THE LOMONOSOV PROJECT FOR SPACE ASTROMETRY

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ABSTRACT. The LOMONOSOV project is aimed at developing a high-accuracy coordinate system of the entire sky to be used for sufficiently long period of time (30 to 50 years) in order to ensure the solution of a variety of applied and basic scientific tasks. This goal can be feasible as a result of comprehensive work, the basis of which is the space experiment, i.e., observations of stars with a telescope on board the Earth satellite. This method can be instrumental in overcoming the distortions characteristic of terrestrial astrometric observations performed through the atmosphere, and to achieve a high degree of efficiency. The other part of the LOMONOSOV project involves international backing of the space experiment through preparation of the input catalogue for 400 000 stars, and organization of high-precision ground observations of stars and other celestial objects in accordance with special programs.

Introduction

The contemporary state of astronomy is such that any serious fundamental scientific results can be obtained only with drawing up a catalogue containing information on several hundred thousand stars in the entire sky with their coordinates' accuracy throughout several dozens of years around 0".005 to 0".0010, as well as with color photometric data ensuring accuracy equal to 0.05 mag. To make up such a catalogue one should perform observations with even higher precision and to repeat them again in some time.

More than a century's experience of classical astronomy proves practical impossibility of achieving the accuracy of the ground-based measurements about 0".10. Among the factors that put the limit of accuracy are local atmospheric fluctuations, insufficient stability of the selected directions which set up zero points, and technical imperfection of the measuring instruments operating under the impact of gravitation. It should be stressed that with a certain limit attained, greater observation frequency does not, in practical terms, result in a higher accuracy. Thus, for the past 300 years a well-known Polaris has been observed thousands of times but its coordinates are known to us with the accuracy of merely several hundredths of an arc second.

Of all conceivable technological innovations and the latest exploration techniques the astrometric satellite alone can, for the first time in history, be instrumental in constructing a homogeneous frame of reference for the entire celestial sphere with one or two orders of magnitude better accuracy

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than any of the available systems (such as the international catalogue FK5 containing information on 3.5 thousand stars with 0"03 to 0"10 accuracy). This system promises to be devoid of the currently existing local nonuniformities and global differences between the two hemispheres of the sky. The totality of absolutely new data obtained by means of this technique will largely render obsolete the labor-consuming work of the past centuries and foster the unheard of progress in many astronomical research projects.

Program of Observation and Expected Results

The LOMONOSOV observation program covers:

- all stars up to 10.0 mag totalling some 400 000 and ensuring thereby, availability of about ten stars per square degree of the sphere;
- fainter stars (up to 13.0 mag) numbering some 8 000 and already selected for the ESA HIPPARCOS program as presenting a special interest for astrophysics and stellar astronomy;
- some 30 of the brightest extragalactic sources;
- some 40 Solar system bodies (planets and asteroids).

Specific results of the LOMONOSOV project involving a space experiment on measuring the angular separations between the above-mentioned objects and their four-color photometry by means of a telescope on board a spacecraft, and ground observations of the selected celestial objects aimed at absolutization of the future catalogue, will provide a possibility to make up a catalogue for scientists and practical workers containing 400 000 stars and complete up to 10.0 mag, covering the entire sky and accurate up to 0"002 to 0"010 with regard to positions, proper motions and parallaxes. This catalogue will remain fairly accurate for 30 to 50 years, while its first version can be ready by 1996.

Method of Observations and Reductions

The proposed experiment is reduced, basically, to the following.

A Cassegrain telescope with a 50 m equivalent focal length, 1 m main mirror diameter (with a 4 m focal length) and a nonaberrational field of view equal to 6 minutes of arc or 90 mm will be mounted aboard a spacecraft. The system of aperture mirror focuses in one field of view the images of two stars, or rather of two sections of the celestial sphere, which are divided in the sky by a 90° angular separation. Due to their reciprocal position the aperture mirrors should form a highly stable reference angle, while the differences of the true angular separation between the stars and the reference value are to be measured in the course of the experiment.

CCD matrices consisting of 800 x 800 elements are suggested to be employed as receiving and recording equipment with each element's dimensions of 15 x 15 μm corresponding to 0"06. Analysis of the matrix signals by means of special digital algorithms makes it possible to determine the distance between stars in the field of view with the accuracy of up to 0.3 μm, this value corresponding to nearly 0"001.

The experiment's strategy involves keeping the spacecraft pointed to the selected star (referred to as the "reference star"), located near the antisolar direction, with subsequent turns of the spacecraft relative to this direction and during the fine stabilization phase measurements of separations from the reference star to all other stars spaced from the former by 90° (referred to as "program stars"). Then the spacecraft is redirected to another reference star, and the separations from this reference star to another set of program stars are measured. During the rough stabilization phase photometric and spectrophotometric measurements of the program and reference stars, respectively, are performed.

The basic requirement to the spacecraft design involves the possibility of its fast reorientation with subsequent tri-axial stabilization. To ensure realization of the above-described measuring techniques it is necessary that following the gradual increase of the speed around the assigned axis it would be equal to, approximately, 0.5 degrees per second. The precision of the spacecraft's orientation after the turn should not be below several arc minutes. Upon achieving the stabilization, the residual angular velocities of the spacecraft should not exceed 0".4 per time second, while the higher degree of stabilization (0".01) required in the process of measurements should be ensured through utilization of a tracking mirror in the optical feedback circuit. Assuming that following each measurement the spacecraft must, on the average make a 1°.25 turn, it is possible to take 2 to 3 measurements each minute, or some 1.2 million measurements during one year's time.

The telescope capacity and characteristics of CCD matrices allow one to accumulate on the matrix during one second approximately 4 x 10^4 electrons from an A0 star of 10.0 mag. Assuming that a star image is distributed over 4 x 4 elements of the matrix, we find that to ensure 1% photometric accuracy in observing faint stars (10.0 mag) an exposure of up to 4 seconds is required. The maximum exposure for the faintest objects (such as quasars) can reach hundreds of seconds. The exposure time for the program stars is selected automatically by the computer aboard the spacecraft.

As has been mentioned above, the current technology will make it possible to take measurements at a rate not exceeding 2 to 3 measurements per minute, or 3000 daily. This allows one to assess the information content of the experiment with allowance for the fact that in measuring the distance between two stars it is necessary to analyse the matrix sections of 32 x 32 pixels, while a reading from each pixel is recorded by 14 information bits:

$$32 \times 32 \times 14 \times 2 \times 3000 = 84 \text{ Mbit/day}.$$

The remaining information, including photometric measurements, reference angle control, readouts of the dark field, etc. is evaluated at 25 Mbit/day. Thus, the experiment's information content makes up about 110 Mbit/day. With normal functioning of the onboard computer, this information will be recorded in memory and transmitted daily to the Earth.

Selection of the spacecraft's orbit is required by the necessity to minimize various interferences. Light interferences from the Earth and Moon, interferences from the Earth's radiation belts affecting the CCD matrices, as well as the desire to keep the spacecraft as long as possible in the useful portion of the orbit, require one to choose a 48-hour orbit with the apogee of some 12 000 km. The inclination of the orbit's plane to the ecliptic should be 50° to 60° in order to reduce the seasonal influence of the magnetospheric tail which creates additional interferences at the matrices. The experience with the ASTRON satellite prove that from a 200 000 km distance the Earth has a brightness of –19 mag, and measurements can be performed not closer than 30° to the luminary's edge.

To accomplish the entire program of observations in the optimal mode one should calculate in advance all the turning angles of the spacecraft, or in other words, have a list of all the stars to be included in the future catalogue with their approximate coordinates (the so-called *input catalogue*). Making up of such a catalogue is an important and labor-consuming task which can be realized on the basis of photographic observations carried out by the USSR observatories in both hemispheres, and the date from the *Carte du Ciel* astrographic catalogue.

The input catalogue has a direct bearing on the planning and optimization of the space experiment which are necessary for (1) collection of the maximum number of independent measurements in the shortest possible period, and (2) deriving the best-defined set of equations for the final stage of reconstructing the coordinates by the distances measured. The optimal plan should meet the following basic requirements:

- selection of some 3 000 reference stars within a ±35° band around the ecliptic. These stars should be single, invariable, relatively bright (7-9 mag), well-recognizable against the background of other stars, and have, as far as possible, precise coordinates;

- selection for each of the reference stars a 90°-space band with the width equal to the telescope's field of view, considering all the stars in this band as program stars;

- ensuring coverage of the entire sky with these bands;

- ensuring that each program star was observed at least with two reference stars so that the separation between the latter was close to 90° in order to allow the effective reconstruction of coordinates by the separations;

- ensuring the two-stage observation of each star at a half-year interval in order to determine its parallax;

- separation of proper motions and parallaxes;

- checking the angular separation from the Sun, Earth and Moon to the observed section of the sky; checking in the telescope's field of view the coverage of asteroids and major planets;

- possibility of selecting out of the entire totality of measurements only those which allow one to make up the final catalogue on the limited number of stars (approximately 20 000).

Following completion of all the measurements and prior to preparation of the final catalogue it will be necessary to bring all observations into a uniform system of coordinates and time. For correct application of the reduction formulae, the following information will be required:

- equatorial coordinates of the observed objects accurate to 1";
- component velocities of the Earth and spacecraft not worse than 20 cm/sec;
- spacecraft's coordinates in the geocentric system not worse than 1 500 m;
- Earth's coordinates in the heliocentric system not worse than 1 000 km;
- coordination of all time scales not worse than 0.01 sec.

Making up of the final catalogue is reduced to solving by one or another method the system of linear equations in which each equation links a specific measurement with ten unknown ones (five for each star). The normal system's matrix possesses dimensionality of 5 multiplied by the number of stars in the program; and since only relative angular measurements are considered, it has the deficiency of rank 6, corresponding to an unknown rotation in the coordinate system and its changes in time.

Solution of the system of normal equations can be achieved with various methods — iterative, for one. Another method is a two-stage solution. In this case one has to select from the best astrometric catalogues a limited number of stars (10 000 to 40 000) with relatively well-known coordinates, and consider only those equations which link them. As a result it is possible to find a solution adjusting the totality of these stars' coordinates inside themselves with zero points which correspond to the system of originally-accepted coordinates. Coordinates of the remaining stars in the experiment's program will be determined by the differences of their coordinates with those of the first-stage stars.

The final stage of deriving the coordinate system, i.e., its absolutization through connecting with various physical bodies' systems will be realized upon completion of the entire LOMONOSOV project.

Numerous astrometric and photometric measurements with a telescope aboard the spacecraft are also planned within the HIPPARCOS project under development by the European Space Agency since 1975.

The LOMONOSOV and HIPPARCOS projects employ different techniques of observing the celestial sphere and totally different methods of registering the star positions in the focal plane. Without doubt both projects will be complementary since there is a chance to find and elinminate possible systematic errors and thus increase the reliability of the data obtained. This task will require coordination of effort between Soviet specialists and their West European colleagues.

Discussion

ANONYMOUS: Could you describe the onboard and ground computers?

CHEREPASHCHUK: The onboard computer is under consideration. Probably our version of a computer will be of the PDP type. We would like to have a powerful ground computer. We hope for international cooperation on this question.

KLIONER: I have two questions. If I understand you correctly, the equipment of the space station will contain the onboard computer with quite complicated software. The first question is what are the principal characteristics of the onboard computer. The second question: if your project is supported, who—what organization—will develop the software for the onboard and ground-based control computers? I do believe that it is a very important question because the loss of one spacecraft was caused by the imperfection of the software in my opinion.

CHEREPASHCHUK: These questions are under study. We have no final decision and we hope we will collaborate with the international community.

HøG: It seems that you only need the two entrance mirrors forming a penta mirror which will give a stable 90° reference angle. So why do you have the third plane mirror at all?
CHEREPASHCHUK: This is only one of the possible schemes. The final plans will be adopted after calculation of thermal qualities.

CHUBEY: Did you resolve the problem of adjustment of large sets of arcs which are near 90° without having the connection between the common objects of the observational program?
CHEREPASHCHUK: Numerical experiments with the SAO star catalogue showed that this problem was solved. Final optimal strategy should be developed after the compilation of an input catalogue.

HøG: Do you obtain scientific data only when the satellite is visible from a ground station?
CHEREPASHCHUK: Yes, we have onboard memory and we transmit the scientific data once per day.

HUGHES: As a follow-up to Dr Høg's question: Did I understand you to say that you receive data (downlink) once per day? I ask this question because of the obvious related requirements for onboard memory, data format, data rates etc.
CHEREPASHCHUK: Yes, and appropriate equipment, both onboard and ground, will be installed.