REVIEW AND COMPARISON OF RECENT METHODS IN SPACE GEODESY

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(Received: March 2, 1981)

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1. Introduction

In the '60s, new methods based on the observations of artifical satellites, such as photovisual, photographic, later laser and Doppler methods have got to an increased importance in geodesy. By the mid-'70s, these "traditional" space methods were complemented by methods involving new technical features. The use of these techniques yielded an increasing accuracy in geodesy. The other advantage of new methods is the possibility of setup of a uniform, global network extended all over the Earth. They are also of use for studying polar motion, solid-earth tides, Earth rotation, for determining orbit, libration and

Table I

Method	Purpose	Accuracy
Laser: SLR	Station position, polar motion, earth rotation, solid earth tides	1—2 cm
LLR	Moon orbit, libration, inner texture, study of lunar orbit evolution	2—5 cm
MOBLAS	Crustal motion, polar motion, earth rotation, Lageos orbit det., plate tectonics	10 cm
SRS	Rapid survey of terrestrial network	2 cm
GPS	Absolute and relative location, instantaneous location all over the Earth	Absolute: 10 m Relative: 1—10 m
SST	Continuous measurement of the gravity potential	0.003 cm/s
Altimetry	Structure of the terrestrial gravity field	10—20 cm
Gradiometry	Measurement of gradient tensor components of the terrestrial gravity field	0.001 E
	Geoid-undulations	10 cm
Magnetic field measurements	Mapping the magnetic field of the Earth	
Radio interferometry VLBI	Baseline length, Earth rotation, polar motion, lunar motion	1—10 cm
SERIES	Baseline length	1 cm

inner structure of the Moon, for investigating plate tectonics and plate-stability, to determine the gravity and magnetic field of the Earth and to measure geoid undulations. In the following a review is presented of different types of laser, radio-interferometric, gradiometric and magnetic methods as well as those based on the electromagnetic range and range-rate measurements, their utility and accuracy. Characteristics of these methods are summarized in Table I.

2. Laser measurements

Essentially, four concepts of laser measurements are applied such as to a satellite, to the Moon, from a satellite to the Earth, and measurements from a moving station.

a) Satellite Laser Ranging (SLR)

Originally, laser ranging in satellite geodesy had been applied for improving the satellite orbit accuracy. Nowadays it is applied for studying the position of the station, the polar motion, the Earth rotation and the solid-earth tides. Satellite laser rangings refer to a geocentric reference system, at better than 10 cm accuracy, and attaining the theoretical limit of 1—2 cm for specially designed instruments.

b) Lunar Laser Ranging (LLR)

It is based on the same concept as SLR but measurements aim at retroreflectors placed on the Moon, intended to determine the Moon orbit and libration, to investigate the inner structure of the Moon, and to determine the evolution of the Moon orbit. These measurements refer to a reference system having as origin the mass center of the whole Earth-Moon system. At present, there are only a few stations on Earth performing such measurements within a few cm accuracy. By 1981, a station (MacDonald Laser Ranging Station) would perform measurements to both the Moon and the satellite Lageos at equal accuracy ($\sim$ 3 cm). SLR and LLR measurements can be accomplished on fix and moving stations as well.

c) Mobile Laser Ranging (MOBLAS)

By 1979, seven moving laser ranging stations were operating in the territories of the USA, Australia and the Pacific Ocean.

A well-equipped station completing range measurements mainly to Lageos is particularly appropriate for studying crustal movements [2]. Measurement accuracy is about 10 cm. Implementing the network of fixed laser stations with such mobile stations would permit precise determination of Lageos orbit elements, continuous observation of polar motion and earth rotation, as well as study of tectonic plate motions and of plate-stability.

d) Spaceborne Ranging System (SRS)

At a difference from the previous three methods, this ranging based on a laser mounted on a space-vehicle, and reflectors are fixed in the points of a network of some hundred kilometers on the Earth (3). It is expected to do a fast relative ranging for crustal movement determinations. The system is actually in experimental stage, to be developed after 1982. It has achieved an accuracy of about 2 cm. It has the advantage to survey a network of $\sim 10^6$ km^2 area in a few days.

3. Global Positioning System (GPS)

The most promising system concerning precise and fast positioning is GPS. By the mid-'80s it would permit threedimensional positioning and velocity determination at ± 10 m accuracy in a very short time — in seconds. The system would consist of 18 satellites on semi-synchronous orbits, with 12-hour periods. On three equally spaced circular orbits six satellites are placed each. Inclinations of the orbits are 63°. These parameters would grant visibility of at least six satellites over the horizon at any instant, at any point of the Earth. Time signals are transmitted by high-stability atomic clocks mounted on the satellites, and a transmitter of 450 W continuously transmits at carrier frequencies would be modulated at 10.23 MHz (the so-called "P-code"). The signal reaching the antenna is received and cross-correlated with the signal generated by the receiver. The maximum correlation value yields the time delay of the signal passing from the satellite to the receiver. Distance can be derived from the time delay. Like in the Doppler system, the satellite message contains information on time and orbit as well. Ranging at two frequencies permits to neglect the ionospherical refraction. The obtained range is termed "pseudorange". Combining pseudo-ranges of four or more satellites permits to compute receiver coordinates in the GPS reference system. There are several other concepts of positioning by means of GPS satellites. One is the so-called "reconstructed carrier frequency" method (RCF). In addition to the P-code, the carrier frequencies are modulated by the so-called "C/A code". It is also a random phase modulation but with a very short code — length of a few milliseconds — contrary to the seven days of P-code. Moreover "C/A" code makes possible the acquisition of P-code. The receiver counts phase-shift of incoming signal to derive range-rate. Then the receiver coordinates can be calculated by a method similar to Doppler data processing. At present (1981), six NAVSTAR satellites are orbiting the Earth, test ranging has been made to over a reference line of about 100 km length in South California.

P-code measurements lasted 19 hours for each pair of satellites. Results are (RMS):

φ: 3—9 cm (2 cm)
λ: 3—6 cm (1.5 cm)
h: 9—13 cm (5 cm)

with values likely to obtain from 24 satellites-configuration in parentheses.

Accuracy of RCF measurements, where data rate was assumed to be one phase measurement per receiver pair per satellite every 10 minutes for two hours, is: $dx = 4.5$ cm, $dy = 0.9$ cm and $dz = 2.7$ cm. Of course these "inaccurate" results would be improved by applying longer measuring interval as well as more satellites [6].

4. Satellite to Satellite Tracking (SST)

This method is capable direct measurement of the gravity potential of the Earth. The measuring system has three fundamental units: one satellite in a geostationary orbit ($h \sim 36\,000$ km) and another one orbiting near the Earth ($h \sim 1000$ km) and a terrestrial telemetry station. The two satellites: ATS-6 and GEOS-C are in a continuous two-way radiofrequency link, and so are the terrestrial station and the satellite in geosynchronous orbit. The high flying satellite can be made into a stable platform for observing variations in the behaviour of low satellites over complete orbits at an accuracy by orders of magnitudes higher than would be possible from the Earth. Namely, accuracy of measurements from the Earth is restricted by the atmosphere; propagation of radio and light waves in atmosphere cannot be suitably modelled. Satisfactory knowledge of the satellite orbit enables to determine the values of the gravity potential of the Earth, and — within continuous measurements — its variations with time. Actual tracking accuracy is 0,003 cm/sec.

5. Altimetry

A satellite-borne radar makes it possible to measure instantaneous range between a satellite and the Earth surface, informing of the short wavelength features of the Earth's gravity field. Combined with terrestrial gravimetry data, a gravity model of order and degree of 36, a resolution of 500 km, and an accuracy of 10 mgal can be established. Ranging accuracy depends on the exact knowledge of the satellite orbit, on the ranging mechanism, etc. Ranging accuracies of GEOS-3 and of SEASAT-A are 20 to 50 cm, and 10 to 20 cm, respectively.

6. Gradiometry

Satellite-borne gradiometer measures five independent components of the gravity gradient tensor. Recently, a triaxial superconducting gravity gradiometer has been developed, measuring at an accuracy of 0,001 Eötvös units at 10 cm distance separation, which can be improved by increasing the distance separation. It is capable of observing short-periodic variations of the gravity field of the Earth, permitting to conclude on parameters of different geodynamic processes such as mantle convection, and plate tectonics. By the mid-'80s, satellites GRAVSAT will perform these measurements at an expected accuracy of 1 mgal per square degree, and of geoid-undulations at 10 cm.

7. Magnetic field measurements

Magnetometers on satellite boards are intended to map the magnetic field of the Earth for the epoch 1980. Completing measurement results with those obtained on the Earth surface and in the atmosphere would permit modelling the magnetic field of the Earth, with spherical harmonic coefficients, up to 14 orders and degrees. This would be the first global, vectorial magnetic field measurement in the space near the Earth.

8. Radiointerferometry

Radiointerferometry, serving originally to improve the resolution of radio telescopes in astronomy, seems to assume an important role in geodesy. It is mostly applied for determining lengths and directions of baselines.

a) VLBI

Measurements are directed towards quasars but can also be used for studying motion of the Moon, taking incoming signals received from ALSEP (Apollo Lunar Science Experiment Packages) transmitters placed on the Moon. Measurements of quasars serve for studying polar motion and Earth rotation, too. These measurements refer to an inertial reference system. Recent accuracy of baseline vector determination is about a few cm.

b) Moving VLBI

Just as in laser measurements, mobile VLBI systems have been developed. By 1981, mobile stations equipped with a 4 m dish-antenna, data processing system, hydrogen maser and water vapour radiometer. They planned to removal from one station to the other in a week. Expected accuracy will be a few cm.

c) Satellite Emission Radio Interferometric Earth Surveying (SERIES)

The advent of NAVSTAR satellites enables to replace weak quasar signals by stronger GPS signals for short baselines ($l \leq 100$ km). Radiointerferometrical processing of GPS signals requires special terminals to yield real-time data [12].

Also these are mobile stations. For baselengths below 100 km, the relative accuracy is ± 1 cm.

Summary

Studying geodynamic processes requires to make use of new-type space-borne geodesy measurements. A terrestrial reference system (TRS) is required for describing geodynamic processes. For this we should have satisfactory knowledge of polar motion, Earth rotation and tidal forces, determined by laser, GPS and VLBI measurements. In addition, gravity and magnetic field of the Earth have to be known, modelled by making use of SST, altimetry, gradiometry and magnetometry results. Motion of the Earth-Moon system, as well as relation between the terrestrial reference system and the inertial system can be determined by means of VLBI measurements.

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