COMMISION 19: EARTH ROTATION (ROTATION DE LA TERRE)

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INTRODUCTION

The period has been marked by the start of the new International Earth Rotation Service (IERS), which benefits from a tight cooperation between astronomers, geodesists, and specialists in satellite geodesy, as well as meteorologists. The scope of the IERS covers not only the Earth's rotation *per se,* but also the conventional terrestrial reference frame, of direct interest to the International Association of Geodesy, and a high accuracy (0.001") celestial reference frame based on extragalactic compact sources observed in Very Long Baseline Interferometry. The IERS conventional celestial reference frame is consistent with the FK5 within the uncertainties of the latter (0.04"). The IERS Standards (1989) which contain the current best estimates of astronomical models and constants are used in many fields of astronomy and geodesy.

Shortly after the adoption of the IAU 1980 Theory of Nutation, VLBI and LLR observations started to show evidence of inaccuracies in some of its components, at the level of 0.001" to 0.01"; in addition, these observations show that the IAU 1976 precession constant requires a correction of about -0.27"/cy. To avoid systematic errors that would result from the use of the conventional models, IERS has complemented the usual three orientation parameters - x, y, which describe the motion of the rotation axis in the Earth, and universal time - by two additional parameters, the celestial pole offsets in longitude and in obliquity. These two parameters can be directly interpreted in terms of nutations in space of the rotation axis.

In parallel to the development of the observing techniques and to their efficient coordination in IERS, the high accuracy (better than 0.001") of today's Earth orientation determinations has encouraged deeper research in the contribution of the various parts of the planet to its rotation variations. Independent analyses converge to ascribe the irregular oscillations in polar motion and universal time to the atmospheric influence, for periods from a few days to several years. The corresponding atmospheric mechanisms are progressively unvealed for the rapid oscillations, but much remains to be understood for the lower frequencies (Chandler term, Southern oscillation), and for the suspected relationships with the solar emissions. The influence of the oceans and groundwater is being clarified. The study of solid Earth effects is also progressing, thanks to the parallel developments of theory and geophysical measurements.

REPORT OF THE INTERNATIONAL EARTH ROTATION SERVICE (IERS)

ORGANIZATION OF THE SERVICE

Terms of Reference

The International Earth Rotation Service (IERS) was established in 1987 by IAU and IUGG and it started operation on 1988 January 1st. It replaces the International Polar Motion Service (IPMS) and the earth-rotation section of the Bureau International de l'Heure (BIH) ; the activities of BIH on time are continued at Bureau International des Poids et Mesures (BIPM). IERS is a member of the Federation of Astronomical and Geophysical Data Analysis Services (FAGS).

IERS should provide the information necessary to define a Conventional Terrestrial Reference System and a Conventional Celestial Reference System and relate them as well as their frames to each other and to other reference systems used in the determination of the earth orientation parameters.

D. McNally (ed.), Reports on Astronomy, Vol. XXIA, 169–186.

IERS is responsible for :

- defining and maintaining a conventional terrestrial reference system based on observing stations that use the high-precision techniques in space geodesy;

- defining and maintaining a conventional celestial reference system based on extragalactic radio sources, and relating it to other celestial reference systems;

- determining the earth orientation parameters connecting these systems, the terrestrial and celestial coordinates of the pole and universal time;

- organizing operational activities for observation and data analysis, collecting and archiving appropriate data and results, and disseminating the results to meet the needs of users.

IERS consists of a Central Bureau and Coordinating Centres for each of the principal observing techniques, and is supported by many other organizations that contribute to the tasks of observation and data processing.

The Coordinating Centres are responsible for developing and organizing the activities in each technique to meet the objectives of the service. The Central Bureau combines the various types of data collected by the service, and disseminates to the user community the appropriate information on earth-orientation and the terrestrial and celestial reference systems. It can include sub-bureaus for the accomplishment of specific tasks. The Central Bureau decides and disseminates the announcements of leap seconds in UTC and values of DUT1 to be transmitted with time signals.

The Directing Board is composed of representatives of

- the International Astronomical Union,
- the International Association of Geodesy/International Union of Geodesy and Geophysics,
- the Federation of Astronomical and Geophysical Data Analysis Services
- the Central Bureau,
- each of the Coordinating Centres.

The chairperson is a member of the Directing Board, elected by the Board for a term of four years, with the possibility of reelection for one additional term. He/she coordinates the activity of the Directing Board. He/she is the official representative of the Service at the meetings of IAU, IAG/IUGG, FAGS, and other outside organizations.

The Directing Board exercises general control over the activities of the service, including modifications to the organisation and participation that would be appropriate to maintain efficiency and reliability, while taking full advantage of the advances in technology and in theory. Most decisions are expected to be made by consensus or by a simple majority vote. Changes in the structure, membership and chairmanship of the Directing Board can be made at any time by a two-thirds majority.

The secretariat of the Board is provided by the Central Bureau. The function includes the distribution of papers and the compilation of the annual administrative and financial reports.

The Board shall meet annually and at such other times as shall be considered appropriate by the Chairperson or at the request of two members.

Directing Board

IAU representatives: G.A. Wilkins, UK, acting chairman until 1988 August; Ya. Yatskiv, USSR, from 1988 August; IUGG representative: K.Yokoyama, Japan, chairman from 1988 August; FAGS representative: O.B.Andersen, Denmark; Central Bureau representative: M.Feissel, France; VLBI Coordinating Centre representative: W.E. Carter, USA; LLR Coordinating Centre representative: C.Veillet, France; GPS Coordinating Centre representative: W.G. Melbourne, USA, from 1989 December; SLR Coordinating Centre representative: B.E.Schutz, USA.

The Directing Board met seven times in the period covered by this report: in Paris (France), 1988 April; Baltimore (USA), 1988 August; Paris (France), 1989 March; Edinburgh (UK), 1989 August; San Francisco (USA), 1989 December; Paris (France), 1990 April, and in Virginia Beach (USA), 1990 October. Copies of the report of the meetings were distributed to the Corresponding Members. Additional copies are available on request to the Central Bureau of IERS.

Observations and Analysis

The data flow and analyses upon which the IERS is based, are organized in the following manner:

• Observations by VLBI, LLR, and SLR networks. The GPS operation for IERS is being organized, starting with campaigns like those of the MERIT program for other techniques.

• Analyses (quick-look and refined) by IERS Analysis Centres. The quick-look results include only the Earth orientation information. They are transmitted weekly in parallel to the Rapid Service sub-Bureau and to the Central Bureau (IERS/CB). The refined results also include information on reference frames. They are transmitted yearly to IERS/CB, and published in the IERS Technical Notes. Table 1 gives the list of refined analyses available in 1990.

• General adjustment of IERS Celestial Reference Frame (ICRF), IERS Terrestrial Reference Frame (ITRF) and EOP by IERS/CB, based on the refined results. The general results are published in the IERS Annual Report and in IERS Technical Notes. Table 2 shows the sites, permanent and temporary, which could be included in the general adjustment of the ITRF (1990).

• EOP determination by IERS/CB. The results are published in the monthly Bulletin B with a 30 day delay between the date of publication and the last date of standard solution.

• EOP determination by the Rapid Service sub-Bureau. The results are published in Bulletin A with a two to five day delay between the date of publication and the last available date with estimated EOP.

• Prediction of EOP. Bulletins A and B provide predictions of EOP at daily intervals, for up to 90 days, and also at monthly intervals for one year in advance.

Table 1: Earth orientation and reference frame results available for analysis (1990)

Earth orientation		Years -1900	No	Celestial frames		No sources	Terrestrial frames		No of sites
VLBI									
EOP(GSFC)	90 R 01	79-89	824	RSC(GSFC)	90 R 01	72	SSC(GSFC)	90 R 01	28
EOP(GSFC)	90 R 02	79-89	1045	RSC(GSFC)	90 R 02	72	SSC(GSFC)	90 R 02	67
EOP(JPL)	90 R 01	78-90	601	RSC(JPL)	90 R 02	197	SSC(JPL)	90 R 02	3
EOP(NAOMZ)	89 R 01	87-88	148	RSC(NAOMZ)	89 R 01	20	SSC(NAOMZ)	89 R 01	6
EOP(NGS)	90 R 01	84-90	469	RSC(NGS)	90 R 01	70	SSC(NGS)	90 R 01	27
EOP(NGS)	90 R 02	84-90	1255	RSC(NGS)	90 R 01	70	SSC(NGS)	90 R 01	27
EOP(SHA)	90 R 01	87-88	119	RSC(SHA)	88 R 01	19	SSC(SHA)	88 R 01	5
EOP(USNO)	90 R 02	88-90	46	RSC(USNO)	90 R 02	77	SSC(USNO)	90 R 02	8
LLR									
EOP(CERGA)	89 M 02	87-88	101				SSC(CERGA)	89 M 01	3
EOP(JPL)	90 M 01	70-89	1290				SSC(JPL)	90 M 01	3
EOP(JPL)	90 M 02	70-90	1287				SSC(JPL)	90 M 01	3
EOP(SHA)	89 M 01	87-89	166				SSC(SHA)	89 M 01	3
EOP(UTXMO)	90 M 01	70-90	775				SSC(SHA)	89 L d01	3
SLR									
EOP(CSR)	89 L 02	76-89	1089				SSC(CSR)	89 L 02	61
EOP(DGFII)	89 L 03	83-87	365				SSC(DGFII)	89 L 03	22
EOP(DUT)	90 L 01	86-89	290				SSC(DUT)	89 L 01	31
EOP(GAOUA)	90 L 01	88-89	122				SSC(GAOUA)	90 L 01	40
EOP(GSFC)	89 L 01	76-88	886				SSC(GSFC)	89 L 01	85
EOP(LPAC)	90 L 01	88-89	117				SSC(LPAC)	90 L 01	25
EOP(SHA)	90 L 01	88-89	150				SSC(SHA)	90 L 01	40
EOP(ZIPE)	90 L 01	87-89	108				SSC(ZIPE)	90 L 01	36
EOP(ZIPE)	90 L 02	87-89	174				SSC(ZIPE)	90 L 01	36
EOP(ZIPE)	90 L 03	87-89	233				SSC(ZIPE)	90 L 01	36

Glossary

CERGA	Centre d'Etudes et de Recherches Géodynamiques et Astronomiques, France		
CSR	Center for Space Research, University of Texas, USA		
DGFII	Deutsches Geodätisches Forschunginstitut, Abt. 1, Ger.	**DUT**	Delft Univ. of Tech., The Netherlands
GAOUA	Main Astron. Ob. of Ukrain. Acad. of Sciences, USSR	**GSFC**	Goddard Space Flight Center, USA
JPL	Jet Propulsion Laboratory, USA	**LPAC**	Astronomical Council of USSR
NAOMZ	National Astronomy Observatory, Mizusawa, Japan	**NGS**	National Geodetic Survey, USA
SHA	Shanghai Observatory, China	**USNO**	United States Naval Observatory, USA
UTXMO	Dept. of Astronomy, Univ. of Texas,Austin,USA	**ZIPE**	Zentralinstitut für Physik der Erde, Ger.

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Table 2: Catalogue of IERS Sites

Name	Country	Name	Country	Name	Country
GRASSE	France	YIGILCA	Turkey	OWENS VALLEY	USA
BREST	France	SHANGHAI	China	WESTFORD	USA
TROMSO	Norway	KASHIMA	Japan	GREENBANK	USA
ONSALA	Sweden	NOBEYAMA	Japan	FORT DAVIS	USA
MARTSBO	Sweden	SIMOSATO	Japan	MAUI	USA
METSAHOVI	Finland	CHICHIJIMA	Japan	OCOTILLO	USA
GRAZ	Austria	HELWAN	Eygpt	WASHINGTON	USA
BOROWIEC	Poland	JOHANNESBURG	S. Africa	BLOOMINGTON	USA
RIGA	USSR	ALGONQUIN	Canada	CARROLLTON	USA
SIMEIS-KATZIVELY	USSR	PENTICTON	Canada	LEONARD	USA
DIONYSOS	Greece	WHITEHORSE	Canada	MILES CITY	USA
ASKITES	Greece	YELLOWKNIFE	Canada	PIETON	USA
ROUMELLI	Greece	PASADENA	USA	SEATTLE	USA
KARITSA	Greece	PALOS VERDES	USA	HAT CREEK	USA
KATAVIA	Greece	PEARBLOSSOM	USA	MARYLAND POINT	USA
XRISOKALARIA	Greece	GOLDSTONE	USA	FLAGSTAFF	USA
LAMPEDUSA	Italy	SAN FRANCISCO	USA	VERNAL	USA
BOLOGNA	Italy	PINYON FLATS	USA	YUMA	USA
NOTO	Italy	FAIRBANKS	USA	PLATTEVILLE	USA
TRIESTE	Italy	POINT REYES	USA	MONUMENT PEAK	USA
CAGLIARI	Italy	AUSTIN	USA	RICHMOND	USA
MATERA	Italy	YAKATAGA	USA	MAZATLAN	Mexico
CHILBOLTON	UK	PATRICK AFB	USA	CABO SAN LUCAS	Mexico
HERSTMONSCEUX	UK	KODIAK	USA	ENSENADA	Mexico
CARNUTSY	UK	VANDENBERG AFB	USA	SANTIAGO DE CUBA	Cuba
MADRID	Spain	NOME	USA	NATAL	Brazil
KOOTWIJK	Netherlands	SANDPOINT	USA	EASTER ISLAND	Chile
WESTERBORK	Netherlands	KAUAI	USA	SANTIAGO	Chile
ZIMMERWALD	Switzerland	SOURDOUGH	USA	CERRO TOLOLO	Chile
MONTE GENEROSO	Switzerland	FORT ORD	USA	AREQUIPA	Peru
POTSDAM	Germany	SANTA PAOLA	USA	BERMUDA	UK
WETTZELL	Germany	BLACK BUTTE	USA	GRAND TURK	Bahama Is.
HOHENBUNSTORF	Germany	DEADMAN LAKE	USA	CANBERRA	Australia
EFFELSBERG	Germany	ELY	USA	YARRAGADEE	Australia
BAR GIYYORA	Israel	QUINCY	USA	HOBART	Autralia
DIYARBAKIR	Turkey	MOUNT HOPKINS	USA	AMERICAN SAMOA	USA
YOZGAT	Turkey	SAN DIEGO	USA	KWAJALEIN ATOLL	USA
MELENGICLICK	Turkey	MAMMOTH LAKES	USA	HUAHINE	France
		BEAR LAKE	USA		

COORDINATING CENTERS

NGS: Very Long Baseline Radio Interferonetry (VLBI)

Three programs continued the routine observing campaigns initiated around 1980, the International Radio Interferometric Surveying (IRIS) project, coordinated by the NGS, the Crustal Dynamics Project (CDP) of NASA, and the Deep Space Network (DSN) operated by the JPL. All programs are analysed for the Earth orientation and reference frames.

Project IRIS operated four major observing programs:

- IRIS-Atlantic: A program of 24-hour observing sessions every 5 days using three stations in the U.S. (Westford, Massachusetts, Richmond, Florida and the George R. Agassiz station (GRAS) in Texas) and the Wettzell station in Germany, with Onsala, Sweden participating about once per month.
- IRIS-Pacific: A program, organized by NAOMZ, which conducts 24-hour observing sessions on a monthly basis using stations in Kashima, Japan; in Fairbanks, Alaska; and in GRAS, and Richmond.
- IRIS-South: A program which conducts 24-hour observing sessions about six times each year using stations in Hartebeesthoek, S. Africa; and in Wettzell, Westford, Richmond, and GRAS.
- IRIS-intensive: a program which conducts one-hour daily sessions using stations in Westford and Wettzell to determine UT1 only.

The NASA CDP program conducts a variety of programs with the following objectives:

- North American Plate Stability: Transcontinental sessions designed to measure the internal stability of the North American Plate.
- Atlantic: U.S. to Europe sessions measuring motion between N. America and Europe.
- Pacific: sessions designed to measure baselines in the Pacific basin.
- Polar: sessions involving stations in Europe, the continental US, Alaska, and Japan. These sessions link the global VLBI reference frame.

The JPL Time and Earth Motion Precision Observation (TEMPO) conducts 3-hour observing sessions twice per week using two of the three DSN stations in Goldstone, California, Madrid, Spain, and Tidbinbilla, Australia. In addition the DSN conducts 18-24 hour observing sessions at irregular intervals for source catalog maintenance.

After a few years of steady but modest improvements to the VLBI Earth orientation monitoring system, 1989 was a year of exceptional achievements. Three major advances were made that set the stage for achieving dramatic improvements in the temporal resolution and accuracy of the VLBI Earth orientation parameters time series in 1990 and beyond.

- The first interferometer formed by two stations in the southern hemisphere, Hobart, Australia, and Hartebeesthoek, South Africa, began regular, year-round operations.
- Agreement was reached between the NGS and USNO, under the auspices of the National Earth Orientation Service (NEOS) to fully coordinate the operations of the USNO NAVNET and IRIS-A networks.
- The NASA Crustal Dynamics Project (CDP) demonstrated improvements to the Mark III instrumentation, observing procedures, and data reduction procedures that yield a factor of 5 to 10 improvement in the accuracy of VLBI determinations of Earth orientation and interstation vectors.

The exciting results obtained by VLBI over the period of the past decade have apparently gained the recognition of senior administrators in several nations and are beginning to pay dividends. The growth of budgets for VLBI activities in Germany, Japan, and most recently the USSR, are particularly noteworthy, and promise to fuel an explosion of activities in the southern hemisphere and areas in the northern hemisphere where the international network lacked stations. By the mid-1990's we should have a truly global network with reasonably good distribution in all regions of the world.

The improvements achieved by the CDP test, when implemented globally in an operational mode, will yield EOP series accurate to a fraction of a millisecond, and a terrestrial reference frame accurate at the 1-3 millimeter level. These greatly improved results will contribute to understanding geodynamics and to the study of such important phenomena as global sea level change.

Six analysis centers, GSFC, JPL, NAOMZ, NGS, SHA, and USNO contributed estimates of the Earth orientation and of the reference frames to IERS.

CERGA: Lunar Laser Ranging

Three stations provided LLR data in 1988-90: Mc Donald (Texas, USA), Haleakala (Hawaii, USA), and CERGA (Grasse, France). Most of the values came from CERGA, as it is the only station completely devoted to Lunar observations.

In addition to the operational network, many efforts have been made at various sites for developing LLR capabilities. The main progress has been achieved in Wettzell, where a new LLR facility is being completed. The first echoes from satellites (Lageos, Meteosat P2), have been received in Spring 1990. It is hoped to have data from this new station sometime before mid-1991.

The Orroral station, located in Australia near Canberra, has been improved in order to be operational on satellites with good quality range measurements. Further attempts to the Moon should be made before the end of 1990. In USSR, the efforts made at Katzively (Crimea) for acquiring echoes from the Moon ceased waiting for hardware upgrades (mainly laser energy and detector efficiency). In China, the LLR station is slowly progressing.

As the LLR Coordinating Center is hosted within the CERGA LLR team, a lot of efforts have been made in order to help the stations in getting more data and developing or improving the systems. This coordination in the technical developments has been made directly with the concerned stations and also through the NASA LLR M/OWG meetings. In the same time, exchanges between JPL, University of Texas and CERGA analysis groups permitted to agree about a common way of deriving EOP from LLR data.

Four analysis centers, CERGA, JPL, SHA and UTXMO contributed estimates of UT1 and terrestrial frames to IERS.

CSR: Satellite Laser Ranging

LAGEOS was the primary laser ranging target in support of IERS. A network of nearly 50 stations participated in the program, totalling approximately 5000 passes per year. Two stations, Herstmonceux and Grasse, observed more than 400 passes per year; 11 stations observed an average of more than 140 passes per year. Statistics of the observations are given in the IERS Annual Report. It should be noted that some of the data were obtained by transportable SLR systems in support or participation with the NASA Crustal Dynamics Project. Although the transportable data were not primary contributors to determination of Earth orientation parameters, they were of considerable importance in contributing to the definition of the terrestrial reference frame. In 1988, the primary emphasis with the European and US transportable systems was to operate at or near VLBI sites to enable detemination of the ties between the VLBI and SLR systems. In 1989, the focus of Transportable SLR Systems was in support of MEDLAS, the Mediterranean project for crustal measurements.

Rapid service Earth rotation results for x, y, UT1, and LOD were computed weekly from Lageos by the Operational Centers: University of Texas Center for Space Research (USA) and Delft Technical University (The Netherlands). In both cases the Earth orientation parameters were computed using quick look data. Full-rate data has been assembled for the European community by Deutsches Geodätisches Forschungsinstitut, for NASA by Bendix and by some individual stations. Compressed data, or "normal points", are commonly used for most analyses. These normal points are computed from the standard algorithm, known as the "Herstmonceux algorithm." A new format to enable transmission of quick-look normal points has been adopted in 1990.

Eight analysis centers have contributed global analyses to IERS: CSR, DGFII, DUT, GAOUA, GSFC, LPAC, SHA, and ZIPE.

A campaign to track the Etalon satellites is planned for September 1 to December 1, 1990. The purpose of the campaign will be to foster the collection of data from which the potential contributions of these satellites for IERS activities can be better assessed.

JPL: Global Positioning System (GPS)

The Directing Board had issued in the Spring of 1989, a Call for Proposals for the function of a IERS Coordinating Center for GPS. At its 1989 December meeting, the proposal submitted by JPL was selected. The new coordinator has set up a two-year program of observation and analysis in order to assess the contribution of GPS to the terrestrial frame and to the Earth orientation determinations.

CENTRAL BUREAU AND SUB-BUREAUS

Central Bureau

The Central Bureau is a joint effort of Paris Observatory, Institut Géographique National (IGN) and the Bureau des Longitudes (BDL). IGN is in charge of the maintainance of the IERS terrestrial frame; BDL is in charge of the maintainance of the IERS celestial frame; the Paris Observatory section determines the corresponding EOP and coordinates the activity of the Central Bureau.

The consistent definition of the IERS terrestrial frame, celestial frame, and EOP was derived from a global analysis described in the IERS Annual Report for 1988. The new definition was meant to be in continuity with the results of the Bureau International de l'Heure (BIH); due to the level of internal inaccuracy in the BIH results, the continiuty was realized at the 0.005" level. Starting with the Annual Report for 1989, the time evolutions of the reference frames and of the series of EOP are controlled independently and their mutual consistency is checked a posteriori. Details on the actual implementations are given in the section on the IERS reference system.

Sub-Bureau for Rapid Service and Predictions (NEOS)

The U.S. National Earth Orientation Service (NEOS) is a joint venture of the US Naval Observatory and the US National Geodetic Survey. Among other duties, NEOS serves as the IERS Sub-Bureau for Rapid Service and Prediction. In this capacity it publishes the IERS Weekly Bulletin A giving quick-look daily estimates of the EOP (x, y, UT1, $d\psi$ and $d\epsilon$), and predictions.

The algorithm used in the determination of the quick-look Earth orientation parameters is based on a weighted cubic spline with adjustable smoothing fit to contributed observational data. It used, in 1988 - 1990, results made available by NGS and USNO for VLBI; CERGA, JPL, and UTXMO for LLR; CSR and DUT for SLR. Contributed data are corrected for possible systematic differences. Biases are determined with respect to the past system of the Bureau International de l'Heure (BIH) and IERS Central Bureau. Possible annual and semi-annual periodic systematic differences are found by analyzing the differences between a weighted cubic spline fit to the LAGEOS 3- and 5-day SLR and IRIS 1- and 5-day VLBI and the individual observations.

Sub-Bureau for Atmospheric Angular Momentum

During the first half of 1989, a series of planning meetings took place to formulate the data specification and implementation of the Sub-Bureau for Atmospheric Angular Momentum (SBAAM). As part of this progress, input by a number of interested scientists was sought by correspondence as well. The operational start-up date was 1 October 1989. It is hosted by the U.S. National Meteorological Center (NMC) and benefits from a cooperation with Atmospheric and Environmental Research, Inc. (AER (USA)). The Sub-Bureau has several goals, the first of which is to serve as a focal point for the collection of meteorological fields and derived quanties which relate to earth orientation parameters. These data, obtained from a number of worldwide meteorological centers, are also made available to the IERS and are archived by the Sub-Bureau.

Additionally, a goal of the Sub-Bureau is to compare the meteorologically derived data to those excitations that produce fluctuations in the geodetic parameters. The IERS Rapid Service requires only the "best" set of analyses and forecasts of atmospheric angular momentum, furthermore, it hopes to attain a reasonable estimation of its accuracy. These topics will be the subject of our research over the two year test period.

The following set of parameters are collected by the sub-Bureau.

Hemispheric values of χ_1, χ_2, and χ_3 for wind to top of model, wind to 100 mb, pressure, and pressure + inverted barometer ; zonal mean zonal winds at 5 degree latitude intervals at 12 pressure levels; zonal mean temperatures at 5 degree latitude intervals at 12 pressure levels; mean surface pressure over the globe; and low-order coefficients of surface pressure. In addition, a file consisting of forecasts of AAM functions is maintianed.

Currently, there are four participating centers in the Sub-Bureau and each produced a portion of the requested data. The centers include the U.S. National Meterological Center (NMC), the United Kingdom Meteorological Office (UKMO), the European Centre for Medium-Range Weather Forecasts (ECMWF), and the NAOMZ.

THE IERS REFERENCE SYSTEM

The IERS Reference System is composed of several parts: the IERS standards, the IERS terrestrial and celestial reference frames, and the corresponding series of the Earth Orientation Parameters, which are consistent with one another at the milliarcsecond level.

IERS Standards

The IERS Standards consist of a set of constants and models used by the IERS Analysis Centers, and by the Central Bureau in the combination of results. The values of the constants are adopted from recent analyses; in some cases they differ from the current IAU and IAG conventional ones. The models represent, in general, the state of the art in the field concerned. The topics covered by the IERS Standards (1989), published in the IERS Technical Note No. 3 are as follows:
Numerical standards; IERS Celestial Reference Frame (ICRF); IERS Terrestrial Reference Frame (ITRF); Nutation; Procedure for computing apparent places; Solid Earth tides; Ocean tide model; Site displacement due to ocean and atmospheric loading; Plate motion model; Tropospheric model; Tidal variations in UT1; Lunar and planetary ephemerides; Geopotential; Radiation pressure reflectance model; General relativistic dynamical model; General relativistic terms for propagation, time, and coordinates.

The IERS Terrestrial Reference Frame

The IERS Terrestrial Reference Frame (ITRF) adopted for either the analysis of individual data sets by technique or for the combination of individual solutions into a unified set of data (station coordinates, EOP, etc.) is realized through a list of coordinates of terrestrial sites.

It is geocentric, the center of mass being defined for the whole Earth, including oceans and atmosphere. Only data which can be modeled by dynamical techniques (presently SLR and LLR for IERS) can determine the center of mass. The VLBI system can be referred to as a geocentric system by adopting for a station its geocentric position at a reference epoch as provided from external information. It is recommended to use a value coming from the initial IERS Terrestrial Reference Frame (ITRF-0).

The unit of length is the meter (SI). The scale is that of a local Earth frame, in the sense of a relativistic theory of gravitation. The scale is obtained by appropriate relativistic modeling. This is particularly true for VLBI and LLR which are usually modeled in a barycentric frame.

For a terrestrial frame associated with a technique, the orientation is defined by adopting IERS (or BIH) Earth orientation parameters at a reference epoch. In the case of SLR, an additional constraint in longitude is necessary. The use of ITRF-0 values is recommended for this purpose. The time evolution of the orientation will be ensured by using a no-net-rotation condition either directly, or by adopting a plate motion model which fulfills this condition. The IERS Reference Pole (IRP) and Reference Meridian (IRM) are consistent with the corresponding directions in the BIH Terrestrial System (BTS) within ±0.005". The BIH reference pole was adjusted to the Conventional International Origin (CIO) in 1967; it was then kept stable independently until 1987. The uncertainty of the tie of the IRP with the CIO is ±0.03".

The IERS Celestial Reference Frame (ICRF)

The ICRF is established at the Central Bureau of IERS on the basis of extragalactic reference frames obtained by the IERS Analysis Centers for VLBI (in 1990: JPL, GSFC, NGS, USNO). These centers use consistent standards in order to make their frames barycentric, and they impose the condition that the sources do not move relative to one another. The appropriate procedures are applied so that the source coordinates are unaffected by the inaccuracy of the precession-mutation model, except for arbitrary offsets in the reference poles. The use of the standard precession-nutation model in computing the coordinates at J2000 introduces a small offset of the pole of the frame relative to the real position of the mean pole. The various ways in which the right ascension origin is fixed also introduce small offsets between the right ascensions systems. The above mentionned offsets are modeled in the Central Bureau combination as three rotation angles for each individual frame relative to the IERS one; they are in general smaller than 3 milliarcseconds.

The IERS Celestial System was initially defined by adopting the coordinates of 23 primary sources. This frame, together with the IERS Terrestrial Reference Frame and the IERS Standards, are the references of the series of the Earth orientation parameters which describe the terrestrial motion of the pole, the motion of the celestial pole relative to its conventionally modeled position, and universal time.

As new information on source positions becomes available, new realizations of the ICRF are introduced, insuring that a new realization has globally no rotation with respect to the previous one. The maintenance process includes the selection of primary sources on which this no rotation condition is applied; this procedure aims at improving the source coordinates and at extending the list of sources (primary and others), while keeping the initial direction of the axes. The 1990 version (IERS Annual Report for 1989) includes a total of 228 radio sources, among which 51 are primary; 113 sources have position uncertainties under 0.001" (vs. 76 in the previous realization) and the rotation angles relative to the previous realization are insignificant at the level of 0.1 mas.

From an evaluation of the relative rotation between the ICRF and a set of 28 quasar optical positions brought in the FK5 system by the Hamburg Observatory, one can conclude that the ICRF axes are aligned on the FK5 ones within the uncertainties of the FK5.

The Earth Orientation Parameters

The IERS Earth Orientation Parameters are the parameters which describe the rotation of the ITRF to the ICRF as a function of time, in conjuction with the conventional precession and nutation models. They model the unpredictable part of the Earth's motion. They consist of five parameters: the coordinates of the terrestrial pole (x, y); universal time (UT1); the offsets in longitude and in obliquity ($d\psi$, $d\varepsilon$) of the celestial pole with respect to its position defined by the conventional IAU precession/nutation models.

In the analyses performed by the Central Bureau, the model used to compare the individual series between themselves or with the IERS ones includes a bias at epoch 1988.0, a linear drift, and annual and semi annual terms. Various additional tests, e.g. spectra, are performed to detect other possible systematic differences.

A known source of relative drifts in x, y and UT1-UTC is the variety of processes chosen by the analysis centres to control the time evolution of the adjusted terrestrial reference frames, complicated by the sampling of the tectonic plates and plate margins by the actual observing networks. In the case of Minster and Jordan models AM0-2 (recommended as an IERS Standard) and AM1-2, the relative rotation vector has a module equal to 0.001"/yr. In the cases when the site motions are adjusted, the various ways in which the time evolution is globally constrained to follow AM0-2 reflect themselves as relative drifts up to 0.0003"/y in either coordinate. In some isolated cases, drifts up to 0.002"/y are found ; it is believed that they pertain to other parts of the modelling. Some examples of seasonal signatures up to the level of 0.0005" are found.

The calibration of the formal uncertainties associated with the EOP determinations which are combined is derived from the pair variance analysis of the differences between series, without considering any combined series in the process. If three or more series of similar quality and time resolution can be differenced, the pair variance of the noise of each series can be evaluated.

From the series of EOP listed in Table 1, the Central Bureau has derived four combined series of x, y, UT1, $d\psi$, and $d\varepsilon$, suited to different uses, and covering the years 1979 - 1989. All series are consistent within 0.0003". The uncertainty of an individual value is at the level of 0.0005" from 1984.0 on.

IERS PUBLICATIONS

•Weekly Bulletin A	EOP (x,y,UT1,$d\psi$,$d\varepsilon$) : Rapid Service, prediction. First issue covering observation dates in the last week in 1987 (rapid service distributed on 1988 January 7).
•Monthly Bulletin B	Earth orientation parameters (x,y,UT1,$d\psi$,$d\varepsilon$) combined solution and individual series. Information on UTC time scale. First issue covering observation dates in January 1988 (mailed early March 1988).
•Annual Report	Earth-orientation parameters, terrestrial and celestial frames of the IERS of the IERS Reference System : combined solutions and analysis of individual results. Two issues published (1988, 1989).

- •Special Bulletin C — Announcement of the leap seconds in UTC (see the Report of Commission 19, Time).
- •Special Bulletin D — Announcement of the value of DUT1 to be transmitted with time signals.
- •Special Bulletin E — Information from the IERS/CB Terrestrial Frame Section
- •Technical Notes — Reports and complementary information of relevance to the work of IERS on Earth orientation and the reference systems.

No 1: The initial IERS Terrestrial Reference Frame.
No 2: Earth orientation and reference frame determinations, atmospheric excitation functions, up to 1988, (Annex to the IERS Annual Report for 1988).
No 3: IERS Standards (1989).
No 4: Evaluation of the realizations of the Terrestrial Reference System for 1989.
No 5: Earth orientation and reference frame determinations, atmospheric excitation functions, up to 1989 (Annex to the IERS Annual Report for 1989).
No 6: ITRF89 and other realizations of the IERS Terrestrial Reference System done by the BIH and IERS (1984 - 1988).
No 7: Connection of the IERS and HIPPARCOS celestial reference frames.

The precision of the published results depends on the delay of their availability. For the operational solutions of earth rotation (weekly and monthly bulletins) it is a few milliseconds of arc. The prediction accuracy is in the range of 0.005-0.020" for x,y, 0.002-0.015s for UT and 0.001" for $d\psi$, $d\varepsilon$ (prediction lags of 10 and 90 days). For the yearly scientific solution it is at the level of 0.0005" (2 cm).

The IERS publications are airmailed; the distribution per country is given in Table 3. Bulletin A is prepared and distributed by the Rapid Service sub-bureau ; the other publications are prepared and distributed by the Central Bureau. Bulletins A and Bulletin B are also available on SPAN, EARN/BITNET and GE Mark 3.

Table 3: Distribution of Bulletin B and IERS Annual Report per country.

Argentina	8	Hungary	5	Poland	8
Australia	14	Ireland	2	Portugal	6
Austria	8	India	4	Romania	1
Belgium	10	Indonesia	6	Saudi Arabia	1
Brazil	7	Iran	1	Singapore	1
Bulgaria	3	Israel	1	South Africa	6
Canada	16	Italy	18	Spain	1
Chile	3	Japan	24	Sri-Lanka	1
China P.R.	20	Kenya	2	Sweden	9
Cuba	1	Korea, Rep. of	2	Switzerland	12
Czechoslovakia	8	Mongolia	1	Thailand	2
Denmark	3	Netherlands	10	Turkey	2
Ecuador	1	New Zealand	4	USSR	24
Finland	5	Nigeria	1	United Kingdom	38
France	60	Norway	5	USA	220
Germany	44	Pakistan	1	Venezuela	2
Greece	5	Peru	2	Yugoslavia	7
Hong-Kong	1	Philippines	1	UNESCO	7

WORKING GROUP ON EARTH ROTATION IN HIPPARCOS REFERENCE FRAME
(Chairman: J. Vondrak)

The final goal of the Working Group is to re-reduce the past latitude and clock correction observations by optical astromerty in a completely new way: the observations of individual stars (instead of group results used so far), referred to a unique celestial reference frame (realized by the HIPPARCOS star catalogue), will be used to derive the Earth Orientation Parameters together with other relevant parameters as e.g. nutation corrections, tidal effects, refraction etc. Thus the task of the WG *before* the HIPPARCOS star catalogue becomes available is basically twofold:

a) To decide which data will be used and collect them in a machine-readable form and appropriate format in one centre.

b) To propose the algorithms of computing Earth Orientation Parameters and work out necessary software.

The Working Group met once, during the IAU Symposium No. 141 in Leningrad, October 19, 1989. After broad discussion among the members of the WG, the president of IAU Commission 19 (Earth Rotation) and other specialists, it was decided to go as far back in the past as possible with latitude observations (in order to obtain new infromation on the secular and long-periodic polar motion) and back to 1955 with UT1-UTC (in order to obtain the length-of-day variations since the introduction of Atomic Time). The list of 47 potential instruments working at 33 observatories was proposed, the criteria for their selection being: i) precision and stability of the results, ii) density and regularity of the observations, iii) length of the interval covered by the observations.

A questionnaire was worked out and sent in May, 1990, to all the selected observatories to map the availability of the data and willingness to make them available for the new reduction. So far (end of July 1990) 21 instruments from 13 observatories responded positively; 1 response was negative.

Simultaneously, the WG started to outline the algorithms to be used for re-reducing the observations, taking into account the most accurate definition of the Earth orientation parameters and modelization of the predictable astronomical and geophysical motions involved. Studies are devoted to the selection of "observables" used in case of equal-altitude instruments, (which is inevitably, no matter how chosen, a combination of instantaneous latitude and clock correction) and its combination with "observables" (i.e. essentially individual latitudes and clock corrections) obtained by the instruments observing in local meridian into a single global adjustment. The statistical modelling of instrumental perturbations, e.g. magnitude, color, environmental effects, has been investigated, considering both the parameteric and the non parametric approaches.

REPORTS FROM OBSERVATORIES

This section summaries the of reports received from the following institutions: Astronomical Council of the Academy of Sciences of the USSR, Observatorium Hoher List Bonn, Borowiec Observatory, Bucarest Observatory, Cagliari Observatory, the Chinese Astronomical Society, the Hydrographic Department of Japan (JHD), the Central Bureau of IERS (IERS/CB), the Jet Propulsion Laboratory (JPL), Kiev Observatory, Institute of Astronomy and Geodesy in Madrid, National Astronomical Observatory at Mizusawa (NAO), Royal Observatory of Belgium (ORB), Paris Observatory, Space Research Centre in Warsaw (PAS), Astronomical Institute in Prague, U.S. Naval Observatory (USNO), Central Institute for Physics of the Earth in Potsdam (ZIPE). The list of bibliographic references which were received with these reports is available on request to the President of the Commission, at Paris Observatory.

Instrumentation, observations and their analysis

The major part of the efforts in this field is reported in the IERS section. Additional information is given hereafter.

SLR. JHD has carried out observations with a newly developped, transportable SLR system (HTLRS). **China** is developping stations in Shanghai, Wuhan and Changchun that have a ranging precision of ±5cm, and with larger noise in Xian, Zhenghou and Beijing.

Kiev Observatory has developped a program, GEODYNAMICS-2, for the global analysis of SLR observations.

By means of the last 5 years' (1983-1988) worth of global SLR data from Lageos, the present day change rate of baseline length between the SLR stations was determined at **Shanghai Observatory** by the "multistage-multiarc" method. The precision estimated is better than 1 cm/yr. Generally the results of this determination showed agreement upon the geologic tectonic rate model of Minster and Jordan . In some situations it was found that the results disagreed with the model in some regions of plate boundary. The plate motion of North America relative to Eurasia was determined by using the optical observations (1962-1982) and the Doppler satellite observations of the years (1973 - 1983). Results of plate motions from two different techniques and those from other techniques agreed.

GPS. Studies of the use of GPS to determine pole coordinates and universal time were performed by **JPL** and **ORB**. Both groups conclude that the results are competitive with VLBI and SLR, at least in the high frequencies; the question of long term stability needs further study. **NAO** has shown that dual frequency observations of GPS or NNSS satellites can be used to evaluate the ionospheric correction to VLBI observations.

LLR. **JPL** reports that the recent equipment and software improvements have resulted in an increased accuracy which permitted the computation of a new lunar ephemeris. The free libration of the Moon was determined at **Shanghai Observatory** by using the LLR data from April 1970 to December 1987. The precision of six parameters, which describe the free libration of the Moon, has improved with respect to earlier evaluations.

VLBI. A 25m VLBI antenna was installed at the Zô Sè station of **Shanghai Observatory**; it participates in geodetic and astrophysical observations. A 6m antenna was installed in Nobeyama (**Japan**); it participates in the IRIS-Pacific operation. The Japanese VLBI project VERA is under new study in order to bring the observing capabilities to a higher level of precision and time resolution. **USNO** has set up the NAVNET VLBI network, using antennas in Green Bank, Richmond, Hawaii, and Alaska; the observations started in January 1989. They are analyzed by USNO and contribute to IERS work with weekly 24 hour sessions and additional short, daily sessions for universal time determination.

Optical astrometry. A subset of the network, which participated in the BIH activity until the end of 1987, continues observing today. 64 observatories in 15 countries contributed time and latitude measurements to the analysis centre in Shanghai. **Shanghai Observatory** issued Quarterly Bulletins giving the series of pole coordinates and universal time at 5 day intervals; their agreement with the IERS results is at the level of 0.01 - 0.02".

Several observatories reported a reorganization of their observations and studies based on optical astrometry towards other fields of astrometry or geophysics. A new method of analysis of the optical time and latitude data, in which the color and magnitude effects are estimated along with other parameters in a strict least-squares scheme, was developped at **NAO** Mizusawa, and applied to the Mizusawa astrolabe data. Improved positions and proper motions are calculated for the Mizusawa astrolabe stars. The relationship between time and latitude observations and earthquakes was investigated in **China**. Some Chinese scientists pointed out that anomalous residuals in the determination of time the latitude might reflect the precursor of an earthquake if the epicenter is within 300km from the observing instrument and if the magnitude is larger than 5.

Astronomical modelling, reference frames

The modelling of Earth orientation observations in a relativistic framework has been studied at **Shanghai Observatory**. The use of the non-rotating origin and of the celestial pole coordinates, instead of the equinox and classical precession and nutation developments, is being implemented at **Paris Observatory** for VLBI and optical astrometry observations.

In parallel to its work for the Service, **IERS/CB** has studied various possible implementations of a terrestial frame based on colocated VLBI, LLR and SLR sites. A sensitivity study of the series of EOP to site motion has shown that it is necessary to consider not only a global plate motion, but also the individual site motions in order to avoid internal inconsistencies which can reach the level of 1cm/yr (0.001" in 3 years). The construction of an optimum terrestial reference frame has also been studied at **PAS**.

IERS/CB and **JPL** have compared various independent VLBI extragalactic reference frames. Both groups find an agreement better than ±0.002" on the individual coordinates and ±0.0005" on the directions of axes. **IERS/CB** checked the mutual consistency of the EOP series and the corresponding terrestial and celestial reference frames obtained by various analysis centers in VLBI and SLR; an internal consistency on the order of 0.001" was shown.

Reference frame studies at **JPL** have included the establishment of a radio frame, the establishment of the dynamical reference frame of the Lunar/Planetary Ephemerides, the determination of ties between the various reference systems, and the development of the concept of the dynamic equinox and the unification of coordinate systems. Ties between VLBI and optical frames have been established via the observations of radio stars (in collaboration with the **Bureau des Longitudes.**) A link between the VLBI and Ephemeris frames had been determined through differential VLBI observations of spacecraft during planetary encounters and natural radio sources; the VLBI-Ephemeris frame tie has also been investigated through careful comparison of terrestrial station locations and Earth orientation determinations from VLBI and LLR observations. Very Large Array measurements of Galilean satellites, Titan, Uranus and Neptune provide both a tie between the outer planet ephemerides and the VLBI frame to the level of 150-200 nanoradians and a means of improving the ephemerides themselves.

Work on an observing proposal for the determination of astrometric positions of radio stars was done at **USNO**, in cooperation with the U.S. Naval Research Laboratory (**NRL**) and **Hamburg Observatory**. Currently there are about 50 stars with astrometric optical and radio positions. The optical positions of two FK5 radio stars (β Per and α Scor) have been studied at **Paris Observatory**. Based on a realistic simulation of HIPPARCOS observations, **IERS/CB** has evaluated the accuracy of the link between the HIPPARCOS reference frame and the extragalatic one. The relative rotation angles are expected to be determined within ±0.002", and their time derivatives within ±0.001"/yr.

Comparison and combination of series of EOP

Regular observations of the Earth orientation are perfomed by VLBI, LLR and SLR. Their analysis over several years provides, for each separate program, a consistent ensemble of a terrestrial frame, a celestial frame and the corresponding time series of EOP. In practice, the same observations are analysed in parallel by several analysis centers, using to a large extent, common standards, e.g. IERS Standards, and more or less independent software and computing procedures. In this context, the *accuracy* of the EOP can be estimated from the consistency of the time series with reference frames.

The accuracy can also be evaluated by cross comparisons of the time series of the EOP. In the analyses, the time evolution of the reference frames is constrained to follow simple laws. For example, the stations are assumed to move horizontally according to a plate motion model, or to have a linear horizontal motion and no vertical motion. In the case of VLBI, the radio sources are assumed to have negligible structure, and no time evolution of it. The corrections of the radio or laser range observation, which depend on the state of the atmosphere at the time of observation and in the direction of sight , might have inaccuracies which would be propagated into the time series of EOP according to the distribution of the network and of the observed objects; in the case of SLR the propagation is made rather complex by the fact that the celestial frame is a satellite ephemeris. It is expected that the unmodelled effects are small, except for the low frequency perturbation of LAGEOS node due to the oceanic tides, but they could accumulate in a random way and give rise to long term spurious variations. Such effects can be investigated by considering time varying differences between the parallel series of EOP.

The accumulation of small defects results in instability in the time series; the *precision* of the series can be evaluated from the random two by two differences. In the case of dense and long series, the statistical law followed by this instablility can be characterized on the basis of comparisons two by two, using in particular the Allan variance analysis.

Such comparisons have been performed by several groups: **JPL, Kiev Observatory, USNO** and **IERS/CB**. The conclusions reached are in agreement; they can be summarized as follow.

- The LLR observations refer to a celestial frame which is independent from the VLBI one and of comparable potential quality; thanks to colocation of the terrestrial stations, they could provide a unique link with the VLBI celestial frame if the number and productivity of stations could be enlarged.

- The VLBI and SLR Earth rotation programs provide results of similar quality for polar motion, following quite closely a white noise behaviour, at the levels of 0.001" for five days and 0.0001" for one year sampling times.

- The VLBI universal time results have the same characteristics as above. The SLR results, valid only for periods under 80 days, also have a white noise error spectrum, at a slightly higher level (0.0015" at five days). The LLR universal time results are of comparable quality, but the sparcity of the network and the relatively low rate of observations at some of the stations restrain their efficiency.

- The celestial pole offsets are measured only by VLBI. The short term uncertainty is about 0.0005". However, the results presently available, show some anomalous systematic differences at the level of 0.001". The LLR observations, spanning over 20 years, permit the clean separation of the 18.6 year nutation term from the precession, which is not the case with the shorter series of VLBI.

- The consistency of time series of EOP with the terrestrial and celestial reference frames is at the level of 0.001" at best, which is relatively large compared to the stability of time series for a one year sampling time.

Based on the evaluation of accuracy and precision of the series of EOP, combined series are elaborated by **USNO** and **IERS/CB** in the framework of IERS, and by **JPL**. The various groups use different algorithms. The discrepancies of the results agreed with the above evaluations of precision and accuracy of the individual series.

A new method was developped at **NAO** Mizusawa to analyse polar motion time series in the complex frequency and Q space. It is shown that the introduction of the 'cross-autocovariance' concept is useful in analyzing EOP data derived from different global networks.

Modelling and prediciton of the EOP

The **Astronomical Council of USSR** considers a set of polynomial, exponential and trigonometric functions. The model is used for the prediction of the Earth rotation parameters. The model was able to detect and take into account short-time irregularities in the Earth's rotation without lowering the prediction accuracy within the interval of the influence of these irregularities. The model is also used for the analysis of a 142-year set of pole coordinates in the system of epoch observations and of a 20-year set of the pole coordinates in the BIH system. In amplitude variations of both annual and Chandler components 6-, 8.85, and 18.6 year periods were detected. The same model is used to analyze a registation of the Earth's surface inclination, just short of 10 years, which were obtained at the Geodetic Institute of Finland. Besides the known half-diurnal and diurnal tidal waves with no less then 99% probability, half-annual, and annual and 435-day components were obtained. It is shown that the vector of the barycentric Earth rotation is subject to a high variation both in value and direction; in the modulus vector, variations of the Earth's barycentric rotation periodicities, 438.33 days, similar to Chandler ones were detected.

After the publication of the *"Results of the International Latitude Service in Homogeneous System"* by S.Yumi and K. Yokoyama in 1980, a new separation of periodical components was made at **Bucarest Observatory**. The main components: Chandler (amplitude 0.162"), annual (0.070") and others with period varying from 0.72 years, 1.88 years, 6.54 years, and 28.45 years to 19.6 years were found. The authors think that some planetary effects may be reflected in these periods.

The **Prague** Group, in cooperation with **USNO**, developped a procedure based on the predicted AAM values and seven parameters defining the initial pole position, the shift between the origins of AAM and polar motion, and the variability of the Chandler frequency as a function of total amplitude of polar motion.

PAS applied statistical analyses to the study of the equatorial AAM function. A third order autoregressive process appears to be adequate for a model of the pressure terms of this function with periods less than 100 days. A method for the precise prediction of polar motion using the least-squares collocation method was also elaborated.

A new prediction scheme has been devised by **USNO** and has been tested for use in the prediction of Earth orientation parameters. The new model dramatically improves the predictions of UT1-UTC and also significantly improves the predictions for polar motion. Work on the prediction of the correction to the current nutation theory was also completed. Least-squares solutions at various nutation frequencies were made and evaluated to determine which frequencies required significant corrections for prediction purposes. Predictions of polar motion and UT1-UTC made using other procedures were evaluated. A new method to generate TDT-UT1 predictions was tested and implemented; the results were provided in the IERS Annual Report for 1989. The average prediction capabilities are summarized in the following table.

Errors for different prediction lengths

Days in future	Terrestrial pole (")	UT1-TAI (s)	Celestial pole (")
1	0.0005	0.00005	0.0005
10	0.005	0.0015	0.001
40	0.013	0.007	0.001
90	0.021	0.015	0.001
180	0.025	0.028	0.001

Oceanic, groundwater and atmospheric effects

High-quality estimates of the atmospheric excitation of Earth rotation and polar motion, provided by the routine analyses of global weather data for operational weather forecasting, together with the modern Earth orientation meausrements, have allowed new insight into atmospheric and non-atmospheric excitation of Earth rotation and polar motion variations. The angular momentum exchange of the atmosphere as well as of the oceans with the solid Earth have been intensively investigated.

The **Bonn** Group has computed the theoretical effect of the ten major ocean tides on UT and searched VLBI data for these effects. They found the signal of the two strongest short period partial tides, M2 and O1 to be at the level of 0.0001s.

Global sea level changes were detected by **ZIPE**, using the inverse solution of the equations describing polar motion.

Short Period Fluctuation of the Earth Rotation (**China**): using the intensive observations of VLBI in the MERIT campaign during April - June 1984, the quasi-periodic components in series of daily LOD and of AAM about 9.33 and 58 days were revealed. It is known that contributions from AAM may increase the variations in LOD at higher-frequency tidal periods.

JPL reports: "We have shown that changes in the Length of Day (LOD) at seasonal and higher frequencies are dominated by the exchange of angular momentum between the atmosphere and the solid Earth. The correlation between AAM and LOD is highly significant (except at tidal frequencies) indicating that AAM analysis and forecast fields may be useful in providing near-real time estimates and prediction of Earth rotation changes. Our studies using the forecasts of AAM from large numerical models of the major forecast centers indicate that these models can forecast the AAM better than the currently used statistical predictors [done in collaboration with **AER, NMC**]. The dominance of the atmosphere in short-period variations and the simple power law spectrum of the AAM made possible the development of a Kalman filter for smoothing and prediction Earth orientation. We have established the existence of rapid polar motion; by comparison with AAM data, we found that it is produced at least in part by atmospheric pressure changes. The atmospheric excitation of the Chandler wobble was investigated using both modern polar motion determinations and meterorological estimates of atmospheric forcing; some correlation was found, but the exact nature of the Chandler wobble forcing remains unclear. The effect of earthquakes on polar motion has been investigated. The relationship between the Southern Oscillation and the LOD was established and investigated."

At **NAO** Mizusawa, the observed LOD series derived from VLBI data were compared with the calculated ones based on the global meteorological data. Results show the predominant role of the atmospheric motion in exciting the LOD variations with timescales from a month to a few years. It is confirmed that the Earth's core is practically decoupled from the mantle in the course of these variations.

The **ORB** group has established empirically a relationship between the short term fluctuations of the Earth's rotation at 50 and 120 days and solar activity changes: the same fluctuations are observed in solar data (Wolf numbers, Sun surface areas, solar wind, interplanetary magnetic field) and geophysical data (Earth rotation, atmospheric angular momentum, geomagnetic indexes Aa). Preliminary results conducting to the same conclusions are obtained for the quasi biennal oscillations.

At **IERS/CB**, in cooperation with the Institut de Physique du Globe de Paris, analyzed a 1962 - 87 time series of the duration of the day. Features in the seasonal and irregular parts of the time series that would be associated with the occurence of an El Niño-Southern Oscillation (ENSO) event were looked for. ENSO Northern Hemisphere winters and the preceding, Southern Hemisphere winter, tend to exhibit an increase in amplitude and frequency of the short term oscillations. The seasonal oscillation, except in the case of the strong 1982-83 event and to a lesser extent, in 1976 - 77, is not highly perturbed.

At **PAS**, variable short periodic oscillations with amplitudes of the order of one to several 0.001" and with periods in several spectral bands between 15 and 110 days have been found in polar motion, and in polar motion velocity. There is a meaningful correlation of short periodic variations as well as individual short periodic oscillations of polar motion and of its velocity in the considered spectrum range with those of AAM variations. It points out an important influence of AAM variations on polar motion. Two periods of especially energetic short periodic variations of polar motion and velocity, that have a high correlation (0.7) with those of AAM variations, were found at the end of 1984 and in the first half of 1988. Common stronger variations of polar motion, LOD and AAM with periods of about 50 days were observed in early 1988, and were studied in cooperation with **IERS/CB**. We showed that AAM is the common source of these LOD and polar motion variations.

The atmospheric excitations of polar motion were studied by the **Prague** Group for constant and variable Chandler frequency. It was shown that a stronger agreement between the observed and atmospherically excited polar motion is achieved if a variable Chandler frequency is assumed, the frequency being exponentially dependent on the total polar motion amplitude. At the same time, the fit is substantially improved if the additional excitation by groundwater storage, modelled by a simple annual wave, is included. These findings were further used to design an algortithm for predicting polar motion.

Studies of the Interaction of Angular Momentum between atmosphere, ocean and solid Earth were performed in **China**: the irregular variation of the Earth rotation, atmospheric angular momentum and sea surface temperature and the thermocline of the tropical Pacific were analyzed. The interannual variation is very consistent with the variation of sea surface temperatures in the equatorial eastern Pacific. The warming up of the equatorial sea water corresponds to the deceleration of the interannual variation of Earth rotation and vice versa. This means that El Niño events usually appear after the interannual acceleration of earth rotation turns to deceleration. Based on statistics, the next El Niño event derived from the predicated series of LOD should happen in 1990 - 91. The prediction of El Niño event especially in the 22nd solar activity cycle was also discussed. The relationship between solar activity and the Earth's rotation was studied. Maximum and minimum values of amplitude in the annual term of LOD correspond respectively to strong and weak solar activity at the same time. This implies that the seasonal angular momentum imbalance between the circulations in Southern and Northern Hemispheres is controlled in some way by solar activity. Information about atmospheric circulation on geological time scale was obtained from the analysis of geological records. Periods about 100, 40, and 20 ka were detected from these data. These periods are in agreement with long-term variations of Earth orbit.

Solid Earth effects and their perturbations

Secular variations in the rate of Earth rotation were studied in **China**. From the ancient observations (17th to 19th centuries), 612 records have been collected. The tidal and non-tidal angular acceleration of earth rotation were obtained.

At **Bucarest Observatory**, the connection between the Earth rotation fluctuation and continental drift was studied. Using the data published by BIH, IPMS and ILS for the period 1956 - 1983, which were obtained from optical astrometry stations placed on different tectonic plates, they found a high correlation between Earth rotation variations and tectonic plate displacement.

Cagliari Observatory reports a correlation study of polar motion, universal time, luni-solar effects and earthquakes, and a study of the long-term variations in polar motion and tectonic motions.

Study of Chandler wobble in **China**: Chandler wobble has several statistical characteristics such as multi-spectral peaks, which vary in number from 1 to 3 in different duration, time-varying amplitude and apparent period. Some theoretical modes such as multi-frequency mode, modulation mode, and phase-reversing mode have been presented to explain these features. The simple mode, which includes a single constant proper period of 1.185 years, a constant original phase and a time-varying amplitude in a real-number range, was presented to explain the above phenomena. No evidence of a quasi-40-year term of the wobble amplitude exists from the available data. According to the AAM function (1976 - 1985) data, which was supplied byNMC, the atmosphere has a small contribution to the observed free wobble; the amplitudes of 0.8 years and 0.5 years in the polar motion series are equal to those estimated from atmospheric excitation; this implies that the atmosphere is a significant source of both a 0.8 year and a 0.5 year wobble.

According to **JPL**, the so-called decade variations can almost certainly be attributed to torques between the core and mantle. Core-mantle torques are probably largely due to dynamic pressure forces associated with motions in the core acting on topographic undulations of the core-mantle boundary and the equatorial bulge. Estimates of such torques are becoming available from a combination of core motion models based on geomagnetic variations and core mantle boundary maps obtained from seismic tomography. The JPL geodetic torques estimate proved a strong constraint on the models and assumptions used and strongly favor the inclusion of the DS layer in the mantle and point to bumps on the core-mantle boundary of about 1/2 km. The magnitude of these undulations is in agreement with the findings from nutation studies. Corrections at the 2 milliarcsecond level are required to the annual term of the Standard 1980 IAU Nutation Model as inferred from the analysis of the IRIS and the JPL Deep Space Network VLBI data as well as from LLR. The JPL findings are in agreement with those of other analysts. Analyses of twenty years of LLR data allowed the calculation of corrections to the IAU accepted values of the longer-term 18.6-year nutation terms and the precession; a significant correction to the precession constant, (-2.7 ± 0.4) mas/yr has been found. A joint analysis of LLR and VLBI data for precession and nutation corrections performed at JPL utilizes the complementary strength of both techniques - the two decades of LLR coupled with the fine resolution of VLBI.

After removing the AAM effects, values of k/C from the 9.12, 13.66 and 27.56 days tidal components were estimated at **Shanghai Observatory**. The short period fluctuation of tides in the new LOD series of ERP (1962.0 - 1982.2) of BIH was detected. Marple spectral analysis reveals sharp peaks at 13.65, 27.58, and 31.74 days. The elastic parameters of the Earth k/C for fortnightly and monthly frequencies were calculated and were found to be slightly different with the theoretical values.

The effective Love number for the zonal tides in UT1 has been derived, at **Paris Observatory**, from all the data available at IERS from 1962 to 1989 and shown to depend on the atmospheric angular momentum and to be sensitive to the oceanic tidal response.

From the study of tidal deformations during the interval 1976.5 - 1988.0, taking into account the mutual exchange of angular momentun between the solid Earth and its atmosphere, the **Prague** Group found the best fittting tidal effect scaling factor $k/C = 0.945'' \pm 0.021''$ according to them, all the remaining fluctuations in LOD at periods ranging from 10 to 180 days can be fully explained by the atmospheric effects, while the small discrepancies in the dominating semi-annual seasonal variations

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can very probably be ascribed to the neglected influence of zonal stratospheric winds. On the other hand, the longer periodic changes must have their origin in other sources of excitation.

At **USNO**, in parallel to the study of the possible application of atmospheric angular momentum data to the estimation of Earth orientation, corrections to the main zonal tide components in the variation of the LOD were derived in the process and used to derive corrections to the zonal tidal coefficients for UT1-UTC.

At **NAO** Mizusawa, UT1 variations due to the zonal tides are derived from the VLBI UT1 series with the proper account of the atmospheric effects. Estimated tidal factors suggest a nonequilibrium behaviour of the world ocean in these tidal bands. Tidal evolution of the Earth-Moon system was calculated with the varying ocean-continent distribution model. Nutations and fluid core resonance were studied; the core resonance effects were derived from the nutation analysis of the VLBI Earth rotation data and compared with those obtained from the superconductiong gravimeter data. A theoretical study was made on the viscoelastic deformation of the Earth due to the secular drift of the spin axis and a new constant on the mantle viscosity was derived. Possible physical connections are suggested between the plumb-line variations and thermal motion in the fluid core near the core-mantle boundary.

At **ORB**, theoretical nutation series for a non-rigid Earth adding the effect of mantle inelasticity, of pressure at the core-mantle boundary, of new rigid nutation values and of non-hydrostatic value of the core flattening, were studied. It was shown that these effects could be responsible for the differences between the theory and the observations in particular on the annual nutation. In cooperation with the Institut de Physique du Globe de Strasbourg, the effects of the presence of a free inner core nutation (FICN) were also investigated, in particular, by developping an analytical solution for the FICN.

At **ZIPE**, correlations between geomagnetic field variations and variations of LOD and polar motion were investigated. It was found that decade fluctuations of LOD are caused by the temporally variable electromagnetic core mantle coupling. The same physical model does not work for explaining correlations between geomagnetic field variations and polar motion. These correlations are caused by mass redistributions in the core due to motions of the solid inner core with respect to the fluid outer core. The inner core motions are indicated by variations of the dipole axis of the geomagnetic field.

A harmonic development of the lunisolar diurnal polar motion for an elastic Earth with a liquid core was completed at **PAS**, using the dynamical theory of Wahr. A strong effect of the Earth's liquid core on polar motion of the angular momentum axis was found, with an amplitude up to 9 m.

A thesis has been passed at **Valladolid University** (Spain) on "A Hamiltonian theory for an elastic Earth."

The variations of geopotentical cofficients of Earth caused by the variational mass distribution, which has an obvious annual variation, and the rotational deformation were studied in **China**. The results showed that the variations of the position of the Earth's mass center is about 0.5mm and the variations of the second momentum inertia are in the magnitude of 10^{-9}.