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The determination of the fluctuations in the rotation of the Earth

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In recent years new space techniques have been used to determine with higher precision the fluctuations in the rate of rotation of the Earth and in the motion of the pole of rotation with respect to the conventional terrestrial reference frame. The international MERIT–COTES programme of observation and analysis is now in progress and is providing a high-quality data set for use in the study of the nature and causes of the fluctuations and in the determination of the relationships between the reference systems of the different techniques. The results and operational experience gained will be reviewed to provide a basis for recommendations about the future international services for Earth-rotation and for the establishment and maintenance of a new terrestrial reference frame.

1. Introduction

The causes of the fluctuations in the rotation of the Earth are of considerable scientific interest because their study gives us information about the interior of the Earth and about the forces acting on the crust that cannot be obtained in other ways (see, for example, Lambeck 1980). This information is of value in such diverse fields as seismology and meteorology. Moreover, the fluctuations must be known accurately for practical purposes in astronomy, space research, geodesy and navigation. The fluctuations occur in both the period of rotation (the 'day') and in the position in the Earth of the axis of rotation. At present, the fluctuations cannot be predicted, but they must be measured accurately and regularly. The motion of the axis of rotation in space (or rather with respect to a standard celestial reference frame) is modelled quite accurately by current theories of precession and nutation; these represent the effect of external gravitational forces on a model Earth, although the adopted value of the constant of precession is based directly on observations rather than on the model of the Earth. Departures from predictions of these theories are only likely to become apparent after detailed analysis of long series of observations. This aspect of the rotation of the Earth is largely ignored in this paper, although it cannot be ignored in a full discussion of the observational data. The long-term fluctuations in the period of rotation that are discussed in the accompanying paper by Morrison & Stephenson are also ignored although it is hoped that the better data that will be obtained in future will make it possible to establish the causes of the long-term fluctuations and to obtain better information about, for example, the interactions between the core and mantle of the Earth. This paper, then, is primarily concerned with the fluctuations in the period of rotation and in the position in the Earth of the axis of rotation that have characteristic times of about one year or less.

The fluctuations in the period of rotation now show themselves most clearly as an irregularity of universal time (U.T.) with respect to atomic time. (Universal time is formally defined in terms of Greenwich mean sidereal time in such a way as to correspond closely to mean solar time on the prime meridian.) The existence of seasonal variations in U.T. was established by Smith & Tucker (1953) using an ensemble of quartz clocks to provide a more uniform timescale; the amplitude of the variation was found to be about 30 ms, corresponding to a change of less than 1 ms (1 part in 10^8) in the length of day. It is now recognized that there are also important effects with characteristic times of the order of 50 days.

The fluctuations in the position in the Earth of the axis of rotation are referred to as 'polar motion', and are seen most clearly in the corresponding variations of the zenith distances of the celestial pole, and hence in the 'variations of latitude' of instruments making astronomical observations. There are also corresponding variations in longitude that must be taken into account in the determination of U.T. The general character of polar motion was established by Chandler (1891–1892) who showed that there are two principal components with periods of about 427 and 365 days. The former corresponds to a 'free nutation' of the axis of figure about the axis of rotation, which moves in space under the influence of the external forces. The possibility of the existence of such a free nutation was recognized by Euler, but he predicted a period of about 306 days on the basis of a rigid model of the Earth. This large discrepancy between theory and observation may be resolved by using an elastic model for the Earth, but Chandler's results were the subject of much controversy at the time. (An interesting account of Chandler's work is given by Mulholland & Carter (1982).)

The recognition of the value of a systematic study of polar motion led to the setting up of the International Latitude Service in 1899. It was at first thought that a few years of observation would be sufficient, but it has been necessary to continue to make regular observations and to use more precise techniques. The analysis of the optical-astrometric data is now done by the International Polar Motion Service (I.P.M.S.) in Japan.

The Bureau International de l'Heure (B.I.H.) was set up in 1912 at the Paris Observatory to provide an international time service following the introduction of the transmission of wireless time signals. At first it was solely concerned with universal time but it now provides a rapid service for the dissemination of information about polar motion and it is also responsible for the international scales of atomic time.

Until a few years ago these Earth-rotation services relied on observations made by the techniques of optical astrometry, that is on visual and photographic observations of stars. From 1969 onwards, however, pole positions have been available as a by-product of the routine analysis of Doppler observations of satellites of a U.S. Navy navigation system. By 1978 it had become clear that the techniques of laser ranging and radio interferometry could provide Earth-rotation data of high precision and that consideration should be given to how best the various techniques should be used to provide improved international services for scientific research and for practical applications.

Since 1978 the potential value of these new techniques for the accurate determination of position on the Earth's surface has also become more widely recognized. The realization of their full potential will depend on the determination of the differences between the reference systems inherent in each technique and on the establishment and maintenance of a new standard terrestrial coordinate system. Such a system would be invaluable for general geodetic purposes (e.g. for resolving discrepancies at boundaries between national or regional geodetic networks) and for scientific purposes in the study of crustal movements.

The following section of this paper contains a brief account of the progress that has been made in the development of the use of the techniques for monitoring the rotation of the Earth

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and for providing a new world-wide geodetic control network. These activities are being done together in a programme of international collaboration now known as 'Project MERIT–COTES'. A review of the techniques is given in §4 while some of the results that have been obtained recently are mentioned in §5. The causes of the fluctuations in the rotation of the Earth are discussed in this symposium by both Rochester and Hide.

2. Progress of project MERIT–COTES

Project MERIT is a programme of international collaboration to Monitor Earth-Rotation and to Intercompare the Techniques of observation and analysis. It has its origins in a resolution adopted at I.A.U. Symposium number 82, *Time and the Earth's Rotation*, which was held at San Fernando, near Cadiz, Spain, on 8–12 May 1978 (McCarthy & Pilkington 1979). It recommended

> 'that the Presidents of Commissions 19 and 31 appoint a Working Group to promote a comparative evaluation of the techniques for the determination of the rotation of the Earth and to make recommendations for a new international programme for observations and analysis in order to provide high-quality data for practical applications and fundamental geophysical studies'.

The first meeting of the Working Group was held, at the invitation of I. I. Mueller and under my chairmanship, at Columbus, Ohio on 5–8 October 1978 immediately after an international symposium on the applications of geodesy to geodynamics. The group drew up an outline programme of activities that included as its first stage the preparation of a proposal for submission the following year to the general assemblies of the I.A.U. and of the I.U.G.G. The acronym MERIT was proposed by M. Feissel at lunch after the first meeting. The proposal contained background notes about the applications of Earth-rotation data, about the techniques that would be used for making the observations, and about other relevant matters, as well as the programme for special campaigns of observation, analysis and review. The proposal was endorsed by both unions and the document was subsequently edited and published (Wilkins 1980).

The detailed planning for the project is done by a steering committee consisting of the chairman and vice-chairman of the working group and the principal coordinators for each technique and associated activity. These coordinators obtain the help of other scientists and in some cases form subgroups which meet as opportunities arise. Each coordinator has the responsibility for seeking the participation of observing stations and of operational and analysis centres. The operational centres collect quick-look data from a group of stations and compute Earth-rotation parameters as quickly as possible, while the analysis centres process in depth the final data provided by the stations. The B.I.H. acts as a coordinating centre for the project and publishes the initial results provided by the operational centres.

The programme consisted of two main stages: a short campaign lasting three months (August to October 1980) and a Main Campaign lasting 14 months (September 1983 to October 1984). The short campaign provided both an initial impetus for the project and an operational test of the procedures for the distribution of information and for the collection and analysis of the observational data. The first MERIT workshop was held at Grasse, France, on 19–21 May 1981 to review the operational aspects of the short campaign and to continue the planning for the main campaign. The proceedings of the workshop together with reports by the coordinators, details about the observations made, and the results obtained by the analysis centres have been published (Wilkins & Feissel 1982).

The MERIT short campaign provided the most precise and dense data set on the rotation of the Earth that had been obtained up to that time. The initial conclusions from the examination of these data and from the comparisons between the results from the different techniques were reported at I.A.U. Colloquium number 63, *High-precision Earth Rotation and Earth–Moon Dynamics*, which was held immediately after the MERIT workshop (see Calame 1982). The short campaign showed clearly the value of an international computer network (GE mark III) for the exchange of data and other information, and drew attention to the need for a wider distribution of information about the progress of the campaign for those groups that did not have access to the network. The attempts to understand the reasons for the differences between results of the analysis centres emphasized the need for the adoption of a standard set of constants and models by all participating groups. The preparation of a set of 'MERIT Standards' has proved to be a very difficult but rewarding task which has been done by a subgroup under the chairmanship of Melbourne (1983). It seems likely that these standards will be adopted quite widely and will be a useful spin off from the project.

The first MERIT workshop provided an opportunity for informal discussions between the MERIT steering committee and members of another working group that was considering how best to establish a new terrestrial reference system. This working group had been set up on the recommendation of the participants in I.A.U. Colloquium number 56, *Reference Coordinate Systems for Earth Dynamics*, which was held in Warsaw on 8–12 September 1980 (Gaposchkin & Kolaczek 1981); the relevant recommendation was as follows:

'*Recognizing*:

(1) that geodynamics has become the subject of intensive international research during the last decade;

(2) that a common requirement for all investigations is the necessity of a well defined terrestrial coordinate system not available at present;

(3) that the use of new techniques, such as Lunar Laser Ranging, L.L.R., V.L.B.I., astrometric satellites, when used in a well coordinated manner can determine and maintain such a system;

Recommends:

that a working group be established by the presidents of I.A.U. commissions 4, 19 and 31, and the president of I.A.G. to prepare a proposal for the establishment and maintenance of a Conventional Terrestrial Reference System. This system is to include provisions for the replacement of the presently used terrestrial reference frame (such as the one partly defined by the C.I.O. and the B.I.H. zero meridian), providing continuity, and conformance with the I.A.U. 1976 and 1979 resolutions regarding astronomical constants and the theory of nutation, or its possible modification, as well as with the I.U.G.G. Geodetic Reference System 1980.'

The chairman of the I.U.G.G.–I.A.U. joint working group for the establishment and maintenance of a Conventional Terrestrial Reference System is I. I. Mueller, who is also

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vice-chairman of the MERIT steering committee; the group has adopted the acronym COTES to indicate its purpose.

The discussions at Grasse have had a major impact on project MERIT and it seems worthwhile to quote directly from the proceedings of the workshop (Wilkins & Feissel 1982, p. 43):

> 'After a general discussion it was agreed that it would be of general benefit if the operations during project MERIT were planned in such a way as to contribute whenever possible to the establishment and maintenance of a new conventional terrestrial reference system. In particular it was noted that it would be necessary to identify precisely the coordinate systems being used implicitly by each of the networks that are participating in the MERIT project; these systems could differ even within one technique since, for example, different gravity-field models are used for different satellites. It would then be necessary to establish the relationships between these systems; this might involve making observations by, for example, both laser ranging and radio interferometry at some sites. It would be useful to determine the positions of all sites by the Doppler technique since this was likely to provide the best method of establishing a secondary reference system. It appeared that the positions of the sites would be best expressed by geocentric rectangular coordinates and their time-derivatives. Observations made in the course of providing a long-term Earth-rotation service would be useful in improving the values of these coordinates and derivatives. In conclusion it was agreed that relevant material prepared for project MERIT, such as contributions to the report on standards, should be made available to the new working group, which should in turn suggest what extra observations might be made during the main campaign to unify the individual reference systems.'

The planning for the MERIT main campaign continued throughout 1981 to 1983 with meetings of opportunity in Las Cruces, New Mexico (Doppler symposium), Tokyo (I.A.G. General Meeting), Patras (I.A.U. General Assembly), and Hamburg (I.U.G.G. General Assembly). A second workshop was also held at the Royal Greenwich Observatory on 16–19 May 1983; particular attention was given to the arrangements for the additional activities associated with the COTES objectives. These include: the making of observations by both laser ranging (to both LAGEOS and the Moon at some stations) and radio interferometry at about 8 well distributed stations; the making of Doppler-positioning observations at these sites and at as many of the other stations as possible; and a period of intensive observations during the three months April to June 1984. The intensive campaign is aimed at detecting the presence of short-period (of order of 1 day) terms in the Earth-rotation parameters obtained by each of the techniques. Diurnal differences between techniques would be indicative of differences in the reference systems implicit in these techniques. It is possible that other short-period terms that have a physical origin will also be found; if they exist they would be found by all techniques that are capable of obtaining Earth-rotation parameters with the necessary time-resolution. At present the parameters are published regularly at an interval of five days, but it is hoped that the density of observations will be sufficient to allow values to be determined at an interval of, say, half a day during at least part of this three-month campaign. It is possible that such an opportunity will never occur again since it involves the dedication of much equipment and effort in many countries. The background and implementation plan for these COTES activities are described by Feissel & Wilson (1983).

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The main campaign has been in progress now for six months and the monthly circulars issued by the coordinating centre show clearly the significant improvement in the quality of the data on Earth-rotation that is now being obtained by each of the techniques in use.

3. Review of techniques

Six techniques are being used during the MERIT and COTES campaigns to determine the parameters that specify the orientation of the Earth at any instant and to determine the coordinates of the participating stations. When the observing campaigns are completed the results from the various techniques will be analysed and intercompared to provide a sound basis for recommendations about the character of the future international services for Earth-rotation and coordinate systems. The general characteristics of each of the techniques and of the procedures used in the derivation of the results have been described in the first MERIT report (Wilkins 1980). In the following notes attention is drawn to some of their advantages and disadvantages, but these comments are to be subjected to critical review before any recommendations are put forward by the working groups. One unexpected outcome of project MERIT has been a surge of interest in the use of the techniques of optical astrometry for the determination of Earth-rotation. The most precise instruments are photographic zenith tubes and astrolabes, which have to a large extent superseded other transit instruments for this purpose, but the method is likely to continue to be limited in precision by atmospheric seeing and to be subject to errors arising from anomalous refraction. A significant improvement in the quality of the results has been obtained by combining the data from a larger number of better instruments, including those contributed by China, and by improvements in the reduction procedures, which can be applied retrospectively to improve earlier determinations. Each instrument relates a local reference frame, in which the prime direction is determined by the direction of gravity, to a celestial reference frame which is determined by the adopted positions of those stars that are observed regularly. The results are therefore affected by local anomalies in gravity and Earth-tides and by systematic errors in the star positions. Careful analysis of the observations from many instruments can be used to reduce these errors and to improve the astrometric catalogue concerned. It seems probable that in the future the principal use of such instruments will be for astrometric purposes and for relating the stellar reference frame to the radio-source and dynamical reference frames of the other techniques.

The use of the Doppler tracking of artificial satellites has two principal advantages; first, the results are obtained as a by-product of observations made for the maintenance of a navigation system, and second, the observations are made by standard commercially available equipment and are, to a large extent, independent of the weather. Errors arise from uncertainties in the gravity-field and in atmospheric drag effects; these errors will be reduced as our knowledge of the gravity field is improved and by the use of the NOVA drag-compensating satellites. It appears that the modelling of ionospheric effects needs further investigation. Additional observing stations and a second analysis centre have been set up for the MERIT main campaign in an endeavour to obtain a set of improved results that, to a large extent, will be independent of the U.S. Navy system. The experience gained will also be useful in discussions about the setting up of an international system for precise positioning that would be free of the restrictions that will be imposed on the use of the new U.S. Global Positioning System.

The greater number of tracking stations during the MERIT main campaign will allow better determinations of the orbits of the satellites and hence better determinations of positions by portable equipment. An attempt will therefore be made to determine the positions of all MERIT stations in the Doppler reference frame and to link regional geodetic networks (such as RETRIG in Europe) to this world-wide frame.

The stimulus provided by project MERIT encouraged the Smithsonian Astrophysical Observatory and other centres to develop operational procedures and analysis techniques for determining, first, pole position and then length-of-day values on a regular five-day basis from laser ranging observations to LAGEOS. These procedures were kept in operation after the short campaign and have contributed to an increasing extent to the regular determination of Earth-rotation parameters by the B.I.H. It has been necessary to obtain a self-consistent world-wide system of station coordinates of high-precision and it is expected that satellite laser ranging will make a major contribution to the new conventional terrestrial reference system.

A regular determination of the orbit of LAGEOS and of the Earth-rotation parameters by a world-wide network of permanent stations is essential to the use of the S.L.R. techniques for the determination of crustal movements due to motions between and within tectonic plates. The permanent network is supplemented by the use of mobile systems which are used to determine at two or more epochs the positions of a more dense network of points in areas of particular interest. At present, to obtain the best results, it is necessary to determine the base-lines between pairs of stations by using observations made during the same period, but eventually it should be possible to determine directly the 'proper motions' of individual stations with respect to the new reference system.

The long series of lunar-laser ranging observations made at the McDonald Observatory with a 107-inch telescope (2.7 m) demonstrated the value of this technique for the study of the rotation of the Earth as well as for the study of the orbit and rotation of the Moon. Up to now it has, however, proved to be extremely difficult to obtain regular observations by using smaller telescopes at other stations. During the MERIT short campaign the observations were insufficient to obtain determinations of polar motion but results on universal time were obtained by four analysis centres. It is hoped that sufficient stations will be operating before the end of the main campaign to allow the determination of polar motion so that the full potential of the technique can be properly assessed. One of its advantages is that the signature of the difference between U.T. and clock time is very clear in the residual differences between the observed and computed ranges so that this time difference is available very quickly. The technique also provides a precise way of linking the terrestrial reference frame to the dynamical reference frame used for the ephemerides of natural and artificial objects in the Solar System.

In one important respect S.L.R. and L.L.R. are complementary; S.L.R. provides good determinations of short-period fluctuations in the length of the day, while L.L.R. provides good determinations of the long-period variations in the rate of rotation even though only one station is at present in regular operation. It may be noted that laser ranging to the Moon cannot be done when the Moon is close to the Sun, so that there is always a gap in the observational data around new moon.

Radio interferometry has its main application in the study of the structures of galactic and extragalactic radio sources but it was shown during the MERIT short campaign that both connected-elements radio interferometry (C.E.R.I.) and V.L.B.I. are capable of producing high-quality data on Earth-rotation, although at the time no network was in full operation.

Since that time much progress has been made and a three-element C.E.R.I. system is in daily operation at Green Bank, U.S.A. A four-element V.L.B.I. system, comprising three stations in the U.S.A. and one at Wettzell, F.R.G., is now observing on every fifth day; other stations also participate less frequently. In addition the three stations of the Deep Space Network (D.S.N.), which is primarily used for the control of U.S. interplanetary spacecraft, are also making observations on a weekly basis.

Radio interferometry has the advantages that the observations do not require clear skies and that the radio sources do not have complex motions. The results do, however, show the effects of variations in water-vapour content of the atmosphere and it is necessary to select the radio sources with care. In C.E.R.I. the signals are correlated in real time and so the results are obtained with very little delay, but V.L.B.I. requires the use of magnetic tapes that must be transported to the correlator facility. The additional delay is however, compensated by the higher precision that is obtained from the use of the much longer baselines. The V.L.B.I. results now make a major contribution to the B.I.H. determinations of Earth-rotation.

The starting point in the adoption of a set of standard constants and models for use during the analysis of the data obtained during the MERIT main campaign was the system adopted by the I.A.U. in 1976 and its subsequent extension in 1979 and 1980. It has, however, been considered necessary to make a few changes as well as to include additional topics to ensure that the results will not be affected by avoidable systematic errors. (For example, the adopted value for the equatorial radius of the Earth is that adopted by the I.A.G. in 1980.

The high precision of the data now being obtained means that special attention must be given to the computation of the effects of Earth and ocean tides. It has also become necessary to recognize that the Earth-rotation parameters contain short-period tidal terms that cannot be properly represented in tabulations at an interval of five days. The standards also cover such topics as relativistic effects and the models for the effect of radiation pressure on satellite orbits.

Some of the differences between the Earth-rotation parameters obtained by different techniques, or by different analysis centres for the same technique, are due to differences in the reference systems implicit in the adopted procedures. Special efforts are therefore being made to identify and eliminate the sources of these differences. Information about the differences between the terrestrial reference systems will be obtained from those places where observations will be made by two or more techniques. Mobile S.L.R. and V.L.B.I. equipment will be deployed at selected sites around the world to compare the coordinate systems directly. Some laser systems can be used for ranging to both Lageos and the Moon, but in other cases it will be necessary to establish by very careful local surveys the actual differences between the coordinates of the two instruments at each place.

The MERIT–COTES campaign in 1983–1984 will eventually provide a first-epoch determination of the coordinates of a world-wide network of points on a unified reference system. It is important that these points should be very carefully identified and 'monumented' so that there are no uncertainties about the locations to which the coordinates refer when second-epoch determinations are made in several years time.

The observations made during the short campaign in 1980 were insufficient to establish the existence of variations with periods of the order of one day, although some results were published at an interval of 2.5 days, or half the standard interval. It is hoped that the observations during the intensive campaign in April–June 1984 will allow diurnal terms arising from physical causes or from errors in the reference systems to be found if present. It is hoped that special efforts will be made to eliminate the 'weekend effect' which is clearly seen in the distribution of the number of observations against the day of the week. It is also hoped that the weather will not adversely affect those techniques that are dependent on clear skies. A meeting of the MERIT steering committee will be held in July to review the activities during the intensive campaign and to decide whether to ask for further special efforts before the end of the main campaign.

5. Results and prospects

There is no doubt that some of the objectives that were identified by the I.A.U. working group on the determination of the rotation of the Earth have already been achieved. Project MERIT has stimulated the faster development and regular operation of the new techniques such as laser ranging and radio interferometry, and the results now being obtained are of higher precision and accuracy than those obtained five years ago. It has also stimulated the improvement of the established techniques of optical astrometry and Doppler tracking of satellites. The progress has been achieved partly by improvements in equipment and by the deployment of additional equipment, and partly by improvements in the coordination and communication procedures and in the analysis techniques. Moreover, the progress has been achieved partly as a result of competition between the different techniques, and partly as a result of greater cooperation between the many groups who are now working together to make a success of MERIT–COTES. One condition for participation in project MERIT is that observational data and results, together with full details of the analysis procedures, must be made freely available to the other participants. Many data are already available and there has been a great deal of interchange of information about models and procedures as the participants have endeavoured to understand the differences in their past results and to reach agreement on the standards to be adopted for the future.

The most striking scientific result that has been obtained as a direct result of the availability of better data on Earth-rotation is the recognition of the very close correlation between the fluctuations in the rotation of the Earth and in the angular momentum of the atmosphere. The existence of the correlation was first shown by a comparison of U.T. data from optical astrometry with data based on meteorological observations made during the First GARP Global Experiment in 1979 (Hide *et al.* 1980). The more detailed comparisons that are now possible are leading to a much better understanding of the mechanisms for the transfer of angular momentum between the solid Earth and the atmosphere. As yet there appears to be no conclusive evidence of a direct link between seismic activity and Earth-rotation although it has been suggested that major earthquakes could be responsible for the excitation of the Chandler wobble in the motion of the pole. The work of Barnes *et al.* (1983) (see also Hide (this symposium)) indicates that meteorological excitation is largely responsible for polar motion, at least over an interval of time corresponding to three Chandler periods when no earthquakes greater than 7.9 occurred. The much improved quality of the MERIT polar-motion data should enable an assessment to be made of the effects of large earthquakes if significant seismic events occur during this period. These topics are discussed in more detail in this symposium by both Rochester and Hide.

The full value of project MERIT–COTES will not be realized, however, until new international services on the Earth's rotation and reference systems are established. These services should satisfy certain conditions (Wilkins 1984, pp. 19–20); it appears that the technical requirements can be satisfied in an economical way by an appropriate combination of cooperating networks of stations and centres. The excellent spirit of cooperation that has permeated the project and the support that has been provided so far indicate that such services will be established to provide high-quality data for practical applications and geophysical studies.

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Abbreviations

C.I.O.	Conventional International Origin (for coordinates of pole)
I.A.G.	International Association of Geodesy
I.A.U.	International Astronomical Union
I.U.G.G.	International Union of Geodesy and Geophysics
L.L.R.	Lunar Laser Ranging
S.L.R.	Satellite Laser Ranging
V.L.B.I.	Very-Long-Baseline (radio) Interferometry

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