about 100 km^2 sr)

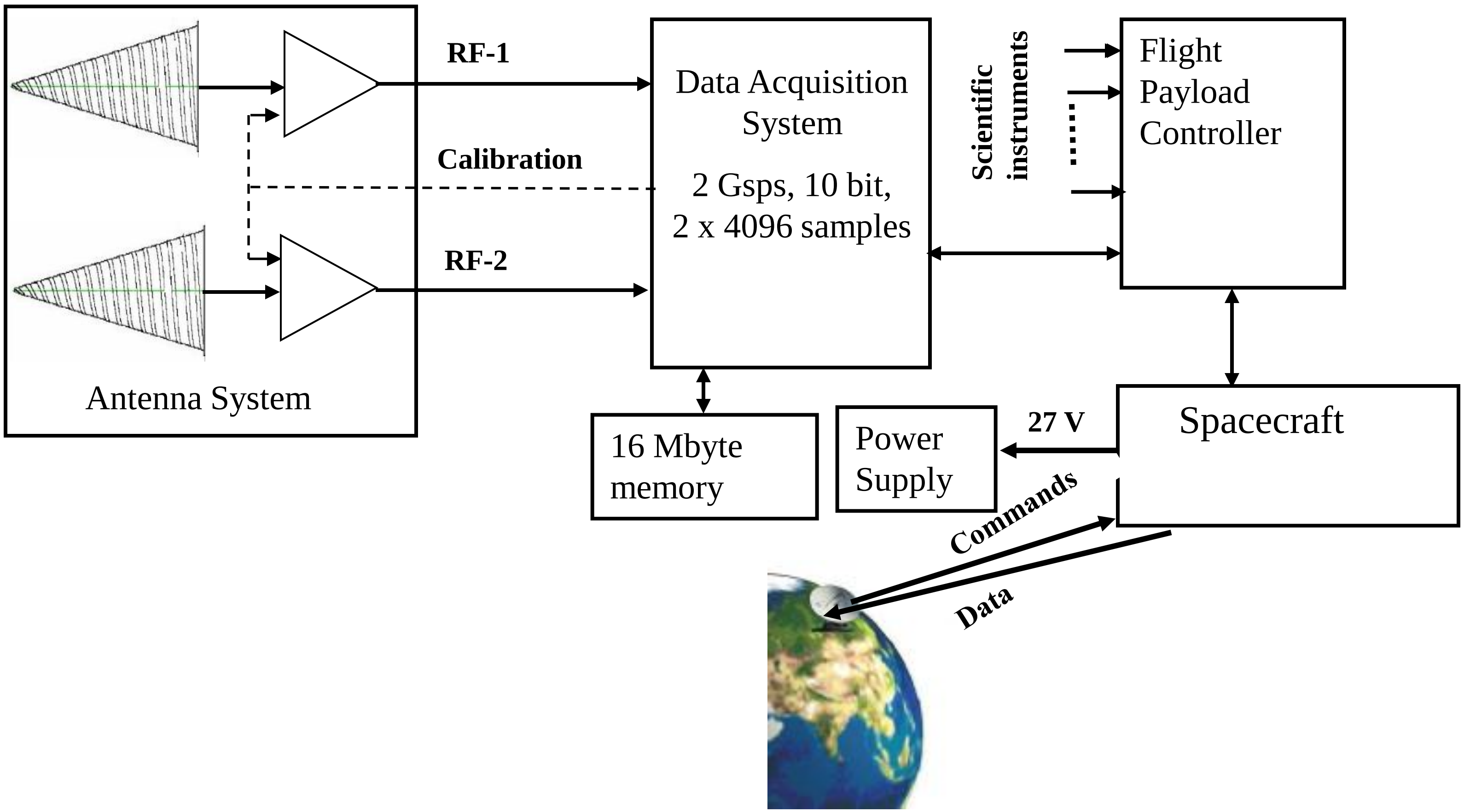
Lay-out of Luna-Glob Apparatus



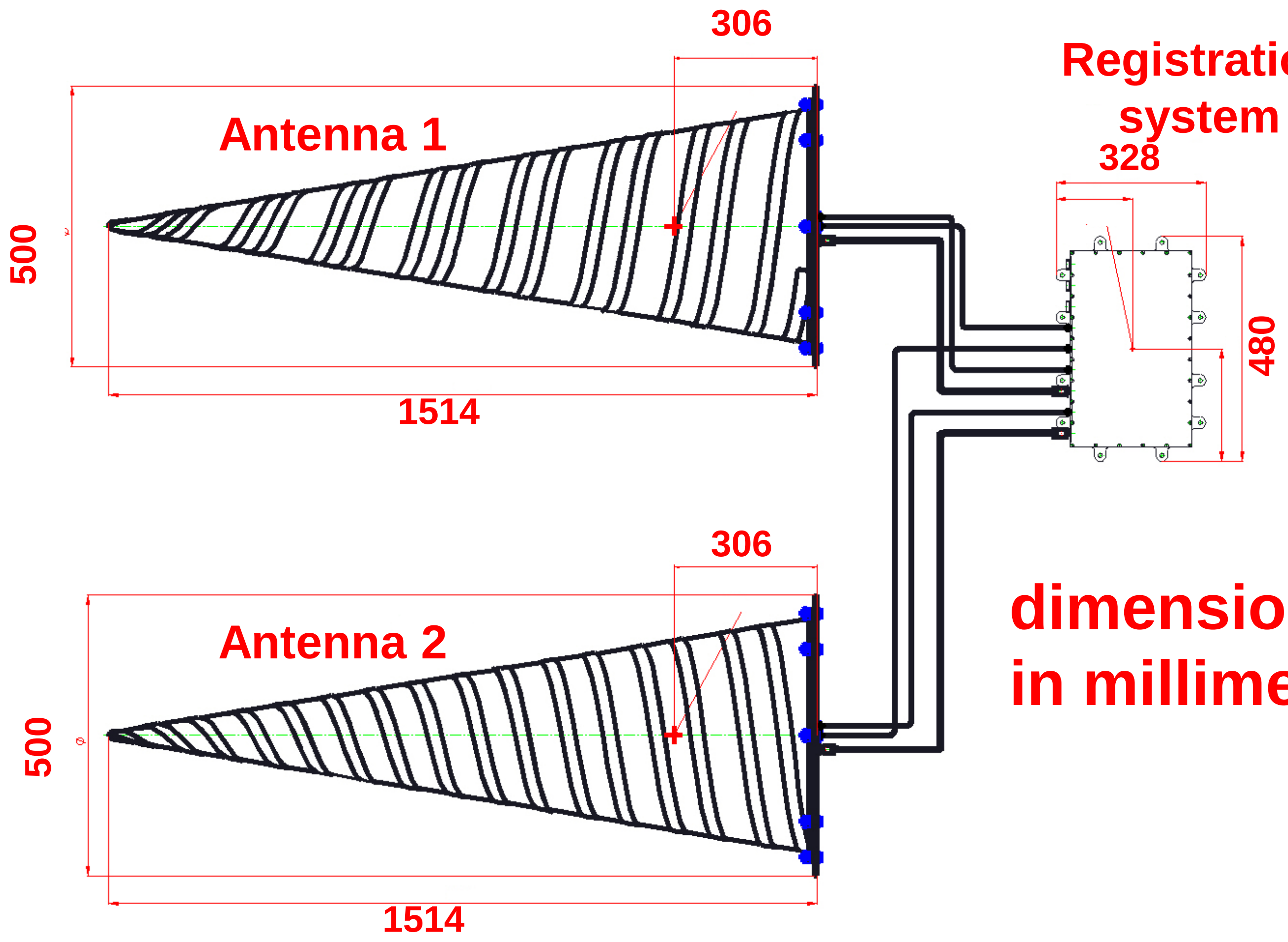
Flight Module of Luna-Glob



Block Diagram of LORD Detector

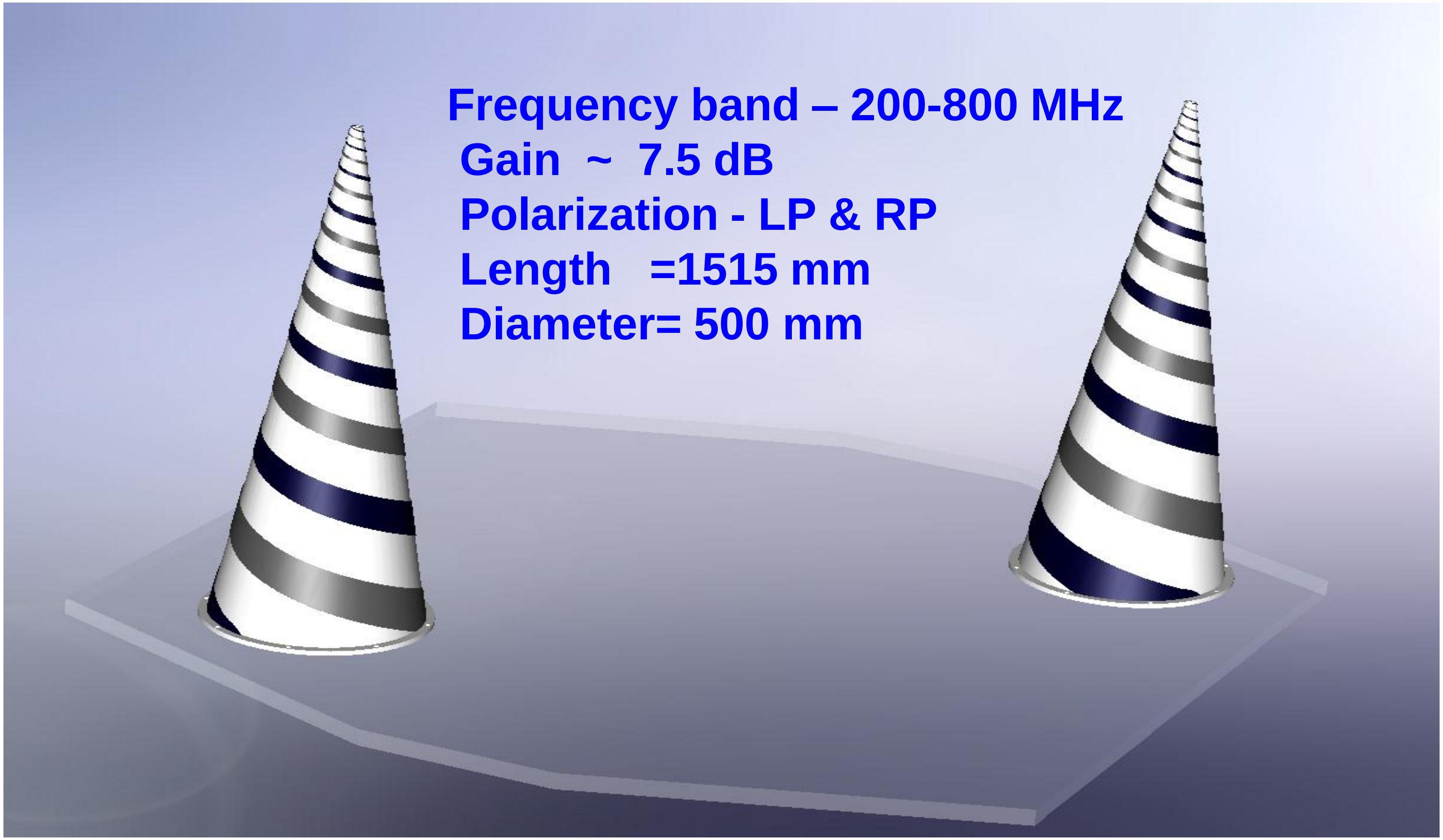


LORD DEVICE



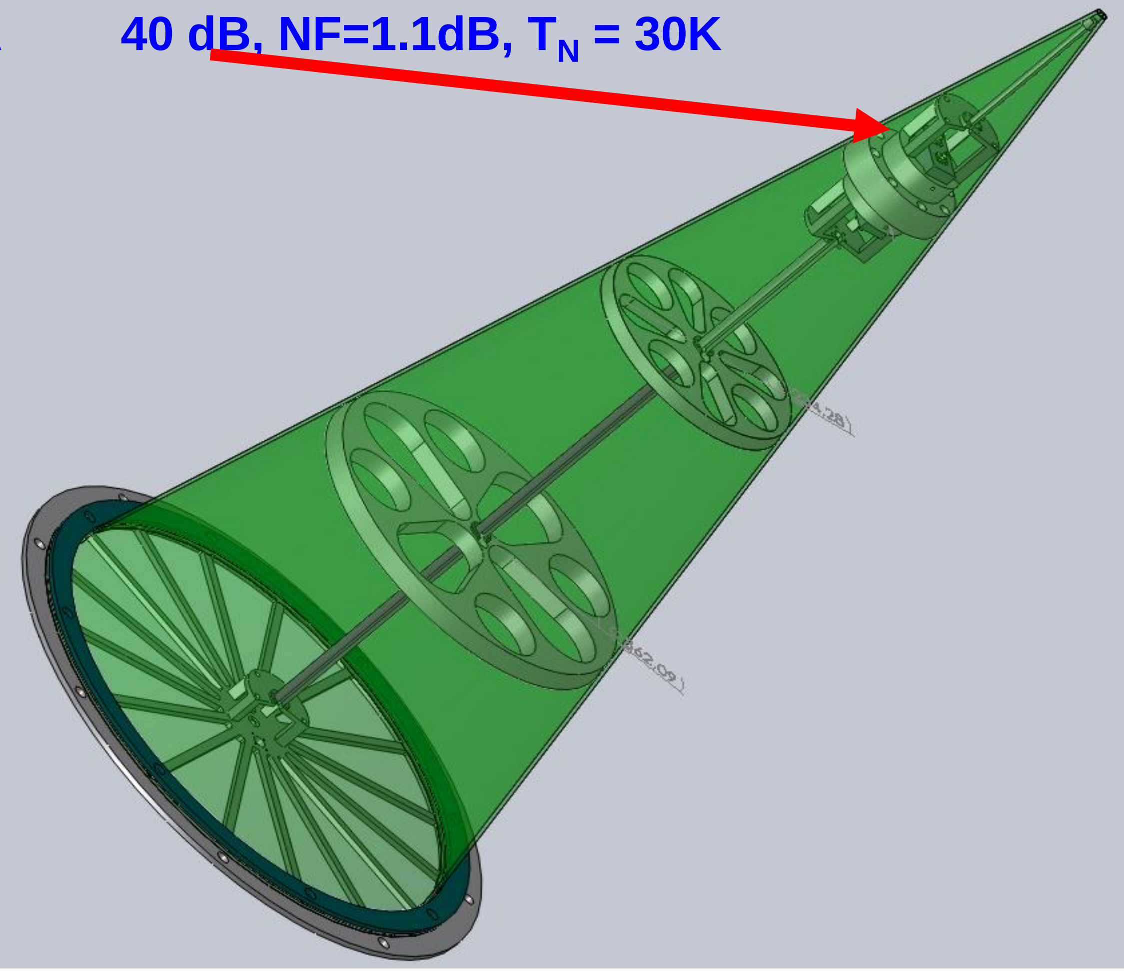
dimensions are in millimeters

Antenna system of LORD device



Antenna with low noise preamplifier (LNA)

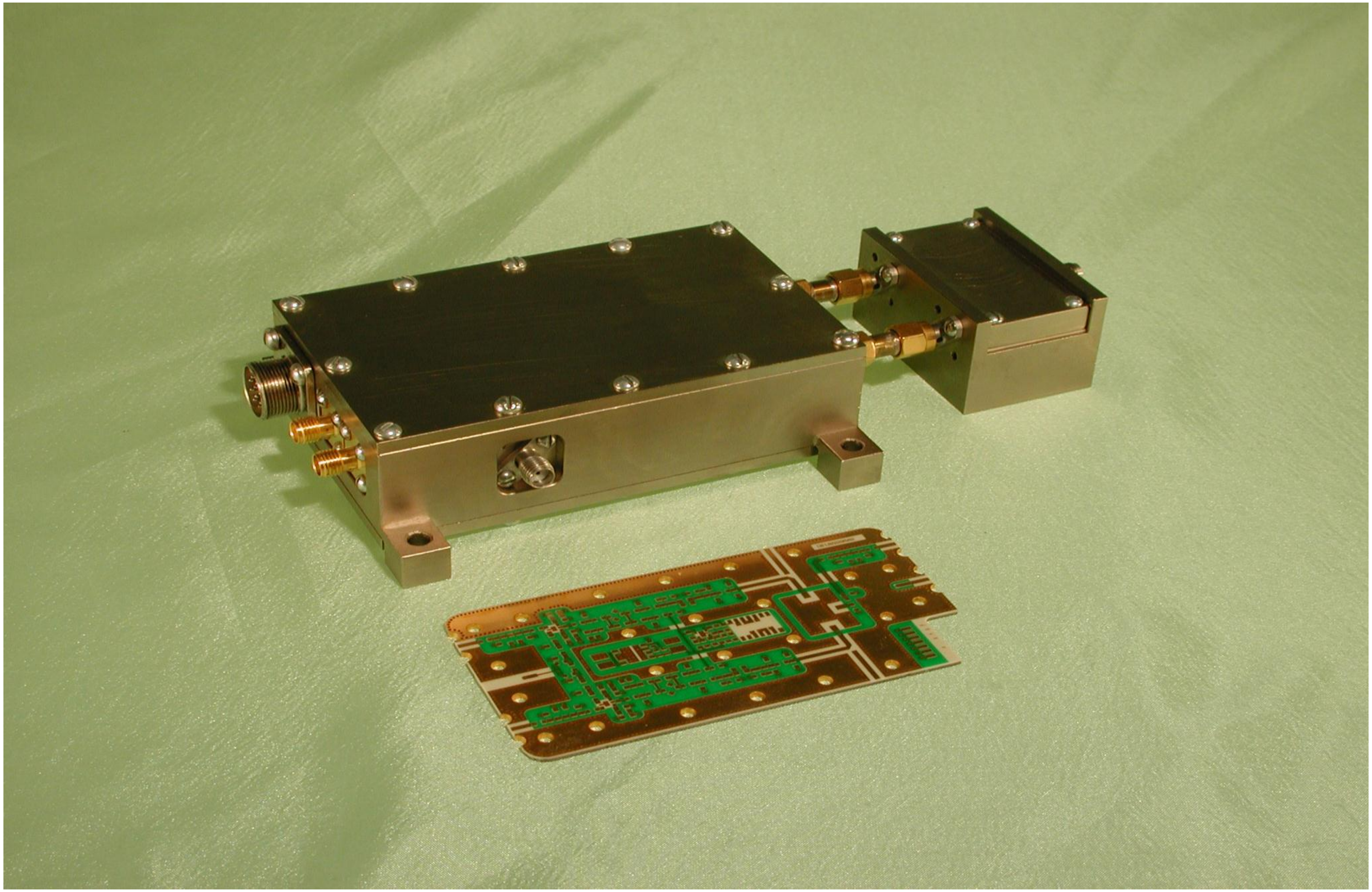
- **LNA** **40 dB, NF=1.1dB, T_N = 30K**



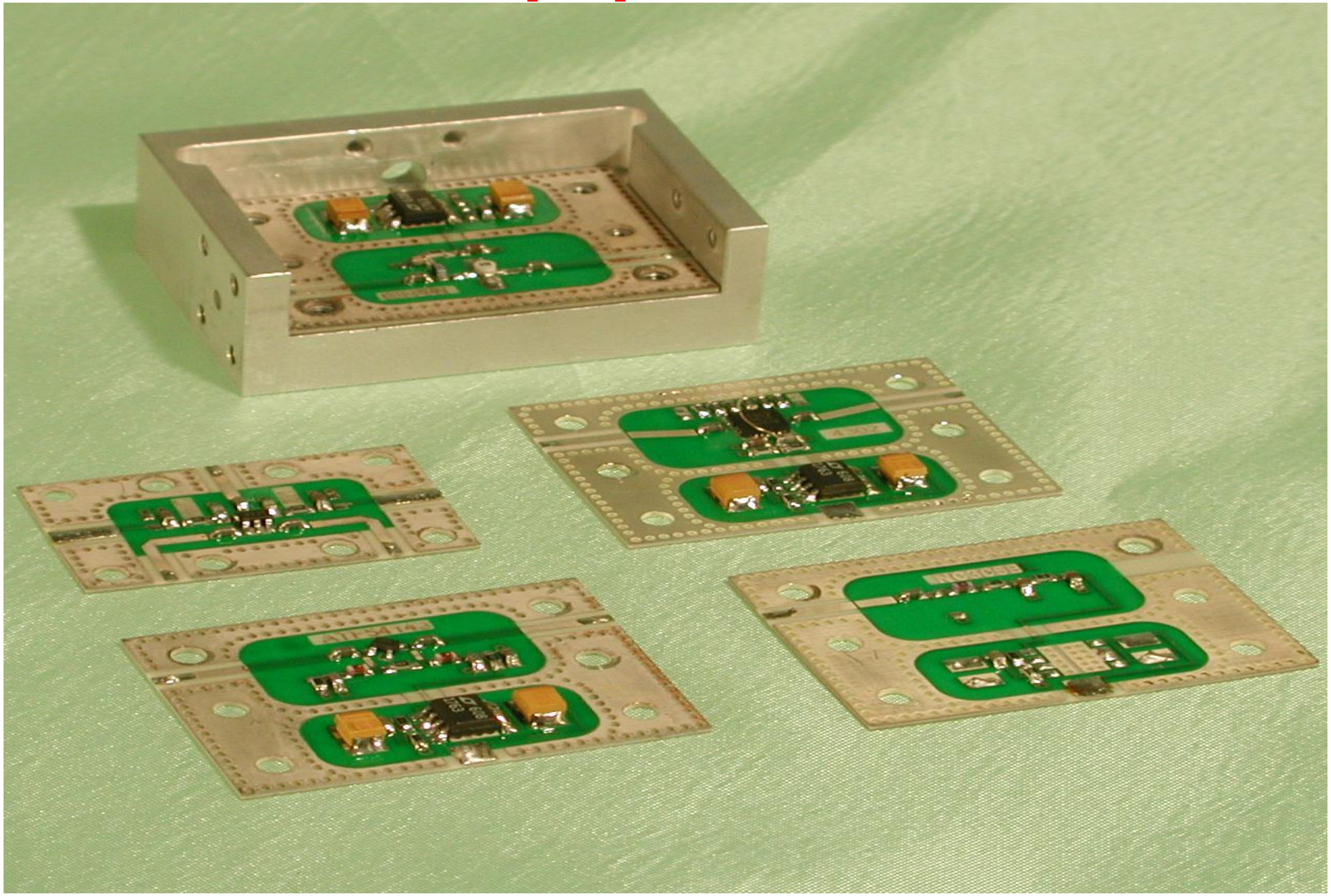
Registration block of the LORD equipment

L×W×H = 420 mm ×320 mm×80 mm,
Weight= 12 kg, Power Supply = 27 V, 60 W

Low noise amplifier for the LORD equipment



E-cards for the LORD equipment

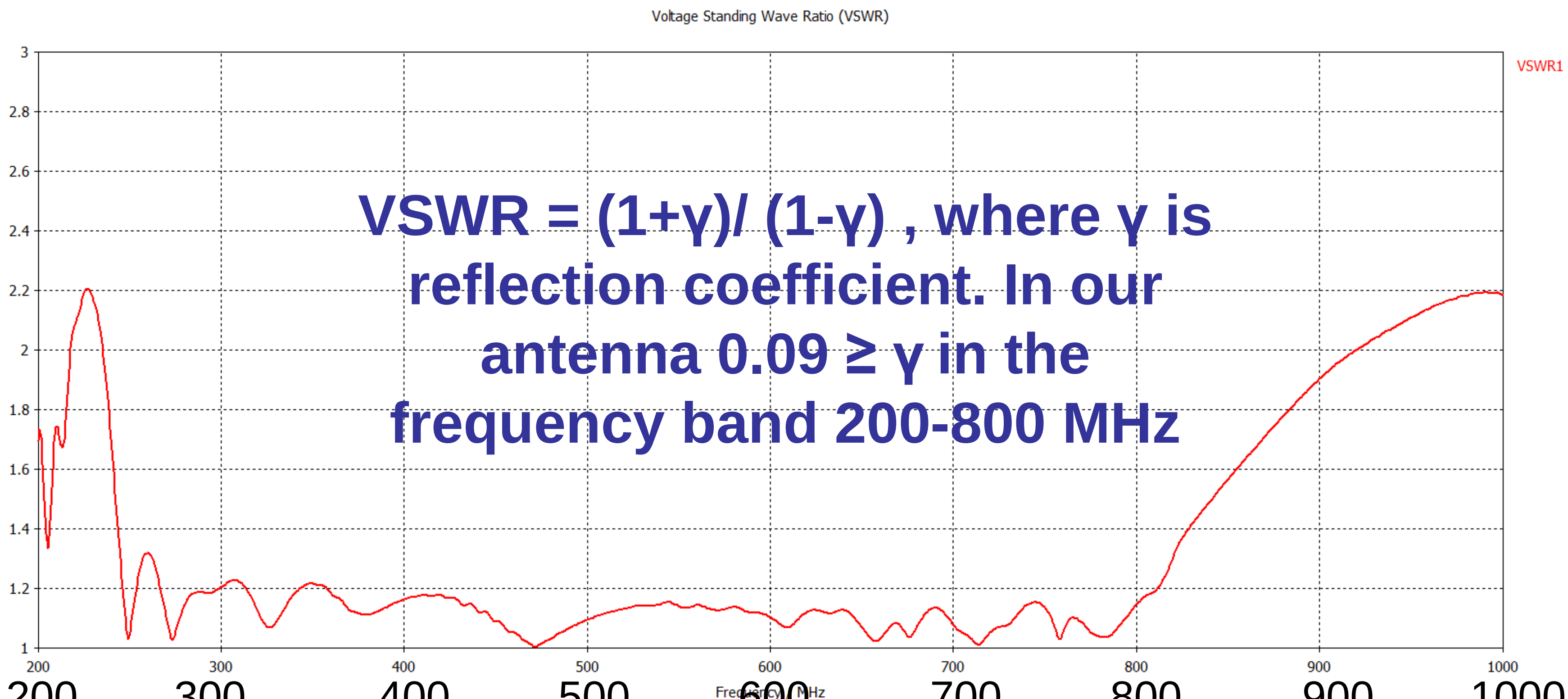


Currently, all electronic components are investigated with a view to develop performance in order to improve the accuracy of determining the physical parameters in the experiment LORD

Main characteristics of broadband (200-800 MHz) antennas

- Voltage Standing Wave Ratio of Antenna (VSWR)
- Directivity diagrams at different frequencies
- Cross polarization directivity diagrams at different frequencies
- 3-D directivity diagrams at different frequencies

Voltage Standing Wave Ratio of Antenna (VSWR)

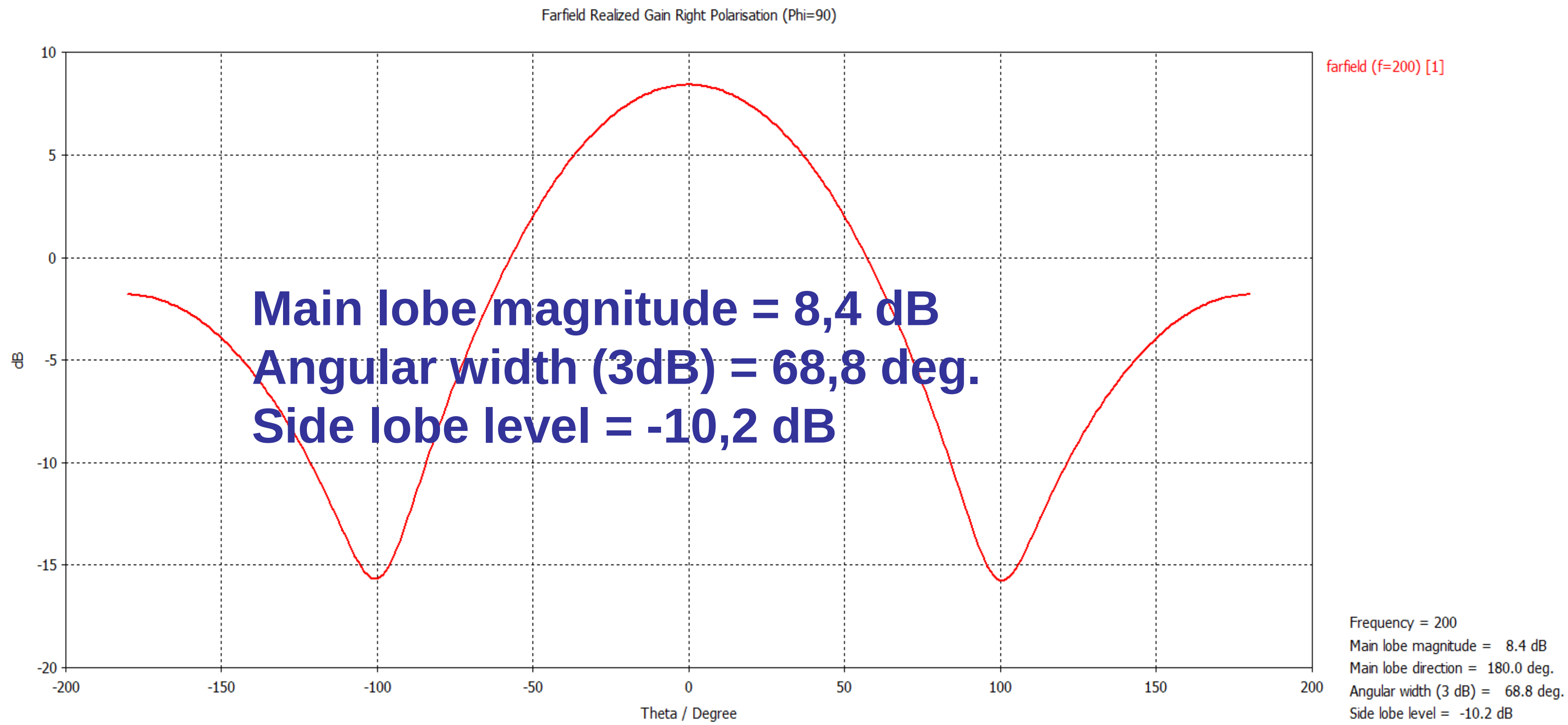


VSWR = (1+γ)/ (1-γ) , where γ is reflection coefficient. In our antenna 0.09 ≥ γ in the frequency band 200-800 MHz

200 300 400 500 600 700 800 900 1000

Frequency (MHz)

Directivity diagram for 200 MHz (Right polarisation)

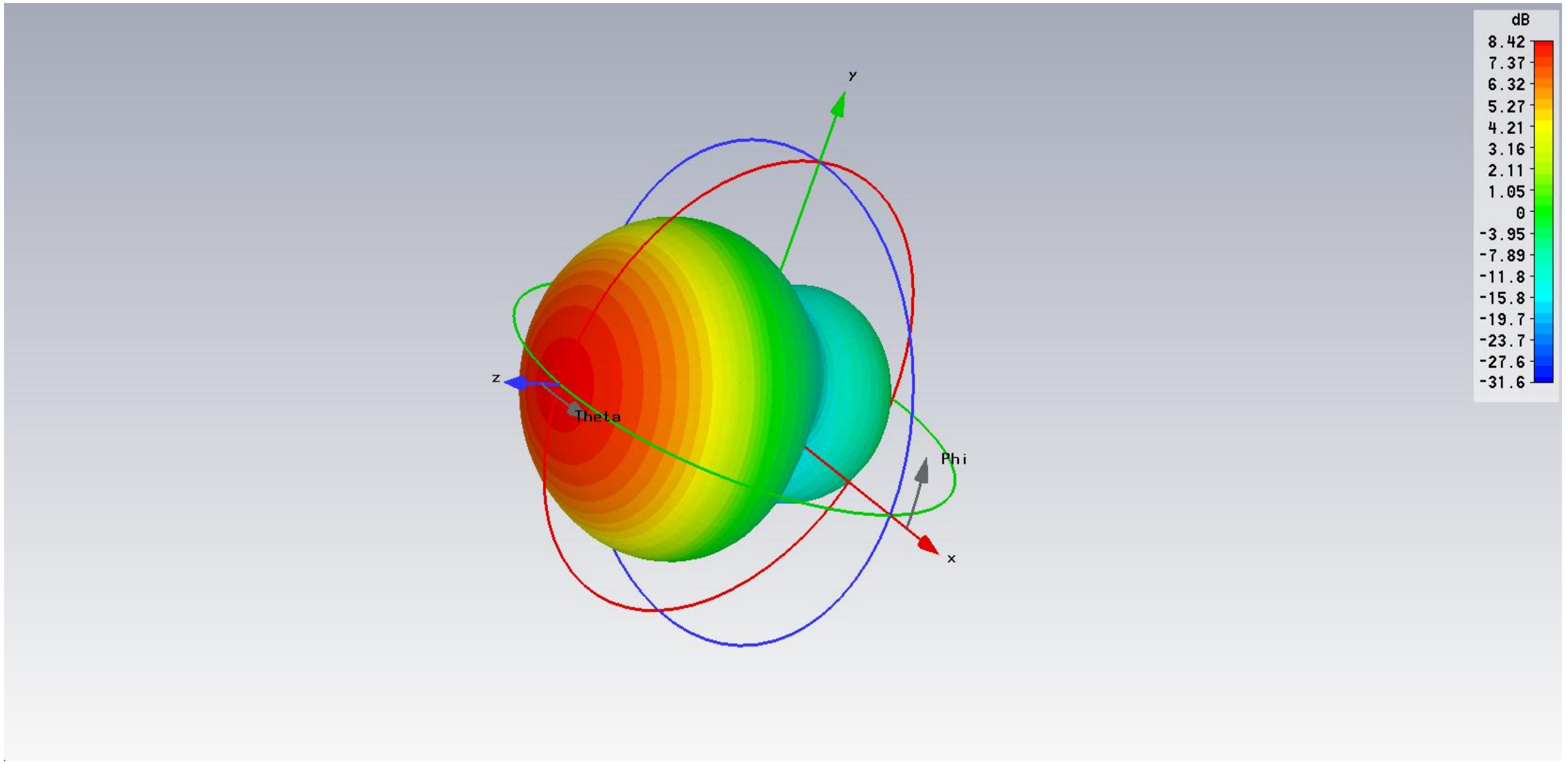


Main lobe magnitude = 8,4 dB
Angular width (3dB) = 68,8 deg.
Side lobe level = -10,2 dB

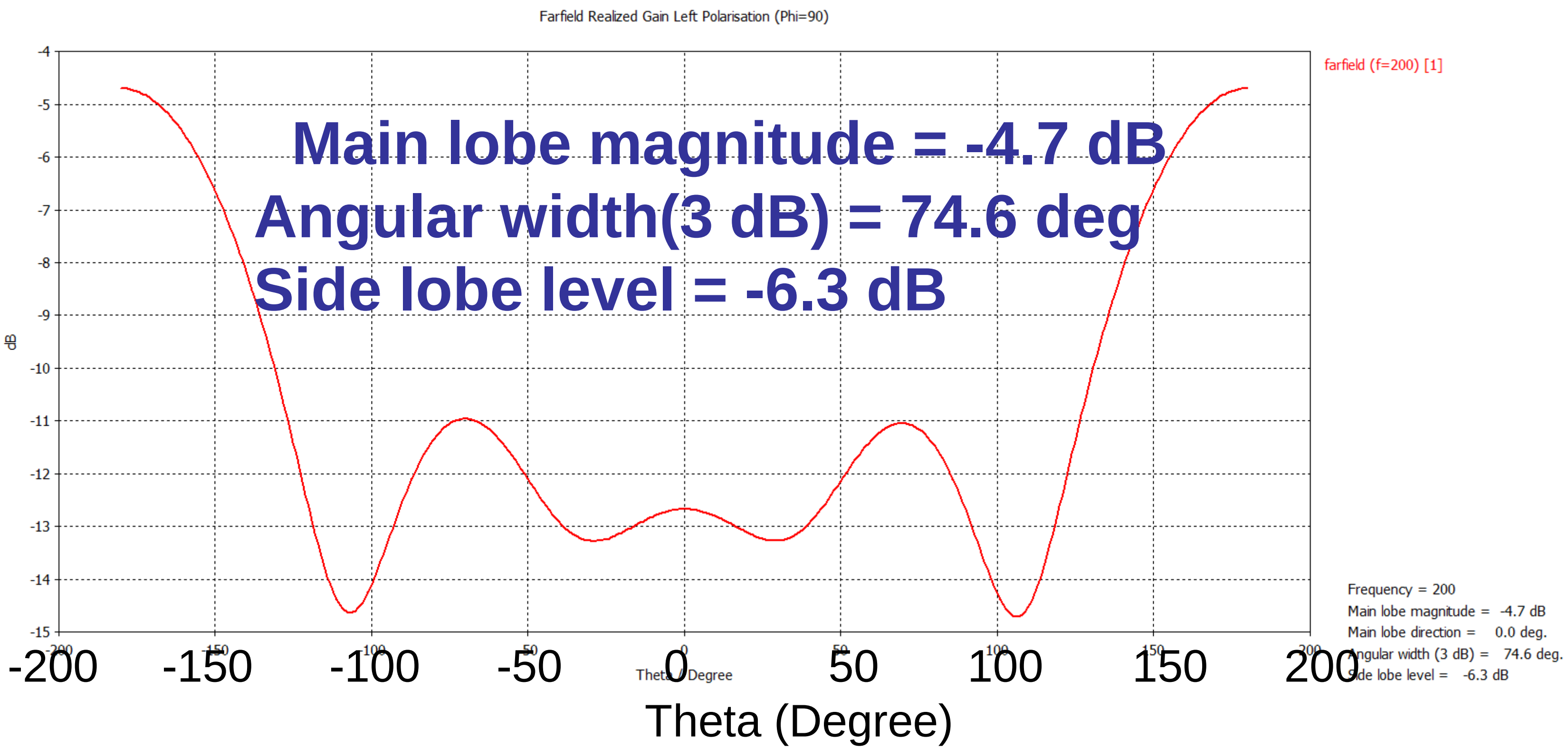
-200 -150 -100 -50 0 50 100 150 200

Theta (Degree)

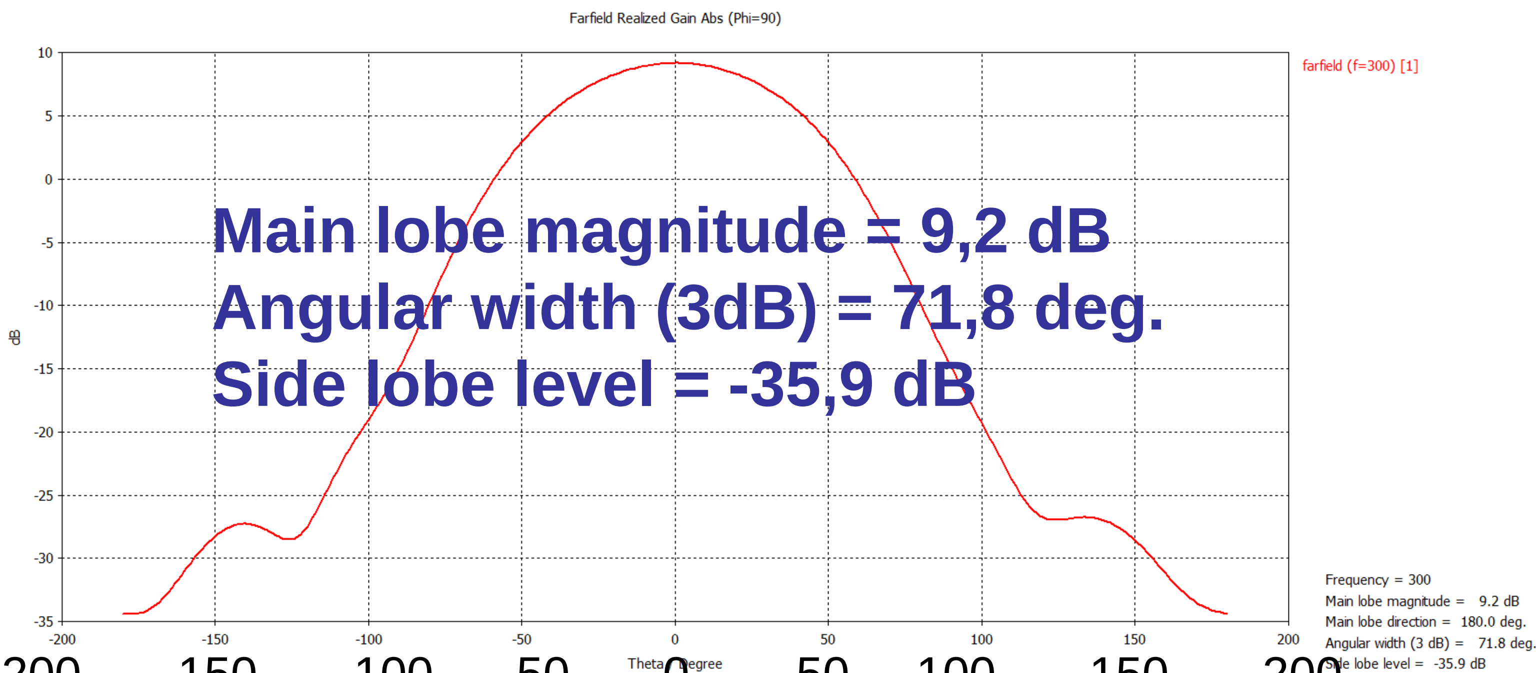
3-D directivity diagram 200MHz



Cross polarization directivity diagram 200 MHz



Directivity diagram 300 MHz (Right polarisation)

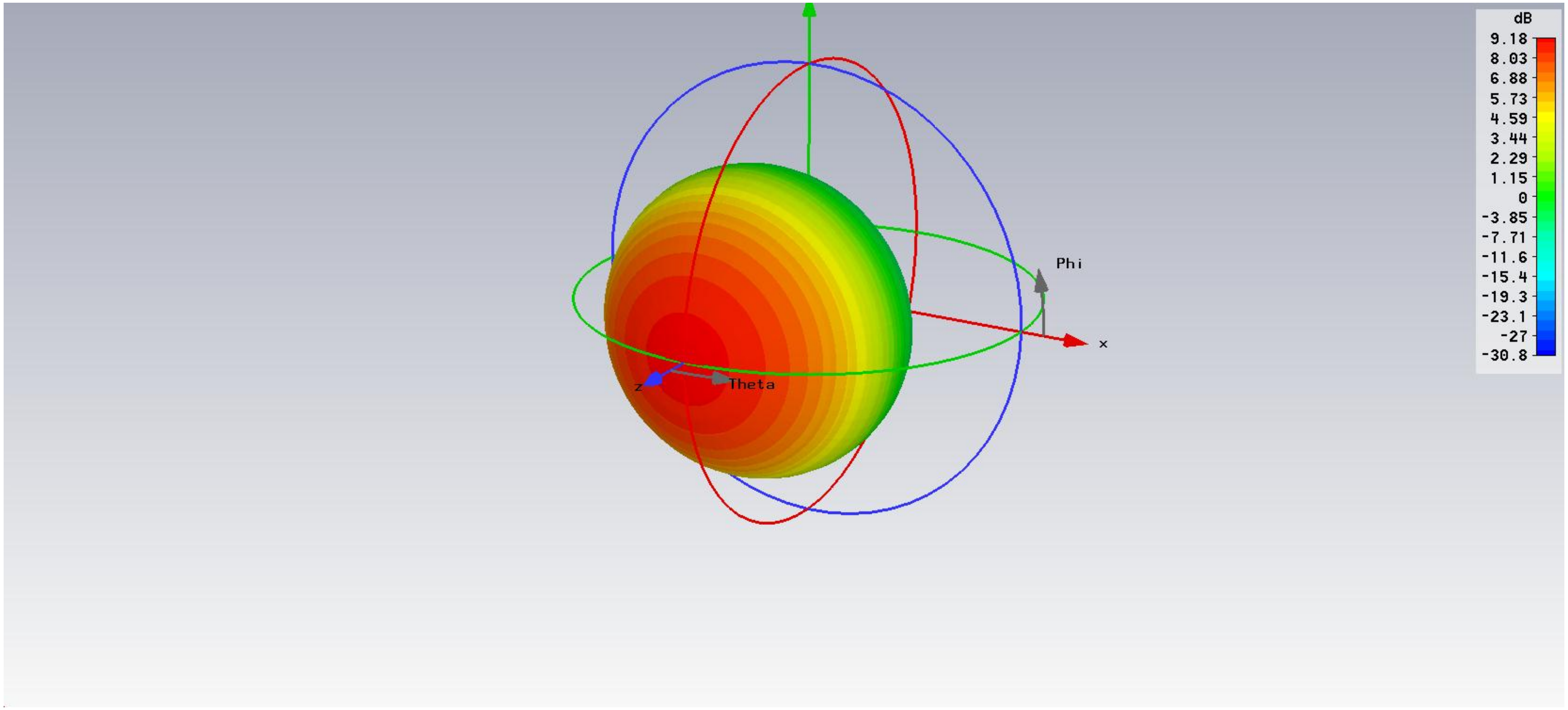


Main lobe magnitude = 9,2 dB
Angular width (3dB) = 71,8 deg.
Side lobe level = -35,9 dB

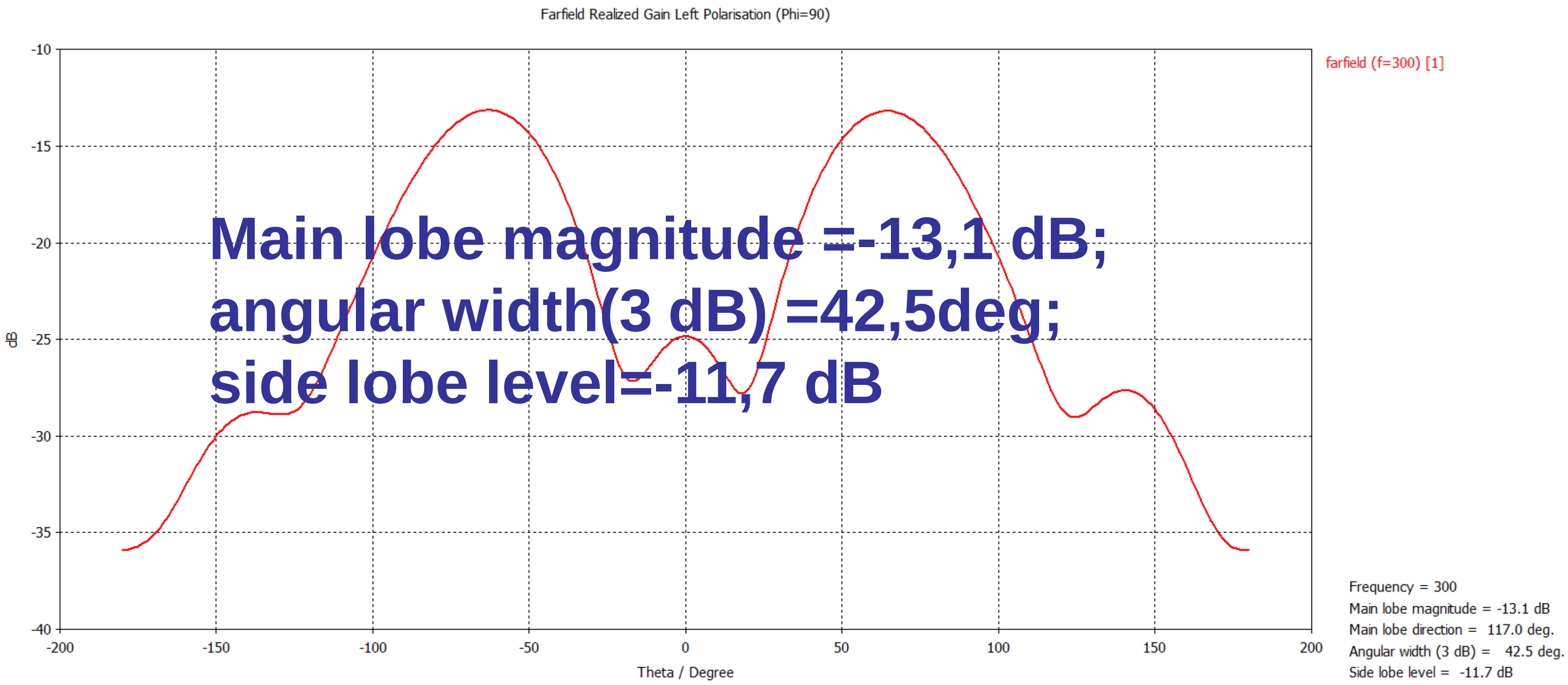
-200 -150 -100 -50 0 50 100 150 200

Theta (Degree)

3-D directivity diagram 300MHz



Cross polarization directivity diagram 300 MHz

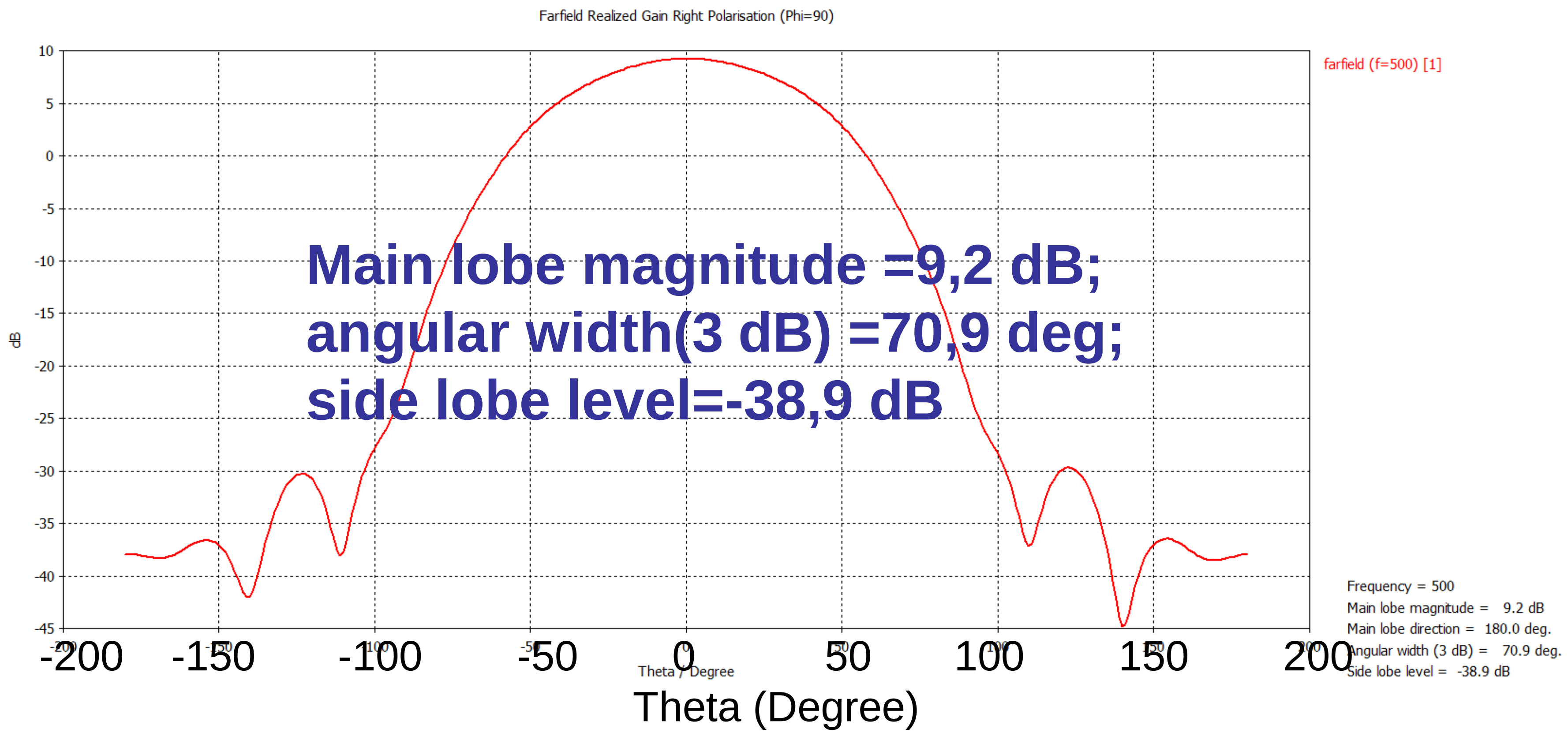


Main lobe magnitude =-13,1 dB;
angular width(3 dB) =42,5deg;
side lobe level=-11,7 dB

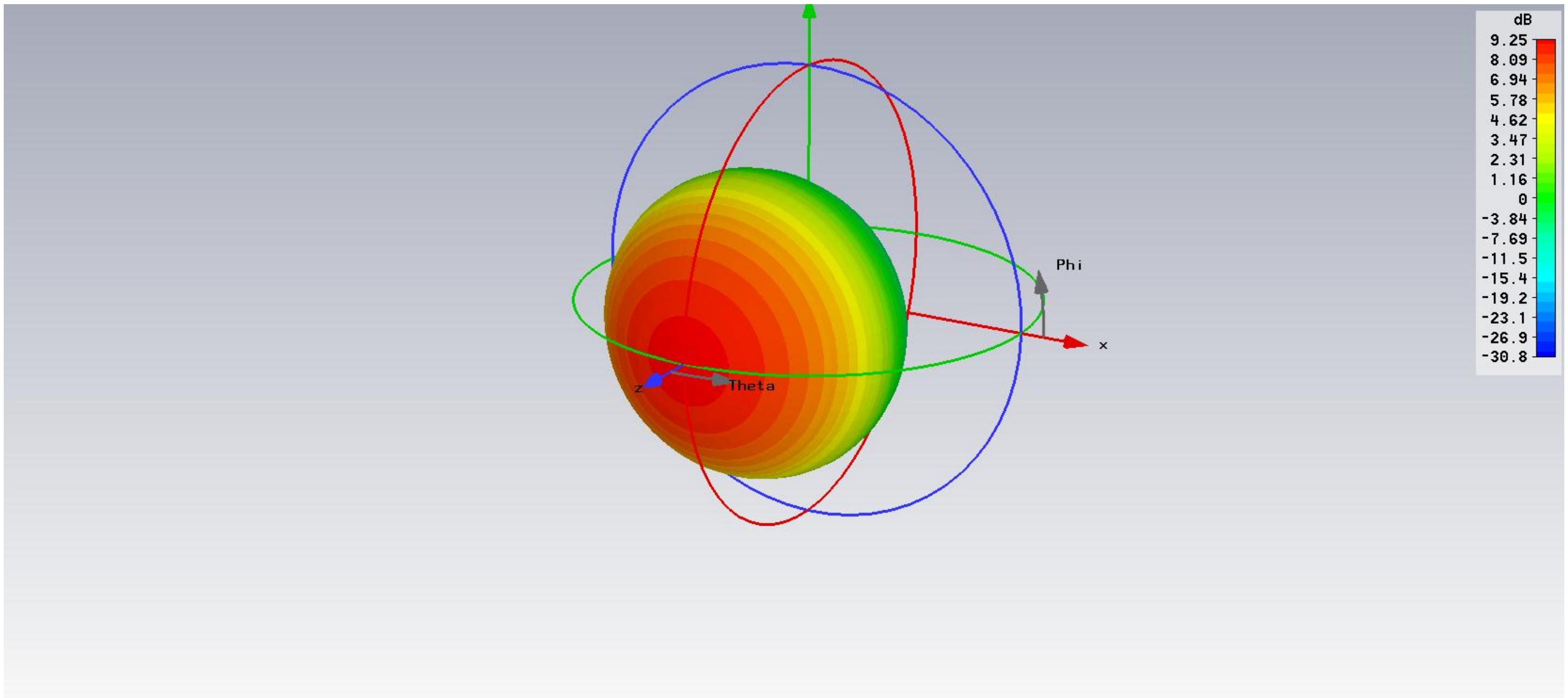
-200 -150 -100 -50 0 50 100 150 200

Theta (Degree)

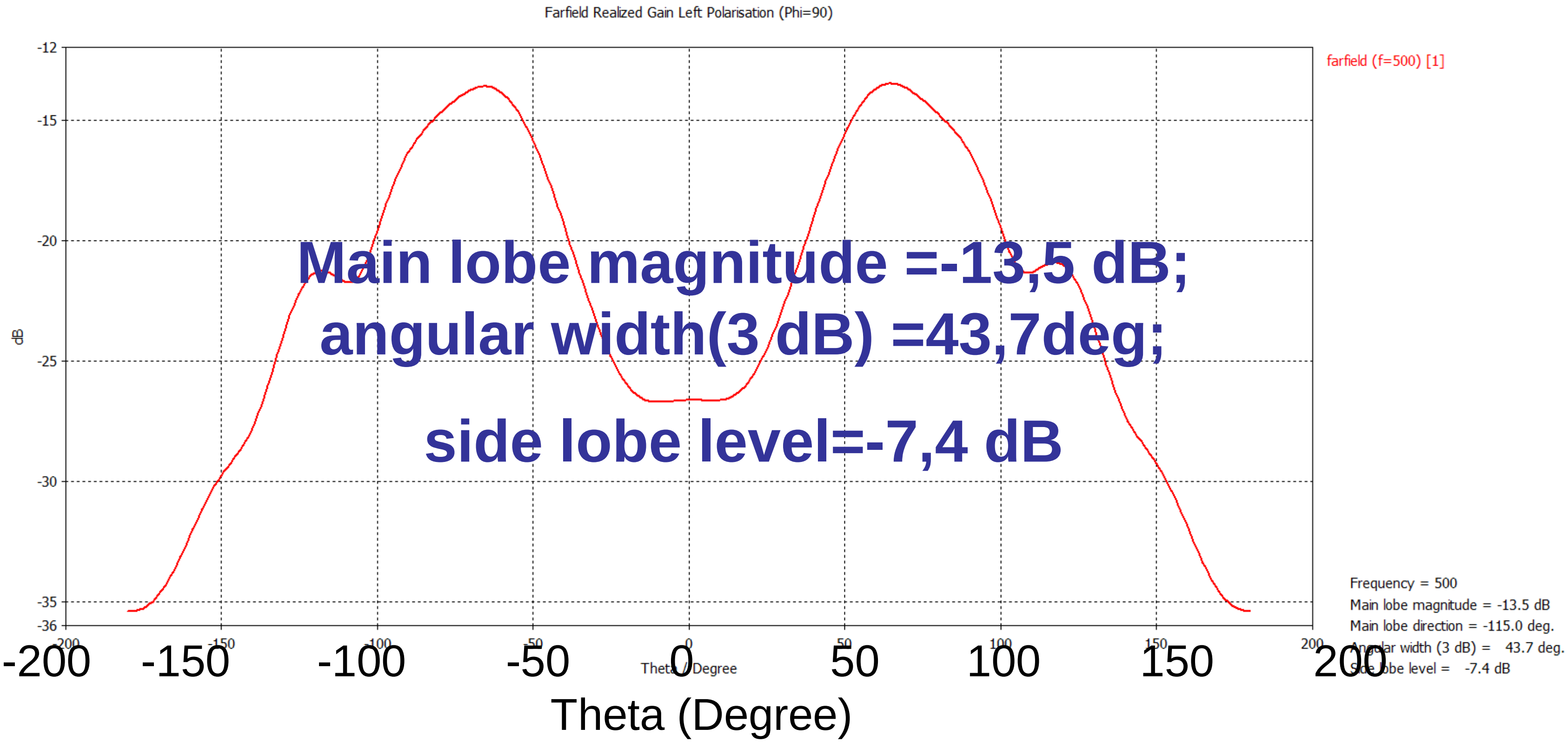
Directivity diagram 500 MHz (Right polarisation)



3-D directivity diagram 500MHz



Cross polarization directivity diagram 500 MHz

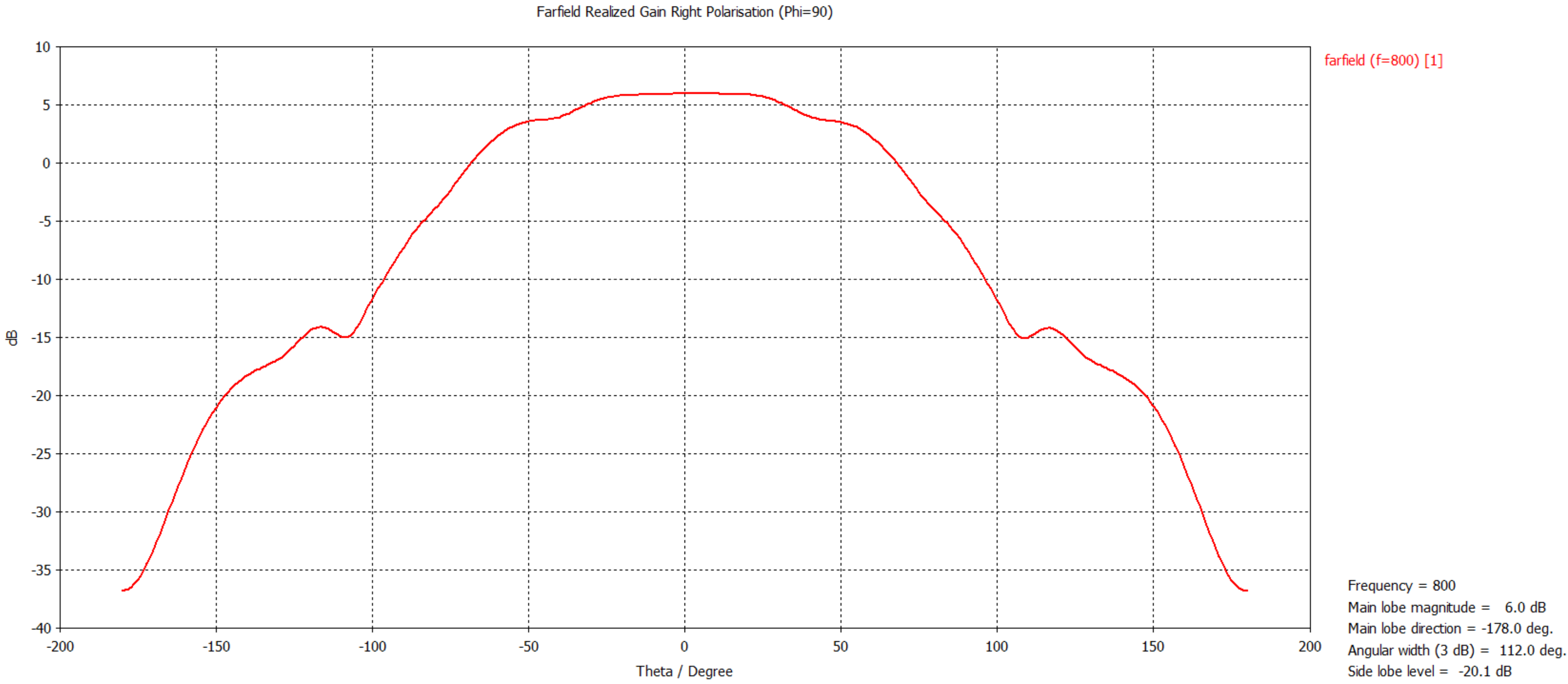


Main lobe magnitude =-13,5 dB; angular width(3 dB) =43,7deg;

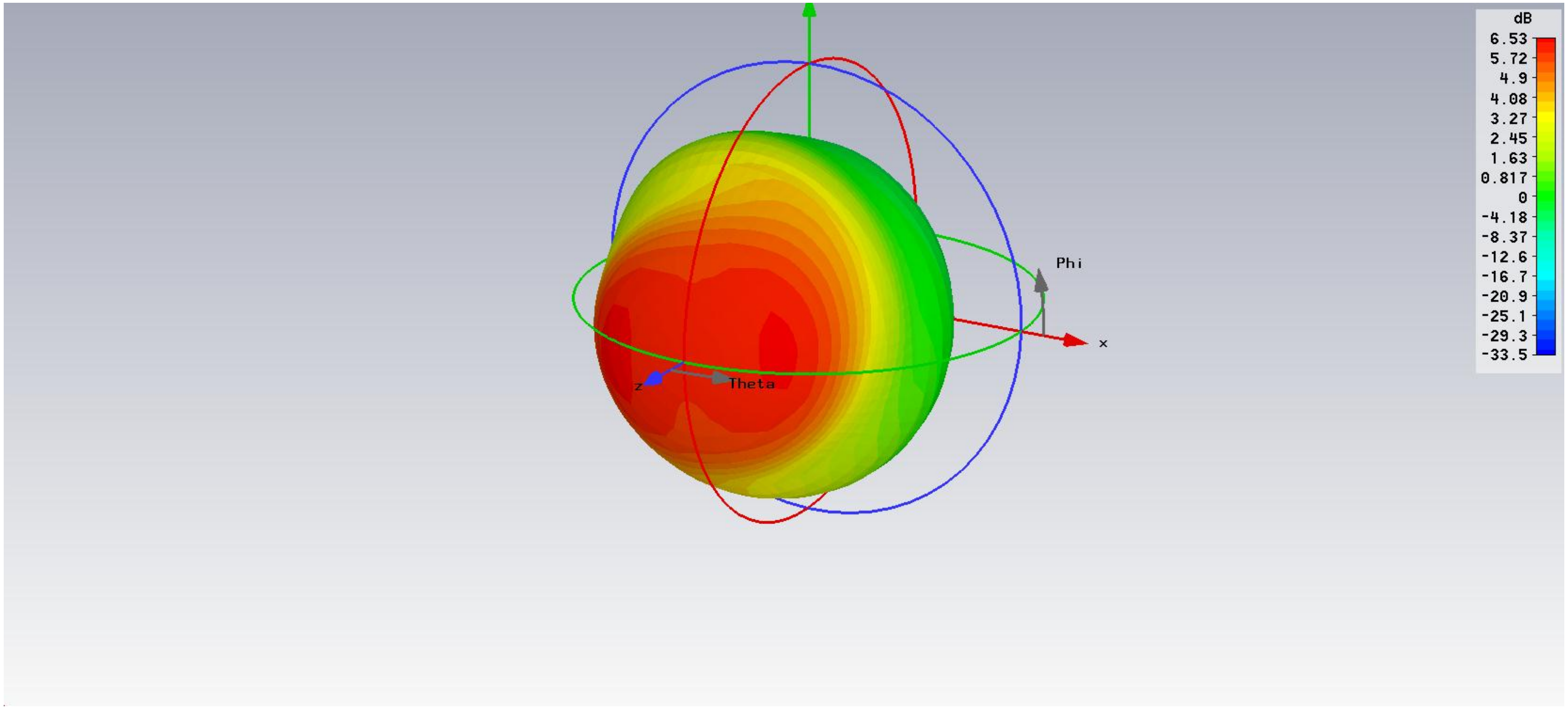
side lobe level=-7,4 dB

Directivity diagram 800 MHz

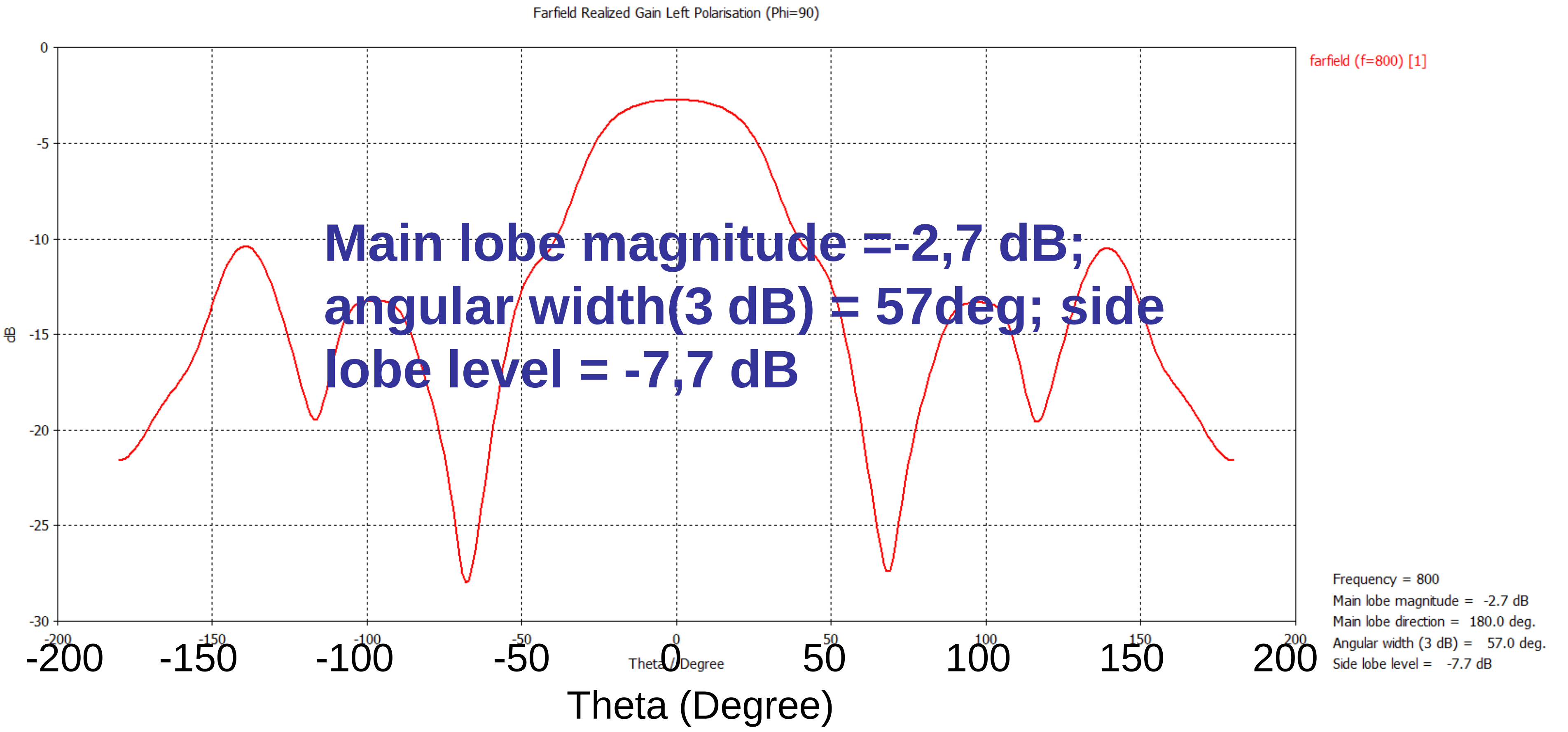
Main lobe magnitude =6 dB; angular width(3 dB) =112 deg; side lobe level=-20,1 dB



3-D directivity diagram 800MHz (Right polarisation)

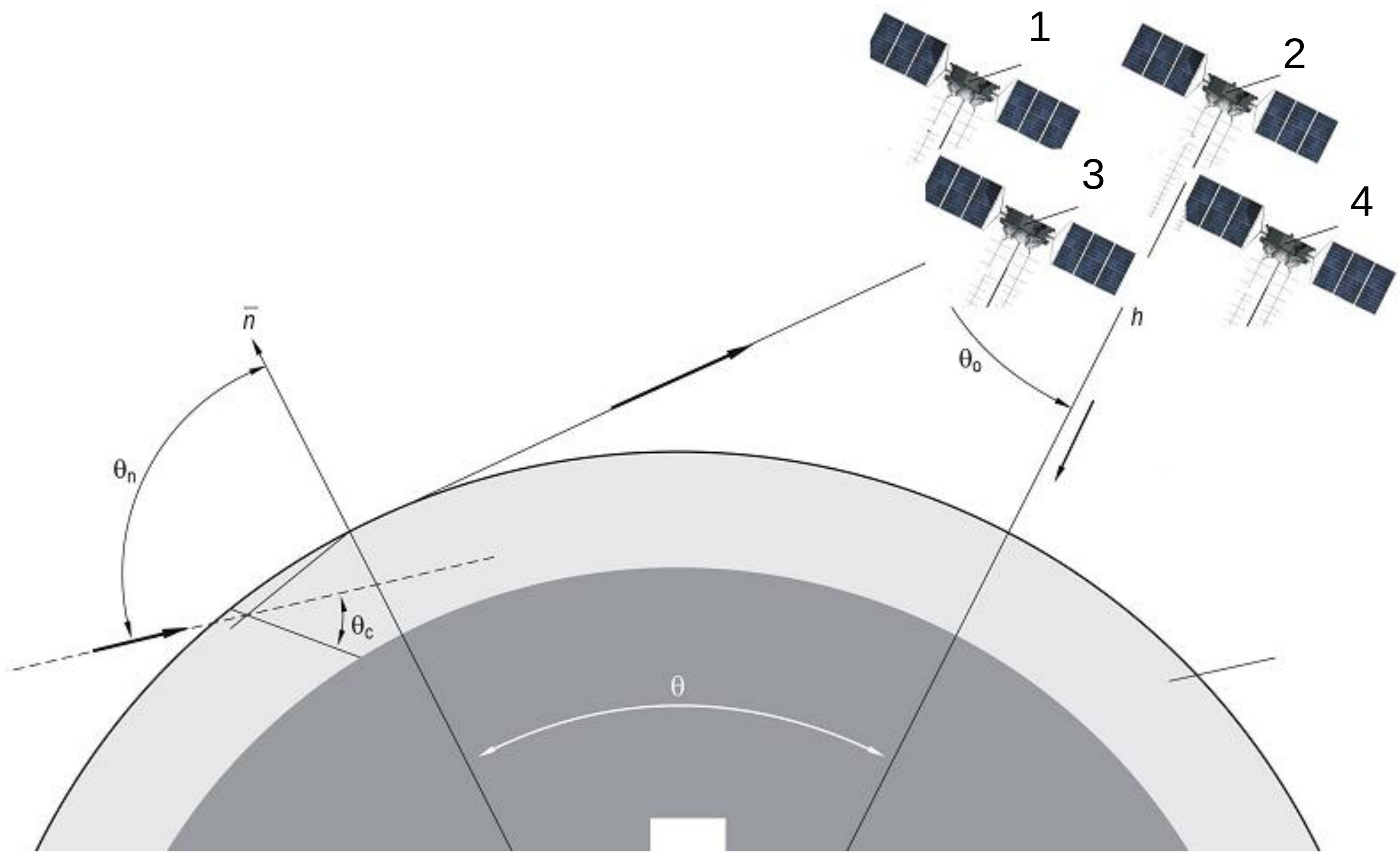


Cross polarization directivity diagram 800 MHz



Some simulation results for an array of circumlunar radio detectors as the LORD

Sketch of four satellite circumlunar array, using LORD detectors



Principles of construction of the lunar satellite system for radio detection of ultrahigh-energy particles

- Minimum number of detectors - 3

- spatial separation - latitude, longitude, altitude

- recording time synchronization

of signals in different detectors allows to localize the source

- maximum distance of separation - 400 km

- minimum distance of separation - 100 km

Why do we need many satellite system radio detection in the context of the LORD experiment? First, the spatial separation of detectors, even at small distances provided synchronization allows us to localize the source of radio emission. This makes it possible to solve the inverse problem of recovering the cascade energy, a large number of measured data being significant. For example, in the case of the four detectors, each event is recorded in 8 channels, so that there are 8 amplitudes and 8 signal spectra in a wide band. In the favorable case, when the scattering is not significant, it becomes also possible to determine the polarization of the electric field in each detector. This allows to discriminate more efficiently the cascade signal from the accidental signals. Second, there is the trivial possibility of using several widely separated and hence independent satellites to increase the aperture of the event logging.

When it comes to choosing the main parameters of the array of lunar satellites, the main they are the height and spacing between them.

As for the spacing in height, it is always due to the inaccuracy of the satellite into orbit.

These discrepancies enough to a spacing in height, sufficient to determine the elevation angle of the beam recorded as antenna spacing in height by several meters provides sufficient accuracy of the elevation.

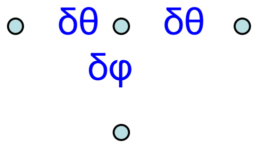


Fig.

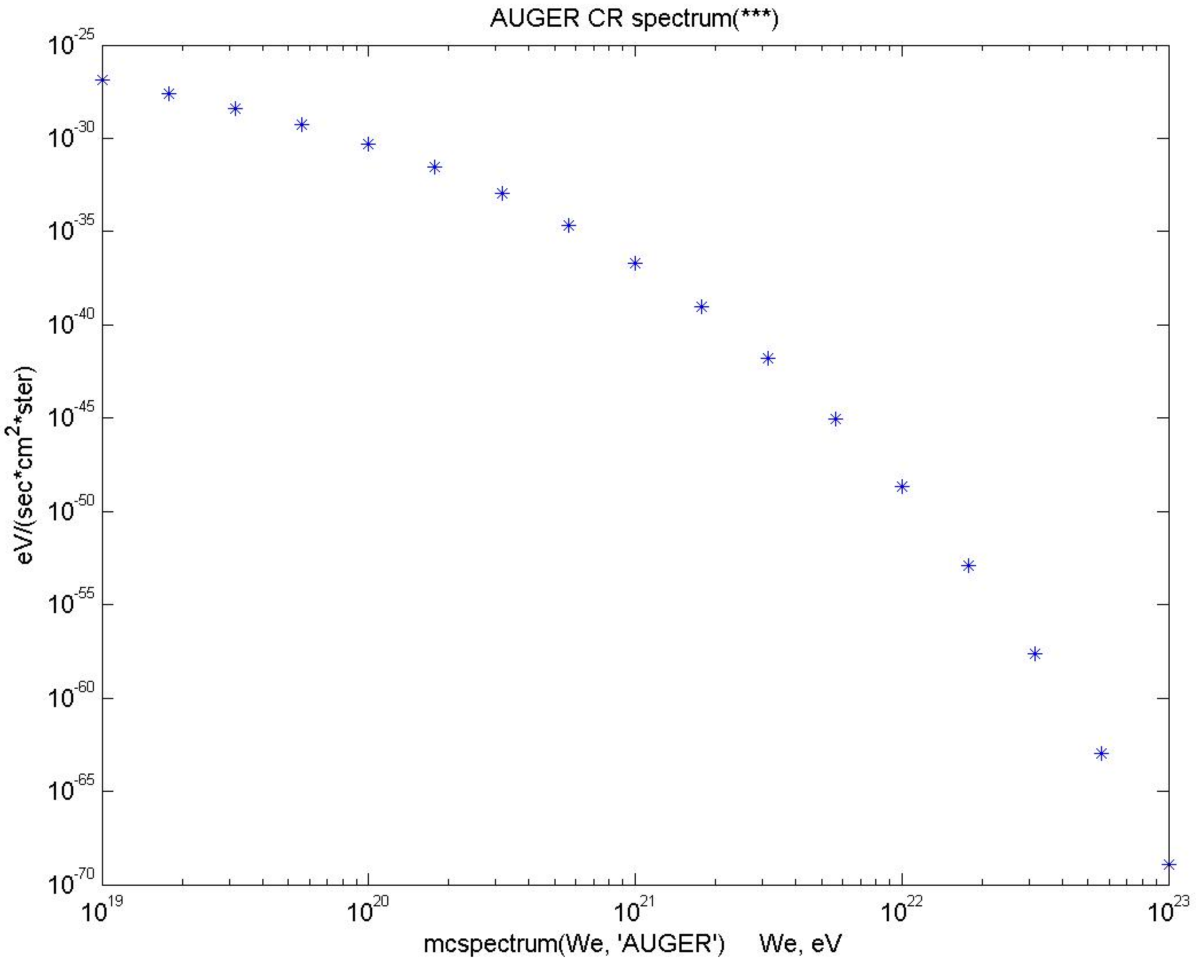
Satellite spacing in latitude and longitude must be such that the «radiation spot " at an altitude satellites was comparable with the distances between satellites, as in this case, all measured at various satellite parameters: amplitude, polarization, angles of escape of radiation from the surface of the moon, time of arrival signals - will be significantly different, allowing us to increase the chances of solving the inverse problem of determining the energy cascade.

For this purpose, we used simulation the registration of Cerenkov radiation from the cascade in an array of four satellites spaced as follows: three satellites are spaced in latitude (at the angle δθ) and one in longitude (at the angle δφ) at the same angular distances (see. Fig.)

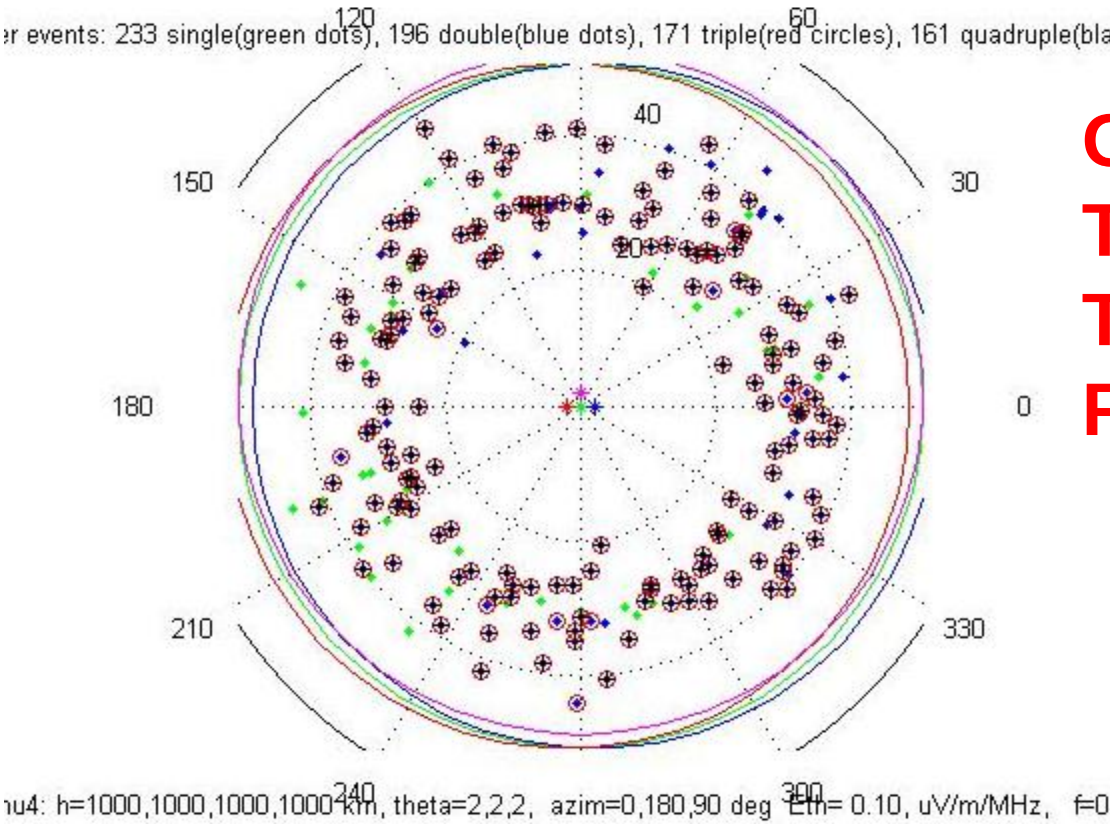
Parameters of radio detector array, used in simulations

Frequency band	**200 – 400 MHz**
Satellite altitudes	**200 – 2000 km**
Latitude and longitude separation	**2 – 15 degrees**
electric field thresholds	**0.1 – 0.2 μV/m MHz**
Exposure time	**1 year**

AUGER CR spectrum, used in simulations



CR registration. Altitude –1000km. Separation – 2 degrees. Threshold – 0.1mkV



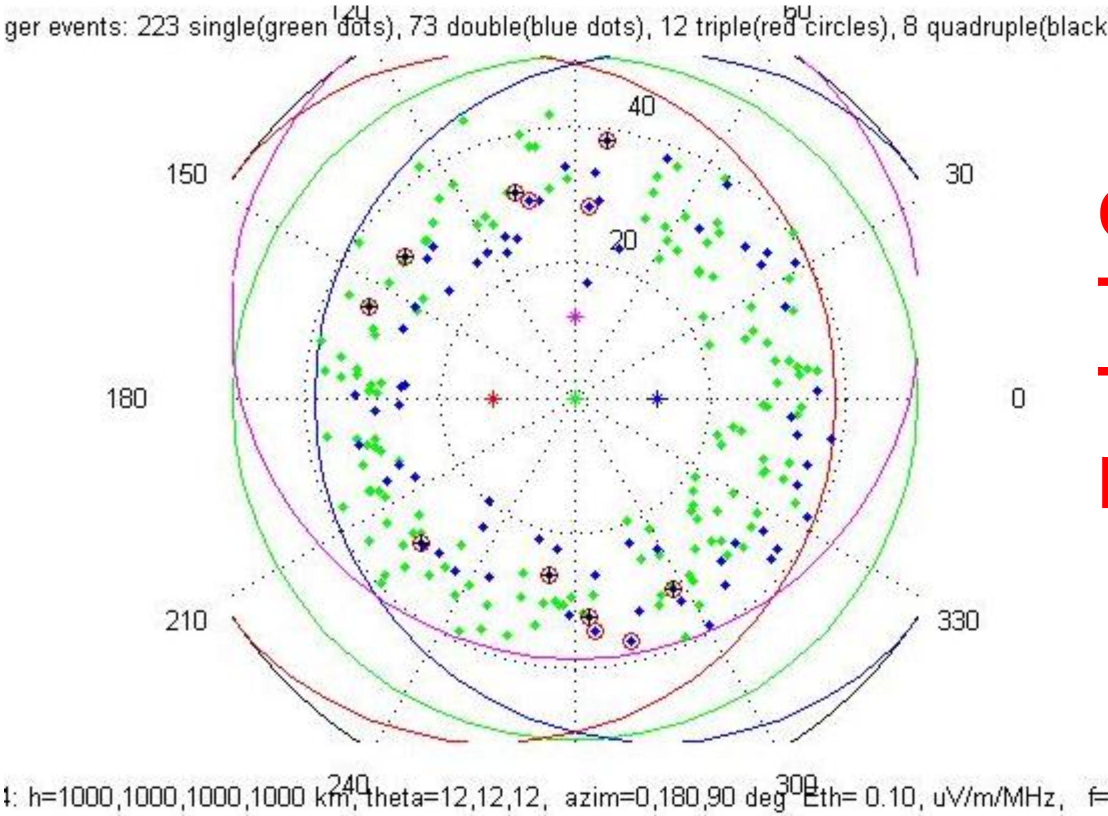
One satellite – 233

Two satellites – 196

Three satellites – 172

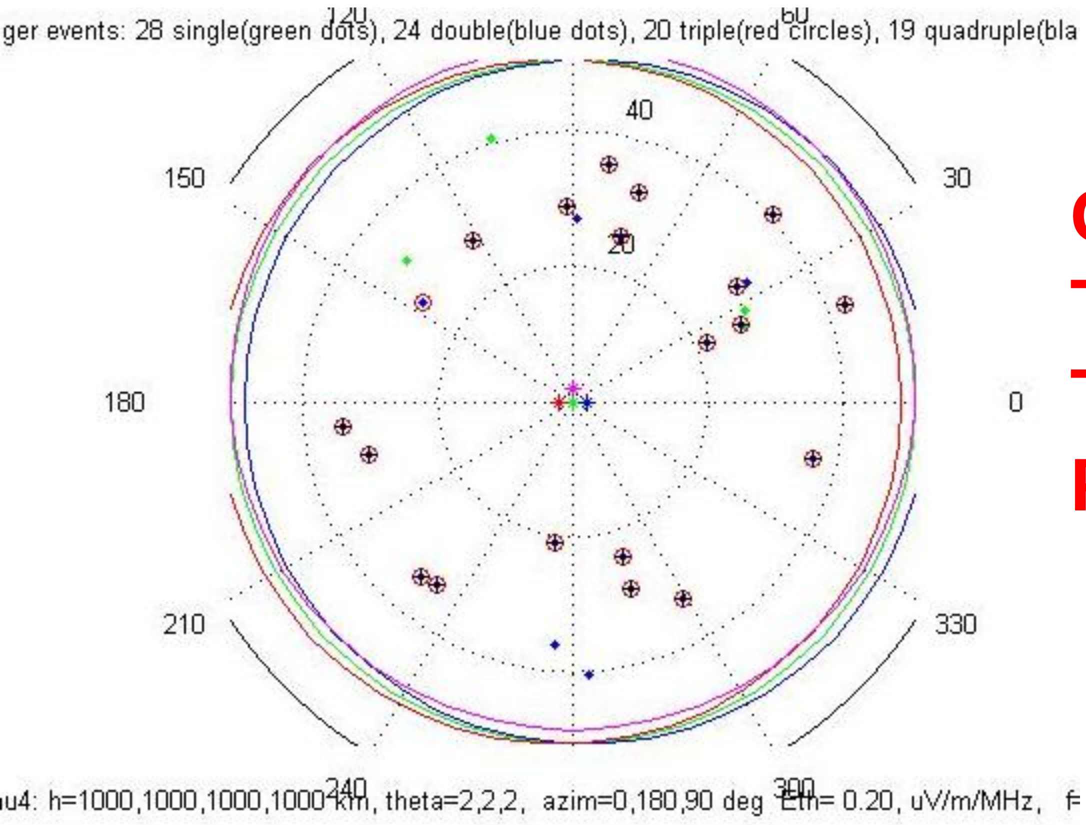
Four satellites – 168

CR registration. Altitude –1000km. Separation – 12 degrees. Threshold – 0.2mkV



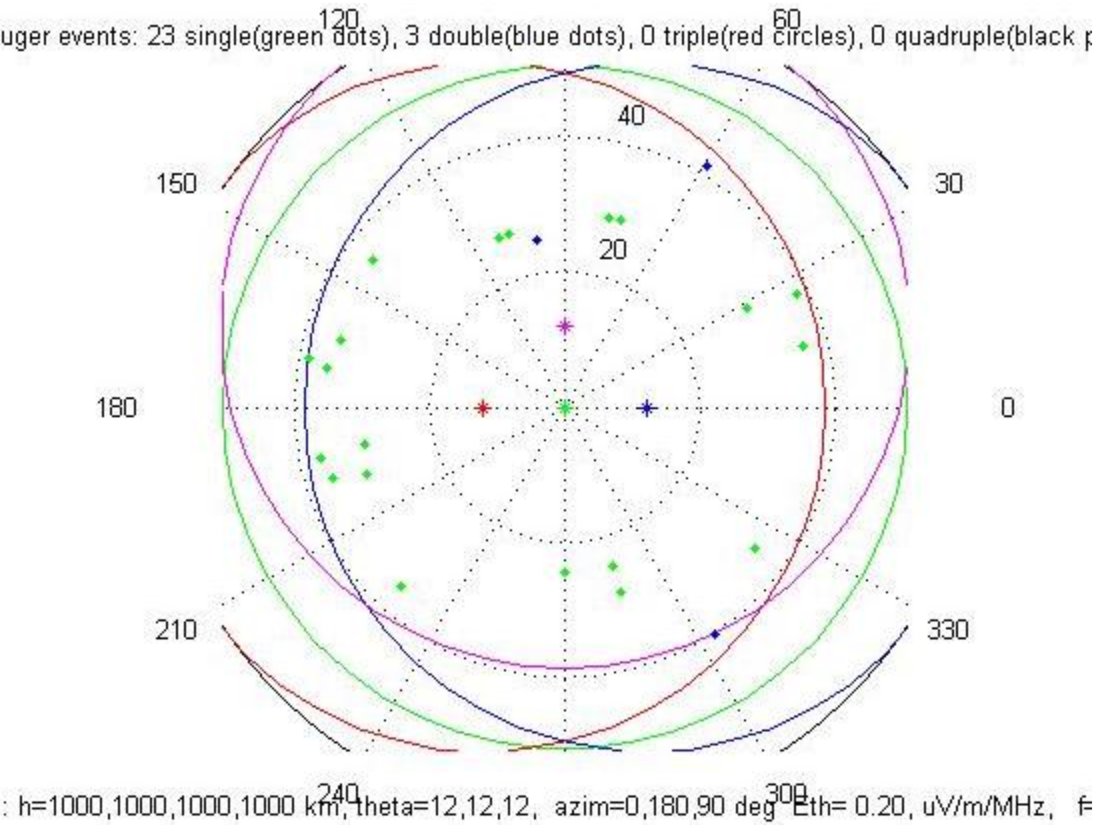
One satellite – 223
Two satellites – 73
Three satellites – 12
Four satellites – 8

CR registration. Altitude –1000km. Separation – 2 degrees. Threshold – 0.2mkV



One satellite – 28
Two satellites – 24
Three satellites – 20
Four satellites – 19

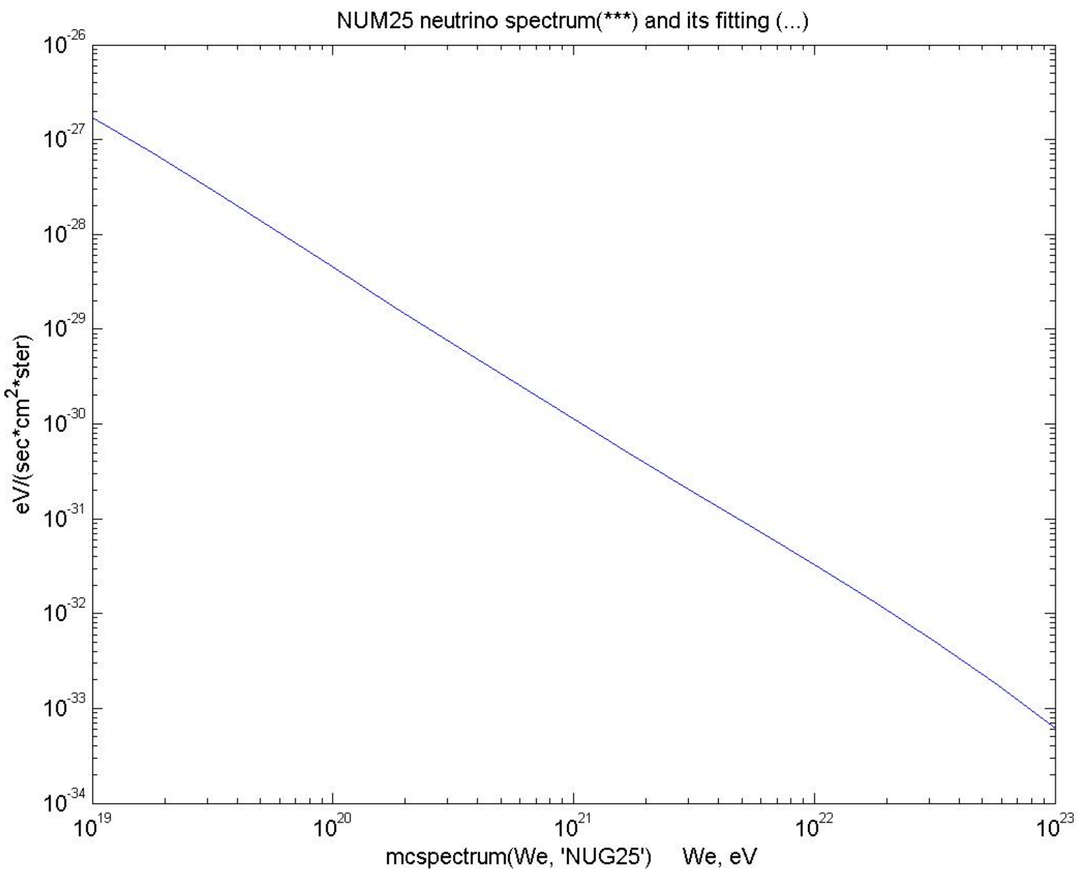
CR registration. Altitude –1000km. Separation – 12 degrees. Threshold – 0.2mkV



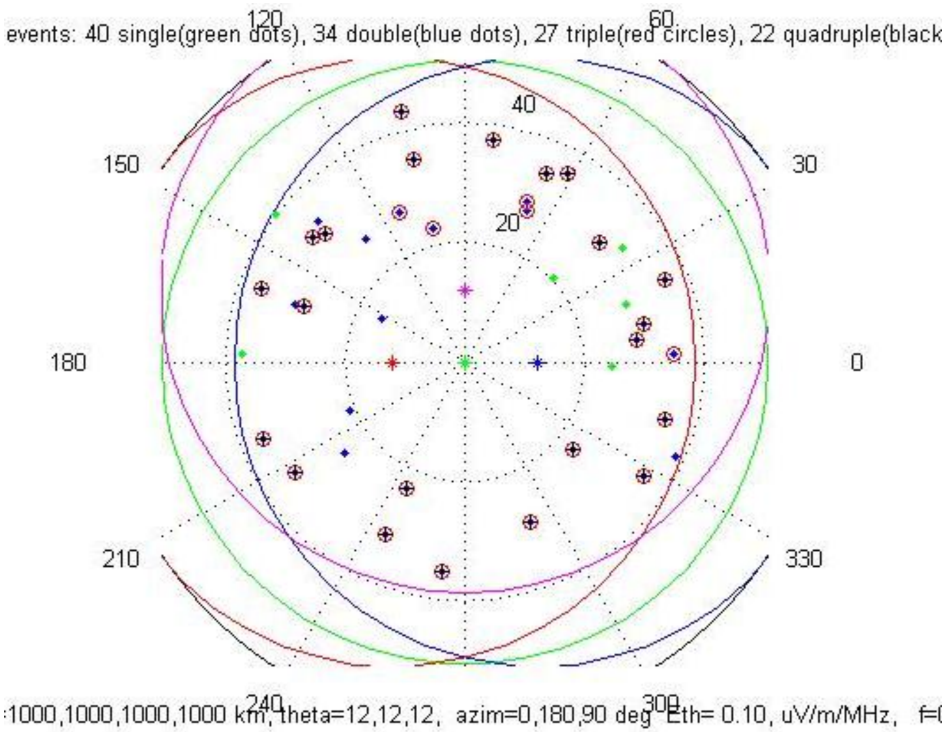
One satellite – 23
Two satellites – 3
Three satellites – 0
Four satellites – 0

We can see that for 4 satellites cosmic ray array (CRA) a large separation of satellites results in fast decreasing array aperture. It means that for separations more than 12 degrees CRA transforms in 4 autonomous LORD detectors, therefore the total aperture of the system of four independent detectors is increased 4-fold. Technical implementation presents no difficulties.

Neutrino spectrum from decay of massive particle with mass 10^{25} ev



Results of joint neutrino event registration by four satellites, having the latitude and longitude difference of 10 degrees



One satellite – 40
Two satellites – 34
Three satellites – 27
Four satellites – 22

$$N_{NS}/N_{CR} = 22/8 \approx 3$$

Interestingly, in the case of registration of neutrinos from the decay of superheavy particles with masses 10^{25} eV, a significant separation of satellites at 12 degrees of latitude does not lead to a marked decrease in statistics (losses 45%, for CR – 97%) as comparing with one detector.

This means that an array (NA) of radio detectors at a large spatial separation of detectors about 15 degrees of latitude is mainly to detect neutrinos.

Further simulations aiming the detection of neutrino

Separation 13 degrees,

altitude 1200 km $N_{NS}/N_{CR} = 19/4 \approx 4.8$

Separation 13 degrees,

altitude 1500 km $N_{NS}/N_{CR} = 5/1=5$

Separation 13 degrees,

altitude 1700 km $N_{NS}/N_{CR} = 15/2.5 \approx 6$

Separation 13 degrees,

altitude 1800 km $N_{NS}/N_{CR} = 15/2 \approx 7.5$

Further simulations aiming the detection of neutrino

Separation 15 degrees,
altitude 500 km $N_{NS}/N_{CR} = 4/0$

Separation 14 degrees,
altitude 500 km $N_{NS}/N_{CR} = 4/0$

Separation 13 degrees,
altitude 500 km $N_{NS}/N_{CR} = 9/1$

Separation 13 degrees,
altitude 700 km $N_{NS}/N_{CR} = 14/1.5 = 9$

Separation 13 degrees,
altitude 800 km $N_{NS}/N_{CR} = 7/1 \approx 7$

Thus, the results of modeling cosmic ray and neutrino multi-satellite system (CRA and NA) (small terrestrial analog arrays) has shown that on the one hand it is possible to create a radio detector, which registers neutrinos with a small admixture of cosmic rays (NA), and on the other hand – the cosmic rays with small admixture of neutrinos (CRA). CRA (4 satellites) aperture exceeds LORD aperture 4-fold. NA aperture is smaller about two times than LORD aperture, but there is no problem of discrimination CR's and neutrinos. Maximum CRA (24 satellites) aperture may exceed LORD aperture 24-fold. It is impossible

to realize array for CR with such aperture in future on the Earth.

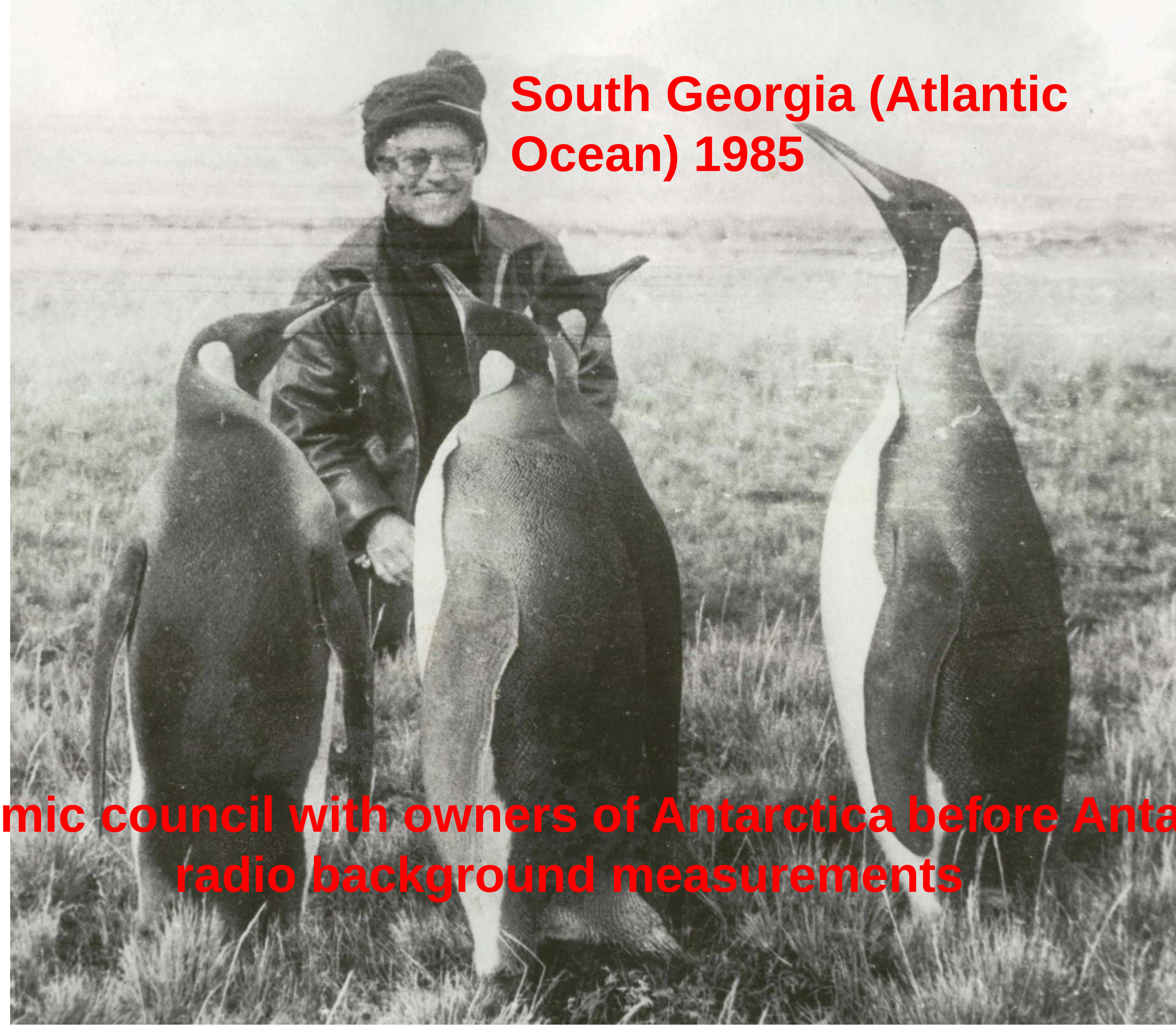
Conclusion

- Main electronic modules and antennas of the LORD are elaborated and now under construction

- Simulation results for circumlunar cosmic ray array (CRA) show the possibility of aperture increasing for cosmic ray registration proportionally the number of satellites, neutrino events being background.

- It is possible to realize neutrino array (NA) with small background of cosmic ray events, its aperture being smaller than LORD's (1 satellite) one.

Thank you for attention



South Georgia (Atlantic Ocean) 1985

Academic council with owners of Antarctica before Antarctic radio background measurements

Background Processes for Radio Antarctic Muon and Neutrino Detector (RAMAND)

A.F. Bogomolov, V.V. Bogorodsky, G.A. Gusev et al.

Proc. 20 ICRC, v. 6, p.472 (1987)

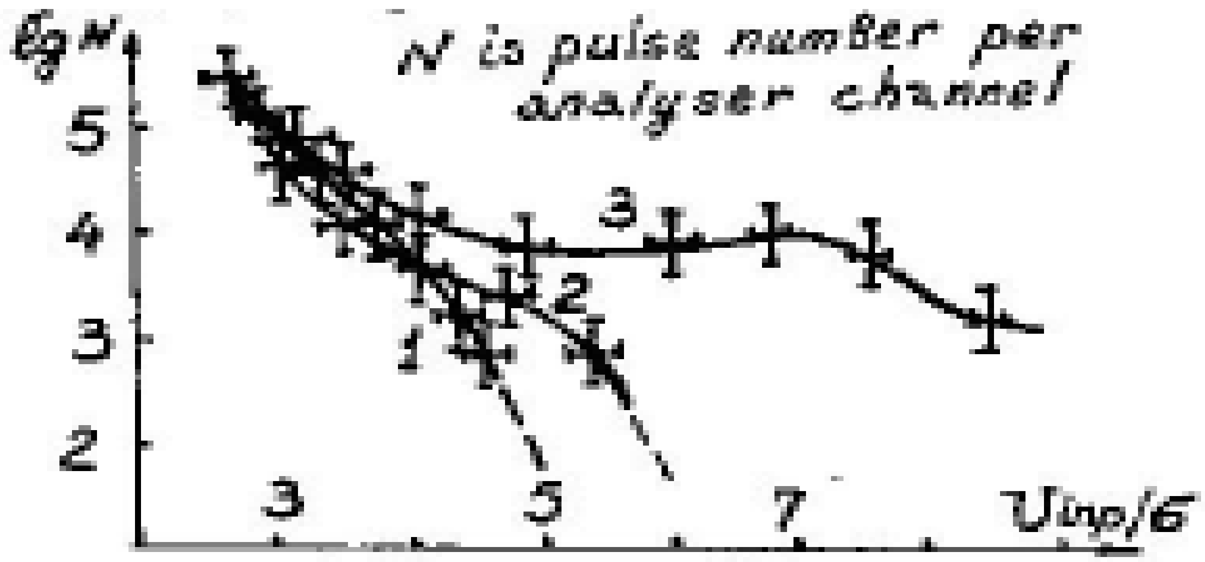


Fig.3. Amplitude spectra of pulses with durations $\tau \geq 6$ ns

The curve 1 corresponds to radio pulse background spectrum at the Russian Vostok station, the curve 2 – at the Mirnii station (20 km from the cost) during good whether, the curve 3 – at the Mirnii during storm (23 m/sec). Here the σ is thermal noise rms for temperature about 3000ºC.