Optical location of the Moon

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As early as the late twenties, N. D. Papaleksi had discussed with L. I. Mandel'shtam the problem of observing electromagnetic signals transmitted from the Earth and reflected by the Moon.[1] The technical possibilities existing at that time did not allow one to expect an experimental realization of this idea. However, N. D. Papaleksi retained interest in it for a long time. Already at the time of the Second World War, he again turned to examining this problem. The development of military radio rangefinding and pulsed techniques served as the basis for finding a prognosis and planning experiments on the radiolocation of the Moon. N. D. Papaleksi carried out and published in 1946 a detailed calculation of such an experiment.[2] At the same time he treated the problem of the optical location of the Moon. Here, in contrast to radiolocation, no serious material prerequisites were available. Nevertheless, the calculations that he performed encompassed practically all the most important aspects of this problem and have maintained their topicality up to the present. N. D. Papaleksi went further, for he showed that direct rangefinding measurements of the distance to the Moon can be employed to solve problems of geodesics and astronomy. Now it seems remarkable that this study was performed at that time, when neither lasers, nor electronic computers, nor space ships existed, on which one could deliver to the Moon rangefinder targets, i.e., the means that have made it possible to convert the optical location of the Moon into a new method of studying the Earth-Moon system—into a new field of science.

Almost two decades passed since the publication of this study until the idea involved in it of optical location of the Moon was realized in practice. By this time, not only had the technical potentialities arisen, but also a pressing need for developing these studies, which was dictated by the increased demands on our knowledge of the dynamics of the Earth-Moon system in connection with space flights.

In our country the first experiment on optical location of the Moon was performed in 1963 by colleagues at the Institute of Physics of the Academy of Sciences and the Crimean Astrophysical Observatory.[3] A diagram of this experiment, which with various complications is still being used, is shown in Fig. 1. A light beam generated by the laser source *LS* is collimated and directed toward the desired point on the Moon by the telescope *T*. The signal reflected by the Moon enters the same telescope and is directed by the "transmit-receive" switch *S* through the diaphragm *D* and the interference filter *IF* to the photoreceiver *PR*. The time of propagation of the light signal to the Moon and back is measured with the time interval meter *TIM*, which is triggered by the laser pulse and stopped by the received signal. Both in this and in all subsequent experiments, the ZTSh telescope of the Crimean Astrophysical Observatory with a principal mirror of 2.6 meter diameter was used. In the first experiment a ruby laser in a free-generation regime was used as the radiation source. It gave pulses of 50–70 J energy of duration ~2 ms. The receiver for the reflected signal was a photomultiplier in a photon-counting regime. The time of propagation was measured with an oscillograph with a slave sweep. With this instrument, primitive by today's standards, they could detect the signal reflected by a region of the Moon's surface at the bottom of the crater Albategnius lying near the center of the lunar disk. The magnitude of the signal amounted to 1.5–2.0 photoelectrons per laser pulse. The problem of distance measurement was not posed in this experiment, since the error in the measurement, which corresponded to the duration of the laser pulse, amounted to about 300 km. The aim of this experiment consisted in confirming the practical possibility of optical location of the Moon and in testing the validity of the calculations on which the experiment was based.

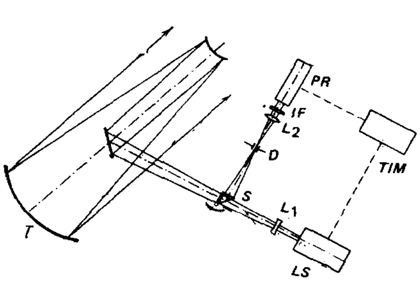

FIG. 1. Diagram of a laser rangefinder.

The first measurements of the distance to the Moon having practical value were performed in 1965.[4] This experiment employed a Q-modulated laser of energy 5–7 J per pulse of duration 5×10^{-8} s, together with a more refined time-interval meter based on scalar cells. The time resolution of this apparatus was $\sim10^{-7}$ s, which corresponded to an error of distance measurement of ~15 m. However, the actual error of the measurements was about 200 m, which arose from the unevenness of the area of the Moon illuminated by the laser (its diameter was ~several km) and from the inclination of this area to the beam. Nevertheless this result already could be used to evaluate the accuracy of the prior calculations of the ephemeris, whose error had been reduced at that time to 1–3 km.

The calculations that we performed in 1965 showed[5] that direct measurements of the distance to the Moon can offer substantial advantages in studying the Earth-Moon system as compared with the traditional angle-measuring observations. These advantages become the

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more appreciable as the accuracy of the distance measurements rises. Even with errors of the order of several meters, the parameters of the Earth-Moon system are determined one or two orders of magnitude more accurately than by angle-measuring methods.

On the other hand, it was evident that further increase in accuracy was possible only under the condition that the points of reflection could be localized, i.e., under the condition that location targets of small dimensions could be installed on the Moon.

Therefore all further studies were conducted according to a program involving the building and delivery to the Moon of special corner reflectors for laser rangefinding. Five reflectors were set up on the Moon during 1969–1973: two French, installed in the "Lunokhods-1 and -2", and three American, delivered in the space ships "Apollo-11, -14, and -15". Thus a network of reference points was created on the Moon that was quite suitable for prolonged regular measurements (Fig. 2). The French and American reflectors substantially differ in design, although both amount to sets of triple prisms fixed on a common panel. Figure 3 shows a French light reflector. It consists of 14 prisms made of a highly uniform glass. The directional diagram of the prism covers ~6". The high requirements on the accuracy of the angles and planes, on the optical homogeneity of the material of the prisms, on the mechanical strength, on the weight characteristics, etc., are heightened further by the need for conserving the optical characteristics under the severe temperature conditions on the Moon. Therefore, in designing such a reflector, a number of complicated engineering and technical problems had to be solved.

In the program of preparing for the observations of the Lunokhod-1 reflector, we built a complex of apparatus to enable an accuracy of measurements of distances ~3 m. However, owing to an insufficient degree of automation and low speed of action (the frequency of repetition of pulses was 1/15 Hz), it was difficult to employ this apparatus for regular measurements. Nevertheless, several distance measurements were performed with it to the "Lunokhod-1" and "Apollo-15" reflectors.[6]

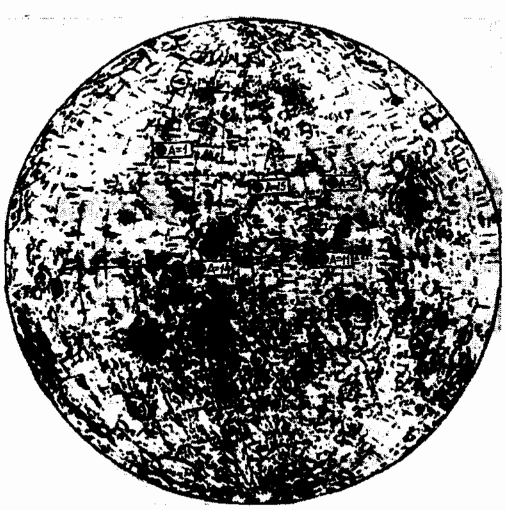

FIG. 2. Distribution of corner light reflectors on the Moon.

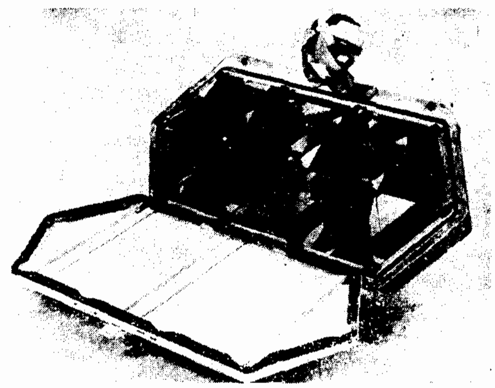

FIG. 3. French corner light reflector.

Owing to a radical redesign of the apparatus undertaken in the program of the "Lunokhod-2", an automated complex of fast-acting apparatus was built with an accuracy of measurement of ± 0.9 m, with which regular distance measurements to all the lunar light reflectors were started in 1973.[7]

And finally, an automatic apparatus was put into service in 1978 whose accuracy had been reduced to ± 25 cm for a single measurement. The statistical error of a series of measurements, which usually contained 10–15 measurements, amounted to 8–10 cm.[8] The optical diagram and an external view of the optical part of this apparatus are shown in Figs. 4 and 5. Its parameters are given below:

Laser

Pulse duration	2 ns
Energy per pulse	2 J
Beam divergence	5′
Frequency of repetition of pulses	0.33 Hz

Photoreceiver

Time resolution	0.4 ns
Quantum efficiency of the photomultiplier	0.1
Passband of the filter	1 Å; 5 Å

Measuring and recording system

Time resolution	1 ns
Strobe pulse	1–50 μs
Accuracy of referencing to world time	10 μs

The actual level of the reflected signal amounts to ~0.05 photoelectrons per laser pulse.

Simultaneously with the studies on realization of laser observations of the Moon, the scientists at the Institute of Physics of the Academy of Sciences of the USSR and the Institute of Theoretical Astronomy of the Academy of Sciences of the USSR solved some problems associated with estimating the prospects of scientific employ-

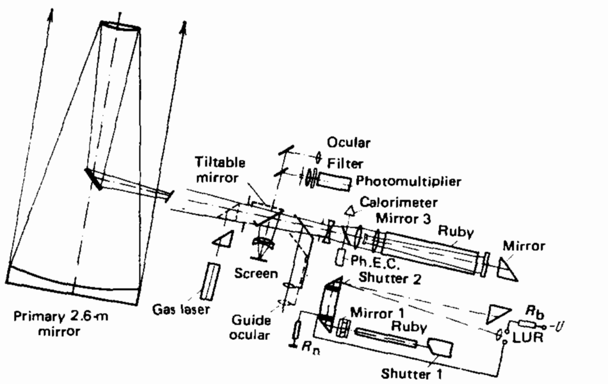

FIG. 4. Diagram of the optical part of the automated laser-rangefinder complex.

ment of the results of laser location of the Moon in astronomy and allied fields of science—geodesics, geophysics, geodynamics—and developed a mathematical apparatus that provides an algorithmic basis for solving practical problems. These studies[9] showed that laser measurements of distances to the Moon enable one to refine substantially the parameters of the geocentric motion of the Moon in its orbit and the parameters of its axial rotation (the physical libration of the Moon), to determine the positions of the corner light reflectors with respect to the lunicentric system of coordinates and the positions of the Earth-based observatories in the geocentric system of reference, and to study the complex daily rotation of the Earth and the oscillations of the Earth's poles. Moreover, studies were performed involving the planning of the laser measurement sessions— estimating the frequency and optimal duration of these observations. The basis for all the stated studies consisted of the equations applicable for calculating the theoretical values of the time of propagation τ_c of the signal. They are derived from the geometry of the problem: One can define the flux-centered position of a lunar corner reflector in the geocentric rectangular XYZ system of reference by the vector $\mathbf{D}$, which is connected to the geocentric radii—the vectors $\mathbf{r}$ of the Moon and ρ_0 of the observatory and the lunicentric radius vector $\mathbf{R}_{☾}$ of the reflector—by the

FIG. 5. Optical part of the automated laser-rangefinder complex.

relationship

$$\mathbf{D} = \mathbf{r} + \mathbf{R} - \boldsymbol{\rho}_0. \tag{1}$$

Thus the precomputed distance D_c (or the precomputed time of propagation $\tau_c = D_c/c$, where c is the speed of light) depends on a set of astronomical and geodesic parameters. For example, one deals with the six constants of the theory of the orbital motion of the Moon [the mean distance r_0, the eccentricity e, the inclination constant of the orbit $\gamma = \sin(i/2)$, the mean longitude ☾ of the Moon at the initial instant, the longitude Γ' of perigee of the orbit, and the longitude Ω of the ascending node of the orbit on the ecliptic]. One also includes the three parameters of the theory of the geocentric motion of the Sun (the eccentricity e' of the orbit, the mean longitude L_0 of the Sun, and the mean longitude of perigee Γ of the orbit), the two parameters of the physical libration of the Moon (the physical-libration constant f and the inclination J of the equator of the Moon to the ecliptic), the coordinates of the observatory (the longitude λ, the radius of the parallel $w = \rho_0 \cos\varphi'$, and the distance from the plane of the geoequator $h = \rho_0 \sin\varphi'$, where φ' is the geocentric latitude), the lunicentric coordinates of the reflector (the selenographic longitude l and latitude b and the radius vector $R_{☾}$). Since the deviations $\Delta D = D_0 - D_c$ of the observed values of the distance D_0 from the precomputed D_c arise from the errors in the adopted nominal values of the stated parameters and the errors of the measurements, then, by using the method of differential correction of parameters, one can solve the redundant system of conditional equations derived by differentiating the expression for D with respect to all the parameters p_i $(i = 1, 2, \ldots, N)$, e.g., by least squares. For each measurement, the corresponding conditional equation has the form

$$\Delta D = D_0 - D_c = \sum_{i=1}^{N} \frac{\partial D}{\partial p_i} \quad (i = 1, 2, \ldots, N). \tag{2}$$

If we choose the stated quantities as the parameters p_i, the conditional equations have the form

$$\begin{aligned}
D_0 - D_c = {} & \frac{1}{D_c}(X-x,\ Y-y,\ Z-z)\Bigg[\bar{p}(-\varepsilon)\Bigg\{\frac{1}{\sin\pi_{☾}}\begin{pmatrix}\cos\beta_{☾} & \cos\lambda_{☾}\\ \cos\beta_{☾} & \sin\lambda_{☾}\\ \sin\beta_{☾} & \end{pmatrix}\Delta a_e \\
& + a_e\frac{\cos\pi_{☾}}{\sin^2\pi_{☾}}\begin{pmatrix}\cos\beta_{☾} & \cos\lambda_{☾}\\ \cos\beta_{☾} & \sin\lambda_{☾}\\ \sin\beta_{☾} & \end{pmatrix}\Delta\pi_{☾} + r_{☾}\begin{pmatrix}-\sin\beta_{☾} & \cos\lambda_{☾}\\ -\sin\beta_{☾} & \sin\lambda_{☾}\\ \cos\beta_{☾} & \end{pmatrix}\Delta\beta_{☾} \\
& + r_{☾}\begin{pmatrix}-\cos\beta_{☾} & \sin\lambda_{☾}\\ \cos\beta_{☾} & \cos\lambda_{☾}\\ 0 & \end{pmatrix}\Delta\lambda_{☾} + \bar{r}[-(\Omega+\sigma)]\,\bar{p}(J+\rho)\,\bar{r}(180^\circ - ☾ - \tau + \Omega + \sigma) \\
& \times\begin{pmatrix}\cos b & \cos l\\ \cos b & \sin l\\ \sin b & \end{pmatrix}\Delta R_{☾} + R_{☾}\Bigg[\begin{pmatrix}-\sin(\Omega+\sigma) & \cos(\Omega+\sigma) & 0\\ -\cos(\Omega+\sigma) & -\sin(\Omega+\sigma) & 0\\ 0 & 0 & 0\end{pmatrix}\bar{p}(J+\rho) \\
& \times\bar{r}(180^\circ - ☾ - \tau + \Omega + \sigma)\,\Delta(\Omega+\sigma) + \bar{r}[-(\Omega+\sigma)] \\
& \times\begin{pmatrix}0 & 0 & 0\\ 0 & -\sin(J+\rho) & -\cos(J+\rho)\\ 0 & \cos(J+\rho) & -\sin(J+\rho)\end{pmatrix}\bar{r}(180^\circ - ☾ - \tau + \Omega + \sigma)\,\Delta(J+\rho) \\
& + \bar{r}[-(\Omega+\sigma)]\,\bar{p}(J+\rho)\begin{pmatrix}\sin[\Omega+\sigma-(☾+\tau)] & \cos[\Omega+\sigma-(☾+\tau)] & 0\\ -\cos[\Omega+\sigma-(☾+\tau)] & \sin[\Omega+\sigma-(☾+\tau)] & 0\\ 0 & 0 & 0\end{pmatrix} \\
& \times\Delta(\Omega+\sigma-☾-\tau)\begin{pmatrix}\cos b & \cos l\\ \cos b & \sin l\\ \sin b & \end{pmatrix}\Bigg]\Bigg\} - \begin{pmatrix}\cos s\\ \sin s\\ 0\end{pmatrix}\Delta w - \begin{pmatrix}0\\ 0\\ 1\end{pmatrix}\Delta h \\
& - w\begin{pmatrix}-\sin s\\ \cos s\\ 0\end{pmatrix}\Delta s\Bigg].
\end{aligned} \tag{3}$$

Here $\pi_{☾}$ is the horizontal equatorial parallax of the Moon, ρ, σ, and τ are the components of the physical libration of the Moon, s is the local sidereal time, $\bar{p}$ and $\bar{r}$ are known rotation matrices with respect to the x and z axes, a_e is the equatorial radius of the terrestrial spheroid, $\lambda_{☾}$ and $\beta_{☾}$ are the ecliptic longitude and latitude of the Moon, which depend on the elements of the lunar orbit, ε is the inclination of the ecliptic to the equator, and x, y, and z are the geocentric coordinates of the observatory.

The presented conditional equations can be employed to solve geodynamic equations. Let us represent the Greenwich sidereal time S in the form

$$S = \mathrm{UTC} + \mathrm{Red}_T + \Delta\psi \cos\varepsilon + \delta S. \tag{4}$$

Here UTC in the instant of time in the system of the uniform scale of coordinated world time, Red_T is the conversion constant from mean time to sidereal time, $\Delta\psi \cos\varepsilon$ is the nutation in terms of right ascension, and δS is the variation in S caused by the variability of the angular velocity of the diurnal rotation of the Earth, which has the form

$$\delta S = \frac{c_1 \cos}{s_1 \sin}(2\pi \cdot 36525T) + \frac{c_2 \cos}{s_2 \sin}(2\pi \cdot 100T) + \frac{c_3 \cos}{s_3 \sin}(2\pi \cdot 86T).$$

Then, in refining the coefficient c_1, e.g., the coefficient for the correction Δc_1 has the following expression:

$$\frac{\partial D}{\partial c_1} = \frac{\partial D}{\partial S}\frac{\partial S}{\partial c_1} = \bar{p}(\varepsilon_0)\,\bar{P}\bar{N}\bar{L}_{\bar{r}}\bar{r}(-S)\,\bar{p}(y_p)\,\bar{q}(x_p)\begin{pmatrix} x \\ y \\ z \end{pmatrix}\cos(2\pi \cdot 36525T). \tag{5}$$

Here $\bar{P}$ and $\bar{N}$ are the precession and nutation matrices, ε_0 is the mean inclination of the ecliptic to the equator in the epoch T_0 to which the time T is referred in terms of the Julian centuries, x_p and y_p are the coordinates of the instantaneous pole of the Earth with respect to the International provisional origin CJO, $\bar{L}_r$ is the Lucas matrix, whose product with the matrix $\bar{r}$ gives an expression for the derivative of $\bar{r}$ with respect to its argument.

Let us introduce the model of the displacement of the continental plate on which the observatory rests by the relationship

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} x_0 \\ y_0 \\ z_0 \end{pmatrix} + \begin{pmatrix} x_1 \\ y_1 \\ z_1 \end{pmatrix} T. \tag{6}$$

Then we find, for example, the expression for the co-

TABLE I.

Parameter	Accuracy of determination by optical observations	Expected accuracy from laser location	Parameter	Accuracy of determination by optical observations	Expected accuracy from laser location
λ	0".1	0".005	r_0	1000 m	2.5 m
w	7 m	0.1 m	Γ'	0".2	0".001
h	7 m	0.1 m	e	$1\cdot10^{-7}$	$5\cdot10^{-10}$
l	300"	0".3	Ω	0".3	0".03
b	180"	0".3	γ	$1\cdot10^{-7}$	$1\cdot10^{-8}$
$R_{☾}$	1000 m	2.5 m	L		0".005
f	0.02	0.00005	Γ		0".03
J	3"—8"	0".1	e'	$7\cdot10^{-7}$	$2\cdot10^{-9}$
☾	0".02	0".002			

TABLE II.

Parameter	MAC: $j = 2$	AE-1	LURE-2
λ		0".1	0".02
w		2.6 m	0.6 m
h		5 m	2.3 m
l		0".2	0".1
b		0".25	0".1
$R_{☾}$		2 m	0.5 m
f		0.0004	0.0001
J		0".9	0".3
☾	0".2	0".01	
r_0	6 m	1 m	
Γ'	0".2	0".02	
e	$3\cdot10^{-8}$	$5\cdot10^{-9}$	
Ω		2"	
γ	$1\cdot10^{-6}$	$3.5\cdot10^{-7}$	
L		0".5	
Γ	6"	0".7	
e'	$5\cdot10^{-7}$	$1\cdot10^{-7}$	
Obs–calc	200 m	15 m	3.4 m

efficient of the conditional equation for the correction Δx_1:

$$\frac{\partial D}{\partial x_1} = -\bar{p}(\varepsilon_0)\,\bar{P}\bar{N}\bar{r}(-S)\,\bar{p}(y_p)\,\bar{q}(x_p)\begin{pmatrix} T \\ 0 \\ 0 \end{pmatrix}. \tag{7}$$

Upon attributing to the quantities ΔD in Eq. (2) the meaning of the errors of measurement, we can make *a priori* estimates of the expected accuracy of determining the parameters Δp_1 by solving systems of these equations. Table I gives the results of such preliminary estimates, which were made under the assumption that $\Delta D = 25$ cm. The errors of determining the parameters according to the best optical observations are given there also.[10] We see that we can expect to refine the parameters of the Earth-Moon system by laser location data by 1–3 orders of magnitude at the already attained accuracy by using long series of measurements.

In the realization of the program of laser light location observations of the Moon during 1973–1980 by the group of scientists at the Institute of Physics of the Academy of Sciences of the USSR with the 2.6-m telescope of the Crimean Astrophysical Observatory of the Academy of Sciences of the USSR, employing the ephemerides prepared at the Institute of Theoretical Astronomy of the Academy of Sciences of the USSR, about 1200 measurements were performed on all five corner reflectors.

Comparison of the measured distances with the distances D_c calculated from the theory of the movement of the Moon bearing the nomenclature index MAC $j = 2$ that is currently adopted in the national astronomical almanacs showed the insufficient accuracy of this theory: the values of the residuals ΔD amount to as much as several hundred meters. Therefore a great effort has been undertaken in the Institute of Theoretical Astronomy of the Academy of Sciences of the USSR to create an accurate numerical theory of the movement of the Moon by the method of numerical integration of the differential equations of the geocentric movement of the Moon, and also to construct a numerical theory of the physical libration of the Moon.

Table II shows the accuracies of determination of the parameters of the Earth-Moon system based on the ephemeris corresponding to the index MAC $j = 2$ and the ephemerides AE-1 (USSR) and LURE-2 (USA), which have been constructed by numerical integration.

We see from this table that most of the parameters of the Earth-Moon system are determined more accurately from laser than from optical observations. However, the expected accuracies have not yet been attained. This involves the insufficient number of measurements and their not fully rational distribution in time. And in turn, this involves the shortage of working time at the telescope ZTSh-2.6, which is overloaded with astrophysical studies.

One of the most important results seems to us to be the determination of the coordinates of the observation point. This is the basis for geodesic constructions and for solving many geodesic problems. In particular, the chord from the Crimean Observatory to the MacDonald Observatory has been determined with an error of about 2 m on the basis of the laser observations performed in the USSR and the USA.[11]

The results that have been obtained allow us to presume that in the near future the laser location of the Moon will become one of the most accurate methods of studying the Earth-Moon system. Today these results have already far surpassed what N. D. Papaleksi at one time expected from this method. However, undoubtedly, the ideas that he expressed many years ago are the basis of the contemporary studies in this field. And this is a brilliant example of the capacity for scientific foresight that N. D. Papaleksi possessed in high degree.

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Parametric infrared generator

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The principle of parametric amplification and generation of electromagnetic waves in the optical range was set forth and developed in 1962 in the studies of S. A. Akhmanov and R. V. Khokhlov,[1] Kingston,[2] and Kroll.[3] Reports on the first successful experiments to study parametric light generation appeared in 1965–1966.[4-6] This initiated the construction of sources of frequency- (or wavelength-) tunable coherent radiation. The range of continuous tuning of wavelength of parametric light generators (PLGs) that has been covered at present amounts to 0.4–16.4 μm.[24,31] This can be made possible by the existence of only four nonlinear crystals: ADP, $LiNbO_3$, $AgAsS_3$, and CdSe.

The scope of this report does not allow us to treat however briefly all the varieties of PLGs existing at present, which are described in a number of reviews.[7-16] Hence we shall restrict the treatment of PLGs only to one example of a parametric infrared generator based on a CdSe crystal that was built in the oscillation laboratory of the Institute of Physics of the Academy of Sciences.

But before proceeding to describe the CdSe-crystal PLG, we must turn to the works of Academician Nikolaĭ Dmitrievich Papaleksi on parametric generators of electric oscillations. Most of these studies were performed by him jointly with Academician L. I. Mandel'shtam. N. D. Papaleksi's studies in the field of parametric phenomena exerted a great influence on the development of parametric generators and amplifiers in the UHF range, whose widespread application started in the fifties, and then on the invention of a PLG in the optical range at the beginning of the sixties. We should note that, although parametric excitation of mechanical oscillations was known even in the last century (Melde's experiment, 1859), L. I. Mandel'shtam and N. D. Papaleksi first pointed out the possible employment of parametric phenomena for amplifying and generating electric oscillations. The first parametric generators of electric oscillations with mechanical variation of the inductance or capacitance in an oscillator circuit containing no sources of emf nor current were experimentally realized by L. I. Mandel'shtam and N. D. Papleksi in 1931–1933.[17-19] They also developed a detailed theory of the phenomena that can be observed when electric oscillations are excited and maintained in the oscillator circuit as the result of periodic variation of the magnitude of one of the reactive parameters of

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