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Development of the Methodology of Measuring Rheological Properties of the Materials for Reflector Structures to Forecast Mechanical Behavior of the Reflector during its Operational Life

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Abstract

Background/Objectives: Today different designs of space vehicle large deployable antenna reflectors are developed intensively. The properties of the materials used for these structures have to be taken into account. **Methods:** The study helps forecast mechanical behavior of the reflector during the entire period of its active existence based on the rheological properties of the applied materials. **Findings:** Current importance of the problem has been stipulated by the fact that the deformations and tensions that occur in the materials often depend not only upon the forces and conditions of the effective loads, but also upon time. **Applications/Improvements:** The study develops the methodology that takes into account the dependency of rheological properties of materials on time.

Keywords: Polymeric Composite Material, Rheological Properties of Materials, Mechanical Behavior of Reflector, Technological Parameters, Rheology.

INTRODUCTION

Over the last years different space-based systems have been developed extensively. Among those systems the leading positions are held by the Earth's surface observation systems applied for the purposes of meteorology and environmental protection, and also by communication, television and navigation systems. Within the frameworks of these systems, the space vehicles (SV) represent either message senders or the technical means of the communication channels. One of the most important and extensively developing areas in the sphere of cosmic engineering is the design of the large deployable antennas for space communications that are installed on space vehicles of different profiles.[1-4]

Among all possible configurations three types of large-sized transformable reflectors are distinguished today as most promising (the pictures are shown below). To evaluate and to compare different designs of space-borne deployable antenna reflectors, the coefficient of deployment (folding) is commonly applied which represents the ratio of the reflector diameter in its unfolded state to its diameter when it is folded. Principal requirements to the reflector designs include the precision of the shape of the reflecting surface, pointing accuracy, high temperature stability and radio-reflecting capacity of the antenna systems, transportability, rigidity of the structure under operational conditions, weight and volume in folded state, high reliability of deployment, low costs, technological efficiency and resistance against the factors of space environment: temperature drops, extreme vacuum, solar pressure, air-flow resistance at low orbits, meteorites, etc.

Umbrella reflectors.

The load-bearing frame is represented by the structure that consists of parabolic ribs which shape the reflecting surface (RS) made of metal or metalized knitted mesh.

Presently, there are three types of umbrella reflectors: those featuring rigid ribs, collapsible ribs and flexible ribs. The collapsible (deployable) design gained wider application as in this case the longitudinal dimensions of the antenna package becomes shorter; the second best are the designs featuring flexible ribs that possess all the advantages of the umbrella reflector, save its rigidity. Figure 1 shows the reflector that contains the central unit represented by coaxially located base frame and flange and also the load bearing frame that is mechanically connected with the mesh through the shape-forming structure. The base frame is made of honeycomb panel. The load-bearing frame is formed of the straight spokes hinged to the base frame and designed as mesh rod structures with the cantilever beams attaches to their ends. On the side opposite to reflector deployment, there is a telescopic mast installed and fixed on the base frame. Its apex is connected to the flexible guy-ropes attached to the abovementioned spokes. The shape-forming structure is designed as the uniformly located flexible bands attached to the operating surface of the mesh. Coefficient of deployment makes ≈ 20. This type of structures possesses a number of such advantages as high thermal stability, rigid operational structure, highly reliable deployment; however, the most important advantage is represented by the opportunity to select the required geometry of the reflecting surface; thereat, the root-mean-square deviation from theoretical profile makes no more than 1.3 mm. At the same time, as the dimensions of the antenna get larger, its weight increases approximately according to the linear law.

Rim reflectors.

Principal structural elements of the rim-type space reflectors are represented by the girder rim that ensures the preset profile of the field pattern and orientation of the reflector, by frontal and rear nets, by RS, and by the cable structure. The girder rim is a rod structure formed of rigid carbon fiber composite elements.[5] Figure 2 shows the rim-type deployable reflector that contains the central unit, the rope-and-pulley deployment system that interacts with the deployment drive, with the strong ring and with the central unit; the mesh is fixed at the main and intermediate flexible support blades to the vertical rod elements that predetermine the profile of the operational surface of the reflector. Coefficient of deployment makes ≈10. This type of the load-bearing structure of large deployable reflector also increases the weight of the reflector which is a considerable disadvantage for any space-borne structure. Another drawback is represented by the complexity of thermal analysis caused by the dissimilarity of structural elements; thus, it is difficult to predict the reflective properties of the structure because of the complex behavior of the geometry of the reflection surface under the conditions of radiation heating. Nevertheless, this type of structures possesses low specific weight, ensures stability of repetitive deployment and makes it possible to effectively employ the drag bars of the guy-rope elements to adjust the shape of RS.

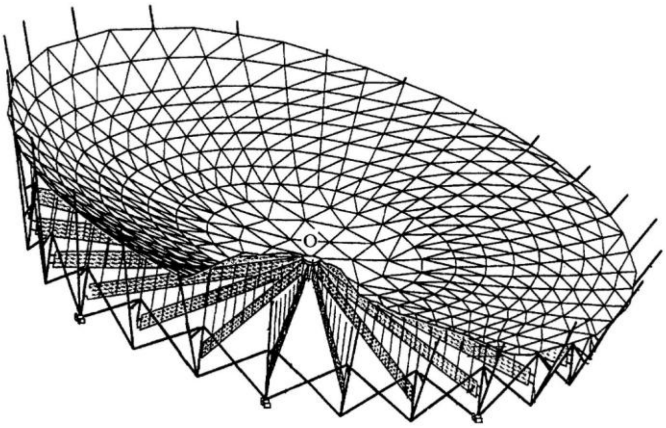

Figure 1. Ubbrella reflector

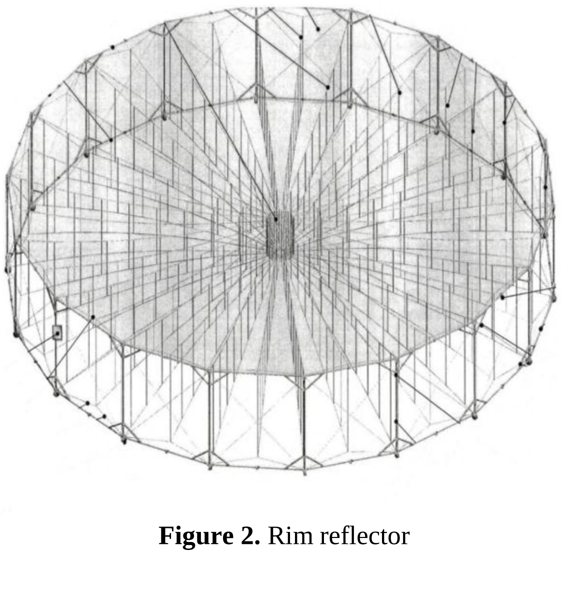

Figure 2. Rim reflector

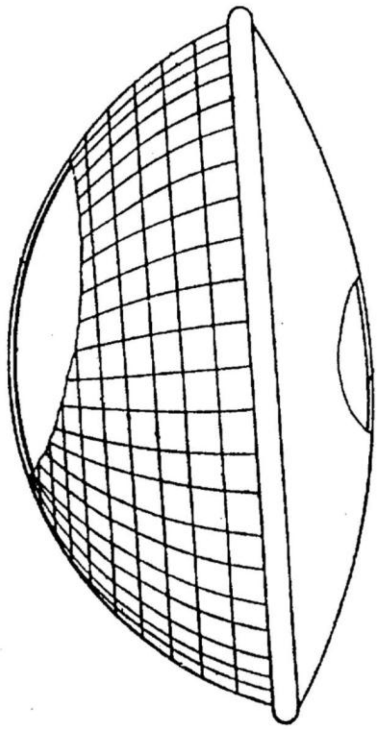

Figure 3. Inflatable reflector

Inflatable reflectors

Inflatable reflector of a space-borne antenna is, in fact, a thin-walled shell made of durable material which is folded before the launch and then, upon orbit injection, it is unfolded by gas pressurization; thereat, it should be noted that the shell of the reflecting surface is often represented by a low pressure membrane. Figure 3 illustrates that this type of reflector in its shape often looks like paraboloid with reflecting rear surface and transparent front. In most cases, the load-bearing frame of this type of structures represents a high-pressure toroidal shell that is usually attached to the reflector shell by the guy-ropes. Among all types of deployable structures, the inflatable designs are the most promising, because their coefficient of deployment is ≈ 100, they ensure the required efficiency at frequencies up to 30 GHz, they possess less weight than their mechanical counterparts with equal reflector diameters; when folded, their size and, potentially, their weight is the lowest; the structural strength can be improved by impregnation with thermally active polymers featuring high temperature of solidification (or by applying polymers containing photoinitiators); they feature the best precision of the reflecting surface as compared to other types of reflectors, especially, when the dimensions are large; also, in the Earth's gravitational field the inflatable structure can be rendered weightless by employing the gas that is lighter than the air. However, despite all the advantages, this type of the structure is largely exposed to the risks of changing its geometry because of the temperature drops and because of gas expansion/compression inside the shell.

Today many different materials are used to construct space-borne deployable antennas. With regard to environmental factors, the following parameters of the antenna materials are of paramount importance:

- high values of resistance against solar radiation

- possibility to withstand interstellar dust penetration
- resistance against oxidation at low Earth's orbit (important for some materials featuring hydrocarbon coating)
- operation within wide range of temperatures from 4K to 350K.

Some of the materials are describe below.

Mylar.

- Mylar is DuPont trademark for the film based on synthetic polyester fiber possessing high mechanical strength and chemical stability under wide range of temperatures and featuring good dielectric properties. It possesses high thermal resistance and durability. Metalized Mylar film meets all the requirements set to the polymers applied for space-borne antenna reflectors. In this study this type of material will be considered for designing all suggested structures of inflatable reflector.

Application:

- It makes the basis for photographic and motion-picture films.
- The screen made of multilayer Mylar used to protect the launch and landing stages of the lunar module in SV Apollo from heat and interstellar dust penetration.
- It is the fundamental material of the cupola and load-bearing structure of satellite ARISE.
- The outer cover of lunar astronaut's spacesuit A7L used to include aluminized Mylar.
- Aluminized Mylar is also employed in the solar photon sails of Cosmos-1 and Light Sail-1.

Polyimids. Kapton.

- Polyimids are a class of polymers containing in their main chain the imide cycles that are usually condensed with aromatic or other cycles. The heat resistant aromatic polyimids, the derivatives of tetrabasic carboxylic acids with five-member imide cycles in their main chains,[6] have been most widely applied. It is a perfect insulator.

Application:

- It is used as protection from ultraviolet radiation at the outer coverings of different astronaut's spacesuits.
- It has been applied as the lunar module heat insulator within the framework of Apollo-11 program.
- It is also used as thermal protection in SV Rosetta.
- It has been applied as insulator in some units of SV Arian-5.
- It was used as the basic material in solar photon sail Sunjammer; in that case the thickness of Kapton film was record-small and made just 5 micron.

Dacron (Lavsan).

Dacron is a thermoplastic material, the most widely used representative of polyester class. It is the product of condensation polymerization of ethylene glycol and terephthalic acid (or its dimethyl ester); it is hard, colorless, transparent matter in its amorphous condition and white and non-transparent when crystallized. It is transformed into its non-transparent state when heated to the temperature of glass melting and it remains in this state after shock cooling and upon fast transition through the so-called "crystallization zone". One of the most important parameters of polyethyleneterephthalate is represented by its characteristic viscosity that is predetermined by the length of polymer molecule. As the intrinsic viscosity increases, the velocity of solidification is getting slower. It is resistant against solar, ultraviolet, thermal and oxidation effects. It possesses good strength and durability; the dielectric properties of lavsan have to be particularly noted.

Application:

- It is widely used for manufacturing threads, fibers, fabric and knitted materials of different types in different application areas.
- It is used for sealing, separating and filtering layers in construction and in other industries.
- It is in demand in electrical and radio engineering industry due to its electric properties and high strength.
- It is used for oil and petrol transportation.
- In Russian and Soviet vehicles it was used for thermal protection purposes.
- It has been used for astronaut's spacesuit Ck-1 which outer covering is made of lavsan fabric.

Polyurethanes.

Polyurethanes are hetero-chain polymers that contain unsubstituted and (or) substituted urethane groups. The number of urethane groups depends on the molar mass of polyurethane and on the ratios of the initial components. Depending on the nature of the latter the macromolecules of polyurethanes can contain other functional groups: ether and ester groups (polyester-urethanes), urea (polyurethaneurea) groups which, along with urethane group predetermine the complex of polymer properties. There are linear and cross-linked polyurethanes and also urethane-containing semi-interpenetrating polymer networks and urethane functions.

Application:

- It can be used as chambers for straining the mesh.
- It can also be used as membranes for further metallization and for the formation of the reflection surface.
- It is in demand in virtually all industries due to its varied properties and due to the availability of different versions of polyurethanes.
- It is used as sealing material in astronaut's spacesuits

Carbon foam.

Carbon nanofoams are allotropic modifications of carbon that represent very light black powder and possess semi-conductor properties. They consist of the nanotubes within irregular tree-dimensional networks. In space-borne antenna reflectors it is used for creating the reflector mirror to ensure the required properties. However, the manufacturing process and the application technology of this material are very expensive.

The majority of weight efficient and thermally stable space communication antennas include the load-bearing rod elements. Such elements should be made of polymeric composite materials that are widely applied in space equipment and supporting structures.[7,8] Also, mechanical behavior of the reflector should be forecasted for the whole period of its active existence which would be impossible without taking into account the rheological properties of the applied materials.

It is known that deformations and tensions occurring in the materials often depend not only on the values of the effective loads and their conditions, but on time as well. The processes of deformation and tension changes over time are considered from the perspectives of rheology. Rheology is the study of deformations and flows of materials, including their elastic and plastic properties. One of the principal rheological processes is represented by creep. Creep is a slow deformation of the body affected by constant load. Sometimes this term is used in more generalized sense to define the non-elastic processes of deformation and tension changes over time occurring in different types of bodies: plastics, metals, composite materials, rocks, construction and organic materials, ice, etc.[9]

Most weight efficient and thermally stable space communication antennas include the load-bearing rod elements that are also employed in the structures of deployable antenna reflectors under investigation. The rheological processes of creep are most likely to occur in the polymeric composite materials of such loaded rod elements as guy-ropes, tubes, etc. Under effective loads on the rod elements the creep can occur in polymeric composite materials when the polymeric matrix reveals the highly elastic nature of deformation manifested under some certain environmental effects, for example, under the conditions of high temperature.[10]

Over the last years rheological investigations have been undertaken in different areas of science. The most intensive development of rheological studies has been observed in material science (conventional and composite materials), in medical science, in fracture mechanics, geology (rock behavior), continuum mechanics, macromolecular chemistry and in many other areas. Thus, for instance, investigations of mechanical properties of polymer membranes enable the creation of artificial lungs. Also, rheology is important for studying the behavior of hydrolized polyacrylamide (PAA) which areas of application are as follows:

- Water cleaning. PAA is a good and inexpensive coagulant and flocculant for potable water cleaning and for waste water treatment
- Production of gels for chemical analyses of complex biological systems
- Mineral fertilizer production
- In molecular biology PAA is used as supporting medium for gel electrophoresis of proteins and nucleic acids
- In oil industry it is used for flooding the formations and for the purposes of repair and insulation in the oil drills
- PAA is used in drilling mud in oil production as water loss regulator and as clay swell inhibitor.

High-impact polysterene is synthesized with sodium methacrylate featuring rheological properties that are affected by molecular architecture.[11-24]

CONCEPT HEADINGS

Creep flow is the process of deformation increasing over time when the material is under strained conditions. Typical creep curve, the function of deformation ε on time τ under the conditions of constant strain σ is shown below (Figure 4).

The creep curve is usually built based on the results of material sample testing. The shapes of the samples and the methods of loading them are usually selected in such a way that in the operating area of the sample there is a unified field of strain (uniaxial stress state or pure shear). The latter condition is required to correlate the properties of the material sample with the properties of the elementary volume of the material of the structure under load. The simplest case is represented by tensile and compression tests with statically loaded samples.

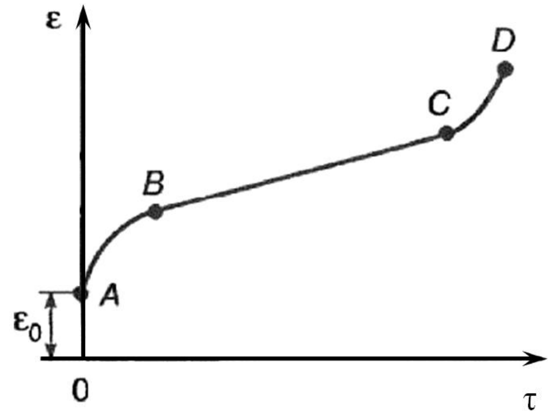

Figure 4. Typical curve of material creep under tension

For the cases of small deformation the changes in sample absolute dimensions can be neglected and the test can be carried out not under the conditions of constant strain, but under the conditions of constant force. Instantaneous static loading cannot be realized in practice; therefore, the load is applied with some certain finite velocity. In this case the deformation that corresponds to time $\tau = 0$ is usually assumed to be the deformation measured directly after the loading has reached its final value. The ordinate of point A (Figure 4) is designated as $\varepsilon 0$ and is called instantaneous deformation which is, to some extent, purely conventional, because in the process of loading the deformation of creep already starts developing. Upon the full load application the deformation increases; thereat, the velocity of its change over time decreases in monotone down to some minimal value. In this respect, the creep at section AB is called transitional. Stabilization of the velocity of deformation change is observed at section BC which corresponds to stationary creep. If the tested material shows brittle fracture, then the test is accomplished with the destruction of the sample at the moment that corresponds to the abscissa of point C. When the fracture is of plastic nature, the tension diagram shows section CD. In this case the destruction occurs at the moment that corresponds to point D. The period during which the sample was placed under load up until the moment of its destruction is called durability of the material.

If at some moment $\tau 1 \neq 0$ the effective load is removed completely, then the deformation ε1 accumulated by this moment will instantly decrease by value ε0 and will continue decreasing over time (Figure 5). The process of deformation change over time that occurs from the moment of load application (deformation increase) is called direct aftereffect; and the process of its change over time immediately upon complete unloading of the sample (deformation decrease) is called reverse aftereffect. The aftereffect is called elastic if the deformations disappear over time completely upon unloading, and it is called plastic when the residual deformation is not equal to zero.

The creep curves (Figure 4 and Figure 5) are, to some extent, conditional. It is known that the profile of the creep curve mostly depends not only on the nature of the material, but also on the conditions of the test. The most important among them are the level of mechanical stress, temperature and the environment of the material. Below (Figure 6) there are typical creep curves under different stress levels.

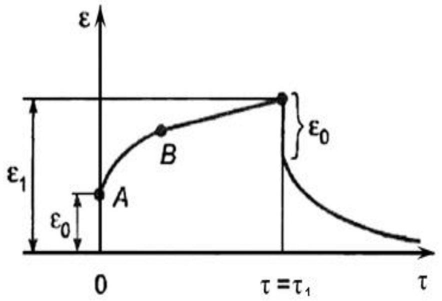

Figure 5. Creep curve at the sections of direct and reverse aftereffects

At the low stress levels that correspond to 10 % up to 20 % of the ultimate tensile stress σ ult., the process of deformation is accompanied by smooth decrease of the creep velocity and by the asymptotical trend of deformation toward some ultimate value of ε∞ (Curve 1). As the stress grows, the deformation increases and the durability of the material becomes shorter. Thereat, the profile of the creep curve changes (Curves 2 - 4) which is manifested through gradual shortening of the stationary creep section that practically disappears under the conditions of the stress approximating the ultimate tensile stress of the material under investigation. The creep curves obtained for compression and pure shear tests have similar profiles.

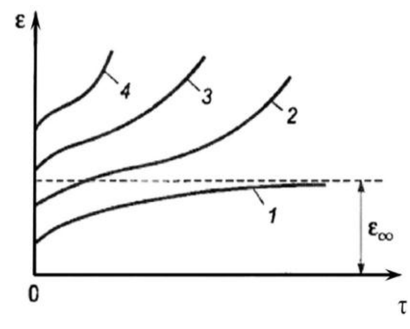

Figure 6. Creep curves (1 - 4) at increasing levels of tension

To determine the nature of the material creep, the isochrones should be built which represent the stress-deformation dependency under the fixed value of time. In order to build isochrones, several samples are tested under different levels of stress (Figure 7). Then, within the fixed time of τ*, the values of deformation and the relevant stresses are determined. The graph that illustrates the dependency σ - ε built for the moment τ* is called isochrone of parameter τ* (Figure 7). The isochrones of other time parameters are built in the same manner.

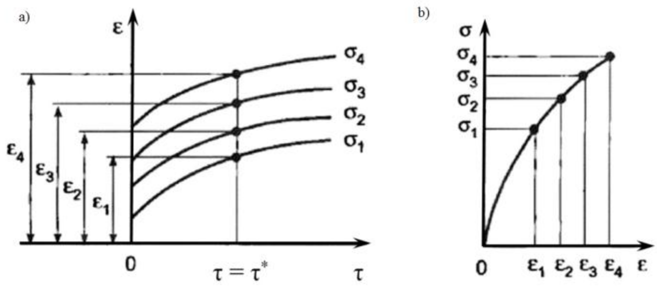

Figure 7. Creep curves (a) built under different levels of tension (σ1 < σ2 <σ3 < σ4) and isochrones featuring parameter τ* (b)

If isochrones of all parameters represent direct lines, i.e. if the deformation increases in direct proportion to the stress increase, then the nature of creep within the investigated range of stresses and deformations is linear; otherwise, the creep is of non-linear nature. Below (Figure 8) there are isochrones of linear creeping and non-liner creeping materials accordingly. The isochrone of parameter $\tau 0 = 0$ cannot be obtained in practice due to the abovementioned reasons; however, under the conditions of instant loading the materials show linear-elastic properties, therefore, the isochrones of parameter τ0 should represent direct lines for both linear creeping and non-liner creeping materials.

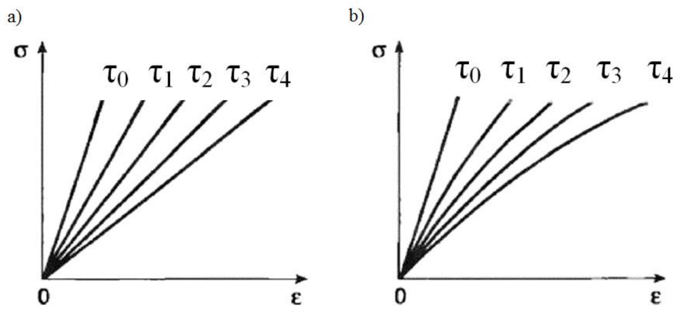

Figure 8. Isochrones of linear creeping (a) and non-liner creeping (b) materials for different periods (τ0 < τ1 < τ2 < τ3 < τ4)

The properties of the materials largely depend on temperature. Temperature growth usually leads to increased deformation and to faster creep process. Thus, to take into account the rheological properties of materials, the creep of the material should be investigated under different conditions of effective stresses and under high temperatures within the operational range. One of the possible methods of material creep investigation is represented by the mechanical tests followed by mathematical processing of the obtained data.

RESULTS

This study developed the methodology for measuring the rheological properties of the materials for reflector structures to predict mechanical behavior of the reflector over the whole period of its effective life.

DISCUSSION

Based on the results of the mechanical creep tests, the methodology describes the rheological prioperties of the materials used in the reflector structures that have to be taken into account to forecast mechanical behavior of the reflector within the whole period of its useful life. This methodology suggests the ideas on maximal relative deformations of the materials of the structure under different temperatures and effective stresses in their dependence on time. Given the above, it can be concluded that this methodology is unique.

CONCLUSION

According to the methodology of measuring the material rheological properties and given the results of the mechanical creep tests, the maximal relative deformations of structural materials have been determined under different temperatures and effective stresses in their dependence on time, i.e. the isochrones of the materials have been built representing the stress-deformation dependency under the fixed values of time and temperature. Based on the obtained isochrones, the value of the maximal relative deformation ε is determined which corresponds to the rated operational time of the structure, thus making it possible to compare the extreme changes of shape and dimensions of the structure caused by the material creep flow with the maximal admissible deformation values. With regard to the described structure, the following assertion will hold: the lower is the frequency range, the larger reflector will be required: and the larger the dimensions, the higher the precision of the reflector surface should be: the admissible deviations should not exceed $\lambda/16$, where λ is the wavelength. Consequently, having the value of the maximal relative deformation ε that corresponds to the rated operational period it is possible to obtain the extreme maximal deviation of the shape and also to predict the effects caused by the changed geometry of the reflecting surface on the radio-technical properties of the reflector.

ACKNOWLEGMENTS

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