EARTH ROTATION FROM THE IRIS PROJECT

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ABSTRACT. Project IRIS (International Radio Interferometric Surveying) was set up under the IAG and COSPAR to provide an operational system that would employ Very-Long-Baseline Interferometry (VLBI) techniques to monitor variations in the rotation of the Earth. Currently the IRIS-A network, with stations at Westford, MA, Ft. Davis, TX, Richmond, FL, and Wettzell, FRG, conducts 24-hour observing sessions every five days to produce determinations of pole position, UT1, and nutation in addition to other parameters of geophysical and astrometric interest. The resulting Earth orientation parameters (EOP) have been shown to have an accuracy of 1 to 2 milliseconds of arc in pole position, and 0.05 to 0.1 milliseconds of time in UT1. In order to observe the relatively large higher frequency variations in UT1, daily 45-minute observing sessions are conducted using the single baseline between Westford and Wettzell. Intercomparison of the UT1 values from the daily and the 5-day series indicates that the accuracy of the daily values is better than 0.1 millisecond of time.

The longer term objectives of the IRIS project include improving the monitoring of Earth orientation by increasing the sampling rate and accuracy of the observations. In April, 1987, the IRIS-P network, with stations in Kashima, Japan, Fairbanks, AK, Ft, Davis, TX, and Richmond, FL began monthly 24-hour observing sessions, and a second series of daily UT1 observing sessions was begun using the stations in Richmond and Bologna, Italy. The additional networks will provide redundancy that will improve the reliability of the system and allow the accuracy of the EOP values to be estimated.

The IRIS UT1 time series provides, for the first time, sufficient accuracy and temporal resolution to look for the few percent increase in k/C caused by the anelastic response of the mantle. Initial results presented here suggest that improved methods of accounting for the dynamics of the oceans and atmosphere may be required before the intertwined variations in UT1 can be fully separated.

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I. INTRODUCTION

By the late 1970's it was clear that VLBI techniques had advantages over all of the new high precision geodetic techniques being developed for observing the rotation of the Earth. A National Geodetic Survey (NGS) review of candidate technologies and instrumentation in 1977 concluded that very long baseline interferometry (VLBI) using the NASA/Haystack MARK III system was clearly the system of choice for developing a modern polar motion and UT1 monitoring service [Carter, 1978; Carter and Strange, 1979]. Project POLARIS (POLar-motion Analysis by Radio Interferometric Surveying) was subsequently implemented jointly by the NGS, the National Aeronautics and Space Administration (NASA), and the United States Naval Observatory (USNO) [Bossler, 1982].

Under project POLARIS, three permanent geodetic VLBI observatories have been developed: Westford, in Massachusetts; the George R. Agassiz Station (GRAS), in Texas; and Richmond, in Florida. Even before the completion of the POLARIS network, the Federal Republic of Germany (FRG) began constructing a dedicated geodetic VLBI observatory at their Satellite Observation Station in Wettzell, Bavaria. To exploit the improved capabilities of the combined POLARIS/Wettzell network the responsible geodetic agencies in the FRG and NGS jointly initiated project IRIS (International Radio Interferometric Surveying) in 1982 [Carter and Robertson, 1984]. The International Association of Geodesy (IAG) and the Committee on Space Research (COSPAR) subsequently approved the formation of a permanent joint IRIS subcommission; organizations in several additional nations have agreed to participate, or expressed interest in participating, in IRIS activities. The Onsala Space Observatory, Sweden, is regularly participating in one IRIS observing session per month, and the VLBI observatories in Bologna, Italy, Kashima, Japan, and Fairbanks, Alaska have recently begun observing sessions under the IRIS project.

The IRIS observations are designed to monitor all of the important components of the rotation of the Earth, including motion of the rotation axis in space (nutation), motion of the Earth's crust and mantle relative to the rotation axis (polar motion), and the angle of rotation about the rotation axis (UT1), in addition to baseline components, radio source coordinates, and other parameters of geophysical and astronomical interest.

II. POLAR MOTION AND NUTATION

Although this paper will focus on the IRIS determinations of UT1, the UT1 estimation process is so critically dependent on accurate polar motion and nutation values that we felt it would be useful to display the IRIS determinations of those quantities before describing the UT1 observing sessions.

Figure 1 shows the pole position determinations from the IRIS observations and Satellite Laser Ranging (SLR) measurements between January, 1984, and March, 1987. The close agreement (2 milli-arcseconds RMS difference) between the two completely independent methods of observation places a tight bound on the total errors in both sets of determinations [Robertson *et al.*, 1985a].

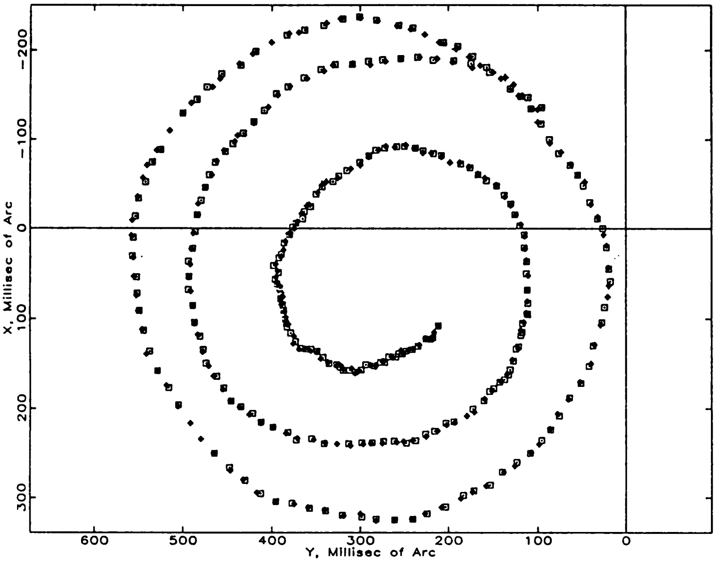

Figure 1. Pole position determinations from IRIS VLBI observations (rectangles) and SLR observations (diamonds).

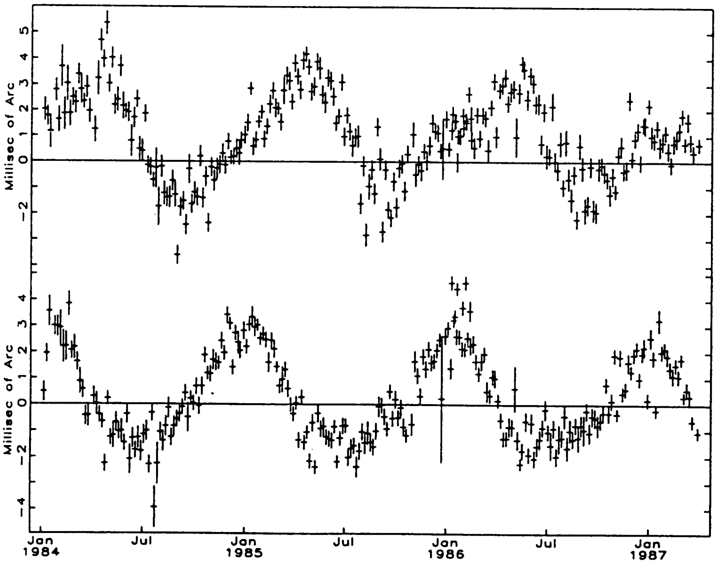

Figure 2. Corrections to the IAU 1980 nutation series as determined from IRIS VLBI observations. The top plot shows nutations in longitude, scaled by the sine of the obliquity, and the bottom plot shows nutation in obliquity.

The IRIS determinations of the nutations of the Earth's spin axis in space are shown in figure 2, displayed as residuals to the IAU 1980 nutation model [Wahr, 1981]. The clear annual signature in these residuals has been interpreted by Herring and his colleagues at the Center for Astrophysics as resulting from an error in the value for the core-mantle coupling assumed by Wahr in calculating the standard nutation model [Herring et al., 1986; Gwinn et al., 1986]. This analysis will be discussed in another paper at this conference [Herring, 1987].

III. UT1 DATA ANALYSIS

Determinations of UT1 have long been hampered by the fact that UT1 has more high-frequency time variations than the other components of Earth orientation. To try to understand these time variations the IAU/IAG project MERIT [Wilkins, 1980] scheduled intensive observing campaigns in 1984 and 1985 with a goal of obtaining daily determinations of UT1. Although there was no technical reason why the IRIS project could not have conducted its 24-hour multi-station observing sessions every day instead of every 5 days, the costs of such an increase in duty cycle were prohibitive. However for monitoring only UT1 a much less costly observing program was found to be sufficient. In principle UT1 could be estimated from a single delay measurement of an equatorial source using one equatorially oriented baseline if the baseline coordinates, radio source coordinates, pole position, nutation, and clock parameters were well enough known. In practice, all of these parameters except the clock error parameters are sufficiently well known from the regular IRIS observations. Therefore all that is needed to monitor UT1 is a brief observing session designed to separate UT1 from clock errors parameters. This can be accomplished by observing a set of sources that cover a wide range in declination. In practice, the observing sessions employed for daily UT1 determinations use the Westford-Wettzell baseline and make eight observations on four sources that span about 70 degrees in declination. These observing sessions take about 45 minutes each day.

It would be nice to be able to verify the accuracy of these observations by intercomparison with determinations from observations based on a different technique, as the VLBI and SLR pole position values were intercompared. Unfortunately there is no independent observing technique that can match the accuracy, stability and time resolution of the VLBI determinations. We can, however, intercompare the UT1 determinations from the daily measurements with the corresponding results from the 5-day, multi-station IRIS observing sessions. Such an intercomparison consistently shows agreement between the observing sessions at the level of about 0.1 millisecond of time [Robertson et al., 1985b]. This value represents a bound on the combined error in both series, plus any real UT1 variations with periods less than about 10 days.

The important geophysical parameters that can be estimated from these high precision UT1 determinations relate to the UT1 variations caused by changes in the Earth's moment of inertia under the effects of the solid Earth tides. Yoder et al. [1981] describe a detailed model for such variations in an elastic Earth with liquid oceans and core. The resulting model is proportional to the elasticity parameter k/C. Wahr has discussed the possibility of using the tidal variations in UT1 to determine the anelastic behavior of the mantle [Wahr, 1987; Wahr and Bergen, 1986]. Qualitatively, the anelastic effects are not difficult to understand: an anelastic Earth is a bit "softer" than a perfectly elastic one, and its response to tidal perturbations is slightly greater than the comparable effects for an elastic Earth. Quantitatively, the magnitude of the amplification is about 2% in k/C. Yoder's estimate for k/C is about 0.944, and Wahr's corrections for anelastic effects indicate that the value for fortnightly terms should be in the range of 0.97 to 1.06, and for monthly terms in the range of 0.96 to 1.00. This corresponds to an increase in the tidal UT1 variations by about 0.02 milliseconds of time. The need to measure such a small effect places a severe requirement on the measurement accuracies.

Figure 3 shows the IRIS daily UT1 time series from May, 1985 through March, 1987, after removing a linear drift, three long-period sinusoids (6,12 and 24 month periods, respectively), and the effects of the tabulated variations in atmospheric angular momentum as compiled by the National Meteorological Center [Rosen and Salstein, 1983]. The high frequency tidal variations in UT1 are easily seen in these data. How accurately do the tidal variations seen in Figure 3 match the Yoder's theoretical model? Figure 4 shows a periodogram of these data together with a periodogram constructed from the Yoder model evaluated at one-day intervals over the span of the VLBI observations. The tidal peaks at 27 and 14 days (13.5 and 26.1 cyc/year) are seen to match nicely, as do the lesser peaks at 9 and 31 days (11.8 and 40.6 cyc/year). Notice that the 9-day peak is outside the Nyquist limit for 5-day sampling, and can be observed only with the daily VLBI observations.

In order to use these data to evaluate the k/C tide coefficients with standard least-squares techniques it was necessary to remove the low-frequency variations. To do this the data were low-pass filtered using a filter with an absolute cut-off at 10 cycles/year (period of 36.524 days). The resulting function, shown in figure 3, was subtracted from the data. About 5 points at each end of the data set were not fit closely by this function, and were deleted in the ensuing analysis. A six-month sample of the differences, together with values calculated from the Yoder model, are shown in figure 5. To these data we fit three amplitude coefficients for the Yoder model, the first applied to the first 12 terms (with periods about 9 days), the second applied to the next 13 terms (with periods about 14 days), and the third applied to the next 16 terms (with periods about 27 days). The results of this fit are tabulated in table 1. The formal errors for the 14 and 27 day coefficients are seen to be substantially smaller than the precision required to determine the anelastic effects. Of course the formal errors are not the same as the total errors in the determinations. Rather, they represent the limiting accuracy which might be obtained in the absence of unmodeled systematic error. Their principal significance in this context is to demonstrate that the measurement errors are not a significant fraction of the true error budget.

To estimate the magnitude of the total error in the determinations of k/C we divided the data into subsets in two different ways and repeated the solutions, as shown in table 1. The resulting differences in the k/C

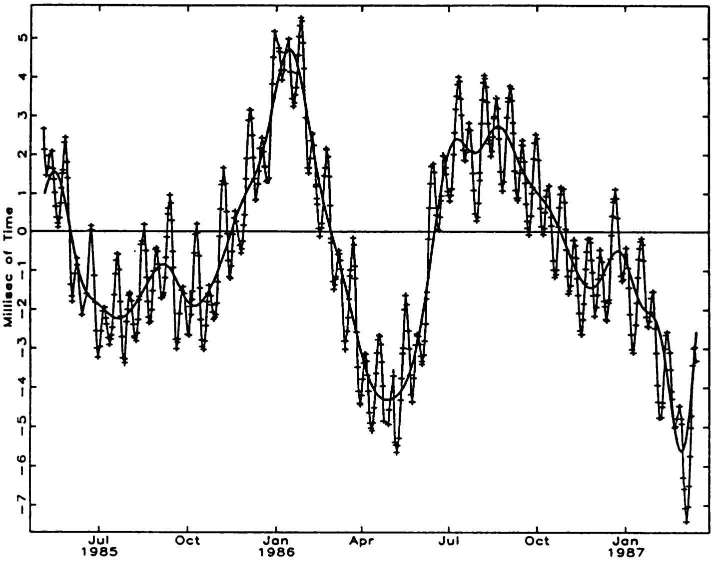

Figure 3. Daily determinations of UT1, after removal of a linear trend and long-period sinusoids. The heavy line was generated by smoothing the observations with a low-pass boxcar filter with a cut-off at 10 cyc/year.

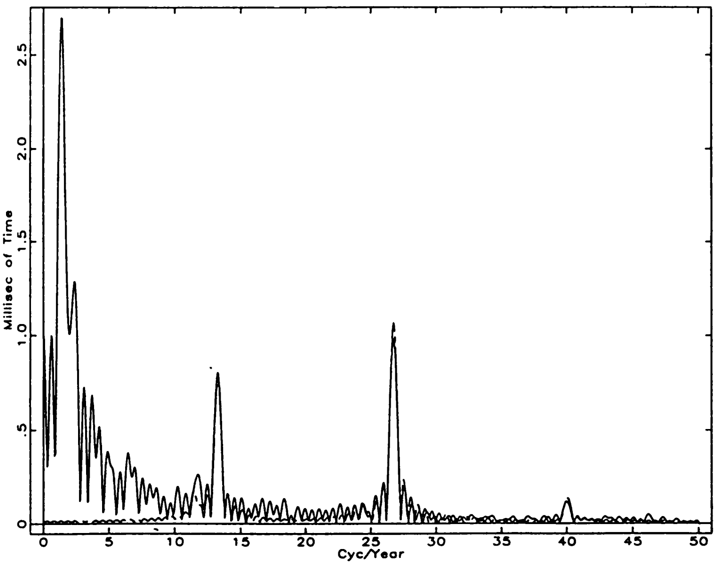

Figure 4. The solid line shows a periodogram of the data shown in Figure 3, and the dashed line is a similar periodogram of a daily tabulation of Yoder's tide model, evaluated over the same time interval as the VLBI data.

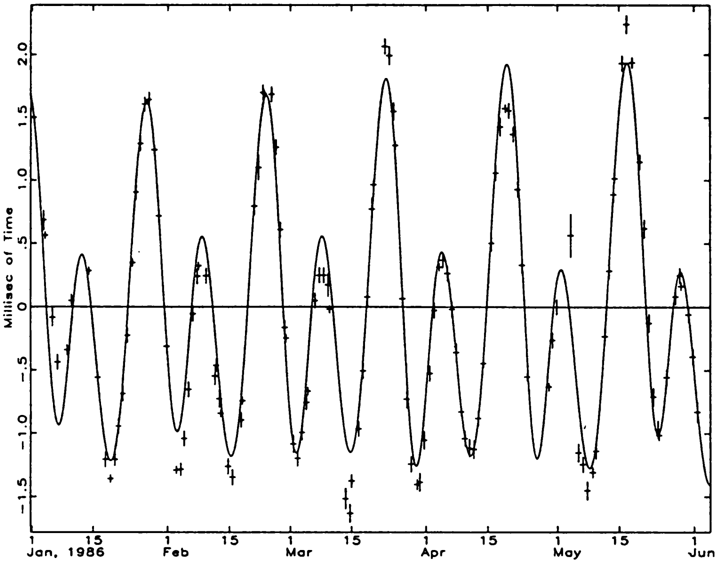

Figure 5. Sample of the data shown in figure 3 after removal of the smooth curve from that figure. The solid line shows the Yoder tidal variation model.

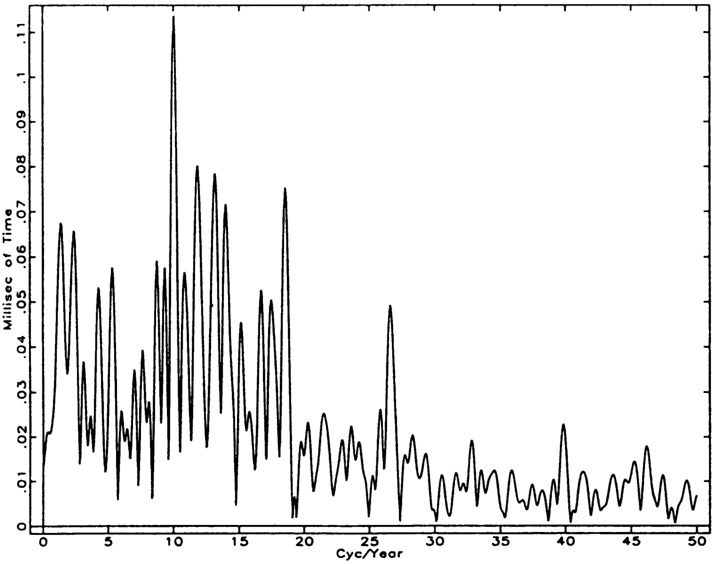

Figure 6. Periodogram of the residuals of the UT1 determinations after fitting three k/C amplitudes as described in the text.

Table 1. k/C determinations. The column labeled "sigma" tabulates the formal standard errors. Under "differences," the first column tabulates differences from interleaved subsets, and the second tabulates differences from the first and second halves of the data set.

Period	K/C	sigma	Differences 1	 2
9 day	0.898	0.02	0.09	0.24
14 day	0.948	0.003	0.02	0.03
27 day	0.986	0.004	0.04	0.09

determinations are generally much larger than the formal errors of the individual determinations. These differences provide much better estimates of the true uncertainties in the k/C determinations than do the formal errors. For the 27 day term and especially the 14-day term these uncertainty estimates approach the level needed for determining the mantle anelasticity. Clearly, however, there is some unmodeled source of systematic error or process noise interfering with the estimations of k/C. If it could be eliminated or substantially reduced then we might be very close to being able to observe the effects of the mantle anelasticity.

The set of possible sources of the observed process noise can be conveniently divided into 5 categories according to their distance from the center of the Earth: extra-terrestrial, atmospheric, oceanic, crust-mantle, and liquid-core effects. The two extreme categories can be largely dismissed out of hand: extra-terrestrial effects (luni-solar torques) are unlikely to hold surprises at any significant level, and the liquid core is unlikely to be able to generate any response at the <30 day periods needed. Of the other three effects, the ones that relate to the crust and mantle are the very ones we are trying to observe. That leaves the oceans and atmosphere as the principal problem areas.

The known effects of atmospheric winds and pressure variations have already been removed from the data, but the error levels in the wind values are poorly known. If there are large errors in the atmosphere data at fortnightly and monthly periods then they could prove to be a serious problem. The large effort that is currently being made to study these atmospheric effects holds some hope for improving our knowledge of the atmospheric variations in the future.

The remaining likely source for errors in estimating k/C is oceanic effects. The oceans respond strongly at the tidal frequencies, and because of local resonances they are commonly significantly out-of-phase with the driving torques. The periodogram of the residuals to the UT1 data after fitting the k/C values, shown in figure 6, shows peaks at the tidal frequencies, exactly as might be expected from such out-of-phase oceanic effects. (There are, of course, other peaks that are not at the tidal frequencies, which may or may not be related to oceanic effects.) Furthermore, Yoder calculates that the ocean tides will cause UT1 variations at semi-diurnal and diurnal frequencies with amplitudes ranging from 0.02 to 0.07 milliseconds [Yoder et al., 1981]. Since this power is above the Nyquist frequency for the daily sampling employed here, it must alias into the frequency band that we are able to observe. There is no ready analytic cure for the process noise introduced by the oceans, but there may be ways to deal with it numerically. For example, given an analytic model for the ocean tide displacements such as the Schwiderski model [Schwiderski, 1980], it should be possible to numerically integrate the variations in moment of inertia of the oceans as a function of time. The implied variations in UT1 could then be compared with the observed residuals. Whether this approach would reduce the scatter in the estimates of k/C to the level that would make possible a useful determination of anelastic effects in the mantle remains to be seen. If the existing level of accuracy of ocean tide models is insufficient to reduce the scatter in the k/C estimates and the corresponding residuals in the UT1 observations, then these UT1 observations may have a role to play as a constraint on future ocean models.

If the semi-diurnal and diurnal tides cannot be modeled with sufficient accuracy to remove their effects from the UT1 values, it may be necessary to increase the sampling rate of the UT1 observations to at least the Nyquist frequency for the semi-diurnal tides, i.e., 4 observing sessions per day. VLBI is the only observing technique that can currently achieve such a sampling rate, and, indeed, sampling rates up to several times higher than this pose no particular technical problems.

IV. CONCLUSIONS:

The extraordinary power of VLBI for monitoring Earth rotation has been demonstrated by the quality of the IRIS results. The observed nutation corrections have placed a constraint on the interactions between the core and the mantle which is unavailable from any other observational techniques. The UT1 measurements have reached a level where the observational uncertainty is not a major part of the error budget, and the geophysical information that can be recovered is limited by our understanding of the complex interactions between the mantle, the oceans and the atmosphere. As these interactions are unraveled we can expect that the VLBI observations will play an important role in measuring anelastic effects in the mantle, and possibly in constraining models of ocean tide motions.

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