SPACE BASED RADAR TO OBSERVE SPACE DEBRIS

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Abstract

Space debris of 1÷3mm size is known to be hazardous for astronauts and space vehicles. At the same time the possibility to notice such objects by ground based optical and radar devices in the nearest future is rather problematic. Here we propose an idea of space radar for obsevation of cicumterrestrial space debris. The radar works in short vawe part of millimetre band, which is mostly suitable for this purpose. The radar provides detecting and tracking of 1mm size objects within 40000m^2 area. The radar antenna is Phased Array Antenna with 2m diameter. The radar's weight is about 100kg, the consumed power - 2.5kW.

The problem analyse and possibilities of its solving

Contamination of cicumterrestrial space with carrier rockets elements and collapsing satellites debris creates danger for space objects functioning, especially inhabited ones.

Debris larger than 1÷2 centimetres in size are potentially hazardous for a space vehicle protected with a screen, debris with dimensions of 0.1÷0.3 centimetres - for astronauts in a space suit.

Altitude statistic distribution of elements larger than 10 centimetres in size is well known /1/. Total number of elements is 7000, about 6000 elements are on orbits up to 2000 kilometres high /3/.

The altitude distribution of small debris (smaller than 10 centimetres). is unknown, however assuming that mechanism of particles interaction with exponentially descenting atmosphere is the same one for all of then, we can evalute the debris density supposing that their arbitrary number at some altitude is uniquely connected with ballistic life time (duration) of their at this altitude. Total amount of debris may be valued as 3.5 millions, moreover, most of them (not less than 99%) are of 0.1-1 centimetres size. Nearby 1 ÷ 2% of them are on the altitude 500÷600km, the rest are on more higher orbits (Fig.1).

Space navigation especially if the density of debris is very high, is connected with the necessity to obtain distribution and precise trajectory date of small objects.

So, two tasks of observation of small objects are expedient:

- the estimation of statistic distribution;
- make up catalogue of all dangerous elements with precision trajectory parameters.

Accoding to present models concerning 1 mm size elements distribution up to ~1000km high , in order to notice 1 particle per 24 hour, and to obtain enought measurements in a short time, it is necessary to observe a zone of 40000m^2 area.

Three main types of sensors for observing the space debris are known now:

- contact sensors (mechanical screens) based on satellites;
- ground or space based optical sensors;
- grand based radar means.

Small covered area and limited possibility of detected objects tracking, are disadvantagis of mechanical screens. Observation time necessary to robtain representative statistic sample is comperable with the time of changing of elements space distribution density.

ALTITUDE DISTRIBUTION OF OBSERVED SPACE OBJECTS

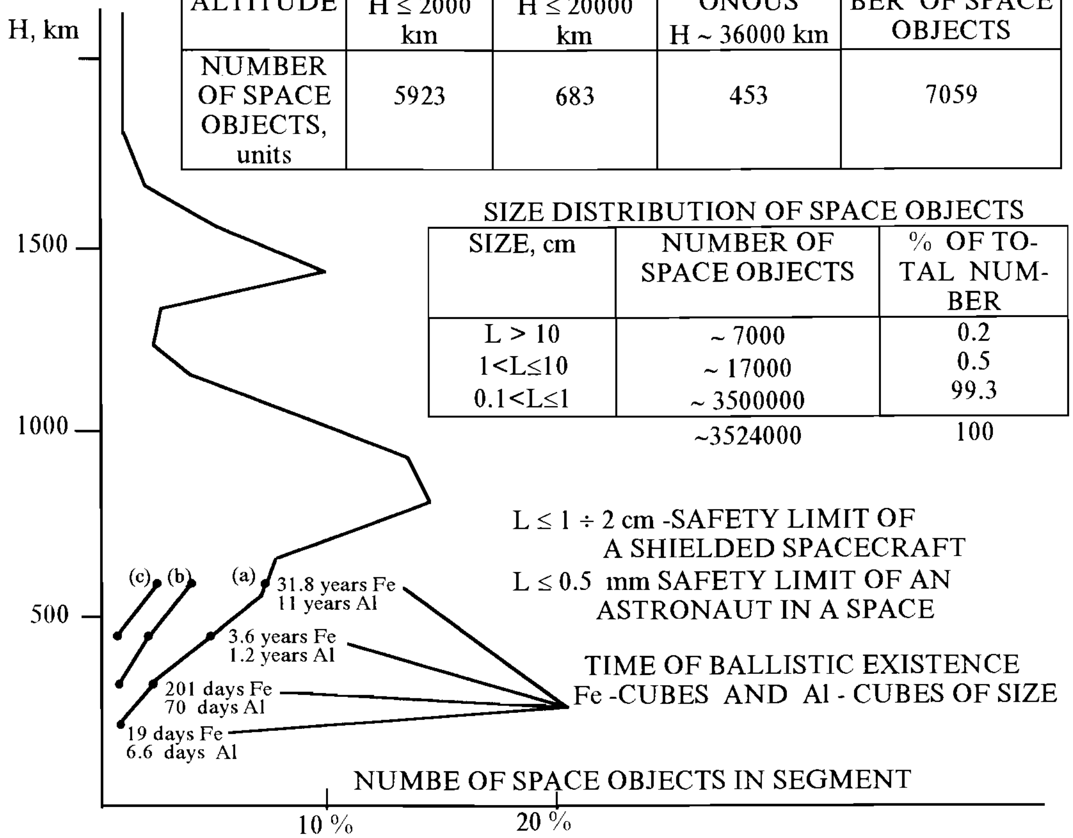
ORBITAL ALTITUDE	LOW $H \leq 2000$ km	MIDDLE $H \leq 20000$ km	GEOSYNHRONOUS $H \sim 36000$ km	TOTAL NUMBER OF SPACE OBJECTS
NUMBER OF SPACE OBJECTS, units	5923	683	453	7059

SIZE DISTRIBUTION OF SPACE OBJECTS

SIZE, cm	NUMBER OF SPACE OBJECTS	% OF TOTAL NUMBER
$L > 10$	~ 7000	0.2
$1<L\leq10$	~ 17000	0.5
$0.1<L\leq1$	~ 3500000	99.3
	~3524000	100

$L \leq 1 \div 2$ cm -SAFETY LIMIT OF A SHIELDED SPACECRAFT

$L \leq 0.5$ mm SAFETY LIMIT OF AN ASTRONAUT IN A SPACE



		10 %	20 %
(a)	L>10 cm -	600	1200
(b)	1 cm< L≤10 cm -	1400	2800
(c)	0.1 cm < L≤ 1 cm -	290000	580000

Fig. 1. Anthopogenic space objects

Optical sensors require lightup of observing object and don't permit to estimate all its coordinates. They demand also complicated setup of observing technique and processing of measured data in order to obtain trajectory characteristics by estimation of two coordinates only.

Radar methods of observing of debris have advantages over other methods. They permit to measure 3 or ever 4 characteristics (including Doppler velocity). Howeverer using of radars for these purposes requires preliminary solving of a number of technical problems: radar based type, frequency used, consumedpower, observation scheme, constrution of a radar.

It is necessary to underline some veatures of observed objects:

- super small effective radar cross section (RCS);
- high velocity and wide rang ofobjects velocities. Ralitive, velocities of debris particles and space vehicle in plane of it's orbit are in range (0...15km/s), - in normal direction to it's orbit plane- (-7.5...+7.5km/s).

It becomes necessary to use the higher carrier frequency, in order to eliminate a significant decrease of RCS in Ralay diffraction area.

The using of a space based radar in W(95GHz) band is mostly suitable for the task of obtaining statistic date about debris 1mm size and larger, in oder to avoid essential decrease of troposphere loss.

However, on this way some new problems, connecked with minimization of size weight, power consumption of radar and its high reliability provision, arise.

Space based radar to observe space debris

At present Russia /2, 3/ and USA /4/ have accumulated considerable experience on creating radars in K_a-band and higher frequencies bands. It was found out that, except for the systems of very small power, the transmittingy stems are expedient to be developed on the basis of vacuum tubers, while the receiving circuits are expedient to be developed with using solid-state devices. Such a construction has just been accepted as main variant for the radar in question.

A possible bloke-diagram of the radar and its links to the space ship equipment are presented in Fig.2.

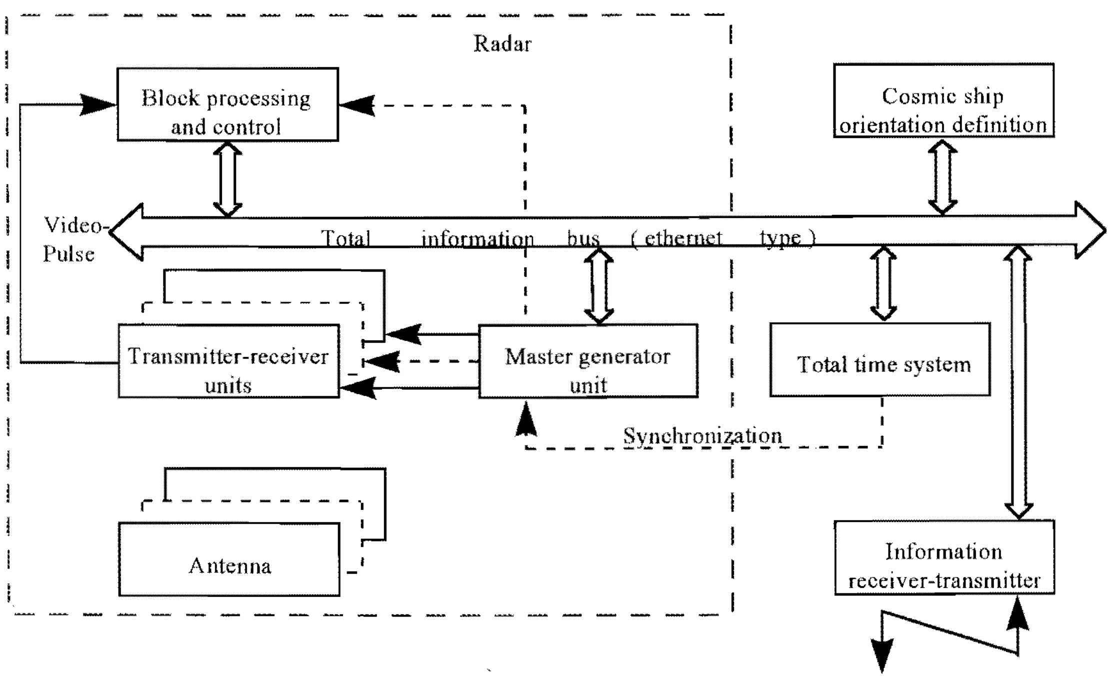


Fig.2. Radar and cosmis ship connections

The radar includes an antenna, transmitting-receiving blocks, a block of master oscillator, a block of information processing and control, and a common information bus of ETHERNET type providing the internal and external links of the radar.

Together with the antenna, the transmitting-receiving blocks provide:

- forming the radiation pattern for transmitting and receiving simultaneously;
- radiation of outgoing pulse and isolation of the receiving circuits for the period of radiation;
- phasing the transmitting and receiving signals;
- reception of the signals reflected from irradiated objects.

The master oscillator block provides excitation of the output devices and synchronization of all the radar components.

It is proposed to use a transmitting-receiving antenna of module type consisting of a few identical blocks. The antenna blocks are arranged in a hexagonal lattice.

The block of information processing and control provides:

- control of the antenna radiation pattern for transmission and reception;
- sampling the signal from the output of the receiving circuits;
- primary detection of the signals within a specified interval of delays when scanning a field of detection;
- detection of the signals during the secondary sounding of the angle direction in which the signal has been detected primarily with the purpose of providing the specified characteristics of detecting the target;

- construction of the detected object trajectories and sending the messages about the trajectory parameters to the ground-based station of tracking space ships.

The transmitting-receiving blocks and block of information processing and control have self-contained power conditioners.

It is assumed that the space ship equipment includes the systems of total time, determination of the space ship orientation, and information reception and transmission providing the on-board radar operation.

Radar characteristics estimation

The minimum value of the object effective scattering cross-section is equal to $10^{-6}m^2$ for an object with diameter more then 1mm.

To evaluate the parameters of viewing the space debris fragments, consider the following possible variant of viewing. For providing formation of the barrier sector, the scanning of the radiation pattern is performed in the plane that is perpendicular to the vector of the space ship velocity, *i.e.* the sector axis is oriented normally to the space ship trajectory. The angle between the radiation patterns is 1.1mrad., the pattern width at the level of - 3dB is 1.6 mrad., the scan sector width is 4mrad., the number of the radiation patterns in the scan sector is 4 (Fig. 3). The minimum time of passing the detection area by an object is 270mks.

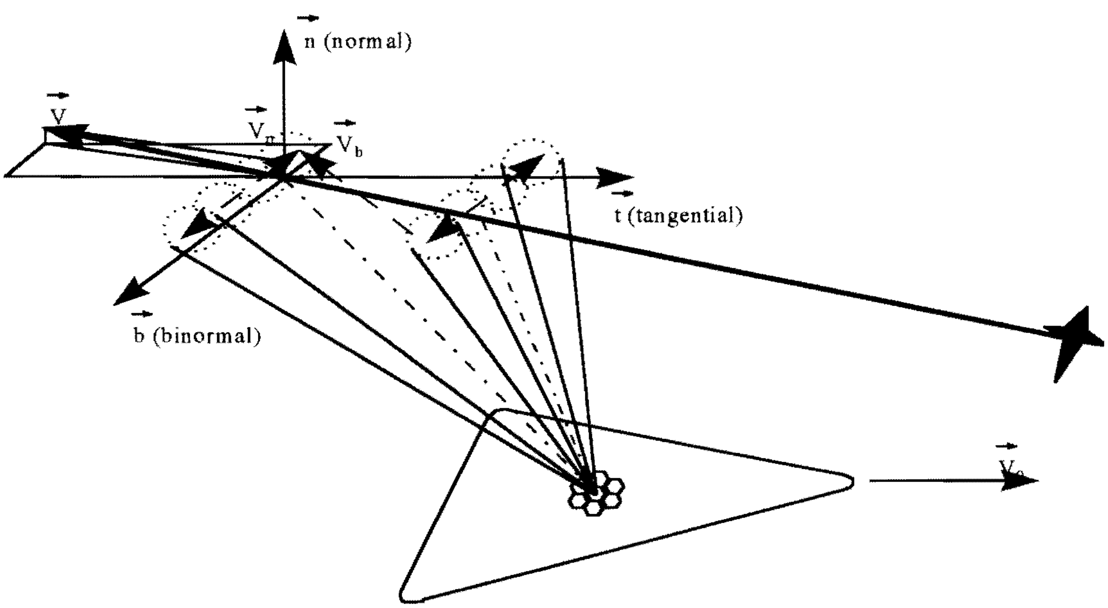


Fig.3. Observation

In oder to provide survey zone of $40000m^2$ area it is necessary to take the maximum range - 5000m, minimum - 2500m., the antenna diameter is -2m, noise temperature of receiving device - 200^0K. We take coefficient of overall loss at scan sector edge is equal 0.1.

It is necessary to take the transemiter pulse duration 0.6μs under output devices pulse power is 1400W now, consumed power is 25W bu pulse recurcence rate, is 30kHz.

To determine the velocity vector components (tangential, normal and binormal to the space ship trajectory) of the object moving, the barrier sector after detection is displayed in the direction opposite to the space ship velocity vector by 10 angular minutes with delay of no more than 70mkc.

In the displaced sector position, the viewing of the sector for detection of an object moving through it is being performed within 0.02s. After expiration of the indicated time, the sector returns to its previous position.

With high probability, the procedures of the object trajectory detection indicated above allow excluding the object trajectory detection by the side lobes of the radiation pattern because their position and level sharply change when scanning.

The use of an active phased array allows forming other configurstions of beams when viewing /1/. The final choice of an expedient beam cofiguration must be made at the stage of the radar development.

The videj signal sampling rate is 2.5mhz, the number of elements of quantization by range is 40.

If the intensity of appearance of the space debris fragments is one object a day, the intensity of wrong detection of the objects is expedient to be chosen of the order of 0.05 a day.

To achieve the required value of the wrong detection intensity, it is supposed to use a procedure of two-stage detection. An object is considered as a detected one in case of detection of the object signal on the first stage during the primary sounding of the angular direction in the area of detection by a single sounding pulse with the subsequent confirmation of detecting the object signal on the secind stage during sounding by a pair of pulses in the same angular direction as that determined on the stage.

The probability of exceeding the detection threshold by noise on the first and second stages is $5 \cdot 10^{-5}$ and 10^{-4}, respectively.

The probability of detecting observable object for the realizing signal-to-noise ratio is no less than 0.95 with taking into account of no less than two irradiations of the object within the time of its going through the barrier sector. For the signal-to-noise ratio indicated above:

- the root-mean-square error of measurement of the object effective scattering surface does not exceed 1-to-2 dB;
- the total root-mean-square error of the angle estimation by the measurement of the signal amplitudes in the neighbour angular directions does not exceed 0.6 angular minutes;
- the total root-mean-square of the range estimation does not exceed 9m.

Transmitting-receiving block

The transmitting-receiving block must provide amplification of sounding signals, reception and amplification of echo signals, protection of the receiving circuits from the penetrating signal. The synchronization of block is performed from the system of the total tame. The block comprises the transmitting and receiving modules /Fig. 4/. The basic element of the transmitting module that mainly determines the scheme of construction of the module is the amplifying microwave device. The module VZB2783 from Company VARIAN complies with the requirements indicated above. It has the following parameters. A device with close characteristics in the close characteristics in band of 95 GHz has been developed in Russia as well.

For providing the requirement on the noise figure, the low-noise amplifier (LNA) of the receiving module can be performed by the technology of monolithic integrated circuits on the basis of pseudomorphic InP HEMT /5/. The monolithic one-cascaded LNA performed by the indicated technology provides the noise figure of 1.3dB for gain of 23dB in the mode of small signal. The device of the LNA protection from penetrating power of the transmitters can be performed either in the form of a semiconductor limiter or in the form of a *pin*-diode switch.

The block of the master oscillator provides excitation of the transmitting modules and the necessary synchronization of the radar equipment.

The transmitting module is a pulse amplifier of microwave signals at the carrier frequency of 95 GHz. A klystron in the module is used as a microwave amplifier. The peak power at the output corresponds to 1.4kW with providing gain of 45dB.

The receiving module performs amplification of echo signals at the carrier frequency of 95GHz, conversion of the signals to the intermediate frequency, and transmission of them to the circuit of forming the sum signal.

Control of phase of the signals when radiating and receiving is performed with using phase shifters installed at the receiving module output and at the klystron input in the transmitting module. The receiving module provides one-channel processing the echo signal within the whole range of the Doppler frequencies.

Control of the phase shifters is performed by the codes coming from the block of information processing and control.

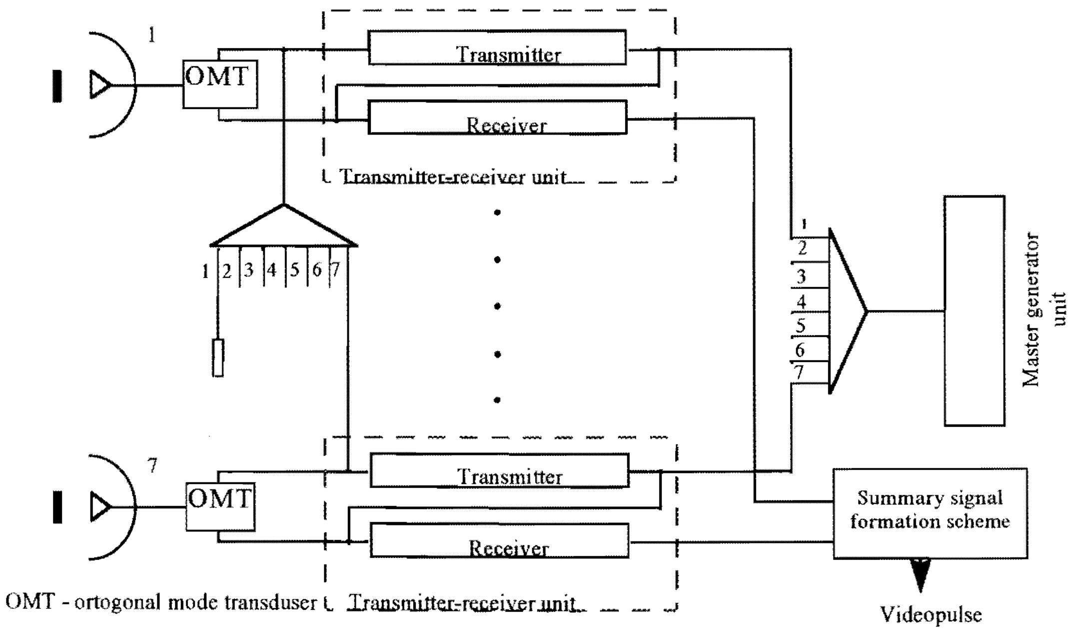


Fig.4. Radar high friquency part

Each module is provided with power conditioners built by the scheme of conversion of a direct voltage into an alternating one with frequency of 100-to-200 kHz and 90% efficiency.

For maintaining the stability of the transmitting and receiving channels. the radar design must satisfy the following conditions. All the seven transmitting-receiving blocks must have the temperature spread of no more than ±10°C. For this reason, they must be shielded by a light-reflecting material with small heat conductivity. The space ship design must be provided with special panels for heat removal from the transmitting-receiving blocks.

The longevity of the block will approximately amount to 50000-to-80000 hours. The equipment longevity is mainly determined by the klystron longevity. High longevity of the klystron is assumed to be achieved at the expense of its using with loading for 50% by average power.

The mass of the transmitting-receiving block will approximately amount to 8 kg.

Antenna

The Phased Array Antenna consists of seven Large Aperture Radiators (LAR), that are arranged on a load-carrying structure. The centers of all LAR apertures lie in one plane in nodes of a hexagonal lattice (Fig.5).

Every LAR is performed as a Cassegrain antenna and contains a main reflector, a subreflector with thrust, a primary feed and a waveguide feeder.

The main reflector is a symmetrical paraboloid. Edges of the reflector are cut so that its projection onto the aperture plane is a regular hexagon with a side of 380mm. In this case the aperture of the array as a whole is inside a circle of 2 m in diameter. The feed of each LAR is a dual-mode Potter horn. The subreflector is hyperbolic and axis-symmetrical.

Coherent signals are given to the LAR's inputs. For scanning by the main beam of the pattern it is necessary to produce linear phase distributions between LAR's in planes of phasing, i.e. to give a signal with a corresponding phase to each LAR input. An angle sector of electric scanning is limited by the beam width of a separate LAR and it is assumed being equal to ±7.5 angle minutes in any plane.

The side lobe level increases up to-2dB with respect to the main lobe maximum in the case of the maximum deflection. A gain of the antenna array main lobe decreases by approximately 2dB at the edge of the scan angle sector.

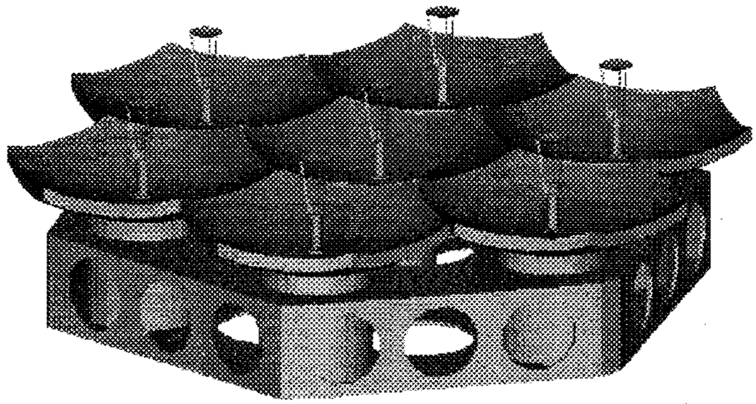


Рис.5. General View of the Antenna

The design of the antenna includes seven identical LAR and a supported structure (rigid framework), on which they are attached rigidly. Because of the antenna should form a very narrow beam there are very hard de mands on accuracy of maintaining and mutual adjusting of all LAR's and also on a mechanical stability of the design during operating.

One of the main factors affecting on antenna is the sun radiation, that can cause an irregular heating and deformation of design. Heat insulation materials, being tratitionally used or covering equipment operating in free space, are hot suitable for an aperture part of antunna. Besides, the antennm mass should be minimized. So, it is necessary to use materials with high specific rigidity and low thermal expansion fact.

The experimence of creating such antennas for space crafts in Russia says about pnecessity of using composite materials on basis of carbon fibers (carbon-plastics).

A mass of the seven LARs is estimated as 12-20kg, a ass of the support structure is about 18-20kg. Thus, a total mass of the antenna is approximately 30-40kg. No active elements are in the antenna, so a consuming of energy is absent.

Block of informattion processing and control

The condition of operating as well as the quirements for the weight and overal dimensions characteristics define the necessity of using microprocessors when creating the block of information processing and control.

The block is realized on the basis of the system bus VMEbus64 and includes a signal processor module DSP and a central processor module V5A. The processor modules are arranged in a VME-crate where a room is provided for arrangement of a board with a hard disk drive (HDD) and a floppy disk drive (FD) to be used for the period of debugging and adjusting the block. An output of the ETHERNET channel is provided from the module V5A to which a computer is connected for software debugging in real time. The VME-crate of a hermetic implementation includes a power conditioner.

The modules DSP and V5A are linked to each other the system bus VME. The module V5A has an output to the common information bus of the space ship through a PCI Mezzanine Card expansion site (PMC Expansion site), and provides information exchange with the space ship equipment. The control of the mode of digitizing the video pulses in the current interval of the sounding pulse is performing the corresponding information at the end of the previous interval of sounding. The pulses with frequency of digitizing the video pulses of 2,5 MHz are sent to the module DSP.

The overall dimensions of the block of information prcessing and control are determined by the VME crate dimensions, and the weight and consumption of the block are negligibly small in comparison with the corresponding power parameters of the radar as a whole

Main characteristics of radar

1.	Mass	no more than 100kg
2.	Consumed power	no more 2.5kW
3.	Carrier frequency of radiation	95GHz
4.	Diameter of antenna	2m
5.	Antenna gain	63dB
6.	Pulse duration of transmitter	0.6μs
7.	Pulse recurrence rate	30kHz
8.	Gain of receiving device	40dB
9.	Noise temperature of receiving device with device of protection	around 200°K
10	Dimension of observable objects	down to 1mm
11	Probability of detecting observable object flying over zone of 40000 m^2	no less that 0.95
12.	Quantity of facts of wrong object detection a day	no more than 0.05
13.	Root-mean-square error in measurement of range	no more than 9m
14.	Root-mean-square error in measurement of angular coordinates	no m ore than 0.6 angular minutes
15.	Root-mean-square error in measurement of effective object cross-section of scattering	no more 1-to-2dB
16.	Root-mean-square error in measurement of tangential and binormal velocity components	no more than 250m/s
17.	Root-mean-square error in measurement of velocity component normal to space ship trajectory	no more 1000m/s

Conclusion

We present space radar capable of observing small space debris objects (1 mm size and lager) and it tracking them in space zone within 40000m^2 area.

The radar provides statistical data for obtaining space distribution parameters of the debris particles.

The main radar elements have been constructered by now and manufactured at present in Russia and abroad.

References

1.Cosmic interdepartment group report to national safety Council on cosmic space contamination problem, Washington, Februoary, 1989.

2. A.A.Tolkachev, V.V. Denisenko, A.V.Shihlov A.V.Shihlov and A.G.Shubov, High Gain Antenna Systems for Millimeter Wave Radar with Combined Electronical and Mechanical Antenna Systems for Millimetre Wave Radar with Combined Electronical and Mechanical Beam Stering. IEEE International Symposium on Phased Array System and Technology, Boston, Massachusetts. October, 1996.

3 A.A.Tolkachev, V.P.Botavin, A.A.Kusmin, A.P.Pytsyk, V.A.Trushin. Radar Means for Detection and Tracking of Orbital Debris. Scientific Conference of the Russian Academy of Science "Technodenous Space Debris Problems and Direction Research",Moscow, February, 1996.

4 M.D.Abouzahra and R.K.Avent. The 100km Millimetre-Wave Radar at the Kwajaleiu Atoll. IEEE Antennas and Propagation Magazine, Vol.36, N2, April, 1994.

5 A Monolithic LNA for a band of 140 GHz. IEEE Microwave and Guided Wave Letters. - 1995. - Vol. 5, N5 - p.p 150-151.

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