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Yuri M. Chesnokov, Alexander S. Vasileisky



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SPACE-BASED VERY HIGH RESOLUTION TELESCOPE BASED ON AMPLITUDE ZONED PLATE

Yuri M. CHESNOKOV, Alexander S. VASILEISKY

*Space Research Institute of the Russian Academy of Sciences,
84, Profsoyuznaya st., Moscow, Russia.
Tel. (7-095) 333-30-11, Fax: (7-095) 330-12-00,
E-mail: asvas@ass.iki.rssi.ru*

This report presents a project of space-based very high resolution telescope with an amplitude zoned plate as a telescope lens. The creation of such a telescope would provide the solution to the problem of imaging far celestial bodies in near ultraviolet, visible and near infrared spectral bands with an angular resolution of 0,005-0,001 arcsec, i.e. one-two orders better, than it could be achieved by existing means, even Hubble Space Telescope. It would make it possible to carry out further fundamental studies of the Sun, galaxies, stars and planetary systems around nearest stars.

In order to achieve the angular resolution of thousandth of arcsec, it is necessary to create telescope with a lens diameter of tens or hundreds meters. Such a telescope, designed according to the traditional scheme, require very high manufacture precision and stability of characteristics with the admissible errors of fraction of wavelength

The optical scheme of space based telescope with Sore amplitude zoned plate as an objective is proposed as the solution of this problem. This zoned plate with the diameter of tens or hundreds of meters is a system of transparent and opaque concentric fringes, placed in accordance with Fresnel zones. Zoned plate may be made of thin elastic film pulled over a frame of folding umbrella type and mounted on a spacecraft. Receiving unit registers the images produced by zoned plate. It is mounted on another spacecraft. These spacecraft may be placed in similar orbits or may be tied by means of rope system. It is also interesting to place both lens and receiving unit on the Lunar surface.

It is shown, that during implementation of the proposed telescope with the use of modern technologies, it is possible to satisfy precision requirements for both zoned plate geometry and for co-location of objective and receiving unit

The angular resolution of the used for observation astronomical instrument determines the volume of potential investigations in astronomical research. The diffraction-limited angular resolution for each telescope is proportional to the ratio of observations or survey wavelength and the diameter of a telescope lens

During the observation of space objects in the optical band through the atmosphere from the ground an angular resolution significantly better than 1 arcsec cannot be achieved even when using large-aperture telescopes. This limitation of resolution is caused by the distortions of a wave front on optical inhomogeneities of the terrestrial atmosphere

The increasing of space based telescopes lens diameters is not limited by atmosphere distortions and lead to resolution improvement. Therefore, placing large-aperture telescopes outside the Earth atmosphere is the only way to improve angular resolution

The usage of the Hubble Space Telescope with the diameter of 2.4 m gives to the astronomical society the ability to provide observations with the resolution about 0.05 arcsec on a wavelength of 0.75 mkm. The usage of a telescope with such a high resolution have resulted and with no doubt will result in further important discoveries in the field of astronomy.

The improvement of the telescope angular resolution is especially significant in studies of space objects outside the Solar system. The creation of a space-based telescope with an angular resolution of one or two orders better than that of the Hubble Space Telescope is a supertask, the solution of which could play a revolutionary role in the development of astronomy. The following actual problems could be solved by means of such an instrument:

- search for planetary systems around the nearest stars;
- observation of fine details of brightness distribution on the surface of large stars;
- research of the fine spatial structure of the galaxies cores, of dense star accumulations etc.

Diameter of telescopes have to be increased up to tens or hundreds meters to achieve such a resolution. At present the creation of lens or mirror telescopes with such a diameter is a technically unfeasible task since these instruments are based on the phase transfer principle of a wave front. Consequently, they have to comply with the severe requirements for the manufacturing accuracy in fractions of a light wavelength. The development of systems with sequential aperture synthesis on the basis of long-baseline interferometers, or array systems with an unfilled aperture or to compact lenses is limited with the same technological limitations.

The scheme of a space-based telescope described below, could be used to solve the problem of the angular resolution significantly improvement. This scheme provides for an amplitude zoned Sore plate used as a lens. Sore plate is in a simplest case a system of transparent and opaque to the light concentric fringes placed in accordance with the Fresnel zones (see Fig. 1). Radiuses r_n of borders separating transparent and opaque zones can be calculated according to the equation

$$r_n = \sqrt{n f \lambda} \quad (1)$$

where f - focal distance of the Sore plate, $n = 1, 2, 3 \dots N$; N - total number of opaque and transparent zones, λ - wavelength. Condition (1) provides positive interference of waves from all transparent zones in focal plane.



Fig.1. Amplitude zoned Sore plate as a telescope lens

The opaque fringes of the plate can be made from a thin elastic film pulled over a rigid unfolding frame. The transparent fringes are blank gaps between the opaque ones. Technological requirements for the manufacturing accuracy of the Sore plate are significantly lower in comparison with the regular lenses due to the fact, that Sore plate is based on the principle of amplitude transfer of wave front.

The plate, the same as the lens, forms real optical images of the objects placed in front of it. In the case of the monochromatic light, the zoned plate is equivalent to a glass positive lens of the same diameter but with the coefficient of transparency equal to 10 percent. Its resolution is inversely proportional to the diameter of the plate.

As distinct from the lens and mirror lens, the zoned plate's design is based on the principles of the amplitude but not the phase transference of the wave front. That's why requirements for the performance accuracy and the stability are several orders less strict for the parameters of the telescope with such a plate instead of a lens as compared with the analogous standards for conditional (mirror or lens) optical systems.

The following equations (2-4) show the relation of the main characteristics of the zoned plate:

$$f = \frac{D(H - H^2)}{\lambda} \approx \frac{D \cdot H}{\lambda} \quad (2)$$

$$D \approx 2\sqrt{D \cdot H} \quad (3)$$

$$\lambda \approx \frac{D}{4H} \quad (4)$$

where D - zoned plate diameter, H - width of the last zone, D_0 - diameter of the central zone (it may be transparent or opaque).

An angular diffraction resolution of the zoned plate is equal to

$$\alpha \approx \frac{\lambda}{D} \quad (5)$$

The diameter of the zoned plate has to be equal to tens or hundreds of meters to provide a good angular resolution of a telescope. In such a case, its focal length (depending on the other parameters) is tens, hundreds and thousands of kilometers. Therefore the receiving unit of a telescope capable to register information should be positioned at the large distance from the zoned plate where optical images of remote objects are formed. Because of such large focal lengths, the incoming and receiving units of the telescope have to be mounted on different spacecraft (Fig. 2). The first spacecraft carries the lens of the telescope - the amplitude zoned Sore plate. The unit for image registration is placed separately on another spacecraft jointly with the blocks of the guidance control system. The receiving unit may also be placed on Earth or both units on the Moon.



Fig.2. The space based very high resolution telescope implemented as a system of two spacecraft
1 - zoned plate, 2 - impulsive lamp for guidance control, 3 - sunshield, 4 - receiving unit

The absence of a single opaque to the light case of the telescope leads to the requirement of a special optical scheme to be designed for the receiving unit of the telescope. The operating principle of the telescope is shown on the Fig.3. The zoned plate is positioned in the plane A1. It forms an image of remote objects within its focal plane A2. A field lens is placed in the plane A2. It images the zoned plate in its focal plane A3. The transfer lens is fixed in the plane A3. It transfers, with the necessary reduction, the image formed by the zoned plate in the plane A2 to the plane A4. An image receiver is positioned in the A4 plane. A CCD-array can be used as the image receiver. Accessory light filters are placed before the objective. Mobile diaphragm before the transfer lens ensures, that only the light beams passed through the zoned plate will reach the receiver.

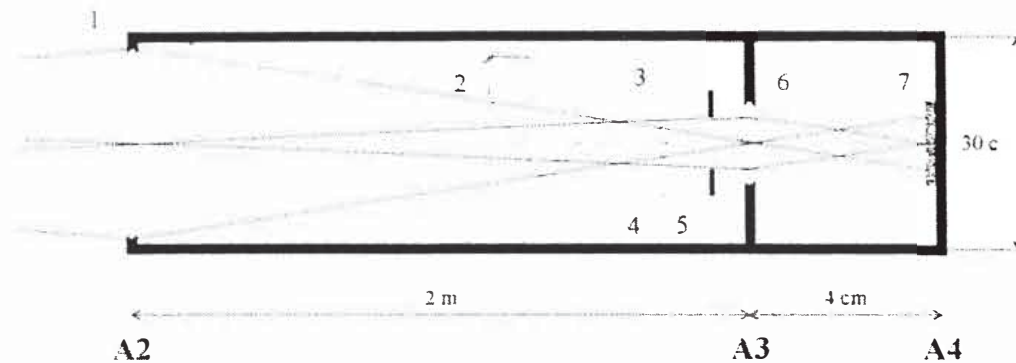


Fig.3. Optical scheme of the receiving unit

1 - field lens, 2 - guidance control system CCD-array, 3 - dichronic mirror, 4 - accessory light filters, 5 - mobile diaphragm, 6 - transfer lens, 7 - image receiver on the CCD-array

The plane A1 is optically aligned with the plane A3 and the plane A2 - with the plane A4. The field lens, the transfer lens and the image receiver are encased in a common opaque container which forms the receiving unit of the telescope. A sunshield screens the field lens from the direct solar light. To increase field-of-view of the telescope, a series of receiving units, installed immediately adjacent to one other, is used

Such an optical scheme of the receiving unit ensures that all light beams from the remote object that have passed the zoned plate and form the image in the A2 plane are gathered by the receiver. Moreover it makes it possible to avoid side lighting of the receiver.

The receiver must be guided onto the zoned plate. Special impulsive light source placed in the center of the zoned plate is used as a target for guidance control system of the receiving unit. The receiver should have a built-in guidance sensor to control the direction onto this source. Spectral bandwidth of the telescope can be overlapped by the spectra of the impulsive lamp in order to avoid an aliasing error during the operation. A spectral composition is specially chosen for this lamp.

Requirements to the performance accuracy are fairly lax for the zoned plate and the receiving unit. An admissible error of relative position for the zoned plate and the receiving unit may be calculated from the following expression

$$S = \pm \frac{D \cdot H}{2} \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2} \right) \quad (6)$$

where λ_1 and λ_2 - are the upper and lower borders of operation bandwidth

The admissible error of measurement of distance between the zoned plate and the receiving unit may be calculated from the expression

$$\Delta_z = \pm \frac{H^2}{\lambda} \quad (7)$$

The admissible displacement of separate parts of the zoned plate along the main optical axis is

$$\Delta_z = \pm 0.1 \frac{H^2}{\lambda} \quad (8)$$

Admissible uniform changes of the zoned plate diameter caused for example by temperature influence is

$$\Delta_{D_1} = \pm H \quad (9)$$

The admissible error of manufacturing of separate zones of the zoned plate is limited by the value of a quarter of the corresponding zone width in accordance to the Rayleigh criterion. For the last zone this value is equal to

$$\Delta_z = \pm 0.25H \quad (10)$$

Admissible errors of the zoned plate manufacturing leads to the quite large size of one diffractive resolution element in a plane of field lens. Its size is equal to width of the zoned plate last zone. In a case of usage of ordinary image sensors on the base of CCD-array the image of remote objects have to be reduced during transformation from the field lens. Each element of the diffraction resolution must be projected to a quite large number of sensors, for example for an subarray of 20x20 elements. In such case the problem of diffraction resolution limit may be overwhelmed.

Parameters of the proposed telescope may be estimated on the basis of calculations and laboratory research. These parameters for two possible schemes of the space-based very-high resolution telescope are listed in the Table 1. A telescope with such parameters may be developed at the first stage of the project implementation.

Values given for different tolerances below, have been calculated on the condition that the linear blurrance of images resulting from the deviations of one or another of the parameters of the telescope from the nominal values, would not exceed the size of the diffractive resolution element.

The admissible operating spectral bandwidth is 30 Å, it can be easily implemented by an interference light filter. Using of one light filter will lead to the definition in depth, or admissible unsharpness of the focus, equal to ±1.2 km. If a set of accessory light filters is implemented to choose an operating spectral band within the wavelength interval of 0.7-0.8 μm, then the range of operating distances between the zoned plate and the receiving unit is equal to 1200±80 km. The value of ±80 km can be regarded as an admissible error of relative position of the zoned plate and the receiving unit.

Requirements to the performance accuracy are fairly lax for the zoned plate and the receiving unit. For example admissible random misalignments are equal to ±120 m for the fringes of the zoned plate (relative to one another, in the direction of the optical axis), admissible variations for the diameter of the zoned plate are ±30 mm, resolution of the optics is enough to be 2 μm/mm for the receiving unit. The most strict requirement is for the correct relative position for the projection of the zoned plate's fringes to a plane which is perpendicular to the optical axis of the system. Admissible error can be a quarter of a fringe's width.

The necessary orientation accuracy of the telescope's units, is characterized by the following tolerances: perpendicular error for the planes of the zoned plate relative to the direction towards the receiving unit and guidance error for the receiver pointed at the zoned plate. These values are 1.8 degrees and 34 arcmin correspondingly. These requirements are also quite lax.

Table 1. Parameters of two possible schemes
of the space-based very-high resolution telescope

Characteristic	Scheme 1	Scheme 2
Diameter of the zoned plate	30 m	15 m
Wavelength	0.7-0.8 μm	0.7-0.8 μm
Diffraction resolution	0.005 arcsec	0.01 arcsec
Width of the outer fringe of the plate	3 cm	1.5 cm
Number of the opaque and transparent zones	250	250
Focal length of the zoned plate	1200 km	300 km
Focal length of the field lens	2 m	2 m
Diameter of the field lens	30 cm	30 cm
Number of the receiving units	20x20	10x10
Number of cells in the CCD-array of the receiver	200x200	200x200
Admissible variations for the diameter of the zoned plate	± 30 mm	± 15 mm
Admissible error of the outer zone position	± 7.5 mm	± 3.75 mm
Resolution of the receiving unit optics	2 pl/mm	2 pl/mm
Admissible error for the planes of the plate relative to the direction towards the receiving unit	± 1.8 degrees	± 1.8 degrees
Guidance error for the receiver pointed at the zoned plate	± 34 arcmin	± 34 arcmin

As has already been mentioned the focal length of the zoned plate is quite large. Thus, the zoned plate and the receiving unit have to be mounted on different spacecraft. These vehicles may be satellites of the Earth or of the Sun and may be linked by a rope system. There are two possible variants (Figs 4,5.) to place the units of the telescope in space. In the first variant (Fig. 4.), the zoned plate and the receiving unit follow each other in the same orbit at a distance equal to the focal length of the zoned plate. To maintain this distance constant, correction is applied for the displacement in the orbit. In such scheme the optical axis of the system rotates with the angular orbital speed. The telescope is directed to the remote object of survey depending on the choice of the orbital parameters and the time of survey.

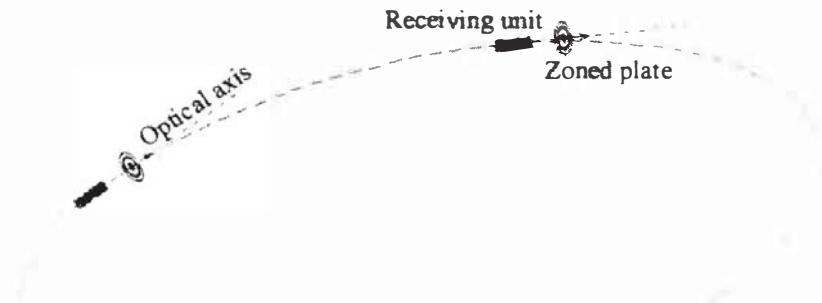


Fig.4. The zoned plate and the receiving unit mounted on two separate spacecraft following each other in the same orbit at a distance of focal length of the zoned plate.

According to the second scheme (Fig.5.) the zoned plate and the receiving unit move synchronously in two similar orbits. In this variant the optical axis of the telescope can be permanently pointed at one direction. High elliptical orbits are acceptable for survey according to this scheme. The survey is possible during the time when spacecraft pass the parallel parts of orbits. Due to the constant orientation of the optical axis a longer time of exposure can be provided to survey remote objects with low brightness. But a certain drift of the optical axis's direction relative to the stars can not be avoided. This results in a limitation in the time of exposure which is defined by the time for the optical axis to displace at the size of a resolution element. This value is equal to 0.005 arcsec in our case.

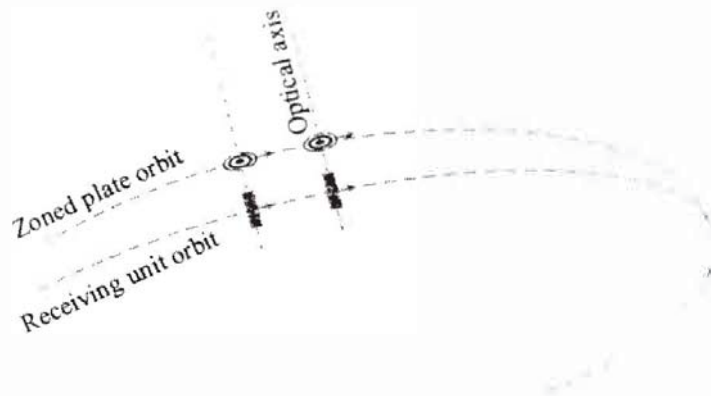


Fig.5. The zoned plate and the receiving unit mounted on two separate spacecraft move in two similar orbits synchronously. The distance between spacecraft orbits is equal to focal length of the zoned plate.

It is possible to increase the time of exposure during survey low brightness objects. The following surveying technique should be used. The law of the optical axis drift is defined before making a survey using information obtained from the CCD-array of the guidance system on which stars and the impulsive lamp of the zoned plate are imaged simultaneously. Based on this data the direction and velocity of the drift can be forecast for a coming survey. This drift may be compensated during a survey by the displacement of the receiving unit or the image receiver in the necessary direction and with the estimated speed. So, low brightness objects can be imaged.

It is not necessary to manufacture continuous transparent and opaque fringes for the zoned plate. Transparent gaps may be divided into sectors or series of transparent circular holes may be arranged to form the similar to the classical Sore plate (Fig. 6.) if the technology of elastic film or rigid unfolding frame produce will require it. The only requirement is that the area of each zone must be calculated according the expression (1).



Fig.6. Some possible schemes to produce the zoned plate.

The analysis of the telescope characteristics, requirements for the performance accuracy of the telescope's units, for the stability of its parameters and the accuracy of its orientation show that creation of the proposed telescope with a lens diameter of 30 m is possible. It is a realistic project, that would provide a new instrument with the unique features for astronomical explorations. There are no obvious obstacles preventing the development of a space-based telescope with a zoned plate of far larger dimensions.

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