Part I

Introduction and Theoretical Considerations

SEARCH'92 Campaign: An Overview
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The Angular Momentum Contents of the Ocean
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SEARCH'92 CAMPAIGN: AN OVERVIEW

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ABSTRACT. High time resolution measurements of Earth rotation and atmospheric angular momentum and torque and their interpretation can provide unique insights into a variety of processes including dynamic coupling between solid Earth and atmosphere, the effects of oceanic tides on the Earth's rotational dynamics, excitation of the polar wobble, and fluid-core resonance effects; hence, an extensive campaign, SEARCH'92, has been held through the coordination of the International Earth Rotation Service (IERS) to obtain these measurements utilizing all space geodetic techniques and to collect the best available complementary geophysical, atmospheric and oceanographic data. This paper discusses its motivation and planning; recent analysis results are highlighted.

1. Introduction

High time resolution measurements of Earth rotation and atmospheric angular momentum (AAM) and torque and their interpretation will improve our understanding of the properties and origin of short-period fluctuations of the Earth's orientation, and will provide new and unique insights into a variety of geophysical processes. These processes include coupling and angular momentum exchange between the solid Earth and atmosphere, the interaction of dynamical ocean tides with the Earth's rotational dynamics and the effects of fluid-core resonances. Hence, a measurement and analysis program has 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" and by the NASA Workshop on Geodynamics and Geology held in July 1989 to plan NASA Solid Earth Science Programs for the coming decade. 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, 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 IGS Campaign (June 21–September 22, 1992). A special intensive period (Epoch'92) extended from July 25 through August 8, 1992.

This paper highlights motivation, planning, and results from SEARCH'92. The second section discusses the rationale and scientific benefits for these measurements, while the third section reviews international cooperation. Section 4 highlights recent advances in analysis and interpretation, while the final section presents a summary.

Recently, Dickey (1993) reviewed atmospheric excitation of the Earth's rotation and provides a detailed account of recent developments. The reader is referred to several more general 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, 1977, 1984, 1986, 1989; Hide and Dickey, 1991; Lambeck, 1988; Moritz and Mueller, 1987; Wahr, 1988).

2. Motivation and Scientific Benefits

The scientific benefits to be obtained from these campaigns include improved 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 (see Fig. 1). 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, together with complementary analyses of geophysical data, 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.

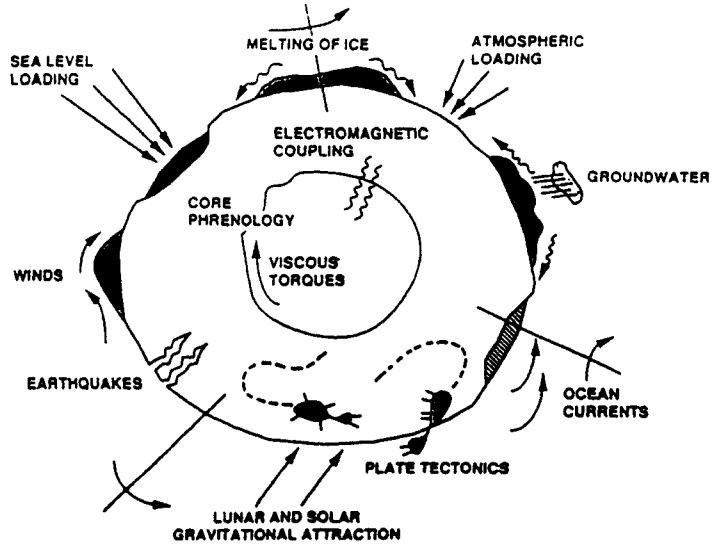

Figure 1. Schematic illustration of the forces that perturb Earth rotation. After Lambeck, 1980.

In particular, the Earth's angular momentum budget (both axial and non-axial) can be examined at high frequencies. The elucidation of the relation between LOD and AAM at high frequencies is central to our understanding of the Earth's angular momentum budget and is currently an area of active research (see for example, Rosen *et al.*, 1990; Herring and Dong, 1991 and 1994; Dickey *et al.*, 1992). Fig. 2 illustrates the striking similarities between these two series. Significant coherence is found between the LOD and AAM at periods down to 8 days, with lack of coherence at shorter periods caused by the declining signal-to-measurement noise ratios of both data types (Dickey *et al.*, 1992). Higher accuracy and more frequent data are needed to resolve the exchange of angular momentum between the Earth and the atmosphere at shorter periods. Although no significant lags or leads at the few day level have been established (indicating little or no non-tidal oceanic contribution), the oceans, via barotropic waves, could contribute on short time scales (a few days or less) to the Earth's angular momentum budget (Ponte, 1990). Hence, a comparison of AAM and LOD at these high frequencies could uncover the ocean's role and further elucidate our understanding of the dynamic interaction between the solid Earth and the atmosphere, allowing the role of the atmosphere and oceans in Earth orientation variations at high frequencies to be quantified. The appropriateness of the inverted barometer approximation for the ocean's response to atmospheric pressure forcing at high frequencies could be investigated, and the respective roles of the mountain and wind stress torque in transferring angular momentum between the solid Earth and atmosphere examined.

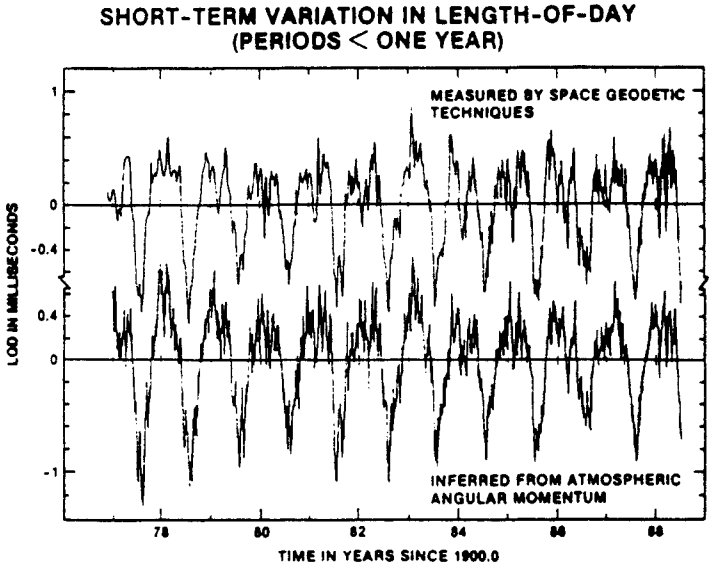

Figure 2. Time series of the sum of the seasonal and intraseasonal LOD components, with the upper curve measured by space geodetic techniques and the lower curve inferred from routine daily determinations of changes in the axial component of the atmospheric angular momentum made by the U. S. National Meteorological Center. Periods greater than one year in both series have been filtered out (after Dickey, 1993).

3. Measurement Campaigns

Thus far, three major campaigns have been coordinated, allowing high temporal resolution measurements of Earth rotation over extended time periods. The NASA Crustal Dynamics Project VLBI (Very Long Baseline Interferometry) Group at Goddard Space Flight Center conducted the first Extended Research and Development Experiment (ERDE) in October, 1989, designed to obtain high time resolution measurements of the Earth's orientation by the VLBI technique and to test improvements in the VLBI measurement system (Clark *et al.*, 1990); these special sessions resulted in nearly continuous sub-hourly measurements over the 17-day period and served as a prototype for future efforts.

The GIG'91 Measurement Campaign (GPS IERS and Geodynamical Experiment), coordinated by the International Earth Rotation Service, was held between January 22 and February 13, 1991 with one of its prime objectives being the evaluation of the ability of GPS to recover Earth rotation parameters. The analysis of these data provided high quality daily measurements of polar motion (Herring *et al.*, 1991; Lindqwister *et al.*, 1992) as well as sub-daily measurements of Earth rotation variations (Lichten *et al.*, 1992).

The SEARCH campaign involved all space geodetic techniques with the best available complementary geophysical, atmospheric and oceanographic data being collected. Coordination was effected by the International Earth Rotation Service (IERS). A joint International Association of Geodesy/International Astronomical Union (IAG/IAU) Special Study Group, Rapid Earth Orientation Variations, has been formed to (1) interface with the IERS in the determination of rapid variations in Earth rotation by the space geodetic techniques; (2) advocate for the best possible auxiliary data from geophysical, atmospheric and oceanographic sources; (3) encourage improvements in measurement techniques (including geodetic, atmospheric, oceanographic and geophysical); and (4) encourage cooperative multidisciplinary studies.

During the SEARCH and EPOCH'92 campaigns, geodetic Earth rotation and polar motion measurements were made from the GPS, VLBI, SLR and LLR techniques; complementary geophysical data sets were also archived. LLR results were sparse and do not support robust subdaily Earth rotation determination. Some results are also described in the IERS Technical Note 14 (IERS, 1993).

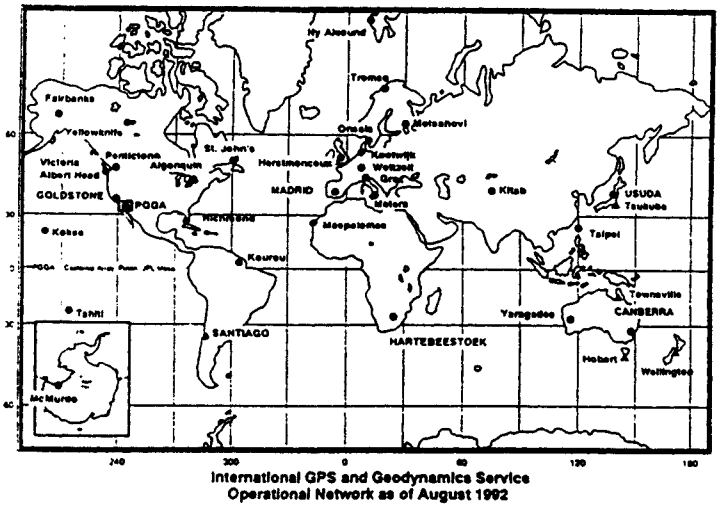

Fig. 3a. GPS Observing Network

3. 1. GLOBAL POSITIONING SYSTEM (GPS)

Recognizing the increasing use of the Global Positioning System (GPS) for geodesy and geophysics and that this system will play a major role in global and regional studies of the Earth, the IUGG in Vienna (August, 1991) recommended through a union resolution that the development of an International GPS Geodynamic Service (IGS) be explored. At its May 1, 1992 meeting the Directing Board of IERS officially adopted GPS as a contributing technique for the terrestrial reference frame and Earth rotation determination. As a test of the IGS concept, the IGS Oversight Committee organized a campaign for the period June 21–September 22, 1992 with a special intensive period (EPOCH'92) extending from July 25 through August 8, 1992. GPS results were received throughout the entire three month campaign (Beulter and Brockman, 1993).

The observing GPS network is displayed in Fig. 3a; it consists of an operational core network of about 30 receivers with up to an additional 80 GPS stations participating during the EPOCH'92 period. Standard GPS ephemerides and polar motion were generated by 7 analysis centers within 2 weeks of receipt of data (Beutler and Brockman, 1993).

3.2. SATELLITE LASER RANGING

An international network of approximately 30 stations supported routine laser ranging to LAGEOS and ETALON (see Fig. 3b). During the SEARCH campaign, estimates of polar motion and Universal Time at 3-day intervals were produced operationally, and in subsequent processing at 1-day intervals. A separate analysis spanning the period 1987-1993 determined tidally coherent diurnal and semidiurnal variations in polar motion and UT1 which were validated during the campaign.

3.3 VLBI

The VLBI measurement program consists both of routine operations (e.g., IRIS-A, NAVNET) as well as intensive observing efforts planned for Epoch'92; the global VLBI Network for SEARCH is given in Fig. 3c. Collectively, IRIS-A and NAVNET operationally provided 3-component Earth rotation (UT1) and polar motion measurements on a twice-a-week basis with 24-hour observing programs; daily intensive UT1 measurements were made utilizing the Westford and Wettzell stations. At other times, there was essentially continuous coverage on two simultaneous VLBI networks during the period July 27-August 10, which are useful in error analysis. During this time, coverage was provided by the NASA-sponsored Extended R&D sessions, the scheduled IRIS A and the augmented USNO NAVNET/NAVEX programs (see Eubanks, Ma and Gipson; and Ray *et al.*, this volume for a fuller discussion).

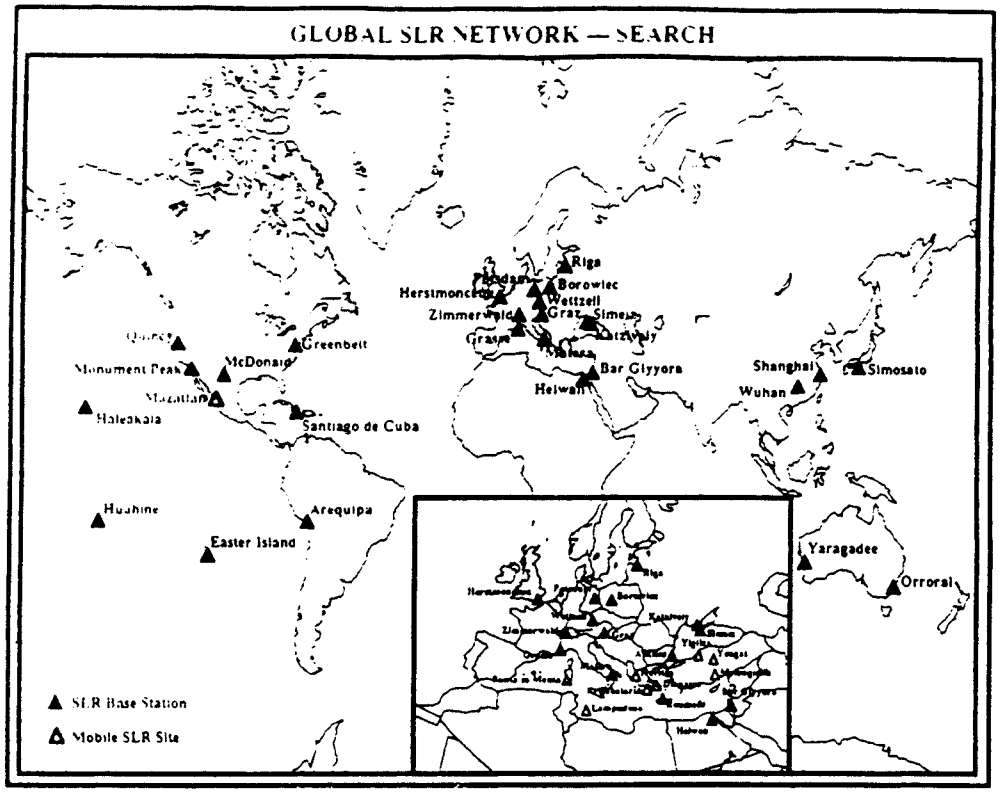

Fig. 3b. SLR Observing Network

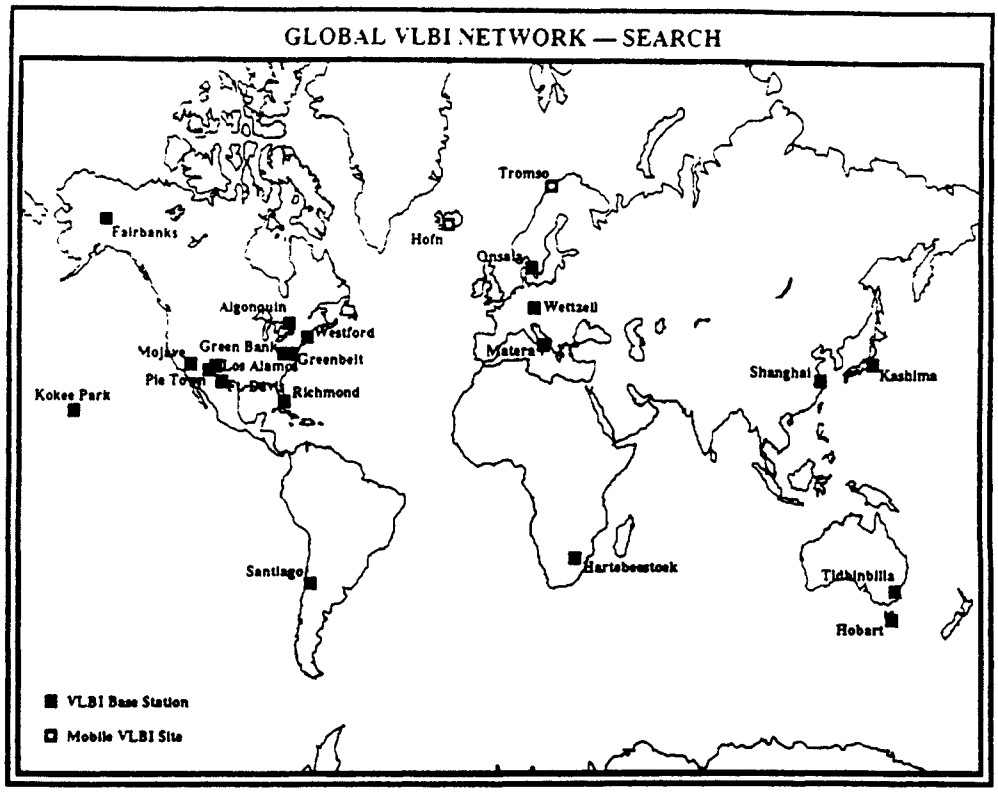

Fig. 3c. VLBI Observing Network

3.4. COMPLEMENTARY GEOPHYSICAL DATA

The primary complementary geophysical data sets collected for SEARCH'92 are series of atmospheric angular momentum functions, in the axial direction related to changes in the length of day and in the equatorial directions related to polar motion, as well as torques at the lower boundary of the atmosphere. There are four meteorological data centers contributing standard AAM products to the IERS Sub-Bureau for Atmospheric Angular Momentum: the European Centre for Medium-Range Weather Forecasts (ECMWF), Japan Meteorological Agency (JMA), National Meteorological Center (NMC) of the United States, and United Kingdom Meteorological Office (UKMO). Data from all centers are available in near real time. Before SEARCH'92, AAM data had been typically archived twice daily, but in response to the requirements of this special campaign, computation and collection of AAM data were initiated at a higher frequency using 6-hourly NMC, ECMWF, and JMA analyses. All data types related to AAM, including ancillary parameters, are outlined in Table 1, and were obtained from the wind, surface pressure and temperature analyses of these centers. Some sets of AAM values include oceanic information indirectly by a modification of the atmospheric mass terms accounting in part for an oceanic inverted barometer response to surface loading. Calculations of Earth-atmosphere torques are now under way at the NMC and will be available to the geodetic community for this campaign. These torques involved the dynamic transfer of momentum between Earth and atmosphere by means of both pressure differences across mountains and friction stresses at the Earth's surface (see Salstein and Rosen, 1994). See Salstein and Kahn (this volume and 1991) or Salstein *et al.* (1993) for further details.

TABLE 1. Atmosphere Data Sets Archived at IERS Sub-Bureau for Atmospheric Angular Momentum (after Salstein and Kann, this volume)

Analysis Parameters	Specification
AAM Equatorial χ_1, χ_2	Hemispheric values for wind,
AAM Axial χ_3	pressure & pressure + inverted barometer (ib)
Zonal Mean Zonal Winds [u]	5°latitude intervals,
Zonal Mean Temperatures [T]	12 mandatory pressure levels
Mean Surface Pressure	Global average
Surface Pressure Coefficients	Triangular truncation to wave 4; zonals only to wave 20
Forecast Parameters	**Specification**
AAM Equatorial χ_1, χ_2	Global forecast values at 12-h
AAM Axial χ_3	intervals to 10 days for wind, pressure, pressure + ib

4. Highlights of Analysis Results

4.1. INTERCOMPARISON

Intercomparison of results are shown in Figs. 4-10. Polar motion results are displayed in Figs. 4, 5, and 6 for VLBI, GPS and SLR, respectively; an analytical model has been used to remove variations over ~ 100 days. One can note similar structure throughout all series, for example, relative maxima in the y-component at ~ 1992.52 and 1992.67 and in the x-component at ~ 1992.57 and 1992.67. Results for UT1 from VLBI, GPS and SLR are shown in Fig. 7; again, one can see quasi-periodic fluctuations in all series with relative maxima at 1992.53, 1992.59, 1992.64 and 1992.69. The celestial pole offset from VLBI analysis is displayed in Fig. 8. Measurements from the intensive period are shown in Figs. 9 (polar motion) and 10 (UT1) with further discussion in the following two sections.

The improved determination of UT1 and its use in determing LOD is currently an area of intense activity. Gambis *et al.* (this volume) discusses the scenario of utilizing the GPS and SLR determinations for short-period UT1 fluctuations, and combining them with VLBI which has long-term stability.

4.2. UNIVERSAL TIME (UT1) RESULTS FROM EPOCH'92

During the full campaign, results were obtained from all techniques (see Figs. 4-10); measurements during an intensive two-week period centered around August 1, 1992, designated as EPOCH'92, were particularly robust with almost continuous VLBI measurements (see Fig. 9-11 and Section II of this volume). Periods of simultaneous observations permit an assessment of data quality by two VLBI networks.

The UT1 series shown in Fig. 11 were estimated from each network every 3 hours after the application of a diurnal and semidiurnal *a priori* tide model [Herring, this volume]; uncertainties varied from 10 to 40 μs and were network dependent. The different VLBI series were then combined from all networks using a mild Gaussian filter to form a continuous series. The GPS series shown was obtained at 30-minute intervals employing a multi-day orbit arc strategy and data from a network of 25 stations using a GPS constellation of 17 satellites (see Freedman *et al.*, this volume and 1994 for details). The data gap in the middle of the time series is due to the use of anti-spoofing (AS) signal encryption; the data before and after this gap were treated as separate arc orbits. For the sake of comparison with VLBI, a light Gaussian smoothing was applied.

A strong diurnal and semidiurnal signature is clearly seen in both data types. 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 M_2 tide and were refined by Brosche *et al.* [1989 and 1991] for the major diurnal and semi-diurnal tides. Seiler [1991] and Wünsch and Seiler [1992] revised the Brosche *et al.* [1989] tidal model using a new numerical ocean model; these calculations were later improved by Gross [1993] through the use of a more realistic rotational model [also see Brosche and Wünsch, 1994]. Herring and Dong [1991, 1994], Sovers *et al.* [1994], and Watkins and Eanes [1994 and this volume] used the approach of empirically fitting the major tidal components to sub-daily Earth rotation observations. Dickman [1993] developed the "broad-band" Liouville equation approach and determined the effects of the dynamic ocean tides on Earth rotation. Comparisons with the independent techniques of VLBI and GPS confirm the reality of a strong diurnal and semi-diurnal signature [~0.1 msec (5 cm) in amplitude — see Fig. 11]. Also evident is a systematic shift of the GPS with respect to the VLBI

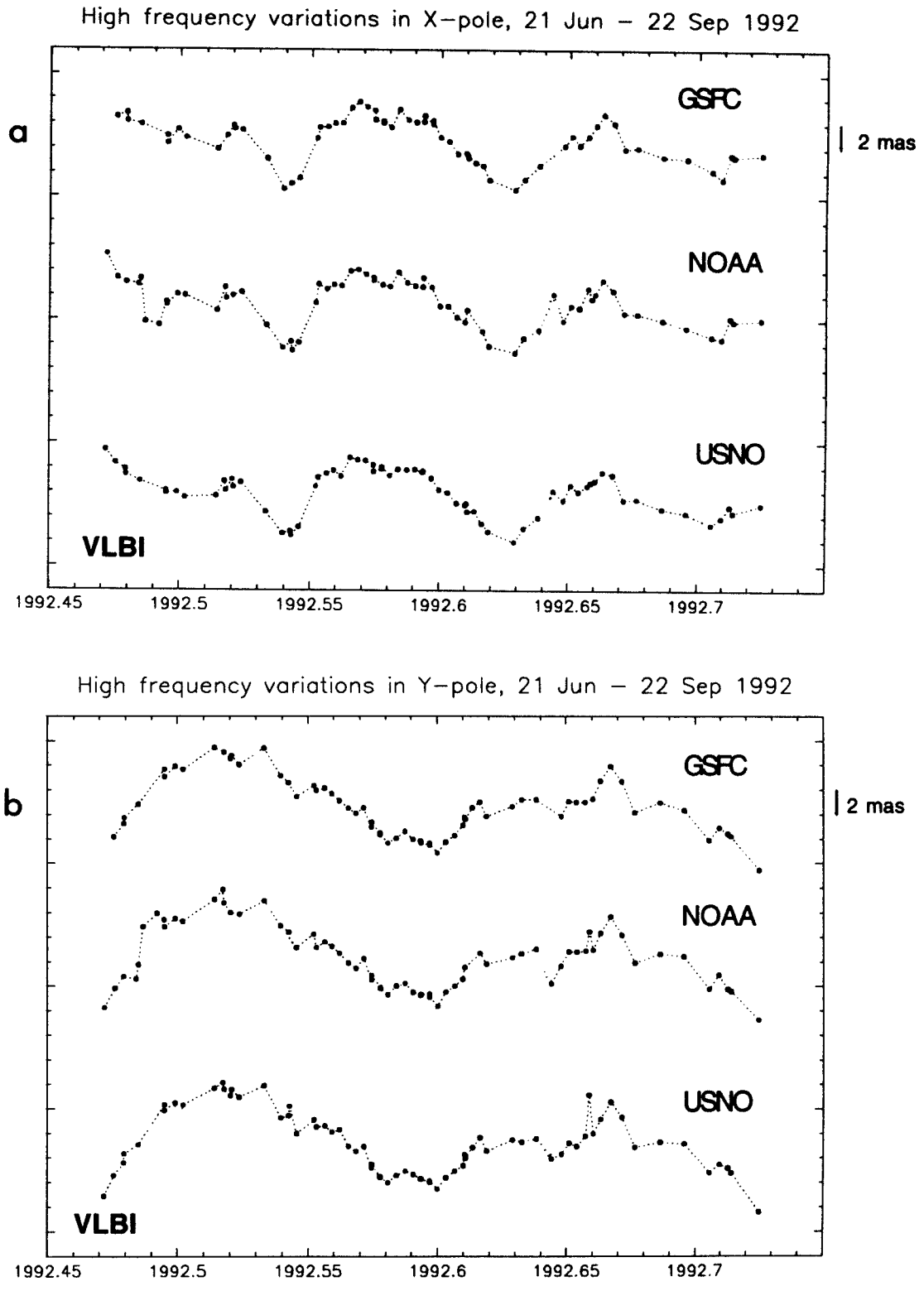

Figure 4. High frequency variations in the coordinates of the pole, 21 Jun - 22 Sep 1992, measured by VLBI.

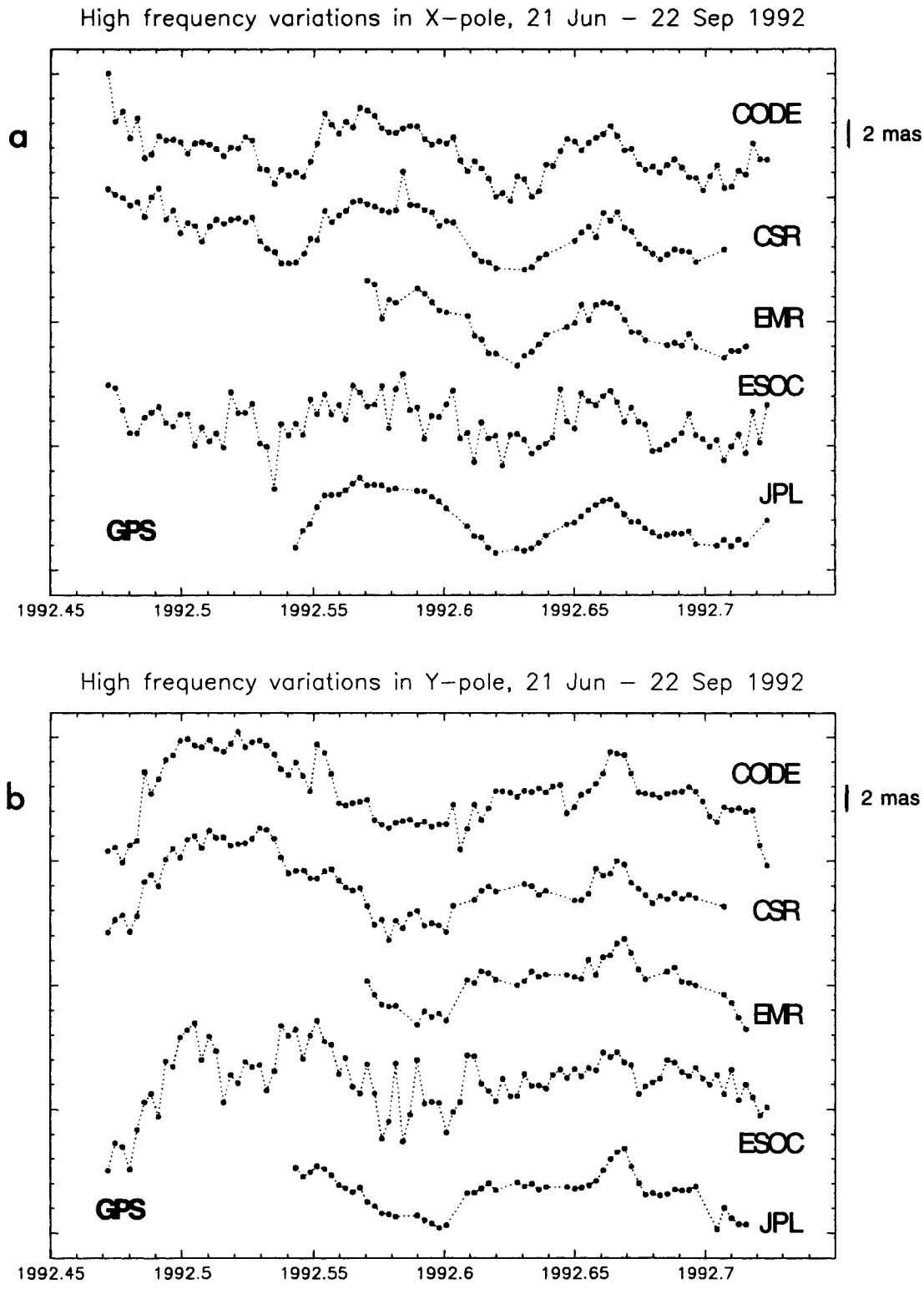

Figure 5. High frequency variations in the coordinates of the pole, 21 Jun - 22 Sep 1992, measured by GPS.

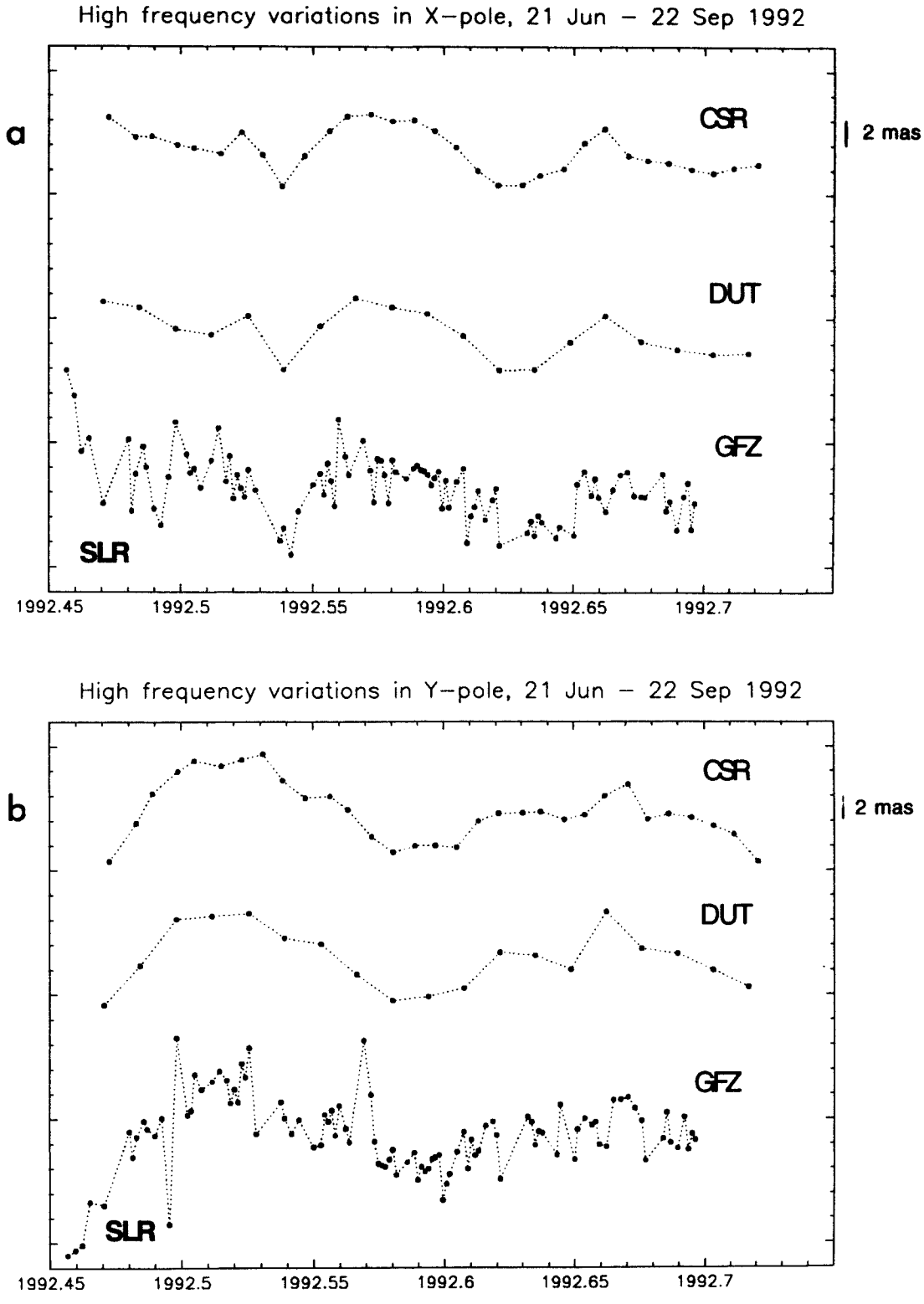

Figure 6. High frequency variations in the coordinates of the pole, 21 Jun - 22 Sep 1992, measured by SLR.

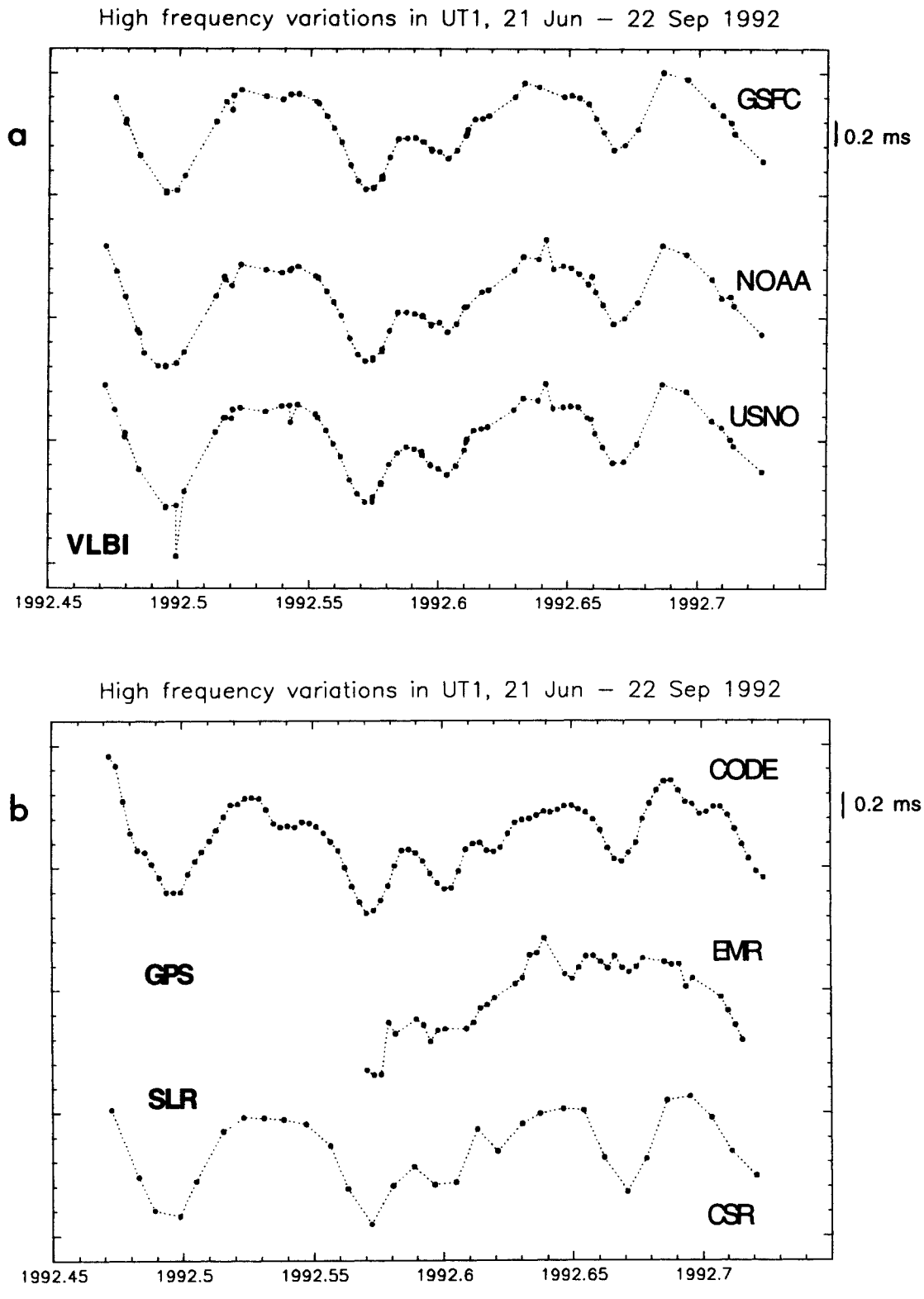

Figure 7. High frequency variations in universal time, 21 Jun - 22 Sep 1992, measured by **VLBI, GPS** and **SLR.**

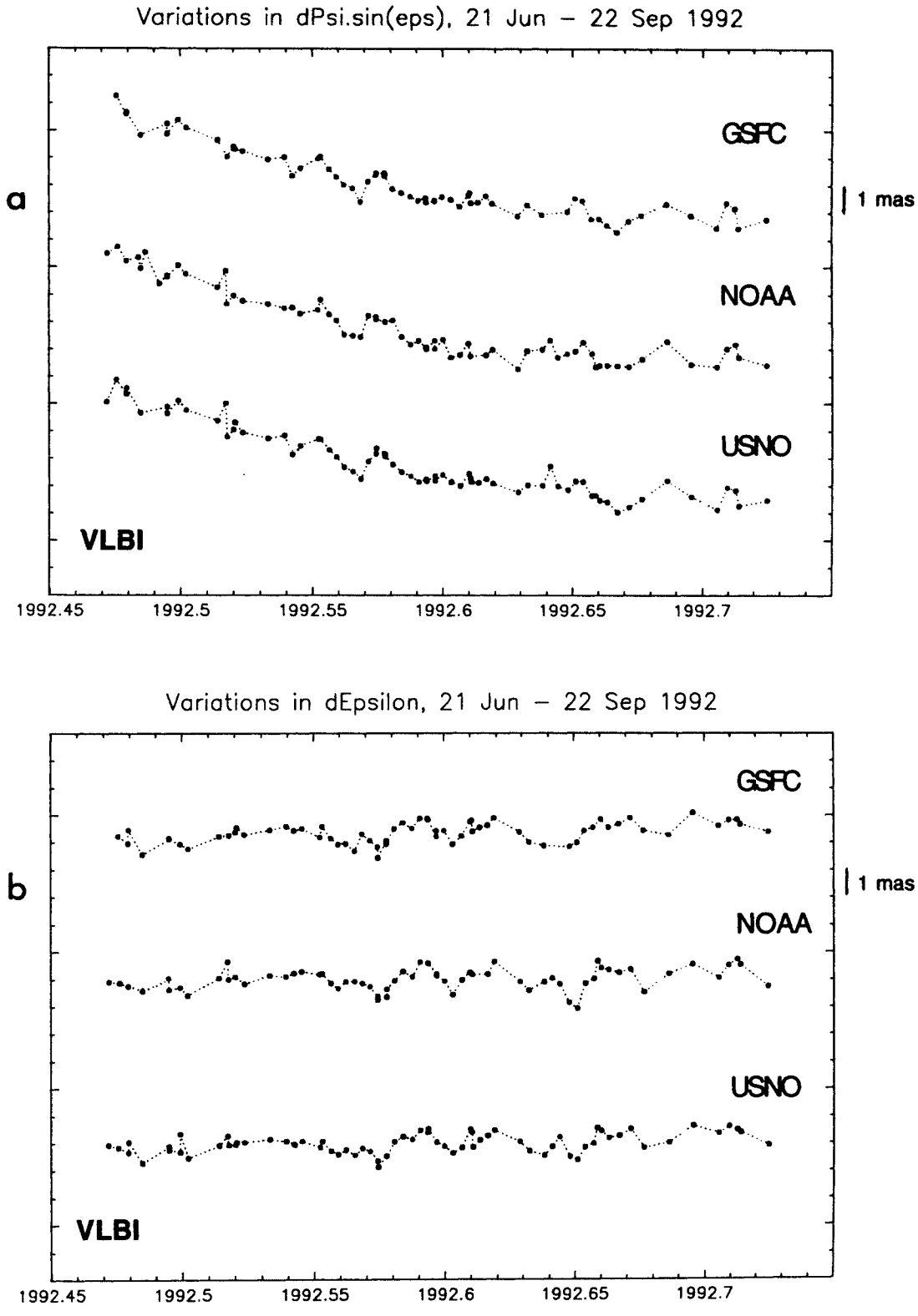

Figure 8. High frequency variations in the celestial pole offsets, 21 Jun - 22 Sep 1992, measured by VLBI.

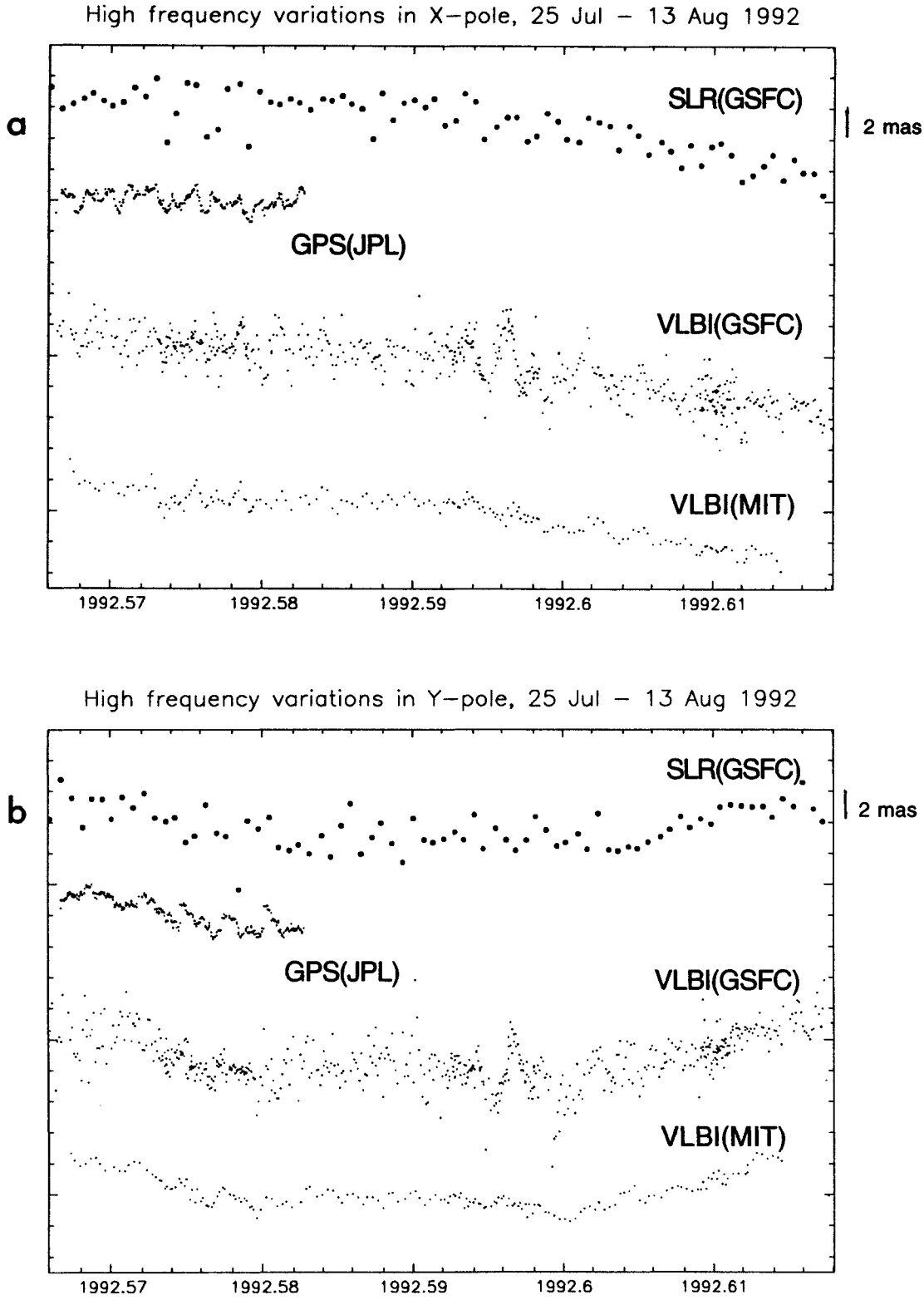

Figure 9. Rapid and sub-daily variations in the coordinates of the pole, 25 Jul - 13 Aug 1992, measured by **VLBI, GPS** and **SLR**.

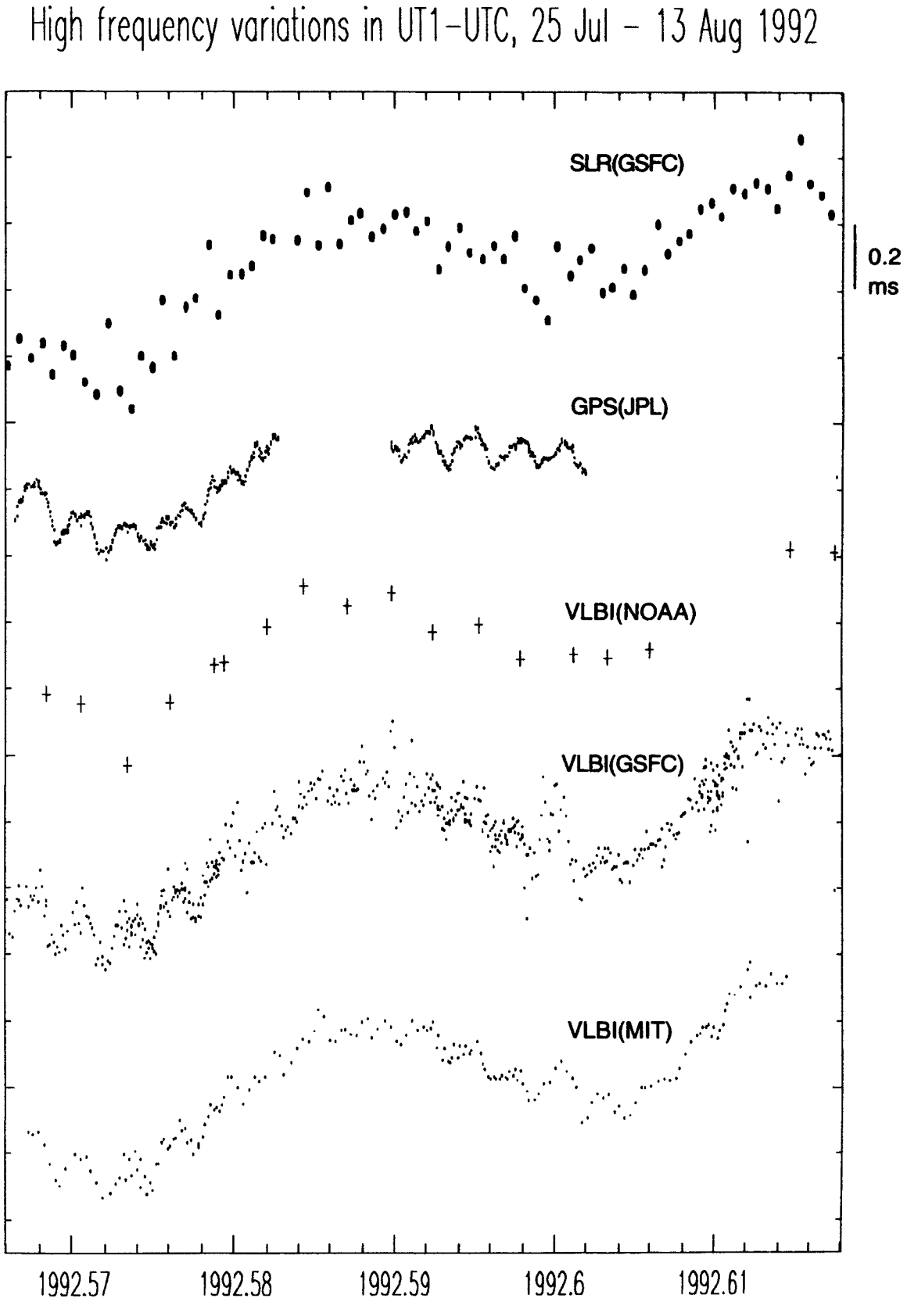

Figure 10. Rapid and sub-daily variations in universal time, 25 Jul - 13 Aug 1992, measured by **VLBI, GPS** and **SLR**.

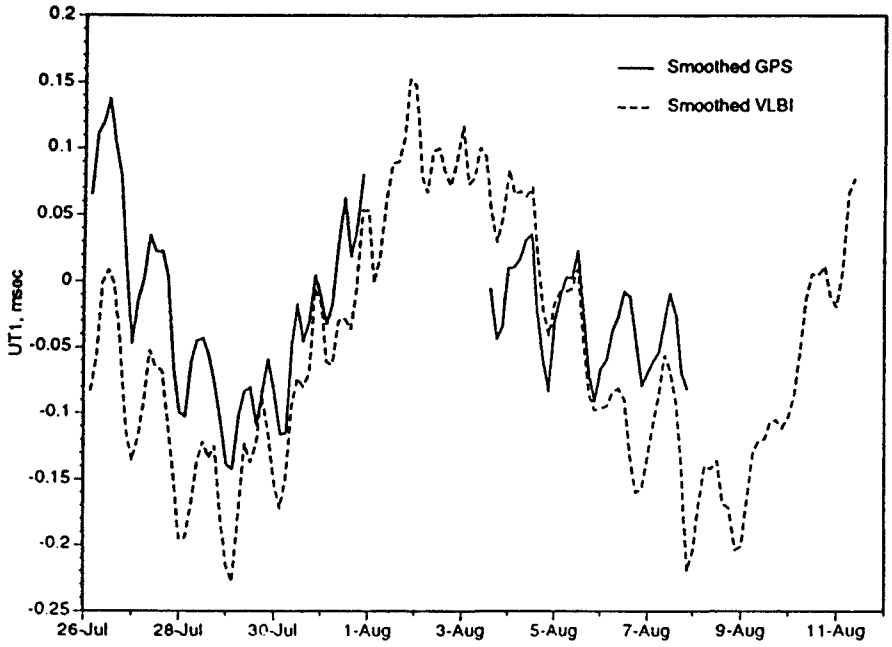

Fig. 11. UT1 from GPS and VLBI evaluated every 3 hours (after Freedman *et al.*, this volume).

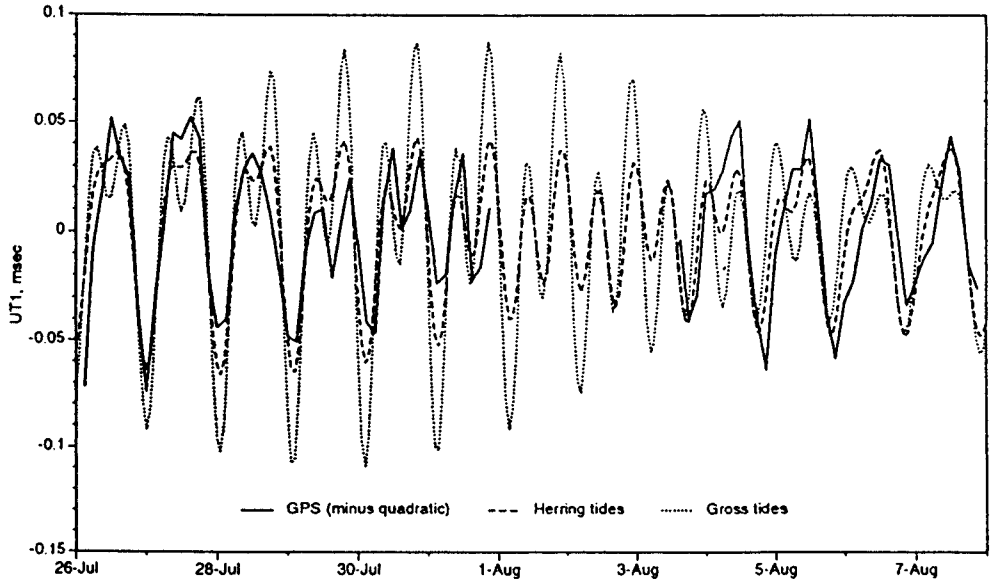

Fig. 12. GPS UT1 compared to two models of tidally induced UT1 variations (after Freedman *et al.*, this volume).

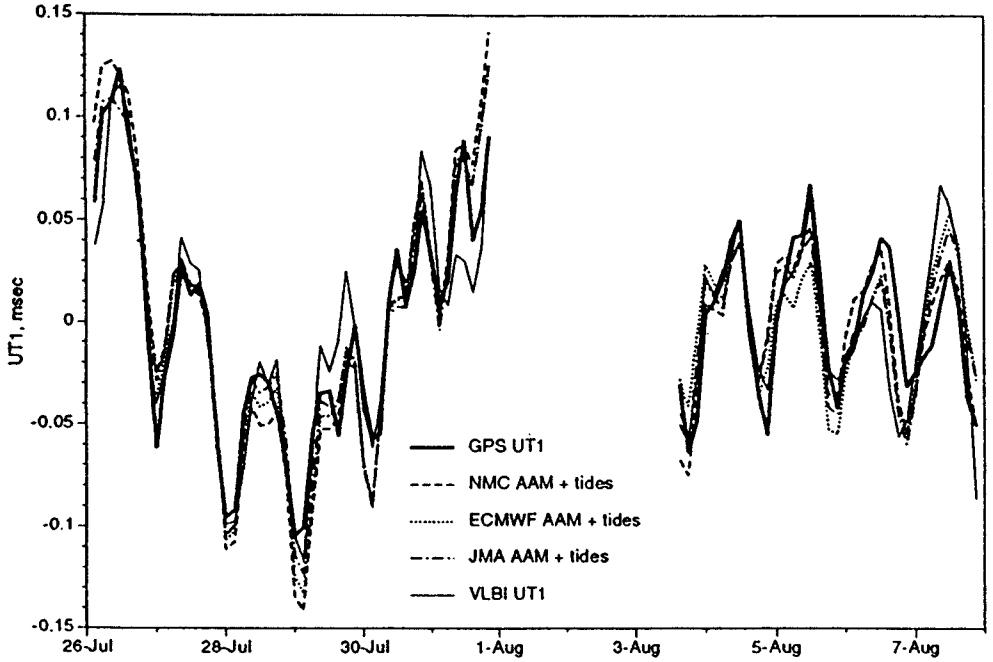

Fig. 13. Comparison of integrated AAM with geodetic UT1 variations (after Freedman *et al.*, this volume).

series, which is most likely due to orbit errors. After removing a quadratic from the GPS series to remove multiday variations (Fig. 12), comparisons can be made directly with results predicted by oceanic tidal models. Two models are examined—a theoretical model computed by Gross (1993), based on an oceanic angular momentum model of Seiler (1991) and an empirical model of Herring and Dong, based on 8 years of VLBI data (1994). As would be expected, better agreement is evident with the empirical model; the RMS scatter decreases from 32 μs to 18 μs (see Fig. 12). Differencing with respect to the Gross tides actually increases the scatter from 32 to 35 μs. Most of the discrepancies arise from the semidiurnal band, where the theoretical model predicts a much larger amplitude. Predicted diurnal variations from the Dickman (1993) model show significant correlation with the observational results, but are too small in amplitude.

Further, one can consider the atmospheric influence by integrating AAM and adding it to the UT1 specified by the empirical tidal model of Herring and Dong (1994). Linear trends were removed from each series for each of the two periods. Most of 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 (see Fig. 13). Therefore, no atmospheric center or geodetic technique can be considered as the best series. There is no residual 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. Improved theoretical tide models are needed to unravel the oceanic and atmospheric signals with geodetic measurements providing strong constraints.

4.3. POLAR MOTION

In contrast to the axial component, the equatorial momentum budget is not closed at any frequency. For example, a study by Kuehne and Wilson [1991] investigated the effect of water storage in combination with air mass redistribution on the observed excitation of polar motion near the annual and Chandler frequencies for the period 1900-1985. They concluded that there is a discrepancy in accounting for more than half the variance of polar motion across a broad range of frequencies, suggesting a source of polar motion excitation due to air and water motion which has either not been correctly estimated or is not yet identified. On shorter time scales, Eubanks *et al.* [1988], comparing observed χ-functions derived from geodetic observations with theoretical χ-functions derived from atmospheric data, demonstrated the existence of rapid polar motions with peak-to-peak variations of approximately 2 to 20 mas, fluctuating on time scales between two weeks and several months. These variations are only partly accounted for by atmospheric surface pressure changes and, like the Chandler and annual terms, require an additional source of excitation. The "missing" excitation may be explained by errors in the data sets used (in either the polar motion series or the AAM series), by oceanic angular momentum, or possibly by groundwater redistribution.

Daily polar motion values determined from observations acquired during the GIG'91 measurement campaign permit an unprecedented high time resolution investigation of the effect of the atmosphere on rapid polar motion variations (Gross and Lindqwister, 1992). The wind and pressure terms are found to be of comparable importance in exciting the observed polar motions during this period with somewhat better agreement seen with the application of the inverted barometer approximation. Correlations as high as 0.88 were obtained between the observed polar motion and the AAM-induced series, with AAM variations explaining as much as 74% of the

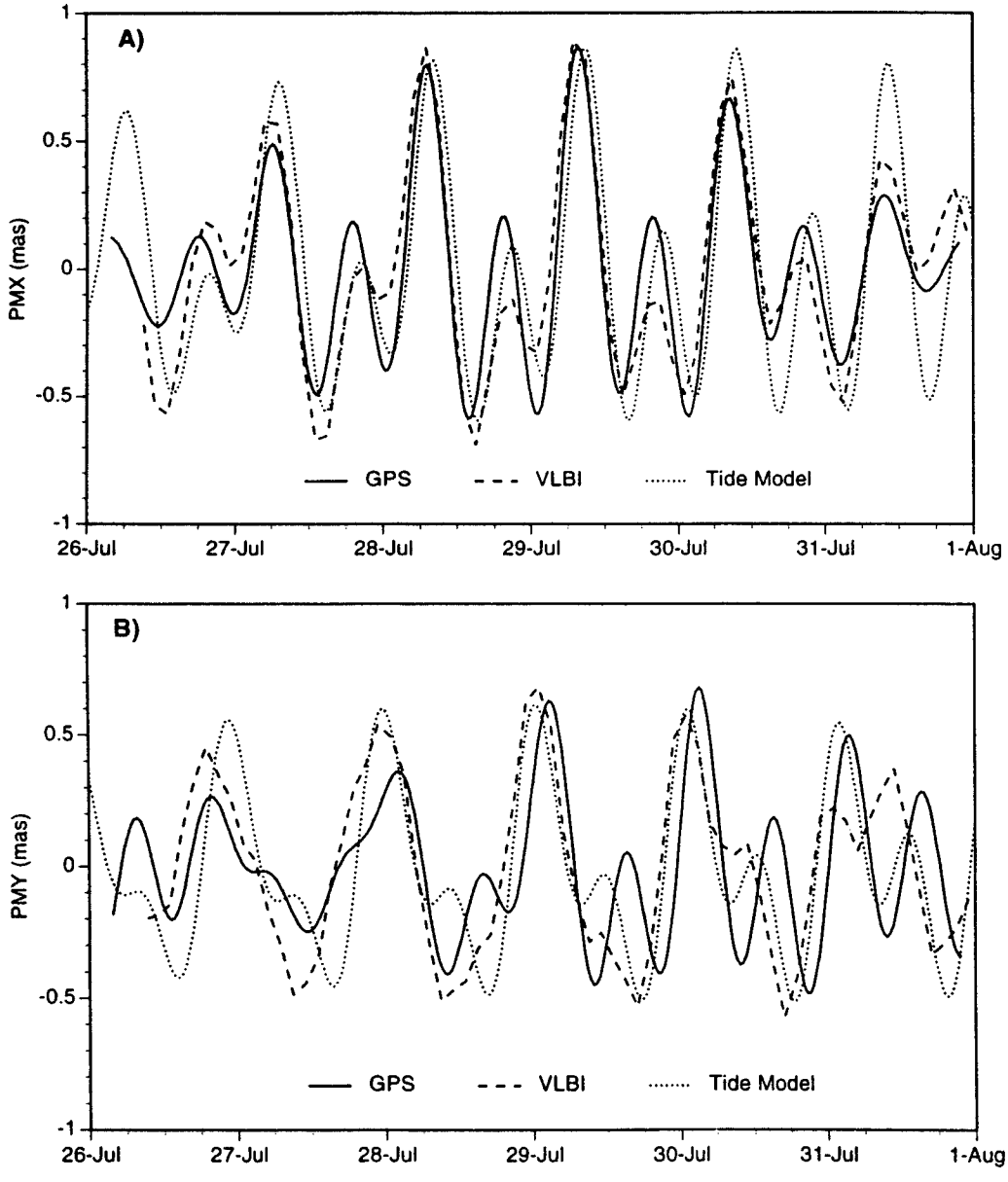

Fig. 14. (a) Polar motion X component for the semidiurnal and prograde diurnal bands for GPS, VLBI, and Herring tide model time series, (b) sames as (a) for the polar motion Y component (after Ibanez-Meier, this volume).

variance of the observed polar motion. Several studies (for example, Kosek, this volume and Hefty, this volume) have also linked the atmosphere to short period (> 1 day) polar motion changes during the SEARCH'92 campaign.

Subhourly polar motion observations (every 30 minutes) were obtained from the GPS tracking network for a six-day period during the EPOCH'92 campaign and were compared to estimates derived from VLBI (see Ibanez-Meier *et al.*, this volume). Like subdaily UT1, subdaily polar motion variations are dominated by a strong diurnal and semi-diurnal signature. Since the retrograde diurnal motion of the pole is degenerate with long period nutations, comparisons are restricted to the semidiurnal (both prograde and retrograde) and diurnal prograde bands. Time domain comparison between these two techniques yields less than 0.3 mas rms differences, which is consistent with their uncertainties (see Fig. 14). Further, comparisons with tidal models confirm the dominance of oceanic tides on these time scales.

5. Concluding Remarks

High time resolution measurement of Earth rotation is an area of intense activity, involving international and interdisciplinary cooperation. The international campaign, SEARCH'92, was successful in obtaining high time resolution (sub-daily and in some cases sub-hourly) measurements of Earth orientation by several space geodetic techniques and in collecting the best available complementary geophysical, oceanographic and atmospheric data. This paper featured the motivation for these measurements, reviewed the progress and planning of SEARCH'92; analysis results were highlighted. The dominance of the atmosphere is seen on time scales of greater than a day to several years with oceanic tides providing the main excitation at diurnal and semidiurnal periods; geodetic measurements provide strong constraints on existing tidal models. Improved theoretical tide models are needed to unravel the oceanic and atmospheric signals. The creation of a new generation of ocean models is now underway through the analysis of TOPEX/Posiedon data. The initial results from SEARCH'92 are indeed encouraging; further analysis of these studies will provide new and unique insights into the properties and origin of short period fluctuations in the Earth's orientation and into solid Earth-atmosphere interactions.

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The angular momentum content of the oceans

While energy has microscopic sources and sinks, the angular momentum is a mechanical quantity which is *macroscopically* conserved. Therefore it is especially suited for the description and understanding of large mechanical systems like the Earth with its 3 main constituents: solid Earth, atmosphere and oceans. Table 1 shows the order of magnitude of the 3 contributions to the average rotation of the present Earth.

Note that the total angular momentum of the Earth-Moon-system is $34.0 \cdot 10^{33}$ kg m^2 s^{-1} (i.e., about 80% represented by the lunar orbit).

The contributions are practically proportional to the mass fractions since the angular velocity is the same for all three parts. Only the larger mean distance from the axis enhances the role of the two last shares (about twice as much for a homogeneous spherical surface than for the actual mass distribution of the whole Earth). The dominant role of the solid Earth ensures the high degree of constancy (or regularity) of Earth' rotation; therefore it served as *the* time standard for most of the human history.

Table 1
Average values

	Mass [kg]	Moment of inertia [kg m^2]	Angular momentum [kg m^2 s^{-1}]
Whole Earth			
≈ solid Earth	6.0×10^{24}	8.1×10^{37}	5.9×10^{33}
Oceans	1.4×10^{21}	3.9×10^{34}	2.8×10^{30}
Atmosphere	5.1×10^{18}	1.4×10^{32}	1.0×10^{28}

The main causes of variability, detected by ever refined clocks and angular measurements, are connected with the two outer nonsolid parts despite of their small mass fractions. Moreover, the relative role of oceans and atmosphere is reversed from Table 1 to Table 2 exhibiting the variations.

The key for this lies in the occurence of much greater *relative motions* in the atmosphere as compared with the oceans.

All but the values of the last line in Table 2 mean amplitudes of periodical changes.

In passing by we should mention that the comparison of

Table 2
Variations

	Torque [kg m^2 s^{-2}]	Angular momentum [kg m^2 s^{-1}]	Corresponding change in Universal Time of the solid Earth [ms]
Atmosphere seasonal	5×10^{18}	2.4×10^{25}	21
Oceans			
seasonal	3×10^{17}	1.5×10^{24}	1
tidal (M 2)	3.4×10^{21}	2.4×10^{25}	0.03
Secular retardation of the whole Earth by tidal friction	5×10^{16} (constant)	1.5×10^{24} (loss per year)	3 (change for 1 year)

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rotational effects by 'size' is a matter of the level of time derivatives: (1) rotation angle (Universal Time), (2) angular velocity (length of day, angular momentum), (3) angular acceleration (torque).

Especially in case of periodic torques of period P and amplitude L_0 it is clear that the amplitudes of level (1), (2) are proportional to L_0P^2 and L_0P respectively. This means that any ordering by the *magnitude* of the effects depends on that level as well.

The changes associated to the oceans could be sorted in a variety of manners:

First by the causes (extraterrestrial or not), second by the time scales (from 1/2 day to infinity) and third by the magnitude of an affected (observed) parameter.

Let us follow the first path. *Exchanges of angular momentum between atmosphere, oceans and solid Earth* are an almost *internal* affair of the Earth. The total angular momentum, i.e. the sum over the 3 constituents is then conserved. This, however, is the only alleviation within an otherwise very complex situation. We are dealing with a so far underexposed branch of weather and climate. From Table 2 we see that the seasonal oceanic effects are of the order of 10% of the atmospheric ones – and this size at present enters the area of measurability! Therefore and for the principal reason of understanding the angular momentum balance in weather and climate problems, now it is indispensable to attack the problem of the distribution and transfer of the oceanic share. Our present state of the art is based on very elaborated numerical hydrodynamical models of the oceans currently used at the Max-Planck-Institut für Meteorologie in Hamburg (eleven depth levels, 3°.5 × 3°.5 mesh size of surface discretization). Our and other models show clearly that the exchange of angular momentum between oceans and solid Earth takes place mainly by the so-called side pressure of the oceans acting on their continental boundaries. This is the analogy to the 'mountain torque' between atmosphere and solid Earth. With regard to the exchange between oceans and atmosphere, a purely theoretical approach is not possible, since, as we all know, our present science is not able to predict the behaviour of the atmosphere for more than a few days. Therefore these models use *empirical wind data* as input.

The surface wind stresses are responsible for the transfer between oceans and atmosphere. We have got results for the average saisonal variation of the winds [1]. At present we try to obtain the effects of the actual wind fields of the last 10 years, since those are the ones for which Earth' rotation is measured with high-precision VLBI. In order to achieve this goal it is not sufficient to run the model for the same years. The oceans have a very long 'memory' of their previous states. Theoretically one should start with a 'state' which implies also all necessary time derivatives as well. In practice, one tries to get the same by integrating over a long time interval with *average* saisonal variations before applying the actual winds. This last part is then used for the comparison with Earth rotation data.

The closure condition for the total angular momentum is especially easy and separable for the axial component. The sum of the angular momenta of the solid Earth J_s and the atmosphere J_A today is observed accurate enough to reveal its non-constancy (see e.g. [2]). Despite of relatively large errors of this partial sum, we would expect some signal in it and that should be mirror-like to the oceanic angular momentum J_0 – so that the total sum is constant. Until now we have found correlation coefficients around

$$r(-J_0, J_S + J_A) \approx +0.30 \pm 0.09$$

thus only slightly significant [3], see Fig. 1.

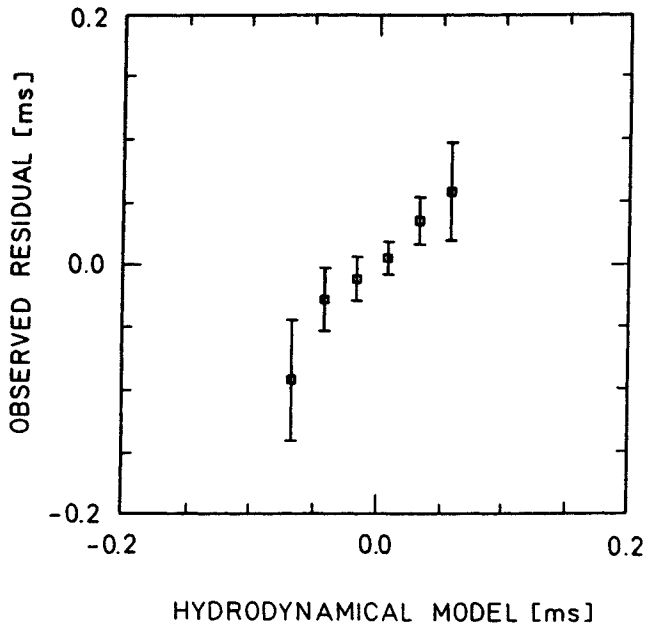

Fig. 1. After subtraction of the mean seasonal variation for the epoch 1981–1989, the residual theoretical values of $-J_0$ are compared with the residual observed $(J_S + J_A)$, both expressed as differences in the length of day and averaged in intervals of $-J_0$.

Since the signature of very important climate events (such as El Nino) has been claimed to be visible in Earth rotation data, it is appealing to look for it in the J_0-results. However, today we cannot say whether the visible peaks in J_0 are only attributable to such an event or to other causes as well.

Let us now turn to a second kind of variations, *the periodic effects of lunar and solar tides*. Although of extraterrestrial origin (and thereby augmenting the number of participating constituents) their treatment is easier for the following reason. Moon and Sun produce forced oscillations in the oceans with the following properties:

(a) The exchange of angular momentum with the disturbing bodies is small; hence the Earth may be seen as a closed system even in this case.
(b) Unlike the surface wind stresses of the foregoing case, the tidal forces are body forces and affect the whole ocean at once. The changes at the surface are small and an exchange with the atmosphere for this reason may be neglected; the exchange with the solid Earth is the only remaining. Practically we are dealing with a two-component system and we expect associated mirror-like changes in oceans and solid Earth.
(c) The periods of the main partial tides are different from other influences so that a separate determination is possible. Especially the solar day (S_1) is not a frequency of our 10 most important tides.
(d) Solid Earth tides do not interfere because the solid Earth is rather symmetric.

The combination of this advantages has allowed us to confirm the existence of these oceanic effects at a 4σ-level despite of their smallness (0.1 ms in UT or a few cm in the position of an equatorial point in space). Fig. 2 compares theory and observations.

Finally, let me briefly mention the secular transfer of angular momentum from the whole Earth into the lunar orbit, better known as *tidal friction*. The physical process is the same as in the foregoing case. Here we are looking at it, however, in the long run. Then the Earth alone is not a closed system

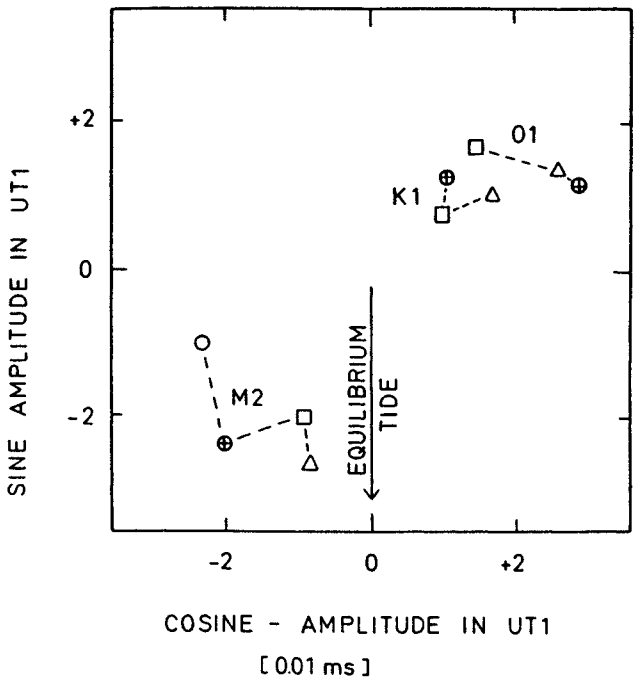

Fig. 2. Periodical effects in UT1 due to oceanic tides: VLBI observations (□ Bonn group [4], Δ HERRING & DONG [5]) versus hydrodynamical models (⊕ 1° mesh size [9] and, for comparison, ○ an older one with 4° mesh size only for M_2 [7])

anymore. Small amounts of angular momentum transferred per tidal period *accumulate* within millenia of human history into UTchanges of hours and change the length of day itself by hours if we go back, e.g. to the Devonian epoch of our Earth' history. It is clear then that these changes must have influenced the Earth' evolution in many ways: the length of day is a primary meteorological parameter, its variation causes concomitant changes in the figure of the Earth and these metamorphoses must have left its signatures in the crust. Ultimately, when going further backwards in time the earliest state of the Earth-Moon-system should be arrived.

For this problem, the oceans have been recognized as the main mediators of the transfer of angular momentum, while the phase lag angle of the solid Earth tides is not large enough for a significant share. The present transfer is shown by historical observations of solar eclipses and lunar laser ranging (LLR). Despite of its smallness, it is quite satisfyingly explained by accurate tidal models (see last line in Table 2).

The large remaining problem is the time dependence of the transfer torque. It is sure that schematic formulae cannot be applied for two reasons: (a) the geometry of the oceans changes through continental drift, (b) the oceans have a very rich eigenvalue spectrum and react very sensitively to such changes and to changes in length of day and tidal periods [8].

The observational evidence from paleontology and, most recent, sedimentology is very appealing. Some tide models for ancient oceans illustrate the potentialities of this kind of research – but its infancy as well [9].

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