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REFERENCE COORDINATE SYSTEMS FOR EARTH DYNAMICS

Edited by E. M. Gaposchkin and B. Kołaczek

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REFERENCE COORDINATE SYSTEMS FOR EARTH DYNAMICS

PROCEEDINGS OF THE 56TH COLLOQUIUM
OF THE INTERNATIONAL ASTRONOMICAL UNION HELD IN
WARSAW, POLAND, SEPTEMBER 8–12, 1980

Edited by

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PREFACE

The IAU Colloquium No. 56, the Second IAU Colloquium, "On Reference Coordinate Systems for Earth Dynamics," co-sponsored by the COSPAR and the International Association of Geodesy of IUGG was held in Warsaw, Poland, on September 8-12, 1980.

The Colloquium was organized by the Space Research Centre of the Polish Academy of Sciences and the Smithsonian Institution Astrophysical Observatory. It was sponsored by the Committee of Astronomy, the Committee of Geodesy, and the Committee of Space Research of the Polish Academy of Sciences. The first Colloquium devoted to this subject was held in Toruń, Poland, in 1974. The Scientific Organizing Committee consisted of:

Cochairmen

Dr. E. M. Gaposchkin	USA
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The duties of chairmen of the sessions were performed by Dr. J. Zieliński, Dr. P. Bender, Prof. W. Fricke, Dr. B. Kołaczek, Prof. K. Lambeck, Prof. H. Moritz, Prof. G. Veis, Dr. J. D. Mulholland, Prof. M. C. Rochester, Dr. C. Murray, and Dr. E. M. Gaposchkin. In addition, the occasion of the Colloquium was used to have a meeting of the IAU Working Group on Nutation organized by Dr. K. Seidelmann and a meeting of IAG Commission VIII headed by Prof. I. I. Mueller. The volume contains the texts or abstracts of papers presented at the Colloquium. An analysis and synthesis of what was learned and the consensus of the meeting on progress made and future prospects written by Prof. J. Kovalevsky and Prof. I. I. Mueller is also included.

This Colloquium was brought about by the unprecedented increase in accuracy of metric measurements from the ground and space, achieved in recent years, especially since the first Colloquium, and in the future, as well as significant progress of theory and model development. Geodesists and geophysicists are re-examining the principles and methods used for establishing terrestrial reference frames in the light of new understanding of the mobile Earth. Satellite and solar system dynamics require more careful definition. Galactic and extragalactic stellar reference frames are being redefined. All of these reassessments are fundamental, and none is independent of the others. This Colloquium brought together a unique combination of geophysicists, geodesists, dynamicists, astronomers, and astrometricists to discuss their common problems with reference frames and reference systems, each from his own point of view. The discussions were penetrating and on many points a consensus was actually obtained.

The editors want to thank Ms. J. Horn and Ms. Korniewicz for assistance in preparing the proceedings, Ms. P. Looney and Mr. S. Terry for excellent typing of manuscripts, the program committee for reviewing all the papers, the referees at the meeting who helped to insure a high standard of the proceedings, and Y. Bock for compiling the index. However, any errors in compiling these proceedings are the responsibility of the editors.

The organizers are very grateful for the financial support of the Polish Academy of Sciences (PAS), the Polish Astronomical Society, the Smithsonian Institution, IAU, COSPAR, and to the Copernicus Astronomical Centre of the PAS for making the meeting facilities available.

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REFERENCE COORDINATE SYSTEMS FOR EARTH DYNAMICS: A PREVIEW

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ABSTRACT. A common requirement for all geodynamic investigations is a well-defined coordinate system attached to the earth in some prescribed way, as well as a well-defined inertial coordinate system in which the motions of the terrestrial system can be monitored. This paper deals with the problems encountered when establishing such coordinate systems and the transformations between them. In addition, problems related to the modeling of the deformable earth are discussed.

1. INTRODUCTION

Geodynamics has become the subject of intensive international research during the last decade, involving plate tectonics, both on the intra-plate and inter-plate scale, i.e., the study of crustal movements, and the study of earth rotation and of other dynamic phenomena such as the tides. Interrelated are efforts improving our knowledge of the gravity and magnetic fields of the earth. A common requirement for all these investigations is the necessity of a well-defined coordinate system (or systems) to which all relevant observations can be referred and in which theories or models for the dynamic behavior of the earth can be formulated. In view of the unprecedented progress in the ability of geodetic observational systems to measure crustal movements and the rotation of the earth, as well as in the theory and model development, there is a great need for the definition, practical realization, and international acceptance of suitable coordinate system(s) to facilitate such work. Manifestation of this interest has been the numerous specialized symposia organized during the past decade or so, such as those held in Stresa [Markowitz and Guinot, 1968], Morioka [Melchior and Yumi, 1972; Yumi, 1971], Torun [Kołaczek and Weiffenbach, 1974], Columbus [Mueller, 1975b and 1978], Kiev [Fedorov, Smith and Bender, 1980] and San Fernando [McCarthy and Pilkington, 1979]. There seems to be general agreement that only two basic coordinate systems are needed: a Conventional Inertial System (CIS), which in some "prescribed way" is attached to extragalactic celestial radio sources, to serve as a reference for the motion of a Conventional Terrestrial System (CTS), which moves and

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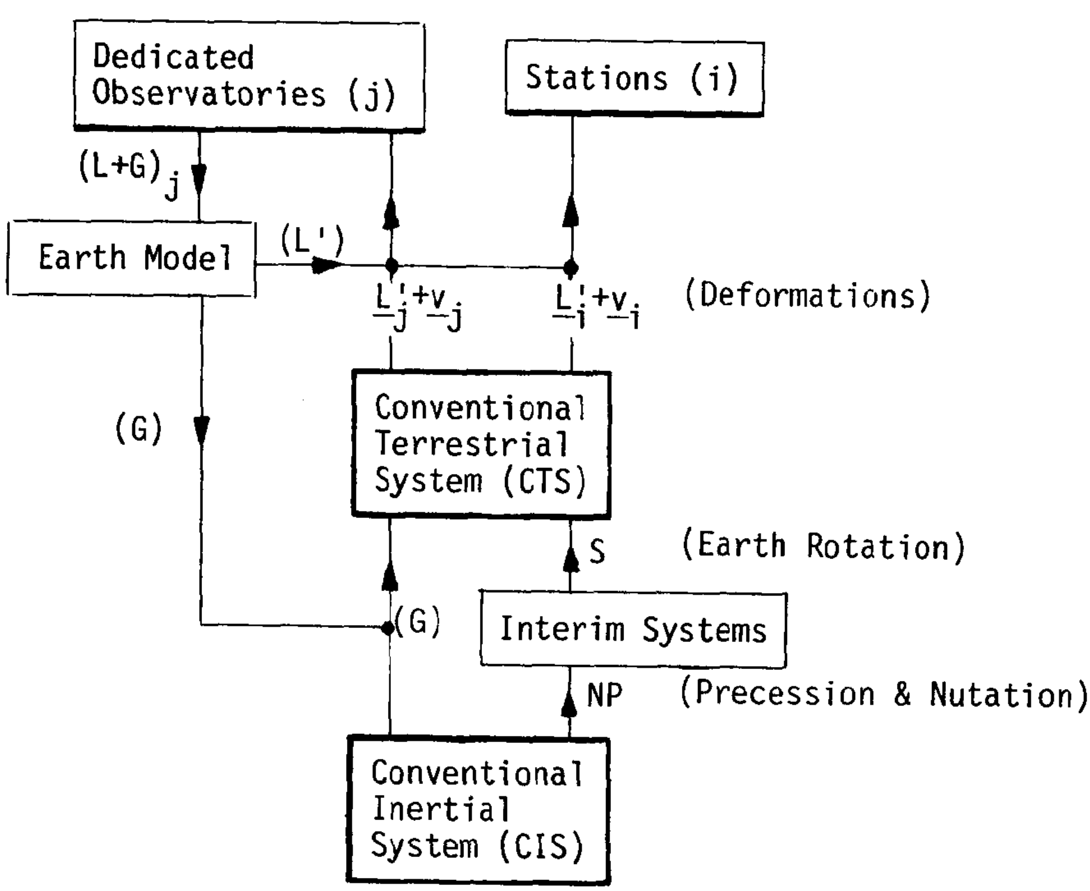
rotates in some average sense with the earth and is also attached in some "prescribed way" to a number of dedicated observatories operating on the earth's surface. In the latter, the geometry and dynamic behavior of the earth would be described in the relative sense, while in the former the movements of our planetary system (including the earth) and our galaxy could be monitored in the absolute sense. There also seems to be a need for certain interim systems to facilitate theoretical calculations in geodesy, astronomy, and geophysics as well as to aid the possible traditional decomposition of the transformations between the frames of the two basic systems. This scheme is shown in the figure below. The Earth Model block represents the current best knowledge of the geometry and dynamic behavior of the earth, partially deduced from the measurements made at the Dedicated Observatories. This model is continuously improving as more data of increasing accuracy becomes available, and it includes both the local (L) and global (G) phenomena which have theoretical foundations based on physical reality and are mathematically describable. In the final and ideal situation, which may be achieved only after several iterations over an extended period of time, the global part of the model should be identical to the connection between the CIS and CTS frames. Departures (v) from the model (L') observed at the observatories (j) or at other stations (i) are of course most important since they represent new information based on which the model can be improved, after observational random and systematic errors have been taken into proper consideration. The model could eventually include the solid earth as well as the oceans and the atmosphere.



As we will see later, there already seems to be understanding on how the two basic reference systems should be established; certain operational details need to be worked out and an international agreement is necessary. There are, however, a number of more or less open questions which will have to be discussed further. These include the type of interim systems needed and their connections to both CIS and CTS, the type(s) of observatories, their number and distribution, whether all instruments need to be permanently located there or only installed at suitable regular intervals to repeat the measurements; how far the model development should go so as not to become impractical and unmanageable; and how independent observations should be referenced to the CTS, i.e., what kind of services need to be established and by whom.

2. CONVENTIONAL INERTIAL SYSTEMS (CIS) OF REFERENCE

2.1 Basic Considerations

The first law of Newton is as follows: "Every body persists in its state of rest or uniform motion in a straight line unless it is compelled to change that state by forces impressed on it" [Newton, 1686]. It should be obvious that the above *law of inertia* cannot hold in any arbitrary reference frame so that only certain specific reference frames are acceptable. In classical mechanics, reference frames in which the above law is valid are called *inertial frames*. Such "privileged" frames move through space with a constant translational velocity but without rotational motion. Another privileged frame in classical mechanics is the *quasi-inertial*, which also moves without rotational motion, but its origin may have acceleration. Such a frame would be, for example, a non-rotating geocentric Cartesian coordinate system whose origin due to the earth orbit around the sun would move with a non-constant velocity vector. Inertial reference frames thus are either at rest or are in a state of uniform rectilinear motion with respect to *absolute space*, a concept also mentioned by Newton and visualized as being observationally defined by the stars of invariable positions, a dogma in his time.

The refinement of classical mechanics through the theory of relativity requires changes in the above concepts. The theory of special relativity allows for privileged systems, such as the inertial frame but in the *space-time continuum* instead of the absolute space [Moritz, 1967]. Transformation between inertial frames in the theory of special relativity are through the so-called Lorentz transformations, which leave all physical equations, including Newton's laws of motion, and the speed of light invariant. The special theory of relativity holds only in the absence of a gravitational field.

In the theory of general relativity, Einstein defined the inertial frames as "freely falling coordinate systems" in accordance with the local gravitational field which arises from all matter of the universe. Thus the inertial frames lose their privileged status. Concerning the existence of inertial frames in the extended portions of the space-time continuum, Einstein [1956] states that

"there are finite regions, where, with respect to a suitably chosen space of reference, material particles move freely without acceleration, and in which the laws of special relativity hold with remarkable accuracy."

In other words, one can state [Weinberg, 1972] that

"At every space-time point in an arbitrary gravitational field, it is possible to choose a locally inertial coordinate system such that, within sufficiently small region of the point in question, the laws of nature take the same form as in unaccelerated Cartesian Coordinate system in the absence of gravitation."

(i.e., as in the theory of special relativity). Our sphere of interest, the area of the solar system, where the center of mass of the earth-moon system is "falling" in an elliptic orbit around the sun, in a relatively weak gravitational field, seems to qualify as such a "small region." Thus we may assume that inertial or quasi-inertial frames of reference exist, and any violation of principles when using classical mechanics can be taken into account with small corrections appropriately applied to the observations and by an appropriate "coordinate" time reference. The effects of special relativity for a system moving with the earth around the sun are in the order of 10^{-8}, while those of general relativity are 10^{-9} [Moritz, 1979]. Since 10^{-8} on the earth's surface corresponds to about 6 cm, corrections at least for special relativity effects are needed when striving for such accuracies. Other than this, the problem, in the conceptual sense, need not be considered further.

2.2 Inertial Systems in Practice

2.21 Extragalactic Radio Source System. This system is attached to radio sources which generally either are quasi-stellar objects (quasars) or galactic nuclei. Very long baseline interferometers rotating with the earth determine the declinations of these sources with respect to the instantaneous rotation axis of the earth, as well as their right ascension differences with respect to a selected source (3C273, NRAO 140, Persei (Algol), etc.). In addition, the observations also determine changes in the earth rotation vector with respect to a selected initial state, the baseline itself, and certain instrumental (clock) corrections. The frame of the Radio Source-CIS can be defined by the adopted true or mean coordinates of appropriately selected sources referred to some standard epoch. The mean coordinates naturally will depend on the model of the transformation from the true frame of date to the adopted mean standard. If, however, the reduction procedure is correct (see more on this later), there are no known reasons for non-radial relative motions of the sources, i.e., for the rotation of the frame. Thus, such a frame could be considered inertial or at least quasi-inertial. The equatorial system of coordinates may be retained for convenience, but the frame could be attached to the sources in any other arbitrary way should this be necessary.

As far as the accuracy of the Radio Source-CIS is concerned, the question has meaning only in the sense of the formal precisions of the source positions in the catalogue. At the Torun meeting, this number was 0".1 [Moran, 1974]; now it is at most 0".01 [Purcell et al., 1980]. It is hoped that within a few years the precision should reach 0".001 (5×10^{-9}). The problem on this level is that the densification of such a catalogue will be very difficult, since only a relatively few well-defined point-like radio sources have been observed. Others have structures such that identification of the center of the radiation with such accuracy may not be possible. This situation may change when the astrometric satellites (see below) are launched.

2.22 Stellar System. This system will be attached to stars in the FK5 catalogue, i.e., the adopted right ascensions and declinations of the FK5 stars will define the equator and the equinox and thus the frame of the Stellar-CIS. The FK5, to be effective in 1984, will be the fifth fundamental catalogue in a series which began with the FC in 1879 [Fricke and Gliese, 1978]. In the fundamental catalogues the equator is determined from zenith distance (or distance difference) observations of the stars themselves, but the equinox determination also necessitates measurements of the sun or other members of the planetary system. It was always tacitly assumed that coordinate systems attached to the fundamental catalogues were quasi-inertial. However, as more and more observations became available for proper motions and on the various members of the planetary systems, certain small rotations were discovered, which require changes in the positions of the fundamental equator and equinox, in the proper motions and in the precessional constant (all intricately interwoven) when one fundamental catalogue replaces the other. This slow and painstaking process should lead to a quasi-inertial system eventually. We hope that the FK5 will be such a system.

When the FK4 was compiled, a small definitive correction to the declination of FK3 was applied, but there seemed to be no need to change the position of the equinox or the precessional constant [Fricke, 1974]. The FK5 will be a considerably different and improved catalogue. The main changes with respect to the FK4, regarding the issue of the coordinate systems, are as follows [Fricke, 1979a]: (1) New value of general precession in longitude adopted by the IAU in 1976 will be used (more on this later). (2) The centennial proper motions in right ascension will be increased by 0^s.086/century (this number is provisional) to eliminate the motion of the FK4 equinox with respect to the dynamical equinox (the FK4 right ascensions are decreasing with time due to an error in the FK4 proper motions, see below). (3) Rotation of the FK4 equinox at 1950 by the amount of 0^s.040 (also a provisional value)so that the FK5 and the dynamic equinoxes will be identical (the FK4 right ascensions at 1950 are too small). (4) Elimination of inhomogeneities of the FK4 system by means of absolute and quasi-absolute observations. (5) Determination of individual correction to positions and proper motions of FK4 stars. (6) Addition of new fundamental stars to extend the visual magnitude from 7.5 to about 9.2. More than 1500 new stars are to be added.

It should be mentioned that the above improvements are possible because of the availability and/or reanalysis of observations of the sun