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Perspective

Moon-based Earth observation

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Innovation and development in the field of Earth observation are motivated by the intrinsic requirements of attempts to achieve a deep understanding of the Earth system. In the course of these developments, a new understanding of the complete Earth system has highlighted the crucial importance of integrated observations, especially in research involving large-scale phenomena. Scientists are increasingly aware of the importance of observing the Earth as a whole, and research into the effects of complex interconnected Earth system processes on large-scale phenomena requires temporally consistent and spatially continuous geophysical data that are obtained at the global scale. Existing Earth observation systems are mainly composed of satellites, aircraft, and ground platforms. As the Earth's natural satellite, the Moon has the potential to be a new and valuable Earth observation platform. The vast lunar surface could support an almost unlimited number of instruments and provide a base for observations that could, essentially, continue forever. These observations, such as the interferometric synthetic aperture radar (SAR), would have a stable baseline and be synchronized with the lunar tides. Thus, using the Moon as a new Earth observation platform introduces the prospect of an ideal Earth observation system that will produce new insights for Earth system science. In this paper, results and conclusions obtained from the recent key project "Moon-based Earth observation for large scale geoscience phenomena", which was funded by the National Natural Science Foundation of China, and some other recent progresses are presented. Problems in the field of Moon-based Earth observation that remain to be addressed in the future are also discussed.

Since 1962, when the term "remote sensing" was promoted for the first time at the first International Symposium on Remote Sensing of Environment in the United States, our understanding of the Earth has continued to develop. Now remote sensing is important in many Earth science fields [1]. Of particular note are observations of large-scale phenomena related to interactions between various Earth system components, such as the interaction between land and ocean, changes in Arctic sea ice, the dynamics of the Earth's external radiation belts, and the interactions between the solar wind and the magnetosphere. The technology used to make observations from space has, at different times, included a range of Earth observation satellites, space shuttles, and space stations, and the sensors used have covered almost all parts of the electromagnetic spectrum from the visible to the infrared to the microwave region.

Earth system science requires long-term global observation data. Since the 1990s, many countries have presented their plans for observing the global environment. At present, the United States has established a comprehensive Earth observation system for observing geodynamics, ocean dynamics, climate change, the impact of the Sun on the Earth, the water cycle. ESA has been systematically deploying a global Earth observation system. The initial stage of this consisted of a global environment and security monitoring plan. In 2012, this plan was renamed "Copernicus", and more emphasis was put on promoting sustainable development and economic growth, increasing employment, and providing key information related to the environment and security. Over the past 40 years, China has also developed a satellite observation system from scratch; this system now consists of meteorological, resource, environmental, ocean, and high-resolution satellites. China is now focusing on improving its Earth observation satellite system in order to realize an efficient global observation and data acquisition system that provides an appropriate mix of high, medium, and low spatial resolution data that are obtained using an optimal combination of different observation techniques.

Although governments and space agencies have established Earth observation systems at particular scales, temporal consistency and spatial continuity are still difficult to guarantee at the global scale. Taking the Earth as a whole, the occurrence of large-scale phenomena and the changes in these phenomena are closely correlated. To help understand the key questions related to the coupling between the various components of the Earth system, a long-term, stable, planetary-scale observation platform that could acquire information about the Earth would be extremely valuable. Fortunately, the Moon can provide such a platform. By deploying multiple sensors on the lunar surface, continuous observations of multiple geospheres could be made. Moon-based Earth observation would be focused on following scientific objectives.

(i) Deepening the understanding of solid Earth dynamics. Crustal movements, e.g., solid tides, global plate movements, continental deformation, and glacial isostatic adjustment (GIA), are associated with large-scale crustal deformation signals, a low deformation gradient, and local anisotropy. By accurately measuring changes in the regional heterogeneity of the dynamic solid

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Earth, a deep understanding of plate movements that provides support to both geodynamic and seismic research can be obtained. Changes in the solid Earth depend on the tide-generating forces associated with astronomical bodies as well as the Earth's internal tectonic composition. Existing measurement methods, including in-site gravity and stress measurements, Global Navigation Satellite System (GNSS) measurement, and satellite radar interferometry, are mainly based on measurements made at point locations or over small spatial areas, and it is difficult to make continuous, high-resolution measurements of this type at a large scale. The Moon is a large and stable platform that could provide a long and stable baseline for making interferometric measurements. An imaging radar system on the lunar surface has a larger mapping swath, a flexible observation period, a range of observation modes, and meter-level resolution [2,3]. By establishing observation sites on the Moon, high-precision, large-scale deformation data could also be obtained for the solid Earth.

(ii) Understanding the Earth's radiation budget. At the top of the atmosphere (TOA), radiation is almost the only means of energy exchange. Changes in the outgoing radiation at the TOA, which reflects the amount of energy absorbed or released by the Earth system, are the most fundamental metric for defining the status of global climate change. Currently, measurements of radiation at the TOA are derived from satellite observations; however, these observations are not sufficiently accurate to determine the net radiation [4]. The use of the Moon as a platform for studying the Earth's radiation budget has unique advantages. First, as viewed from the Moon, the Earth can be regarded as a point, which means that measurements made from the Moon can be considered representative of the Earth's near-Moon hemisphere or near-Moon disk. Therefore, these measurements do not need to be meshed and re-integrated in the way that satellite data are. The use of a model called the global angular distribution model (ADM) based on satellite observations and reanalysis data has been proposed for describing the relationship between the radiance measured on the Moon and the actual total amount of outgoing radiation from the Earth [5]. In addition, to establish a reliable global ADM, a large amount of disk-integrated observation data would be required, and the Moon provides possibly the best place for acquiring these data [6]. Viewed from the Moon, the areas of ocean and land in the Earth's disk continuously change throughout the course of the diurnal cycle; the phase angle also continuously changes throughout the course of a lunar revolution but at a much lower angular speed. Therefore, data corresponding to almost all configurations of disk view and phase angle can be acquired within the space of only one month. The use of the Moon as a platform thus has huge advantages in terms of the speed of acquisition of data.

(iii) Enhancing understanding of the Earth's overall long-term reflected radiation signal and its polarization characteristics. Finding extraterrestrial life and a "second Earth" has long been the dream of humans. With the rapid development of space observation technology, the opportunity now exists to detect the atmospheres and surfaces of distant planets and to search for signs of life. Generally, the direct light of stars is non-polarized, whereas the light reflected by planets is usually polarized; in particular, circularly polarized light is often considered to be related to the presence of chiral organic compounds [7]. Clues related to the existence of extraterrestrial life can thus be obtained by analyzing the spectral polarization characteristics of light from distant stellar systems. Earth, the only planet known to support life, reveals the presence of life through its reflectivity, scattering properties, and atmospheric composition, and so is an ideal sample on which to base studies that attempt to detect life on exoplanets. The Moon is far enough from the Earth and its long-term motion sufficiently stable to make it the idea platform for detecting signals related to the presence of life on Earth, and the Moon is also used as a "mirror" to obtain information about the radiation reflected from the Earth; these data were then used to look for signs of life on the Earth [6,8]. In recent years, using direct observations made on the Moon to search for signs of life on Earth has also been proposed [9].

(iv) Monitoring the near-Earth space environment and near-space targets. Most satellites operate in near-Earth space, so more distant platforms are needed to observe this region. The distance between the Earth and the Moon is about 378,000 km, which means that Moon-based sensors are located far enough from the Earth to be able to observe the entire near-Earth space. Observing changes in the space environment is one of the main scientific goals of near-Earth space observation. In 1972, the United States positioned a far-ultraviolet camera on the Moon, and China landed an extreme ultraviolet camera on the lunar surface in 2013; these cameras were used to observe the Earth's plasma and capture its dynamics during magnetic storm activity. New research also shows that a Moon-based X-ray imager could be used to image the Earth's magnetosphere, thus allowing its interaction with the solar wind to be studied [10]. Moon-based sensors can also be used to detect artificial or natural targets in near-Earth space. In contrast to a ground-based monitoring network, these sensors would not be affected by the Earth's atmosphere, would be more sensitive to targets approaching the Earth, and would have a larger field of vision than satellites.

(v) Discoveries based on observations of interconnections between different geospheres. Observations made using the Moon as a platform are carried out at a large spatial scale and have a high temporal resolution. In a lunar observatory, active and passive sensors could be integrated, thus enabling multi-band observations that could provide "three-dimensional" information about large-scale geoscience phenomena in all of the geospheres. This could include information about global atmosphere–ocean-land interactions, atmospheric processes, coastal zone process, etc. Special attention could be paid to regional differences, cumulative changes, spatial teleconnections, lagged correlations, scale correlations etc. A Moon-based platform would have advantages in some areas where traditional satellite remote sensing has weaknesses, such as the ability to observe large-scale processes and phenomena. These areas include (1) the dynamics of the global and hemispheric atmospheric circulation and how it drives the weather; (2) ocean currents and their impact on the redistribution of heat in the atmosphere; (3) the intercontinental transport of air pollutants; (4) the occurrence and development of extreme intercontinental climate events and the spatial teleconnections between them; and (5) the synchronicity or asynchronicity of the snow and ice freeze–thaw cycles in the three "polar" regions.

Establishing a complete Moon-based Earth observation platform that has the ability to observe multiple geospheres would be a major, complex engineering project. The needs of both scientific and social development as well as technical capabilities need to be considered when formulating medium- and long-term goals and plans related to such a development. The establishment of a Moon-based Earth observatory would consist of two main phases. The first phase would be the establishment of an unmanned observatory comprised of small instruments. In the second phase, the observatory would be improved and expanded, which would require the establishment of a permanently manned Moon base. Guo et al. [11] considered the potential performance of a variety of remote sensing instruments on the Moon and proposed the optimal types of sensors—including radiometers, spectrometers and SAR systems—that could be part of a lunar observatory. Fig. 1 shows a conceptual illustration of Moon-based Earth observation with optical telescope, radar under the support of a large Moon base and a data relay satellite.

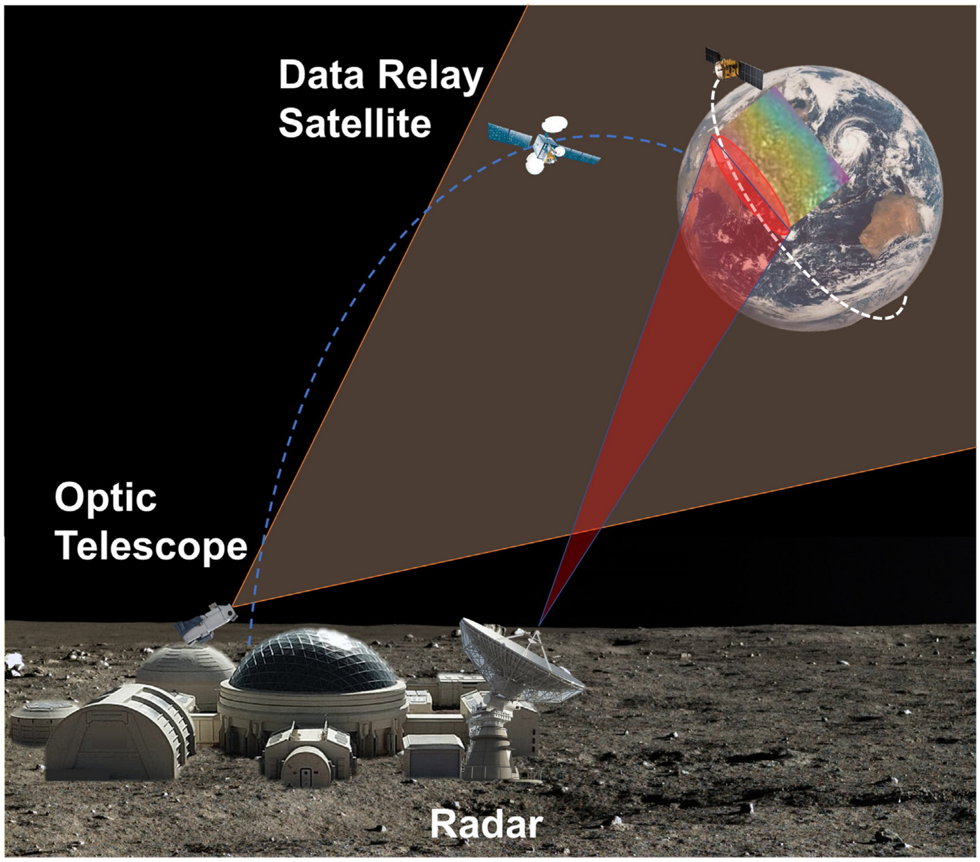

Fig. 1. A conceptual illustration of Moon-based Earth observation.

The tasks involved in the establishment of such an observatory would need to be carried out in sequence according to difficulty. Moon-based observations of the Earth's outgoing radiation would require a combination of a broadband radiometer and an array imaging spectrometer, using the former to measure the radiance in the direction of the Moon and the latter to make simultaneous observations of the composition of the Earth's atmosphere and surface and the state of the clouds. The use of these two types of sensor presents no obvious technical obstacles, and the mature methods applied to existing satellite systems could be used as a basis for the data acquisition and processing. At present, the measurement system has entered the stage of parameters precise design such as measurement accuracy, stability, and sampling rate. It is anticipated that a system for measuring the Earth's radiation balance will be established on the Moon within the next 10 years, thus providing a new means of monitoring climate change [12].

Large-scale deformations of the Earth's surface due to crustal movements can be traced using Moon-based interferometric synthetic aperture radar (InSAR) [13]. Recent studies have mainly focused on signal properties and the configuration of InSAR systems [14,15], and examples of systems used for different applications have been presented. Simulations indicate that the swath of a Moon-based SAR system would be large enough to make continuous measurements of deformations of the Earth's surface and that its sensitivity would be high enough to determine the deformation gradient [15]. Due to the large distance between the Earth and the Moon, the power requirements and antenna size of a Moon-based SAR system would present great technical challenges. Future efforts toward this goal should concentrate on the best compromise between different systems designed for different applications and on the necessary support technologies.

A lunar platform would be a major innovation in the field of Earth observation; however, the most important concerns are the observation objectives and the related scientific issues. Potential objectives could relate to the oceans (temperature), climate (precipitation, temperature, and radiation), vegetation and the composition of the atmosphere (greenhouse gases), focusing on the couplings involved in the key processes that are part of the energy budget, carbon cycle, and water cycle. Moon-based Earth observation will face great technical constraints related to transportation (into space), construction, and energy supply. Integrated design, hardware optimization, and improved data-processing methods are needed to reduce costs and help with the achievement of goals. Considering that it will take a relatively long time to fully establish a Moon-based Earth observation system, related research should take into account the overall development of technology over the next 20–30 years. The establishment of a Moon-based Earth observation system would involve many scientific and engineering disciplines and constitute one of the largest feats of engineering in human history. It would be very difficult for such a system to be established by one country acting on its own, and international cooperation will be necessary to achieve this goal. As one of countries most active in lunar exploration, China can play an important role in international cooperation in the field of Moon-based Earth observation. We believe that a Moon-based Earth observation system will be constructed to serve the sustainable development of humankind.

Conflict of interest

The authors declare that they have no conflict of interest.

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Appendix A. Supplementary materials

Supplementary materials to this perspective can be found online at https://doi.org/10.1016/j.scib.2022.08.014.

References

[1] Reid WV, Chen D, Goldfarb L, et al. Earth System Science for global sustainability: grand challenges. Science 2010;330:916–7.
[2] Guo H, Ding Y, Liu G, et al. Concept research of Moon-based imaging radar for global change detection. Sci China: Earth Sci 2013;43:2450–60.
[3] Renga A, Moccia A. Moon-based Synthetic Aperture Radar: review and challenges. New York: IEEE; 2016. p. 3708–11.
[4] Johnson GC, Lyman JM, Loeb NG. Improving estimates of Earth's energy imbalance. Nat Clim Chang 2016;6:639–40.
[5] Shang H, Ding Y, Guo H, et al. Simulation of Earth's Outward Radiative Flux and its radiance in Moon-based view. Remote Sens 2021;13:2535–61.
[6] Pallé E, Goode PR. The lunar terrestrial observatory: observing the Earth using photometers on the Moon's surface. Adv Space Res 2009;43:1083–9.
[7] Sparks WB, Hough J, Germer TA, et al. Detection of circular polarization in light scattered from photosynthetic microbes. Proc Natl Acad Sci USA 2009;106:7816–21.
[8] Pallé E, Osorio M, Barrena R, et al. Earth's transmission spectrum from lunar eclipse observations. Nature 2009;459:814–6.
[9] Hoeijmakers HJ, Arts MLJ, Snik F, et al. Design trade-off and proof of concept for LOUPE, the Lunar Observatory for Unresolved Polarimetry of Earth. Opt Express 2016;24:21435–53.
[10] Guo YH, Wang C, Wei F, et al. A lunar-based soft X-ray imager (LSXI) for the Earth's magnetosphere. Sci China: Earth Sci 2021;64:1026–35.
[11] Guo H, Liu G, Ding Y. Moon-based Earth observation: scientific concept and potential applications. Int J Digit Earth 2018;11:546–57.
[12] Xu L, Zou YL, Jia YZ. China's planning for deep space exploration and lunar exploration before 2030. Chin J Space Sci 2018;38:11–2.
[13] Li DW, Jiang LM, Jiang HJ, et al. InSAR phase simulation of solid Earth tide and its influence on surface deformation monitoring at wide-area scale. Chin J Geophys 2019;62:4527–39.
[14] Xu Z, Chen KS. Effects of the Earth's curvature and lunar revolution on the imaging performance of the Moon-based synthetic aperture radar. IEEE Trans Geosci Remote Sens 2019;57:5868–82.
[15] Wu K, Ji C, Luo L, et al. Simulation study of moon-based InSAR observation for solid Earth tides. Remote Sens 2020;12:123–42.

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