ISSN 0038-0946, Solar System Research, 2020, Vol. 54, No. 7, pp. 685–689. © Pleiades Publishing, Inc., 2020.
Russian Text © The Author(s), 2019, published in Vestnik NPO imeni S.A. Lavochkina, 2019, No. 4, pp. 6–10.

Conceptual Design of the Chinese-Russian On-Orbit-Assembling Space Telescope (OAST)

Xu Boqian[a, *], Yu Funan[a, **], A. S. Shugarov[b, *], M. E. Sachkov[b, ****], I. S. Savanov[b, *****], Gao Yan[a, ******], Wang Shuaihui[a, *******], Ju Guohao[a, ********], Zhang Chunyue[a, *********], and Kuang Ye[a, **********]**

[a]*Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun, Jilin, 133033 China*
[b]*Institute of Astronomy, Russian Academy of Sciences, Moscow, 119017 Russia*
**e-mail: ciomp_xubq@126.com*
***e-mail: 84738033@qq.com*
****e-mail: shugarov@inasan.ru*
*****e-mail: msachkov@inasan.ru*
******e-mail: isavanov@inasan.ru*
*******e-mail: ynogg@163.com*
********e-mail: wshcan912@hotmail.com*
*********e-mail: juguohao@ciomp.ac.cn*
**********e-mail: zhangchunyue1992@163.com*
***********e-mail: kuangyecn@foxmail.com*

Received November 20, 2019; revised November 20, 2019; accepted November 20, 2019

Abstract—Astronomical space telescopes with large apertures of various spectral ranges have become one of the main tools of exploring the Universe. Conventional technologies do not allow increasing the space telescope aperture above several meters. This article describes the conceptual design of an UV and IR On-orbit Assembling Space Telescope (OAST) with an aperture of 10 m. Unlike conventional space telescopes, the OAST will be modularly designed, manufactured, and then assembled and alignment in space.

Keywords: space telescope, segmented mirror

DOI: 10.1134/S0038094620070205

INTRODUCTION

One of the main trends in the development of space telescopes is the construction of telescopes with a thin segmented main mirror of very large aperture. The use of segmented mirrors has allowed significant reductions in the specific cost of a collecting area of the main mirror and surpass the ten-meter limit. For example, the estimated postbuild budget of the 798-segment Extremely Large Telescope (ELT) project in construction with a main mirror aperture of 39.3 m is estimated to be 1.5 billion Euros. Compare this with the Large Synoptic Survey Telescope (LSST) project with a monolithic mirror of 8.4-m aperture whose cost is 600 million US dollars.

Despite significant progress with ground-based telescopes, their natural restrictions cannot meet all the modern requirements of astronomers. The adaptive optics systems of these telescopes are able to efficiently correct an image only in a very limited field of view (FOV), whereas the atmosphere reduces the photometric accuracy of ground-based observations in all spectral ranges. The Earth's atmosphere does not allow exploring embryonic objects in the early Universe with a large red shift. This requires making observations in the IR-range strongly absorbed by the Earth's atmosphere. The UV range is also absorbed by the Earth's atmosphere but carries a large amount of information and can also be used for searching for biomarkers in exoplanet atmospheres.

These and other reasons make it necessary to build new UV and IR space telescopes with large apertures and adopt new technologies for making these telescopes cheaper.

Conventional technologies limit the space telescope aperture to several meters. The overall budget of the Hubble space telescope with a monolithic mirror of 2.4-m aperture has reached truly astronomical value.

Despite using the segmented mirror technology, the James Webb Telescope is also very expensive (Lightsey et al., 2012).

The segmented main mirror with a 6.5-m aperture has a central block of 12 segments and two foldable side mirrors of three segments each.

The JWST's excessive cost seems to be related to the fact that this project is the intermediate solution between the classical telescope technology with a monolithic mirror and its fully on-orbit assembling counterpart.

Robotic manipulators suitable for assembling large structures in space have long been used with success at the International Space Station (ISS). The rapid development of robotics will eventually allow turning to the new concept of constructing orbital telescopes with large apertures, i.e., the telescopes will be assembled in space from relatively cheap standard modules with the possibility of replacing broken parts.

This article presents the conceptual design of an UV and IR On-orbit Assembling Space Telescope (OAST)—a relatively new idea for future space telescopes with a large aperture. The project's key elements are module design and optimization, the possibility of modular launching, on-orbit maintenance, and alignment of the telescope and science instruments after launch in orbit.

The project is proposed for implementation by an international consortium.

OAST Project: Research Tasks and Equipment

The set of science instruments of the future large-aperture space telescope must include:

—Multipurpose instruments able to solve a broad range of current and prospective research tasks (Boyarchuk et al., 2016). The requirement for having these instruments is stipulated by the need for meeting the demands of the largest possible amount of users.

—Unique instruments optimized for solving specific research tasks that have no optimal solution using multipurpose instruments but whose importance makes it worth making a specialized scientific instrument.

An example of a universal multipurpose instrument is the Space Telescope Imaging Spectrograph (STIS) of the Hubble Space Telescope (HST). This spectrograph is one of the HST's oldest instruments, was installed during servicing mission two (SM2) in 1997, has proven to be efficient, and still supporting up to 13% of applications.

A possible UV and optical spectral instrument for installation on the OAST is the Universal Orbital Spectrograph (UOS) with a similar design to STIS. The spectrograph must have a spectral range of at least 115 to 1100 nm, a spatial resolution of at least 0.1 arcseconds, several detectors (MCP, CCD, CMOS) and operational modes with different resolutions R from 1000 to 200 000. A special emphasis should be placed on the high resolution mode that will allow significantly surpassing the performance of the HST's UV spectrographs.

The research tasks it will be possible to solve with the UOS are: dynamics of stars, gas dynamics in the vicinity of galactic nucleus and black holes, absorption lines in quasar spectra and cores of active galaxies, nebulae and related objects (Herbig-Haro objects, H II regions), interstellar environment spectroscopy, protoplanet disks, exoplanets, Solar System aurorae, stellar activity, radial velocities and identification of new lines, ultrahigh-resolution stellar line profiles, etc.

The OAST must have onboard UV and optical Universal Orbital Camera (UOC) of high information capacity based on a CMOS or CCD detector (Shugarov et al., 2014) with a format of at least 9 × 9 k and an optimal pixel scale (at least 0.02 arcseconds/pixel). In terms of FOV, angular resolution, photometric accuracy, and long-term photometric and astrometric data, this camera will surpass the most cutting-edge ground based telescopes. The camera's main research tasks are obtaining direct images of various astrophysical objects using light filters, conduct ultradeep-field (UDF) surveys with very high-limiting magnitude and resolution.

According to the sensitivity of IR detectors, the IR range can be divided into the near and far IR ranges. Each of them needs a spectrograph and a camera for direct imaging.

Considering the predicted inaccessibility of US-made IR detectors, one of the main issues with designing IR channels will be the supplier of large IR detectors with specs acceptable for astrophysical research, as well as issues with cooling. The intensive recent developments of China's industry in this domain allows us to hope that the Chinese-Russian project will be equipped with the most modern and efficient radiation receivers.

The unique research instruments for consideration are those for exploring exoplanets (Fossati et al., 2014) and solving classical high resolution spectroscopy problems (Sachkov et al., 2004; Sachkov, 2010, 2014). There is no doubt that the number of discovered exoplanets, including those in habitable zone, will rise continuously in future decades. The OAST can have onboard a specialized UV spectrograph similar to the WUVS spectrograph of the WSO-UV project (Sachkov et al., 2014a, 2014b). This UV spectrograph can be used successfully for studying the atmosphere of exoplanets similar to Earth or Venus using H-Lyman alpha (122 nm)/O I (130 nm) transient intensity curve correlations. Due to the combination of the complex process of detecting the atmosphere of exoplanets and the very high significance of the research task, this instrument must be maximally optimized and have a separate FOV on the focal surface of the OAST.

Other specialized instruments worth mentioning are multipupil or long-slit spectrographs, including

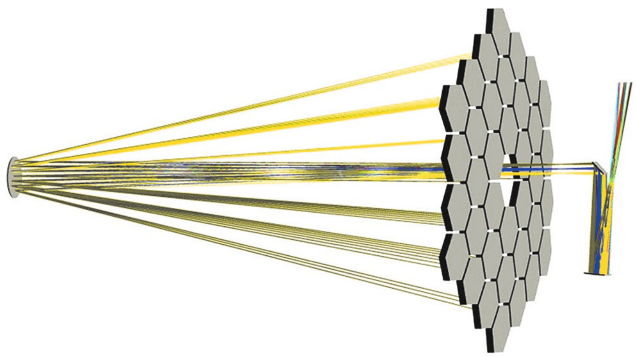

Fig. 1. Optical layout of the OAST with an aperture of 10 m (possible option).

the UV range (Panchuk et al., 2014). The technological feasibility of this spectrograph requires a more detailed elaboration.

Specialized space missions for exploring exoplanets are currently in development, for example, the HabEx project (Martin, 2018) maximally optimized for operation in the coronograph mode. The OAST's operational efficiency in this mode is a subject for investigation.

2. Conceptual On-Orbit Assembling Telescope with 10-m Aperture

According to (Lilie et al., 2010, 2017), the transition to the new technology of designing large-aperture space telescopes will allow changing the trend set by the conventional telescopes with a monolithic mirror. The OAST design concept with a 10-m aperture was developed to demonstrate the new approach. For the OAST triple-mirror axial optical system similar to the JWST was chosen (see Fig. 1). The optical path can accommodate additional flat mirrors for the active optical systems or for switching among the various science instruments. It is also possible to install instruments near the tertiary mirror in the main focus of the telescope.

When choosing between the axial and the off-axis optical configuration, the first one was preferred despite the fact that the second allows you to reach a larger FOV. The main issue of the off-axis configuration is asymmetrical reflecting elements, make difficult maintenance and repair of the OAST in orbit, since the mirror modules will not interchangeable.

The telescope's operational range is supposed to be from the near UV to the middle IR. We hope that in the future, it is possible to develop more effective coatings, capable of working in both UV and IR regions. The telescope is planned for operation in point L2 of the Earth—Sun system.

For the results of estimating of the wavefront error in the FOV at a wavelength of 632.8 nm, taking into account the expected errors of alignment, see Fig. 2.

The main parameters of the OAST observatory are shown in Table 1.

To build a large orbital telescope, it is first of all necessary to resolve several key issues.

(1) Manufacture a mirror with an aperture of 10 m. The thin segmented mirror with active shape control of each segment is apparently the only possible solution for large-aperture telescopes. To resolve the issue with the nanometer-precision phasing of segments, it is necessary to have a wavefront measurement system and a mirror control system (Contos et al., 2006); some robotic mechanisms will probably be required as well.

The telescope's primary mirror consists of 36 hexagonal segments, each of which is made as a discrete module. The Sun protection cover and the frame of the secondary mirror are made in the form of folding structures, which will allow saving space in the launch vehicle fairing.

(2) The standard scale of the assembly and alignment facility is comparable with the size of the main mirror, which makes very difficult and expensive to build it to operate with 10-m mirror, since the environment cannot be controlled at such scale. Another almost unresolvable issue is the gravity-free unloading of the large-aperture main mirror. These issues can be

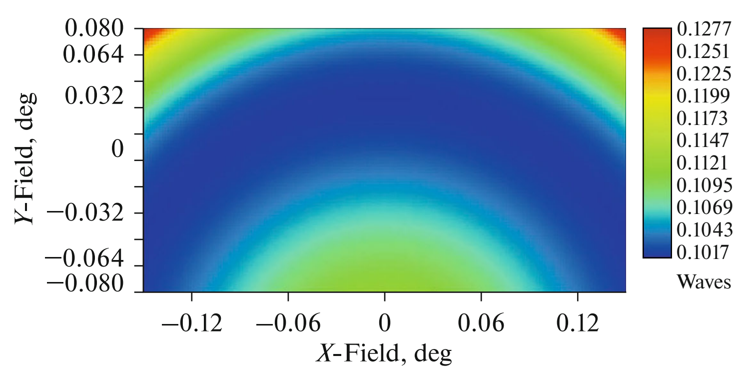

Fig. 2. Wavefront error in the field of view (FOV) at a wavelength of 632.8 nm.

Table 1. Main specifications of the OAST project

Parameter	Value
Aperture, m	∅10
Effective focus, m	200
Effective collecting surface, m^2	61.1
Spectral range, μm	0.2–29
FOV, arcmin	9.6 × 18 (WFE < 65 nm)
Image scale, arcsecond/μm	0.001
Wavefront error, RMS	λ/10
Orbit	L2 Sun–Earth
Available observation area	The whole sky throughout the year
Maintained service life, years	>30

resolved by refusal the assembly and alignment of the telescope on Earth and developing techniques for assembling and alignment in orbit (Feinberg et al., 2013).

(3) A large-aperture telescope can be inserted into orbit in a single-launch cycle using an advanced super-heavy Russian launcher with a fairing of about 7.5 × 20 m or by a triple-launch cycle using a heavy launcher, for example, a CZ-5B with a fairing of 5.2 m (Fig. 3).

(4) To assemble the telescope in orbit, it will be necessary to use at least two robotic manipulators. Since the procedure for capturing and installing of the modules can be a very complex procedure, each manipulator will need at least six degrees of freedom for fulfilling their respective tasks. The robotic manipulators will possibly have to exchange objects for fulfilling complex tasks, such as the assembly of the secondary mirror.

The telescope can be assembled in low orbit with the help of manipulators near a space station, which will reduce the project risks in the initial phase, after which the assembled telescope will be sent to libration point L2.

The possibility of launching a second spaceship with repair modules and the repeated use of the telescope's manipulators for replacing the telescope's science instruments or service systems at libration point L2 will reduce the long-term risks of the project.

CONCLUSIONS

The OAST project is one of the most feasible ways to build a 10-m class space telescope and has the following strengths:

—The problem of production of monolithic mirror is solved by using segments of moderate size.

—Modular design makes it unnecessary to test the assembled telescope on ground based facilities, and individual modules will be tested individually on existing equipment.

—Most of the OAST modules can be deinstalled and replaced, which makes the OAST more reliable

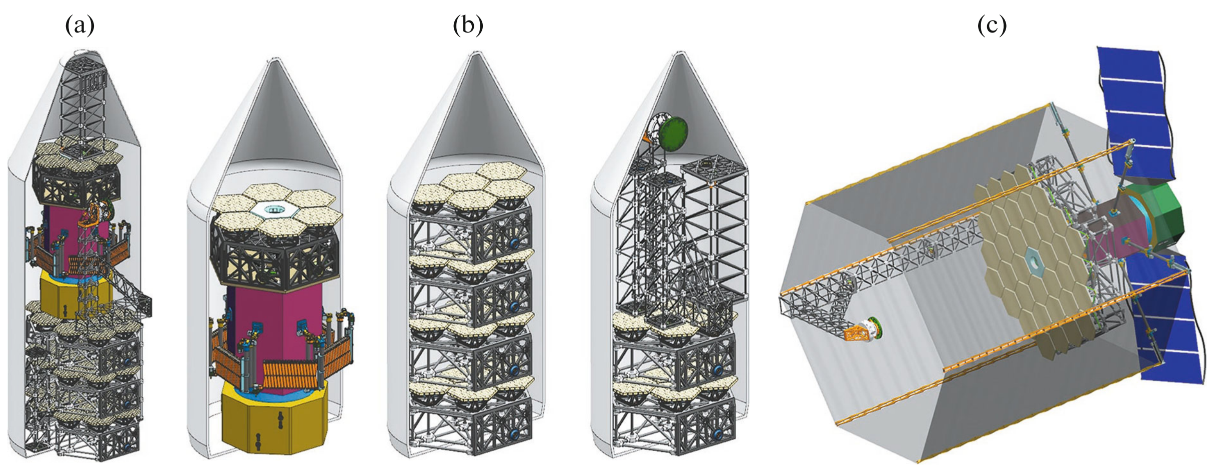

Fig. 3. General layout of the OAST: (a) the OAST with a disassembled single-launch approach; (b) the OAST with a disassembled triple-launch approach; (c) the assembled OAST.

and maintainable as compared with conventional telescopes.

—With international cooperation on the project, modular architectures make the interpartner collaboration much simpler.

—The project can be launched by several launchers, and the fairing size and the payload mass are no longer strict restrictions.

—The project cost and the mission risks are much lower than in the conventional approach.

—The equipment can be upgraded in orbit after launch.

At the moment, major space agencies are discussing the next-generation post-2030 UV or optical telescope projects. A large optical, UV, and IR space telescope will certainly be one of the key tools for exploring the Universe in this period.

ACKNOWLEDGMENTS

The CIOMP team is grateful to Professor Xiu Shuang for academic advice, many years of engineering experience, and the innovative ideas and research works mentioned in this article.

We also are grateful to the Ministry of Science and Technology of China for supporting and contributing to the development of new optical telescopes.

FUNDING

The works by the CIOMP were financially supported under China's key program of research and developments, project no. 2016YFE0205000 of the Ministry of Science and Technology of China.

REFERENCES

Boyarchuk, A.A., Shustov, B.M., Savanov, I.S., Sachkov, M.E., and Bisikalo, D.V., Scientific problems addressed by the Spektr-UV space project (World Space Observatory—Ultraviolet), *Astron. Rep.*, 2016, vol. 60, no. 1, pp. 1–42.

Contos, A.R., et al., Aligning and maintaining the optics for the James Webb Space Telescope (JWST) on-orbit: The wavefront sensing and control concept of operations, *Proc. SPIE*, 2006, vol. 6265, no. 62650X.

Feinberg, L.D., et al., Modular assembled space telescope, *Opt. Eng.*, 2013, vol. 52, no. 9, id. 091802.

Fossati, L., Bisikalo, D., Lammer, H., Shustov, B., and Sachkov, M., Major prospects of exoplanet astronomy with the World Space Observatory—UltraViolet mission, *Astrophys. Space Sci.*, 2014, vol. 354, pp. 9–19.

Lightsey, P.A., et al., James Webb Space Telescope: Large deployable cryogenic telescope in space, *Opt. Eng.,* 2012, vol. 51, no. 1, art. ID 011003.

Lillie, C.F., et al., A 4-m evolvable space telescope configured for NASA's HabEx mission: The initial stage of LUVOIR, *Proc. SPIE*, 2017, vol. 10398, no. 103980R.

Lillie, C.F., Polidan, R.S., and Dailey, D.R., Key enabling technologies for the next generation of space telescopes, *Proc. SPIE,* 2010, vol. 7731, no. 773102.

Martin, S., et al., HabEx space telescope exoplanet instruments, *Proc. SPIE*, 2018, vol. 10698, no. 106980T.

Panchuk, V., Yushkin, M., Fatkhullin, T., and Sachkov, M., Optical layouts of the WSO-UV spectrographs, *Astrophys. Space Sci.,* 2014, vol. 354, no. 1, pp. 163–168.

Sachkov, M., UV observations of sdB stars and prospects of WSO-UV mission for such studies, *Astrophys. Space Sci.,* 2010, vol. 329, nos. 1–2, pp. 261–266.

Sachkov, M., Study of pulsations of chemically peculiar A stars, *Astrophys. Bull.,* 2014, vol. 69, no. 1, pp. 40–45.

Sachkov, M., Shustov, B., and Gómez de Castro, A.I., Instrumentation of the WSO-UV project, *Proc. SPIE,* 2014a, vol. 9144, art. ID 914402. https://doi.org/10.1007/s10509-014-2087-4

Sachkov, M., Shustov, B., and Savanov, I., WSO-UV project for high-resolution spectroscopy and imaging, *Astron. Nachr.,* 2014b, vol. 335, pp. 46–50.

Sachkov, M., Ryabchikova, T., Kochukhov, O., Weiss, W.W., et al., Pulsational velocity fields in the atmospheres of two roAp stars HR 1217 and γ Equ, *ASP Conf. Proc.*, 2004, vol. 310, pp. 208–210.

Shugarov, A., Savanov, I., Sachkov, M., Jerram, P., et al., UV detectors for spectrographs of WSO-UV project, *Astrophys. Space Sci.,* 2014, vol. 354, no. 1, pp. 169–175.

Translated by S. Kuznetsov