FINAL REPORT OF THE IUGG/IAG SPECIAL STUDY GROUP S-143, RAPID EARTH ORIENTATION VARIATIONS

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ABSTRACT
This report highlights the goals, program of activities and accomplishments for IUGG/IAG SSG 5-143. Progress has been made on all fronts; main highlights include: (1) three major campaigns to measure rapid Earth orientation variations; (2) improvements in measurements including the increase in the frequency of the archived atmospheric angular momentum and the calculations of atmospheric torques; and (3) the encouragement of cooperative multi-disciplinary studies and organization of several scientific meetings.

INTRODUCTION AND MOTIVATION
High time resolution measurements of Earth rotation and atmospheric angular momentum (AAM) have been proposed as a major research area for the 1990s, both by the workshop held at Erice in 1988 on the "Interdisciplinary Role of Space Geodesy" [Mueller and Zerbini, 1989] and by the NASA Workshop on Geodynamics and Geology held in July 1989 to plan NASA Solid Earth Science Programs for the coming decade [NASA, 1991]. The importance of the determination of rapid Earth rotation variations and its implication for geodynamics was recognized by the International Union of Geodesy and Geophysics (IUGG) in Vienna (August 1991) through a union resolution. As a result, this special group was formed jointly with the international Astronomical Union to advocate for special measurement campaigns for the determination of rapid variations in Earth rotation and to provide a forum for their interpretation (see next section),

The scientific benefits to be obtained from these campaigns include increased understanding of the properties and origin of short-period fluctuations in the Earth's orientation, improvements to the tidal models at sub-monthly periods, and improved ability to predict changes in the Earth's rotation up to a month in advance. A major goal is to observe and understand the interactions of the atmosphere and ocean with the rotational dynamics of the Earth, and their contributions to the excitation of Earth rotation variations over time scales of hours to months. At these frequencies, a number of geophysical processes are thought to be capable of affecting the Earth's rotation, including atmospheric wind and pressure changes, oceanic current and sea level changes, oceanic and solid Earth tidal motions, and seismic motions. High-frequency measurements and complementary analyses can be expected to lead to delineation of short-period tidal, atmospheric, oceanic, and seismic effects on length-of-day (LOD) and polar motion. These in turn will improve our understanding of broad-band wobble excitation processes, fluid-core resonance characteristics, and mechanisms of oceanic/atmospheric dynamic coupling to the solid Earth.

This paper highlights the activities of SSG 5-143 over its four year lifespan. The second section presents the goals and the program activity, while the third section discusses the accomplishments. The final section summarizes and presents prospects for the future.

The reader is referred to several more detailed accounts of the excitation of Earth orientation changes; references to early work can be found in the classical monograph on the subject by Munk and McDonald (1960) and to more recent work in various monographs and other publications [Cazenave, A., 1986; Dickey and Eubanks, 1986; Eubanks, 1993; Hide, 1989; Hide and Dickey, 1991; Lambeck, 1988; Moritz and Mueller, 1987; Wahr, 1988].

OBJECTIVES AND PROGRAMS OF ACTIVITIES
Our goal is to observe and understand the interactions of the atmosphere and ocean with the rotational dynamics of the Earth, particularly their contributions, as well as those of

seismotectonics, to the excitation of Earth rotation variations over time scales of hours to months.

The program activities includes:

•Interface with the IERS in the determination of rapid variations in Earth rotation by the space geodetic techniques, especially during intensive campaigns.

•Advocate for the best possible auxiliary data from geophysical, oceanographic and atmospheric sources,

• Advocate for improvements in measurement techniques (including geodetic, atmospheric, oceanographic and geophysical),

•Encourage cooperative multi-disciplinary studies; provide a forum for discussion.

ACCOMPLISHMENTS

The past term has been active and productive; main accomplishments include: (1) three major measurement campaigns both to measure high-frequency (< 1 day) Earth orientation variation; (2) improvements in measurements including increase in the frequency of the archived atmospheric angular momentum and the calculations of atmospheric torques; and (3) the encouragement of cooperative multidisciplinary studies and organization of several scientific meetings including the Symposium, Sub Daily Measurements of Earth Rotation held at the IAG General Meeting in Beijing, China (August, 1993) and special sessions at the American Geophysical Union Meetings. Membership is given in Table. 1,

J. O. Dickey	(USA) Chairman
P. Brosche	(Germany)
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K. Yokoyama	(Japan)

Table 1 SSG Membership

A major campaign, SEARCH'92 (Study of Earth-Atmosphere Rapid CHanges), for high time resolution (sub-daily) measurements of Earth rotation by all of the space geodetic techniques was coordinated by the International Earth Rotation Service (IERS) and was held in conjunction with the International GPS Service (IGS) Campaign (June 21- September 22, 1992). A special intensive period (Epoch'92) extended from July 25 through August 10, 1992. An IERS Technical Note. [Dickey and Feissel, 1994] documents the observational program as well as its analysis; an overview is given by Dickey *et al.*, 1994.

GPS measurements were obtained from a core network of ~ 30 receivers with 80 additional sites in place during EPOCH'92 [Beutler and Brockman, 1993]. The SLR global network consisted of 30 sites, two of which are dual SLR/LLR stations and obtained LLR results as well. The VLBI measurement program consisted both of routine operations (IRIS-A, NAVNET) as well as intensive observing efforts. There was essentially continuous coverage on two Simultaneous VLBI networks during the period July 27- August 10 (for an overview, see Dickey et *al.*, 1 994). Special efforts were made to obtain the best possible auxiliary data from geophysical, oceanographic, and atmospheric sources. The frequency Of archived atmospheric angular momentum calculation was increased from twice to four times daily and atmospheric torque calculations were begun.

A second campaign, CONT'94, was held in January 1994, which allows for a study of solid Earth-atmosphere interaction during the Northern Hemisphere winter. This activity featured 15 days of continuous VLBI with 21 stations in three simultaneous networks coupled with participation by the other techniques. The result was the best VLBI to date: 6 mm repeatability on 10,000 km baselines, and highly accurate hourly measurements of Earth rotation (6 ms in UT1 and 250 mas in PM ,1, A third campaign CONT '95 is scheduled for late August 1995 and will be complementary to CONT'94, being held in the Southern Hemisphere winter.

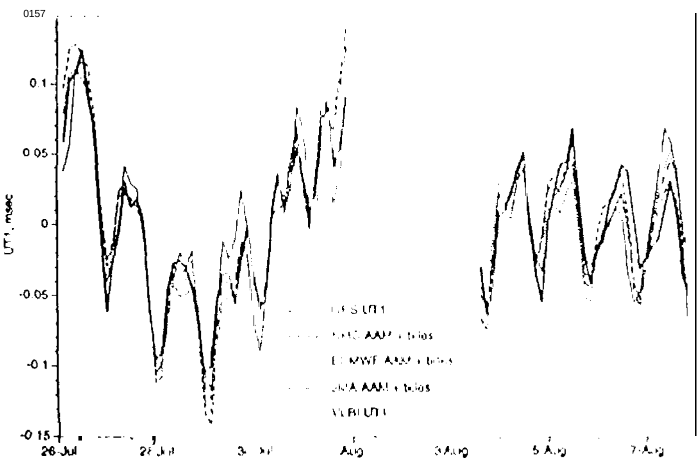

Fig. 1. The sum of the integrated atmospheric angular momentum (AAM) and diurnal, semidiurnal, and longer period tides compared with the observed UT1 variations from GPS and VLBI. Three AAM series are shown: U.S. National Meteorological Center (NMC), European Centre for Medium Range Forecasts (ECMWF), and Japanese Meteorological Agency (JMA). After [Freedman *et al.*, 1994b].

A strong diurnal and semidiurnal signature is clearly seen in all data types (see Fig. 1); comparisons with the independent techniques of VLBI and GPS confirm the reality of this signature [~ 0.1 msec (5 cm) in amplitude]. The data gap in the middle of the time series is due to the use of anti-spoofing (AS) signal encryption in the GPS. Diurnal and semi-diurnal rotational variations were postulated by Yoder *et al.* (1981), who proposed that such signatures should arise from the interactions of the ocean tides with the solid Earth. Estimates of these variations were made by Baader *et al.* (1983) for the M2 tide and were refined by Brosche *et al.* (1989 and 1 991) for the. major diurnal and semidiurnal tides. Seiler (1991) and Wünsch and Seiler (1992') revised the Brosche *et al.* (1989) tidal model using a new numerical ocean mock]; these calculations were later improved by Gross (1993) through the use of a more realistic rotation model [see also Brosche and Wünsch, 1994]. Dickman (1993) developed the "broad-band" Liouville equation approach and determined the effects of the dynamic ocean tides on Earth rotation. The models mentioned thus far are unconstrained in that the solutions are not required to fit *in situ* tidal measurements and depend only on knowledge of the global bathymetry. Such an approach requires sophisticated hydrodynamic modeling with fine spatial resolutions in shelf areas, as the tidal energy dissipation occurs mainly in the shallow seas.

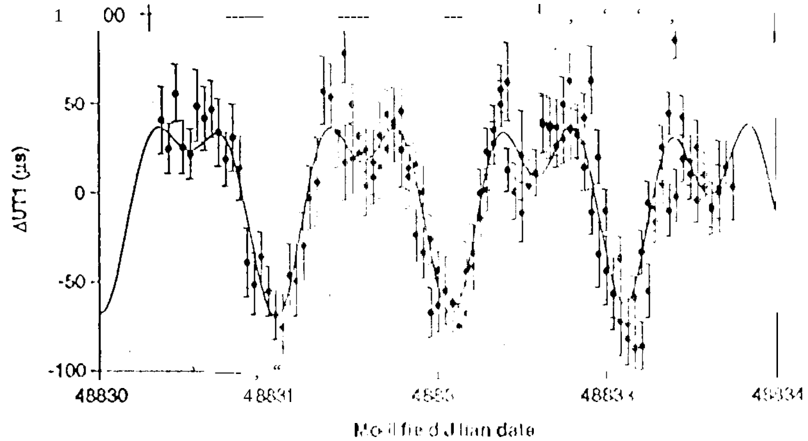

Fig. 2.. Predicted and observed variations in ΔUT1. The predictions (solid curve) are based on a tidal-height model. The observations with 1s standard errors, are the product of five overlapping VLBI experiments carried out during late July 1992 (modified Julian date 4883(: 2 / July 1992). Each experiment was about 1 day long, and each has been adjusted here empirically by a single t, is. After Ray *et al*, 1994.

A class of global tide models have been developed that are constrained by tide observation.s (gauge measurements at coastlines and at islands, and satellite altimetry). This alleviates to a certain degree the need for high spatial resolution models with complex physics packages. In a recent study, Ray *et al* (1994) utilized the model of global tidal heights derived by Schwiderski (1 980), which is constrained by more than 2000 coastal, island and bottom pressure measurements. In addition to the effect of' the global height fields, the impact of the tidal currents inferred from a modified form of Laplace's momentum equation were included. A complementary approach is the development of empirical models obtained by fitting the major tidal components to sub daily Earth rotation observations. This approach has been applied to VLBI analysis by Sovers *et al*. (1993) and Herring and Dong (1 994) and to SLR analysis by Watkins *et al* (1 994). As one would expect, the empirical and constrained models result in better fits than the unconstrained. Differencing with respect to the Brosche *et al*. (1989) mode.] as modified by Gross (1993) actually increases the scatter. Most of the discrepancies arise. from the semidiurnal band, which the theoretical model predicts to have a much larger amplitude (Freedman *et al*., 1994b). Ray *et al.* produce tidal variations in Universal Time that agree with VLBI observations at a 2 microsecond level (see Fig. 2) and thus establish oceanic tides as the dominant mechanism for producing Earth rotation variations at these periods.

Moving to multiple day timescales, one can add the atmospheric effect to the tidal variations (here the empirical model of Herring and Dong (1 ')94) is used) by integrating AAM to obtain the atmospheric variability (Fig]). Linear trends were removed from each series for each of the two periods. The geodetic signal can be described by the sum of AAM variation and tidally induced UT1, with tides acting at periods of one day and less and AAM dominating variations at periods greater than a day. The differences between GPS and VLBI are at least as large as those between the AAM series themselves and the AAM and geodetic series. There is nonresidual signal that exceeds the formal errors. The subdaily variability of the AAM is quite small and at this point cannot be separated from the oceanic effects; however, limits can be expressed [Freedman *et al.*, 1994]. Improved theoretical tide models arc need to unravel the oceanic and atmospheric signals, with geodetic measurements providing strong constraints. The creation of a new generation of ocean models is now underway through the analysis of TOPEX (Ocean Topography Experiment)/Poseidon satellite altimeter mission data. These developing models, particularly those that utilize data assimilation, should provide greatly improved predictions of tidally induced Earth rotation variations [Ray *et al.*, 1994].

During a 6-day subperiod (July 31-August 5, 1992) within the SEARCH Campaign, a strong rise in both LOD and AAM was observed, which was caused primarily by zonal wind variations. Analysis of equal area belts of AAM data indicates that the low-latitude Southern Hemisphere belts arc the dominant contributors to these effects [Salstein and Rosen, 1994]. While angular momentum variations provide information on the center of activities during the period of interest, additional insight into the mechanisms involved can be gained through the analysis of the atmospheric torques. In the study of Salstein and Rosen (1994), both mountain torque (which results from differences in normal pressure forces across mountain barriers) and friction torque (which arises from tangential frictional stresses at the atmosphere's lower boundary) are considered. Mountain torques accounted for most of the momentum transfer between the. solid Earth and atmosphere, with the Southern tropics (0°–30°S) making the largest contribution. Note that this campaign was held in Southern Hemisphere Winter; hence, the bulk of the activities are expected there. Torques across South America are particularly important. This event is associated with a high-pressure system east of the Andes Mountains that produced a strong zonal pressure gradient, thus inducing the observed AAM and LOD variations.

SUMMARY AND PROSPECTS FOR THE FUTURE

Here, we have highlighted recent advances in the high-frequency measurement of Earth orientation and their interpretation. International cooperation through the IERS and the. IUGG/IAG Special Study Group 5-143 was stressed. The future is even more promising with the anticipated technological advances envisaged for space geodesy and developments that are being planned in related areas. The availability of accurate Earth relation and polar motion data along with AAM results and other ancillary data, such as torques, and their coupled analyses arc keys to unraveling the causes and implications of Earth orientation changes. The continual improvement in the accuracy and density of data from the new techniques will allow the study of the Earth's exchange of angular momentum with its fluid envelope over even shorter time scales.

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