El Niño and VLBI Measured Length of Day

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Abstract VLBI is unique in its ability to measure UT1 and is an important contributor to measuring the Length of Day (*LOD*). In this paper I study *LOD* and demonstrate that it has structure at all time scales, and decompose it into into Tidal, Seasonal, and Long Period and Residual terms. I show that the Multivariate Enso Index is strongly correlated with the Residual *LOD*. I compare the impact of the current El Niño with that of the 1997–98 El Niño. Both events result in an increase in *LOD* of 750 μs and a cumulative impact on UT1 of 0.1 seconds.

Keywords El Niño, *LOD*, AAM

1 Introduction

"Never underestimate the joy people derive from hearing something they already know." —Enrico Fermi

This paper reviews some of the properties of Length of Day (*LOD*). There is no new science here—the key results have been known since the 1980s and 1990s. The motivation for this paper is the current El Niño, which is the strongest one since the 1997–98 El Niño. In 1998, Gipson and Ma [1] wrote a paper on the impact of the 1997–98 El Niño on *LOD*. It caused an increase in *LOD* of 750 μs. As the El Niño dissipated, so did the change in *LOD*. I was interested in the impact of the current El Niño on *LOD*. The two events are very similar, and the current El Niño is on track to have a similar or larger impact. To demonstrate this we need to decompose *LOD* into various pieces to isolate the impact of the El Niño.

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2 Angular Momentum and *LOD*

It is useful to decompose the angular momentum of the Earth system as follows:

$$J_{Earth} + J_{Ocean} + J_{Atmosphere} + J_{Core} = J_{Total}. \quad (1)$$

Here J_{Earth} is the Earth's Angular Momentum (*EAM*), J_{Ocean} is the Oceanic Angular Momentum (*OAM*), $J_{Atmosphere}$ is the Atmospheric Angular Momentum (*AAM*), and J_{Core} is the Earth's Core's Angular Momentum (*CAM*). In the absence of external torques, the total angular momentum is conserved:

$$\frac{dJ_{Total}}{dt} = 0 \quad (2)$$

which leads to

$$\Delta J_{Earth} + \Delta J_{Ocean} + \Delta J_{Atmosphere} + \Delta J_{Core} = 0. \quad (3)$$

If the angular momentum of one component changes, the others must compensate. The Sun and Moon (and to a lesser extent the planets) do exert torques on the Earth which lead to nutation and precession of the Earth spin axis. But over short time scales these effects can be ignored, and the above equation is a reasonable approximation.

VLBI does not directly measure the angular momentum of the Earth. Instead it measures the *LOD* which is related to J_{Earth} and the Earth's moment of inertia I_{Earth} by:

$$J_{Earth} = \omega I_{Earth} = \frac{2\pi}{LOD} I_{Earth}. \quad (4)$$

Small changes in *LOD* cause changes in J_{Earth}:

$$\Delta J_{Earth} = -\Delta LOD(\frac{2\pi}{LOD^2} I_{Earth}). \quad (5)$$

3 VLBI Measured *LOD*

Figure 1 shows VLBI measured *LOD* since early 1980. The curve appears smoother at the start because the data was sparse. The *LOD* appears to be a quasi-periodic signal superimposed over long term variation. Figure 2 is a close-up of the data since 2010. Two striking features of both figures are the seasonal signals and the regular 'spikes'. Both of these are evident when we Fourier transform the data to the time domain as shown in Figure 3. The 'spikes' show up as sharply defined peaks in the spectrum, whereas the seasonal signal shows up as broad peaks centered around the annual and semi-annual periods.

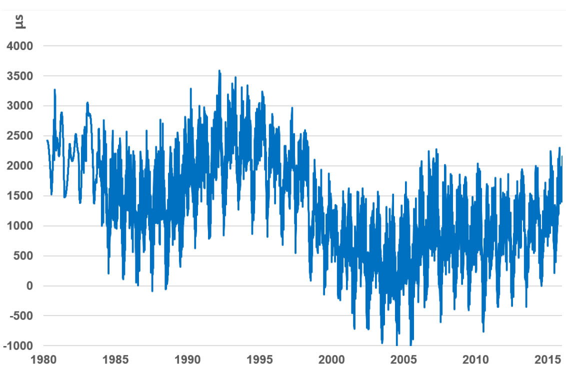

Fig. 1 VLBI measured *LOD* (with tidal terms).

4 Decomposition of *LOD*

One of our goals in this note is to decompose *LOD* into terms which are separated by cause and/or period.

LOD = Tidal Terms + Seasonal Terms
+ Long Period + Residual

In the remainder of this section we do this separation.

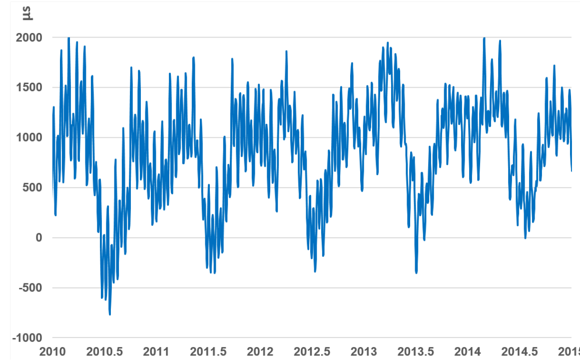

Fig. 2 Close-up of LOD with tidal terms.

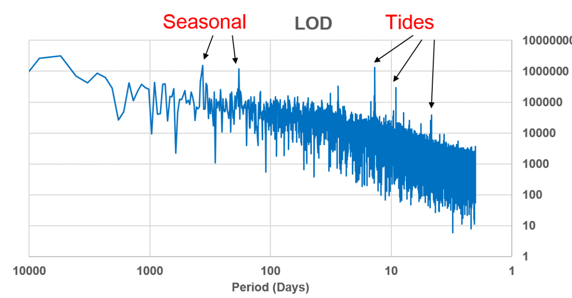

Fig. 3 *LOD* spectrum.

4.1 Tidal Terms

The sharp peaks in the spectrum of *LOD* occur at tidal frequencies. The gravitational force of the Sun and the Moon changes the ocean heights and currents. This results in a change in the *OAM*, and the *EAM* changes to compensate for this so that the total Angular Momentum is conserved. The tidal behavior of *LOD* is well understood, and the IERS provides a good model for it [2]. If we subtract the IERS model from the VLBI measured data we obtain the series shown in Figure 4 and the corresponding spectrum shown in Figure 5. In the remainder of this note *LOD* will mean *LOD* with the tidal terms removed.

4.2 Seasonal Terms

Figure 4 exhibits strong seasonal behavior superimposed on a slowly varying signal. To extract the seasonal component we calculate the average *LOD* as a function of the Day of the Year (*DOY*). For leap years

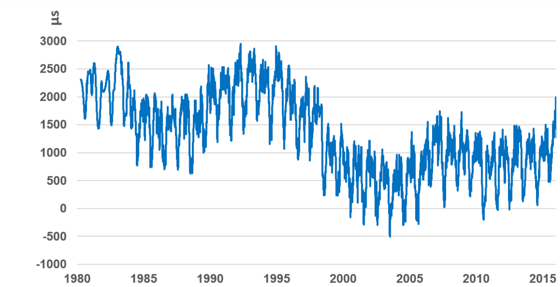

Fig. 4 VLBI measured *LOD* with tidal terms removed.

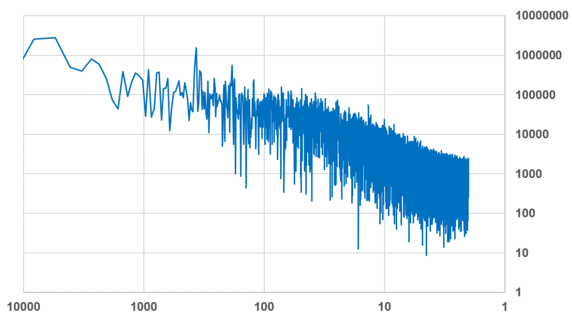

Fig. 5 Spectrum of *LOD* with tidal terms removed.

we assume that $LOD(366) = LOD(365)$. This seasonal behavior is plotted in Figure 6.

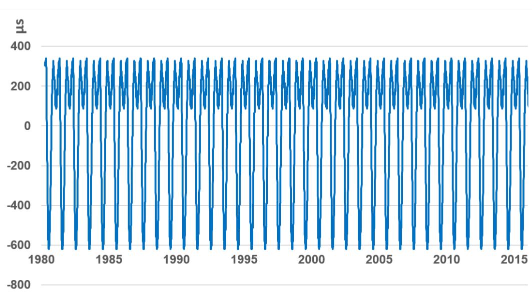

Fig. 6 *LOD*'s seasonal dependence in microseconds.

4.3 Atmospheric Angular Momentum

The atmosphere plays a vital role in exciting small but measurable changes in the rotation of our planet. Recognizing this, the International Earth Rotation and Reference Systems Service invited the U.S. National Meteorological Center to organize a Sub-bureau for Atmospheric Angular Momentum for the purpose of collecting, distributing, archiving, and analyzing atmospheric parameters relevant to Earth rotation/polar motion. These parameters are calculated from the output of numerical weather models, and have been publicly available since 1989 [3]. Figure 7 plots the *AAM* calculated using as input the NCEP re-analysis model and is scaled so that it can be interpreted in terms of *LOD*. On time scales of one to two years, this looks very similiar to Figure 4.

Figure 8 plots the VLBI measured *LOD* together with *AAM* since 2014. I removed a constant offset from *LOD*. The correlation between the two series over this period is 0.96. The striking level of agreement is testimony to the accuracy of the numerical weather models on which the calculation of *AAM* is based and to the accuracy of measurements of *LOD*.

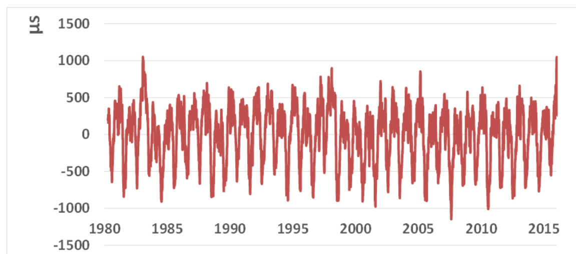

Fig. 7 AAM calculated from the NCEP re-analysis model.

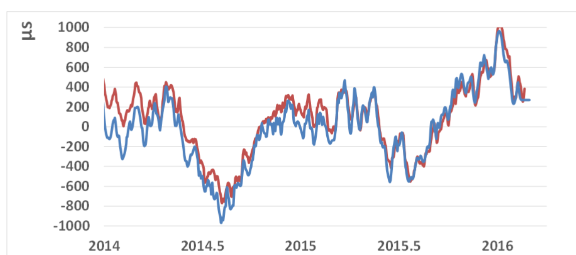

Fig. 8 LOD (bottom line) and AAM (top line).

4.4 Long Period and Residual *LOD*

Figure 9 plots the difference between the VLBI measured *LOD* and the rescaled AAM values. Apart from the noise in the signal, the dominant structure is a long-period variation of the *LOD*. This is thought to be due predominantly to changes in the interior angular momentum of the earth, that is, changes in J_{Core}.

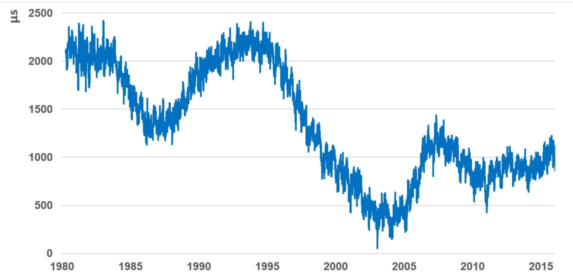

Fig. 9 "Long period" *LOD* obtained by subtracting AAM from *LOD*.

Figure 10 plots the Residual *LOD* obtained from the measured *LOD* by removing: 1.) Tidal Terms; 2.) Seasonal Terms; 3.) Long Period Terms.

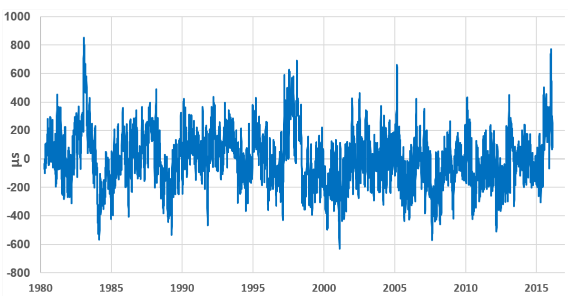

Fig. 10 Residual *LOD*.

5 EL Niño and *LOD*

El Niño is a global phenomenon affecting the weather all over the world. One measure of the strength of El Niño is the Multivariate Enso Index (MEI) which depends on six weather related variables observed over the Pacific. These variables are: sea level pressure, zonal and meridional components of the surface wind, sea surface temperature, surface air temperature, and cloudiness [4]. The values for the MEI are available from 1950 through the current time at http://www.esrl.noaa.gov/psd/enso/mei/table.html. Figure 11 plots the MEI between 1980 and 2015.

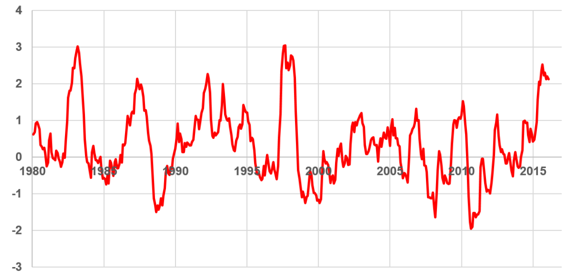

Fig. 11 The Multivariate ENSO Index.

Figure 12 combines Figures 10 and 11 to show the similarity between MEI and residual *LOD*. Three El Niño events and two La Niña events are circled. The 1996–97 El Niño caused an increase in *LOD* of about 750 µs, and the affect of the current one is similar.

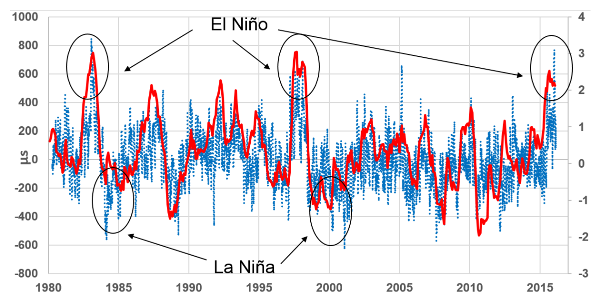

Fig. 12 MEI (solid line) and residual *LOD* (dotted line).

6 Earth as a Clock and the Relationship Between *LOD* and $UT1$

One can view the Earth as a clock. *LOD* is related to the rate of the clock by *LOD*=1/Rate. If the $LOD > 86400s$, then the clock is running slow, whereas if $LOD < 86400s$ the clock is running fast. In this analogy $UT1$ is the accumulated error in time and is given by:

$$UT1 = \int (86400s - LOD)dt \qquad (6)$$

To illustrate these concepts, consider Figure 13 which shows *LOD*'s seasonal behavior over a two-year period. This has peaks in Northern Hemisphere (NH) Winter and troughs in NH Summer. The difference between Winter and Summer is due to the North-South asymmetry of the continents, which leads to more storms in NH Winter. These storms increase the *AAM*, which results in a slowing down of the Earth. The NH Winter days are about 1 ms longer than Summer days.

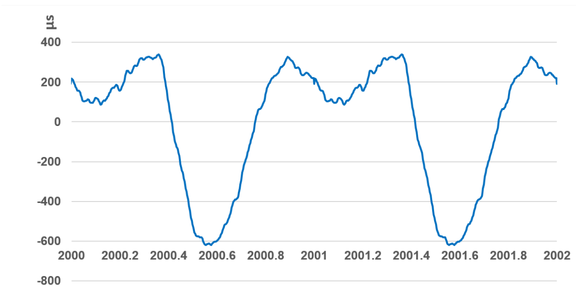

Fig. 13 *LOD*'s seasonal behavior in µs.

Figure 14 shows the seasonal effect on UT1 over two years. This is obtained by integrating the seasonal *LOD* starting on January 1. UT1 has a maximum of +30 ms around June 1, and a minimum of −18 ms around October 1.

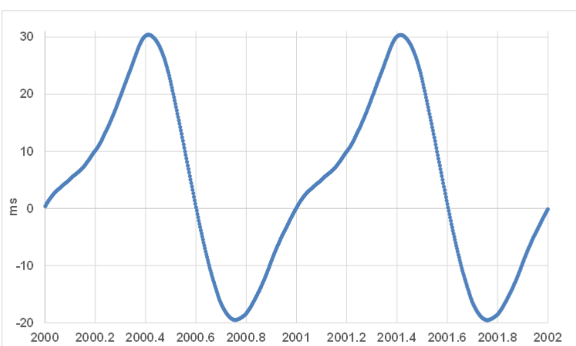

Fig. 14 Seasonal UT1 in milliseconds.

In the previous section we saw that the 1997–98 and the current El Niño events caused an increase in *LOD* of about 750 µs in the residual *LOD*. If we integrate this we can find the impact on UT1. Figure 15 shows the change in UT1 for the two El Niños. The 1997–98 El Niño had a cumulative effect of 0.1 seconds, and the current event is on track to repeat this. This is three times larger than the normal seasonal changes in $UT1$.

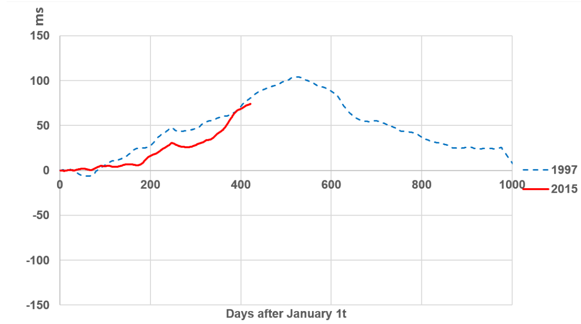

Fig. 15 Change in UT1 in milliseconds from the 1997 El Niño (dashed line) and the 2015 El Niño (solid line). The X-axis shows days after January 1.

7 Conclusions

In this note we looked at VLBI measured *LOD*. The spectrum of *LOD* demonstrates that there is structure at all time scales. We decomposed *LOD* into several components based on their period and the origin of the effect. We also showed that there is clear correlation between MEI and the residual *LOD*. Lastly we looked at the impact of the El Niño on *LOD*. The current El Niño results in a significant increase in *LOD* (the day gets longer). As the 1997–98 El Niño dissipated, *LOD* returned to its baseline value, and we expect the same to happen with the current event.

References

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