Quantum Electronics **33** (1) 45 – 47 (2003)

PACS numbers: 06.30.Bp; 96.20.Jz; 42.55.-f
DOI: 10.1070/QE2003v033n01ABEH002363

Lunar laser ranging: 40 years of research

Yu.L. Kokurin

***Abstract*. The history of the origin and development of the lunar laser ranging is described. The main results of lunar laser ranging are presented and fundamental problems solved by this technique are listed.**

Keywords: *lunar laser ranging, relativistic and gravitational effects, applications in astrometry, geodesy, geodynamics, geophysics.*

In 1962, Nikolai Gennadievich Basov advised the scientists of the Crimean research station of the Lebedev Physics Institute (FIAN) in the settlement of Katsiveli to use the ruby laser, designed at FIAN, for lunar laser ranging. In the very next year, a laser ranging equipment was mounted on the ZTSh-2.6 telescope, and signals reflected from the Moon were detected with the help of this equipment [1]. This research was carried out jointly by the scientists from FIAN and the Crimean astrophysical observatory. Chronologically, this was the second experiment after the one conducted in the USA a year earlier [2]. These experiments paved the way towards a new branch of research work, the laser ranging of space objects. Although the technical details of the two experiments were slightly different, free-running ruby lasers emitting 1 – 2-ms pulses were used in both, corresponding to an error of $\sim 150 - 300$ km in the measurement of the distance to the Moon, and hence the problem of measuring distances was not posed. These experiments were aimed at confirming the possibility of lunar laser ranging in actual practice.

First measurements of the distance from the Moon, having a certain practical significance, were made in 1965 [3]. A laser with a pulse duration $\sim 5 \times 10^{-8}$ s (corresponding to the distance measurement error of 7.5 m) was used in these experiments. However, the actual error in the distance measurement was determined not by the parameters of the equipment, but by the 'depth' of the object being located, i.e., the roughness of the lunar relief within an area illuminated by the laser beam and the inclination of this area to the laser beam. This error was found to be of the order of 200 m, and the results could be used for evaluating the precision of the lunar ephemerides (a precision of up to 3 km had been attained by that time in measurements of the topocentric distances from the lunar surface).

It became clear from the first simple estimates [4] that lunar laser ranging will lead to a considerable refinement of the basic parameters of the Earth – Moon system, resulting in a significant progress in the solution of many problems of selenodesy, astrometry, geophysics. It follows from these and subsequent estimates [5, 6] that this requires a high degree of precision in the measurement of distances to the Moon. The advantages of laser ranging become evident for errors of a few meters: the basic parameters of the Earth–Moon system are determined with a precision that is an order of magnitude higher than the precision inherent in classical goniometric methods. Such results could be attained by localising the reflection points at the lunar surface, i.e., by installing small targets on the Moon for an efficient reflection of light towards the observer. Five such targets (corner reflectors) were brought to the Moon between 1969 and 1973. Of these, three were carried by American expeditions (Apollo-11, Apollo-14 and Apollo-15) and two French reflectors were mounted on Soviet self-propelled vehicles Lunokhod-1 and Lunokhod-2. New laser ranging devices were fabricated in a number of countries for measurements involving corner reflectors.

Regular measurements of the distance to lunar reflectors were started in 1969 at the Macdonald observatory in the USA with the help of a 2.7 m diameter telescope. The initial measuring error of ~ 3 m was subsequently reduced to ~ 15 cm by 1972. Between 1984 and 1987, laser ranging operations were gradually shifted to the specially created station MLRS equipped with a telescope of diameter 0.76 m [7, 8]. The ruby laser was replaced by the YAG crystal laser. This station now carries out regular measurements of distances to the Moon and to high-orbit geodynamic artificial Earth satellites (AESs). The measuring error has now been reduced to 1 – 3 cm. During the last three decades of observations at the Macdonald observatory, data arrays containing over 6000 normal points have been accumulated. Lunar laser ranging projects started at other observatories in the USA (AFCRL observatory and the Harvard University observatory) were terminated for various reasons. A brief cycle of measurements was carried out in the late 1980s at the Haleakala observatory (Maui island) of the Hawaii University.

For a long time, preparations for laser measurements of the Moon were made in France at the Pic-du-Midi Observatory where a multi-element telescope of diameter 6m was constructed for this purpose. Its parameters could not be brought to the required level, and the lunar laser ranging

Yu.L. Kokurin Crimean Laser Observatory, ul Shuleikina 13, 98688 Katsiveli, Crimea, Ukraine

Received 15 July 2002
Kvantovaya Elektronika **33** (1) 45 – 47 (2003)
Translated by Ram Wadhwa

work was transferred to the newly created CERGA geodynamic observatory at the Cote d'Azure, where regular laser observation of lunar targets (Apollo-11, Apollo-14, Apollo-15 and Lunokhod-2) were started in 1983 [9]. The measurement error is only 1 – 2 cm at present, and efforts are being made to bring it down to subcentimeter range. The number of normal points obtained by this observatory since 1983 exceeds 8000.

Measurements of distances to lunar reflectors were started in the USSR in 1969 at the Crimean astronomical observatory, but they acquired a regular status only four years later when the automated laser ranging complex with a measuring error not exceeding 0.9 m was commissioned. By 1978, a new model of the laser radar with a single measurement error of ~ 25 cm was constructed. A total of about 1400 single measurements of distances mainly to two reflectors (Lunokhod-2 and Apollo-15) were made at the Crimean astronomical observatory [10]. Following the winding up of the lunar space research programmes in the country, these measurements were terminated in 1983.

Simultaneously with the lunar observations with the help of the ZTSh-2.6 telescope, five transportable stations with 1-m diameter telescopes were constructed at FIAN for laser ranging of AESs. One of these stations was intended both for AESs and lunar ranging. However, this station could not be perfected for lunar ranging and it is currently used for regular observation of AESs with orbits up to 40 000 km. Three other stations from this series are being used for regular observation of low orbit and geodynamic AESs.

Currently, the construction of a laser ranging station in Matera (Italy) is in its final stages. This station employs a mode-locked laser emitting 50-ps, 100-mJ pulses. Test observations from this station were performed successfully in 1998.

Attempts at lunar laser ranging made during 1960s and 1970s in Japan (Okayama observatory) were not successful and were gradually ceased.

A similar situation occurred in Australia (Ororal observatory) where a 1.5-m telescope was relocated from the AFCRL observatory in the USA for this purpose. However, many years of activity in this observatory directed at lunar laser ranging did not yield any perceptible results.

A multipurpose geodynamic observatory was constructed in Wetzel (Germany) with lunar laser ranging as one of its objectives. However, only some trial measurements were made here and regular observations of the Moon are not carried out at this observatory.

China is also planning to create lunar laser ranging equipment, but work in this direction is only at its initial stage.

It must be mentioned that high-precision lunar laser ranging is an extremely complex scientific and technical problem. Suffice it to say that the reflected signal received for really attainable parameters of the laser ranging equipment is just a few tenths of a photon per laser pulse. The detection of such a signal with a precise ($10^{-6} - 10^{-7}$ s) matching to the universal-time scale in the presence of stray illumination requires the application of statistical signal accumulation together with an efficient spectral and space – time selection. Therefore, a lunar laser recording system is a unique complex that can be created only by highly developed nations that have the most advanced technologies at their disposal.

Despite the fact that an array of laser targets has been established on the Moon for investigations in the fields of astrometry, selenodesy and lunar physics, only two observatories on the Earth are carrying out regular measurements of distances to these targets, which somewhat restricts the applicability of this method for investigating the problems connected with the Earth. The establishment of at least one more observational point would considerably enhance these possibilities.

Together with the experimental studies, further advances have been made in developing the techniques for solving a wide range of problems using the lunar laser ranging data. These include the problems of geodesy, geodynamics, geophysics, astronomy, selenodesy, lunar physics, and theories of relativity and gravitation.

The results of lunar laser ranging are analysed mainly in the USA (the Texas University and the Jet Propulsion Laboratory (JPL) of the California Institute of Technology) and in France (the Paris observatory).

Consider now briefly the results obtained from the lunar laser ranging data.

Geodesy, geodynamics, geophysics. The potentialities of lunar laser ranging were demonstrated for the first time in 1975 when the chord connecting the Macdonald observatory and the Crimean astrophysical observatory was measured. The initial error of about 2 m in determining the length of the chord was subsequently lowered to 0.6 m [11]. At present, the geocentric coordinates of the observational points can be determined to within $\sim 1 - 2$ cm.

It was mentioned above that there are only two observatories (SERGA and MLRS) at which regular lunar laser ranging measurements are being made. This is not sufficient for large-scale geodesic and geodynamic measurements. In particular, the possibilities of investigations of tectonic phenomena, i.e., studies of the deformation of the Earth's crust and the drift of continents, are quite limited. Nevertheless, lunar laser ranging has made it possible to investigate the slowing down of Earth's rotation caused by lunar tides, correct the parameters of Earth's precession and nutation, and to refine its main moments of inertia. In the field of geodynamics, lunar laser ranging is mainly used for determining the parameters of Earth's rotation: the duration of the day is found with an error of no more than 0.1 – 0.2 ms, while the coordinates of the pole are determined to within 2 – 3 cm. These results supplement the data base of the International Earth Rotation Service (IERS).

Astrometry, selenodesy, lunar physics. One of the most significant applications of lunar laser ranging is the construction of new and more perfect mathematical models of the Earth – Moon system, and creation of precise ephemeries of the Moon. These investigations are performed within the framework of a more general model (Solar system model) taking into account the mutual influence of the Sun, the Earth, the Moon, planets and large asteroids. The error in the preliminary calculations of the topocentric distances to corner reflectors on the Moon is 10 – 40 cm at present. The main parameters of the Earth – Moon system are determined from the laser ranging data with an accuracy several orders of magnitude higher than from the classical angle measurements. For example, the mean radius of the lunar orbit has been refined by more than four orders of magnitude, the mutual orientation of the planes of the Earth's equator, the lunar orbit and the ecliptic have been refined by two orders of magnitude, ect. Measurements of the motion of the baricentre of the Earth – Moon system around the Sun have resulted [12] in the evaluation of the ratio of the mass of this system to the mass of the Sun with a high degree of accuracy ($\sim 10^{-8}$).

The tidal acceleration of the lunar orbital motion leading to an increase of 3.8 cm per year in the lunar orbit radius was also studied.

Lunar laser ranging has been used for finding the selenocentric coordinates of corner reflectors, which forms the basis of lunar cartography [13]. The proper rotation of the Moon (physical and free libration), its tidal deformation and gravitational field have been studied with a much higher degree of precision than by using classical methods. The moments of inertia of the Moon with respect to its principal axes have been determined. All these data are used for constructing a model for the internal structure of the Moon. An analysis of the mass distribution in the Moon suggests the existence of a liquid core whose radius is estimated as ~ 350 km [14].

Relativistic and gravitational effects. Lunar laser ranging is being used successfully for verification of the relativistic and gravitational theories for bodies in the solar system. Note the most significant results obtained in this field. A violation of the principle of equivalence of the the gravitational and inertial masses must lead to a displacement of lunar orbit towards the Sun by an amount $\Delta r = 12.8\eta\cos(\omega t)$, where ω is the orbital velocity of the Moon, and Δr is measured in metres [15]. An analysis of the results of lunar laser ranging led to the value $\eta \leqslant 10^{-3}$ for the Nordvedt parameter. This corresponds to a departure from unity of about 3×10^{-13} in the ratio of the gravitational and inertial masses, which confirms the validity of the principle of equivalence for bodies of the cosmic scale with a high degree of accuracy. Studies of the orbital motion of the Moon revealed that the secular decrease in the gravitational constant $G^{-1}(\mathrm{d}G/\mathrm{d}t)$ does not exceed 10^{-11} per year [16]. The relativistic (geodesic) precession of the lunar orbit associated with the motion of the Earth and the Moon around the Sun was also investigated. According to the general theory of relativity, its value (angular velocity of the lunar orbital nodes) is 19×10^{-3} angular seconds per year. The actually observed value agrees with the theoretical value to within 2 %.

Even this partial list of the problems and the results obtained in the course of their solution lead to the conclusion that lunar laser ranging, which was initiated forty years ago by simple experiments, has now become an efficient modern research tool that is being used in various fields of science.

Lunar laser ranging is not the only field of applications of lasers in space research. Many of the above-mentioned problems make wide use of the laser ranging of AESs. However, this subject is beyond the scope of this paper.

References

1. Grasyuk A.Z., et al. *Dokl. Akad. Nauk SSSR*, **154**, 1303 (1964).
2. Smullin L.D., Fiocco G. *Proc. IRE*, **50**, 1703 (1962).
3. Kokurin Yu.L., Kurbasov V.V., Lobanov V.F., Mozhzherin V.M., Sukhanovskii A.N., Chernykh N.S. *Pis'ma Zh. Eksp. Teor. Fiz.*, **3**, 219 (1966).
4. Kokurin Yu.L., Kurbasov V.V., Lobanov V.F., Mozhzherin V.M., Sukhanovskii A.N., Chernykh N.S. *Kosmichesk. issled.*, **IV** (3), 414 (1966).
5. Abalakin V.K., Kokurin Yu.L. *Usp. Fiz. Nauk.*, **134** (3), 526 (1981).
6. Mulholland J.D. *Reviews of Geophysics and Space Physics*, **18** (3), 549 (1980).
7. Shelus P.J. *X International Laser Workshop* (Shanghai, 1996) Vol. 2, pp 183, 185.
8. Shelus P.J., Ricklefs R.L., Wipple A.L., Wiant J.R. *AGU Geodynamic Series*, **25**, 183 (1993).
9. Veillet C., Mangin J.F., Chabaudie J.E., Dumalin C., Ferraudy D., Torre J.M. *AGU Geodynamic Series*, **25**, 189 (1993).
10. Kokurin Yu.L., Kurbasov V.V., Lobanov V.F., Sukhanovskii A.N. Preprint FIAN (127) (Moscow, 1974).
11. Calame O. *Compt. Rend. B*, **280**, 551 (1975).
12. Shelus P.J., Ries J.G., Williams J.G., Dickey J.O. *XII International Laser Workshop* (Matera, 2000).
13. Davies M.E., Colvin T.R., Meyer D.L. *J. Geophys. Rev. B*, **13**, 92, 14177 (1987).
14. Williams J.D., Dickey J.O. *ILRS Annual Report*, 208 (1999).
15. Nordvedt K. *Phys. Rev.*, **170**, 1186 (1968).
16. Williams J.D., Newhall X.X., Dickey J.O. *Phys. Rev. D*, **53**, 6370 (1996).