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Introduction

By A. R. Robbins

Department of Surveying and Geodesy, University of Oxford,
62 *Banbury Road, Oxford OX*2 6*PN, U.K.*

Station coordinates can be determined at present by Doppler satellite tracking to an accuracy of about 1 m in the Navy Navigational Satellite System (N.N.S.S.). The internal precision of measurement is at the decimetre level and the main theme of the meeting is to explore means of increasing coordinate accuracy to a level approaching that of the measuring precision available. This introduction briefly reviews the impact of the space age on geodesy, outlines the history of the N.N.S.S., discusses the datum on which station coordinates are determined and looks to the future.

My task in this introduction is to set the scene for the meeting, first by reviewing very briefly the impact of the space age on geodesy, then by outlining the history of Doppler satellite tracking in the field of geodesy up to the present day and, finally, by giving a brief look to the future. The papers presented in this volume discuss methods by which improved accuracy is sought and achieved, culminating with a description of a proposed new satellite radio navigation system which promises decimetre relative accuracy from only one day of observations. The organizers of the meeting hope that, when it is over, scientists will have benefited from the publication and mutual discussion of their most recent work, and the practical user will have benefited from a deeper understanding of the principles and techniques involved, and of the accuracy currently achievable.

IMPACT OF THE SPACE AGE ON GEODESY

The science of geodesy may be described in brief as that which deals with the determination of the size and shape of the Earth and of its gravity field. It has undergone a veritable revolution in the past 20 years, made possible by the advent and development of artificial Earth satellites, electromagnetic distance measurement and large, fast computers. Veis (1976) illustrated this when he stated, with much justification, at the first international symposium on 'Satellite Doppler positioning': 'I seriously believe that what [geodetic information] has been obtained during this last twenty years exceeds what had been gathered in the last thousand years'. In fact the precision and accuracy in world-wide point positioning and distance measuring is now such that geodesy may be truly stated to be four-dimensional, the fourth dimension being time. This is an old concept for geodesists who instigated what was then the International Latitude Service in 1899, which has continuously measured latitude since that date at five observatories (occasionally only four or three during outbreaks of hostilities) on the same latitude, deducing the motion of the pole from their variations. However, the concept is now much more widespread and, for the first time ever, it will shortly be possible to determine, by direct measurement over a time span of 5 years or so, whether there is intercontinental plate tectonic

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movement at present. If such movement is found, it will verify geophysical theory; if it is conclusively not found, it will at least demonstrate that such movement is discontinuous.

Geodesy by its very nature is international, with the whole world its laboratory, and during the last 20 years it has become multidisciplinary. The recent major advances have only been made possible by a fruitful cooperation with physicists and astronomers who have become interested in geodetic problems. The result is that geodetic observations of artificial Earth satellites may now be used to determine and monitor the following, with ever-increasing accuracy:

Polar motion and variations in the Earth's rate of rotation, leading possibly to improved knowledge and understanding of core–mantle interactions of the Earth, the excitation and damping of the Chandler wobble, tidal torques of the Sun and Moon, forced secular polar motion, nutation and precession; plate tectonic movement leading possibly to improved knowledge of the internal rheology of the Earth and of earthquake mechanisms, and of large aseismic motions possibly associated with earthquakes; more and more parameters of the Earth's gravity field, and possibly seasonal variations of J_2 and J_3, leading *inter alia* to increasing accuracy in the determination of the geoid: solid Earth tides, ocean tides and 'sea surface topography', leading to advances in the knowledge of mean sea level changes, of ocean currents and the dynamics of ocean circulation generally, the linking of variations in the Earth's rotation rate with lower atmospheric winds, and the study of the winds and circulation of the upper atmosphere; and finally, the gravity field of the Moon, leading to great improvements in lunar orbital and libration theory, and to a more advanced knowledge of lunar dynamics, including assessment of relativistic effects.

The techniques used, or about to be used, for such work are largely:

(i) laser ranging to the Moon and to artificial Earth satellites, with a precision of a few centimetres possible with the new generation of lasers which, it is hoped, will become operational during the next few years,

(ii) very long base-line interferometry, or v.l.b.i., which can determine the length and azimuth of the line joining the two antennae of radio telescopes separated by up to several thousand kilometres to a claimed accuracy of a few centimetres, and

(iii) satellite Doppler tracking, the topic of this meeting.

It should be added that the remarkable increase in quality and quantity of the results obtained from these techniques during the last 5 or so years is due to the fact that they were based on about 15 years of development of theory and of solid results from optical camera observations at the 5–10 m level. Every scientist stands on the shoulders of his predecessors.

Satellite Doppler tracking

The principle of Doppler tracking is very simple. A very stable crystal oscillator is carried in the satellite which controls the satellite clock and the continuous transmission of one or more frequencies. The frequency received at a ground station is continuously altered by the ever-changing relative motion of the satellite and of the receiver which moves and rotates with the Earth. A measurement of the Doppler shift of the received frequency directly gives a value of the relative velocity of the transmitter and receiver and, knowing the forces acting on the satellite, frequent determinations enable the parameters of the orbit to be determined. In fact,

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in the Transit system, the change in the received frequency, or the Doppler count, is determined to 1 Hz over some 200 integration periods of 4.6 s during each good pass, and each corresponding change in the satellite range is therefore determined to c/f, or $\frac{3}{4}$ m at 400 MHz (where c is the velocity of light and f the transmitted frequency). Doppler tracking is thus a very simple and elegant method of determining range differences to 2.5 ns at an extraordinarily high rate.

Of course the real situation is not as simple as stated above, and it becomes more complicated as the required accuracy increases. For instance, the range rate determined is contaminated with error due to tropospheric and ionospheric refraction, and there are many very small perturbing forces acting on the satellite in addition to those due to the departure of the Earth's gravity field from that due to a point mass. However, many of these sources of noise have different signatures and they can, to a large extent, be modelled or eliminated. In particular, improvements to the gravity field model have enabled station positions to be improved which, in turn, has enabled the gravity field to be improved. Then improved instrumentation gave better resolution so that the whole process was iterated, but with the necessity for determining and modelling many smaller effects such as those due to air drag, solar radiation pressure, polar motion, Earth and ocean tides. The whole process will no doubt continue, giving ever-increasing accuracy from shorter periods of observing time, as instrumentation continues to improve. In fact the Bureau International de l'Heure, the BIH, has for some years regularly combined Doppler satellite determinations of polar motion with the classical astrometric determinations to provide pole coordinates.

In another area, the effects of ionospheric refraction are eliminated to a first order by combining measurements on two frequencies, such as 400 and 150 MHz: a different combination of these measurements will give valuable information about the electron content of the ionosphere and its variations in time and space. Doppler satellite tracking thus well illustrates the well known dictum that one man's noise is another man's signal.

The N.N.S.S. or Transit system

Many satellites have been tracked by Doppler methods, but geodetic results have been largely obtained from the Doppler satellite system that is known as the Navy Navigation Satellite System (N.N.S.S.) and also as the Transit system. It has had a remarkable history. The initial concept was due to G. C. Weiffenbach and W. H. Guier in 1957–58. They made measurements of the Doppler shift exhibited on signals received from the first Sputnik and, later, from the Sputnik 2, Explorer and Vanguard satellites, and they were the first to show that the satellite orbit could be deduced from them to a reasonable degree of accuracy. The late F. T. McClure realized that the inverse would be possible: if the orbit could be predicted from measurements at stations of known position, then measurements from any other station could be used to determine its unknown position. This was the basis of the development of the Transit system by the U.S. Navy as an all-weather, night and day, precise navigational system which is fully automated and demands no skill or special knowledge of the navigator (Black *et al.* 1976; Dunnell *et al.* 1977; Kershner 1976). The initial position-fixing accuracy was $\frac{1}{2}$–1 mile (*ca.* 0.8–1.6 km) from a moving platform, such as a ship, 0.1 mile (*ca.* 0.16 km) from a fixed platform, with the use of what was then a very sophisticated receiver. Now, 20 years later, relatively inexpensive, portable receivers, for unattended use in the field with power supplied by a

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12 V car battery, enable positions to be fixed, and computed on line in a microcomputer, with an internal standard error of about ± 0.7 m in each coordinate from about 3 days of continuous observations.

The Transit system consists of five operational satellites in near-circular, near-polar orbits at about 1100 km altitude, and a satellite should be 'visible' approximately every 2 h. All of the satellites continuously transmit nominal frequencies of 400 MHz and three-eighths of this, namely 150 MHz, both modulated with time markers and information sufficient to compute the rectangular Cartesian coordinates of the satellite at the instants of the beginning and end of the integration of each Doppler count. This information is termed the 'Broadcast Ephemeris', the data being given to the nearest 10 m, and commercially available receivers demodulate and record it. This ephemeris is therefore predicted in advance and it is updated every 12 h. It is derived from four fixed stations, three on the U.S. mainland and one in Hawaii, and its accuracy is therefore limited by the errors of prediction and, probably, by the lack of global coverage of the tracking stations. In addition, the U.S. military authorities maintain the 'Precise Ephemeris' of one, sometimes two, of the five satellites. This gives satellite coordinates, computed in arrears to 1 m, from continuous observations at the Tranet stations, a system of thirteen permanent and four mobile stations well distributed around the Earth.

DOPPLER DATUM

The Datum on which unknown station coordinates are computed is unique, being slightly different for computations on the two ephemerides, and it cannot be defined in a manner similar to classical geodetic datums. The terrestrial Cartesian reference frame used is, to observational accuracy, geocentric, with z-axis parallel to the CIO (the Conventional International Origin which is essentially the mean pole of 1900–05, now used as the origin of the coordinate system in which the position of the instantaneous pole is determined), and x-axis parallel to the Conventional Zero Meridian (defined by the time system of the BIH). It depends on, and will vary with, the computer model of the force field acting on the satellite (not only on the values and number of the harmonic coefficients used to portray the Earth's gravity field, but also on the model or method used to compute the direct effects of the Sun and Moon, solar radiation pressure and air-drag, and to determine or compensate for other perturbations such as those due to polar motion and Earth and ocean tides), on the values used for GM (the product of the gravitational constant and the mass of the Earth) and the velocity of light which will scale the model, and on the number and positions of the tracking stations as well as their adopted coordinates.

Two points should be mentioned. First, both current ephemerides are computed with the old value of the velocity of light, namely 299792500 m s^{-1}, rather than the new value of 299792458 m s^{-1} adopted by both the I.A.U. and the I.A.G., a difference of 0.14×10^{-6}. Secondly, the Precise Ephemeris uses a value for GM of 3.98601×10^{14} m^3 s^{-2} but the Broadcast Ephemeris uses 3.986008×10^{14} m^3 s^{-2}, a difference of 0.5×10^{-6}, while a very recent value determined from laser tracking of Lageos is $3.9860044 \pm 2 \times 10^{14}$ m^3 s^{-2} (Lerch *et al.* 1978). Such discrepancies have been well within the noise limit of results in the past but they are beginning to be significant now.

Both the Precise Ephemeris Doppler Datum and the Broadcast Ephemeris Doppler Datum will, in theory, change if any one of the above parameters are changed. In the past, many

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changes have been made, as the system evolved, to reduce the noise level and improve accuracy, and the resultant change of Datum has had little practical effect. However, with current repeatability of about 0.7 m in each of the three station coordinates and instrumental resolution of 11 cm (Anderle 1976), and with 10 cm relative coordinate accuracy foreseen from G.P.S. within the next decade as will be described in the last paper of this meeting, any future changes will be significant, and I do hope and urge that they be fully documented, published and well publicized. It is essential, even now, to record with each station computation both the date of observation and the ephemeris used.

When 10 cm accuracy is achieved, or even approached, many new problems will arise. Examples include tectonic plate movement which, at a postulated 2 cm per year, will give significant relative displacement of the tracking stations over 10 years or so (which will alter the Datum), possible instability of the coordinate reference frame which is not directly tied to a celestial reference frame, and possible seasonal variation of J_2 and J_3. In the further future, allowance may have to be made for the seasonal motion of the centre of mass of the Earth: a motion with a maximum departure from the mean position of 4.3 mm due to variation in air mass and moisture stored on the Earth's land surface has been postulated by Stolz (1976), with a probably greater effect due to the oceans and polar ice caps.

THE FUTURE GLOBAL GEODETIC REFERENCE SYSTEM

Doppler Datum and reference system is independent of any other. It cannot be directly linked with a celestial or a terrestrial reference system other than by observation at sites fixed in those systems: neither the right ascension and declination of the satellite, nor the local station vertical, can be directly observed. Therefore I would suggest that, in about 20 years at most, our global geodetic reference system will consist of a few zero order lunar laser points, connected by v.l.b.i. observations, a first order system of v.l.b.i. and satellite laser points, and a second order system (of similar accuracy) of Doppler points interpolated between the previous ones, with third and fourth order systems fixed by inertial equipment, the zero, first and second order points having a date and a velocity vector associated with them. This meeting will take us a little way along the road and give ourselves and future scientists some more shoulders on which to stand. The revolution in geodesy has only just begun and we are privileged to be taking part in it.

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