99. Schelev M Ya, Serdyuchenko Yu N, Vaschenko G O, in *Proc. 22nd Intern. Congr. High-Speed Photography and Photonics* (Proc. SPIE, Vol. 2869, Eds D L Paisley, A M Frank) (Bellingham, Wash.: SPIE, 1996) p. 154
100. Bryukhnevich G I et al., in *Proc. 22nd Intern. Congr. High-Speed Photography and Photonics* (Proc. SPIE, Vol. 2869, Eds D L Paisley, A M Frank) (Bellingham, Wash.: SPIE, 1996) p. 157
101. Monastyrski M A et al. *Nucl. Instrum. Methods Phys. Res.* **427** 225 (1999)
102. Vorobiev N S et al., in *Proc. 22nd Intern. Congr. High-Speed Photography and Photonics* (Proc. SPIE, Vol. 2869, Eds D L Paisley, A M Frank) (Bellingham, Wash.: SPIE, 1996) p. 735
103. Nolle E L, Prokhorov A M, Shchelev M Ya *Dokl. Ross. Akad. Nauk* **348** 45 (1996) [*Phys. Dokl.* **41** 193 (1996)]
104. Chernikov A C et al., in *Proc. 19th Intern. Congr. High-Speed Photography and Photonics* (Proc. SPIE, Vol. 1358, Eds B Garfield, J Rendell) (Bellingham, Wash.: SPIE, 1990) p. 134
105. Bryukhnevich G I et al., in *Proc. 20th Intern. Congr. High-Speed Photography and Photonics* (Proc. SPIE, Vol. 1801, Eds D Dewey, R G Racca) (Bellingham, Wash.: SPIE, 1992) p. 836
106. Vorob'ev N S et al. *Kvantovaya Elektron.* (Moscow) **28** (2) 181 (1999) [*Quantum Electron.* **29** 737 (1999)]
107. Zewail A H *Science* **242** 1645 (1988); *J. Phys. Chem.* **100** 12701 (1996); *Nature* (London) **386** 159 (1997)
108. Mourou G, Williamson S *Appl. Phys. Lett.* **41** 44 (1982)
109. Bryukhnevich G I et al., in *Proc. 20th Intern. Congr. High-Speed Photography and Photonics* (Proc. SPIE, Vol. 1801, Eds D Dewey, R G Racca) (Bellingham, Wash.: SPIE, 1992) p. 115
110. Schelev M Ya et al. *Opt. Eng.* **37** 2249 (1998)
111. Kinoshita K et al., in *Proc. Intern. Symp. Photoelectronic Detection and Imaging. Technology and Applications '93* (Proc. SPIE, Vol. 1982, Ed. Zhou Liwei) (Bellingham, Wash.: SPIE, 1993) p. 180
112. Bowley D et al., in *Proc. 22nd Intern. Congr. High-Speed Photography and Photonics* (Proc. SPIE, Vol. 2869, Eds D L Paisley, A M Frank) (Bellingham, Wash.: SPIE, 1996) p. 76

PACS numbers: 07.07.Df, **07.87.+v**, **95.55.–n**, 95.55.Pe
DOI: 10.1070/PU2000v043n09ABEH000791

Scientific instrument making in space exploration

Yu A Surkov

1. Introduction

Just a little over four decades ago the first Soviet space probes (SPs) launched to the Moon, Venus, and Mars started a new stage in the exploration of bodies of the solar system other than Earth by spacecraft. In this period a huge volume of entirely new scientific data has been gathered, which has made it possible to make considerable progress in developing mankind's knowledge about the surfaces of these bodies, their crusts, and their inner structure.

In a report so brief there is no hope of giving a full account of the progress made in scientific instrument making over the years. Therefore the report focuses on the three main trends in scientific instrument making in space exploration, the trends to which the Soviet and post-Soviet scientists contributed the most in their exploration of the Solar system.

2. Building of scientific instruments and experiments in exploring the Moon and the planets

The design of onboard scientific instruments and the preparation for scientific experiments began in the 1950s at the V I Vernadsky Institute of Geochemistry and Analytical Chemistry (GEOKHI in Russian) of the USSR Academy of Sciences at the same time that preparations began in our country for launching space probes to the Moon, Venus, and Mars. The Academy of Sciences and later the Soviet government decided to make GEOKHI the leading organization in studies of extraterrestrial matter by space probes and of samples of such matter brought to Earth by the probes. From that time on, practically all space probes that flew to the Moon, Venus, and Mars carried equipment designed and built at GEOKHI with which numerous experiments were implemented.

Here is a list of space probes that were used by the staff of GEOKHI to carry out the most successful experiments: Luna 10, Luna 12, Luna 16, Luna 20, Luna 24, Venera 4, Venera 5, Venera 6, Venera 8, Venera 9, Venera 10, Venera 12, Venera 13, Venera 14, Vega 1, Vega 2, Mars 5, Phobos 1, Phobos 2, Salyut 7, and Mir.

The devices designed at GEOKHI and mounted on these space probes were intended for determining the chemical composition and the physical properties and structure of rocks, for studying the atmosphere and cloud layer of Venus, for gathering and analyzing cosmic dust, and for other purposes. Various models of mass spectrometers, gamma-ray and X-ray spectrometers, conductometers, densimeters, moisture meters, and other instruments were used.

The first onboard devices were relatively simple and produced little information. The reason for this was that at the time there were no solid data for designing and building devices. For instance, unknown were the basic composition of the Venusian atmosphere (the composition determines the g-loads that the SP experiences when it enters the atmosphere) and the strength of the atmosphere (this led to the loss of the first space probes landing on Venus before they even reached the surface), and nothing was known about the surface of Venus (whether it was liquid or rocky), so that by analogy with Earth the first descent modules were designed for landing in an ocean. However, even the results of the early voyages to Venus of space probes with landing modules (Venera 4, 5, and 6) suggested that the planet's surface shows evidence of being incandescent desert (with temperature close to 500 °C), and that the atmosphere at the surface is mainly carbon dioxide at a pressure of about 100 atm. The results of each of these pioneering flights to Venus brought about many discoveries and explained the differences between Venus and Earth — planets that in many other parameters are quite similar.

In time the devices used in space exploration became more sophisticated and the number and the range of problems covered by experiments increased dramatically. Detailed studies of the surface of Venus were on the agenda. The space probes Venera 8, 9, and 10 were first to land on the Venusian surface and in the extreme conditions mentioned earlier determined, through the use of the earliest Venusian gamma-ray spectrometers built at GEOKHI, the type of rocks by the abundance of natural radioactive elements such as uranium, thorium, and potassium. The time finally came for carrying out probably the most complex studies of Venus, i.e. determining the elemental composition of Venusian rock on the planet's surface. This problem was originally solved by the Venera 13 and 14 descent modules, whose landing sites were in flatlands, and later by the Vega 2 space probe, which ejected a balloon-borne instrument package that landed in the Aphrodite mountainous area. In order to determine the composition of Venusian rocks, a soil-sampling device took samples of rocks. These samples were automatically placed into hermetically sealed bays of the landing module and later analyzed by X-ray radiometric equipment for composition.

The data on Venusian soil we gathered for the first time by gamma-ray spectrometers in five landing areas and by X-ray spectrometers in three landing areas and analyzed at GEOKHI is used in Russia and abroad as fundamental data in developing our ideas about the formation of the Venusian surface and crust and the inner structure of Venus.

The example of Venus in demonstrating how scientific instruments and scientific studies were developed for space exploration was taken only because Venus is so exotic a planet and because it is extremely difficult to study. Notice, however, that our first gamma-ray spectrometric research on the Moon and Mars also brought many unexpected results concerning the history of formation of their surfaces and inner structure.

3. Admission and study of lunar soil delivered by re-entry space probes to Earth

From 1970 – 1976, the Soviet automatic space probes Luna 16, 20, and 24 delivered samples of the lunar soil to Earth. These missions were carried out successfully with all the necessary requirements met. These requirements included (a) sterilization of the space probe, (b) a quarantine for the re-entry space vehicle, (c) the admission and storage of the soil samples in a neutral environment, and (d) the investigation of the soil samples in well-equipped centers in the Soviet Union and abroad.

The re-entry space vehicles landed in Kazakhstan (the former Kazakh Republic of the Soviet Union). After the vehicles were located and evacuated, the capsules with the soil were delivered to GEOKHI, where they were sterilized and passed to a special admission laboratory. The key factor in solving the problem of sampling, transportation, admission, and investigation of lunar soil on Earth was the design and building of the following highly reliable devices and equipment:

(1) A soil-sampling device capable of drilling and forming a core sample at a depth of about 2.5 m on the Moon's surface and packing this core into a small capsule without destroying its stratification for further delivery to Earth;

(2) An admission chamber equipped with an airlock, glove ports, portholes for a panoramic view of the samples, devices for oil-free pumping and filling the chamber with a noble gas (helium), and a high-temperature heating unit installed in the actuation-gas pumping out channel for destroying harmful and dangerous substances that could have been brought from the Moon;

(3) An ultrahigh-vacuum assembly (roughly 10^{-13} mm Hg) used in studies of the physical properties of the soil in conditions similar to those that existed at the time the soil was formed on the Moon. The assembly was equipped with mechanical manipulators for conducting experiments with the soil in ultrahigh vacuum, and

(4) A low-background device intended for measuring the exceptionally low radioactivity of the soil samples. The device was placed in an underground container with meter-thick concrete walls serving as passive protection from cosmic rays. The container also had a gamma-ray spectrometer with additional active scintillation protection from cosmic rays and a measuring detector (a crystal with a 'well').

All these machines were equipped with the proper scientific instruments intended for preliminary studies of lunar soil samples.

4. The building of penetrators for studying bodies of the solar system

As is known, the surfaces of small bodies of the solar system (the Moon, asteroids, and cometary nuclei) and planets whose atmosphere is not dense (e.g., Mars) are covered with a layer of fine-grain unconsolidated residue (regolith) formed primarily by factors of cosmogenic origin. Regolith is a finely granulated and well-mixed soil of average chemical composition, physical properties, and structure. It covers almost the entire surface by a layer of varying thickness. Hence, studying such a surface by traditional methods (from an orbiting station, a landing vehicle, or a rover), one gets the same characteristics of the soil. However, to understand the history of formation of the surface, crust, and inner structure of a celestial body it is very important to study the primary, or unchanged, soil.

In view of this the important problem emerged of developing entirely new research apparatus for space exploration, called penetrators. The simplest penetrators for various purposes were developed by the United States, Japan, and the European Space Agency. However, the biggest progress in this area of research and engineering was made in Russia. The first gliding penetrators intended for studies of the atmosphere, surface, and inner structure of Mars were designed and built under the aegis of the author of the present report and mounted on the Mars 96 space probe.

The penetrators constitute self-contained space probes equipped with service equipment (a communication and telemetry unit, a power unit, and a control unit) and a set of scientific equipment consisting of 8 to 10 instruments. Penetrators are dropped from orbital stations, decelerate in the descent stage, and penetrate the surface at a speed of about 100 m s^{-1}. At the moment of surface penetration the probe splits into two parts: the nose cone penetrates the soil to the designed depth, while the remainder remains at the surface. Both parts carry scientific equipment. The nose part carries out the measurements under a layer of regolith: it measures the chemical composition, physical properties, and the structure of the soil. The part at the surface studies the atmosphere and the surface of the planet in the penetration area. The two parts are connected by a cable.

In addition to Martian penetrators, GEOKHI has lately been developing penetrators for the search and study of volatile components (ice, in particular) in the permanently shadowed craters in the polar regions of the Moon (no lunar soil samples brought to Earth by Soviet and US space probes contain volatile components). The discovery of volatile components (ice, in particular) would not only be an event of extreme scientific importance but would also have important practical implications, since such components could be used in rocket fuel and in life-support systems.

Finally, penetrators are being developed for studying small bodies of the solar system (asteroids and cometary nuclei).

In conclusion it must be noted that the penetrators developed at GEOKHI not only substantially broaden the areas of scientific and practical research in studying and exploring outer space but can also be used on Earth in extreme conditions, for instance, in catastrophes (accidents at atomic power plants and other hazardous objects), in monitoring volcanic activity, at stations monitoring the situation in distant or arduous areas, etc.