GEOPHYSICAL RESEARCH LETTERS, VOL. 29, NO. 20, 1967, doi:10.1029/2002GL015883, 2002

# Degree-1 Earth deformation from very long baseline interferometry measurements

D. Lavallée and G. Blewitt[1]

Nevada Bureau of Mines and Geology, and Seismological Laboratory, University of Nevada, Reno, USA

Received 15 July 2002; revised 20 August 2002; accepted 21 August 2002; published 22 October 2002.

[1] The presence of degree-1 deformations in very long baseline interferometry (VLBI) measurements is detected for the first time. We compare VLBI measurements with the deformation field predicted using a GPS-determined load moment. Degree-1 series in the center of figure frame have root mean square values up to 3 and 1.5 mm in the up and horizontal components respectively. The predicted baseline series are compared with VLBI baseline series where there are >50 matching points. For the period 1996–2001, 14 baselines out of 35 are significantly correlated (5% significance level). For the period 1985–2001, a sinusoidal fit to the GPS load-moment series predicts baseline series at all VLBI epochs, 49 out of 110 baselines are significantly correlated (5% significance level). Comparison between annual signals estimated from the VLBI and predicted baseline series shows that degree-1 deformation most likely dominates the annual phase of the VLBI series. *INDEX TERMS:* 1223 Geodesy and Gravity: Ocean/Earth/atmosphere interactions (3339); 1247 Geodesy and Gravity: Terrestrial reference systems; 1299 Geodesy and Gravity: General or miscellaneous. **Citation:** Lavallée, D., and G. Blewitt, Degree-1 Earth deformation from very long baseline interferometry measurements, *Geophys. Res. Lett.*, *29*(20), 1967, doi:10.1029/2002GL015883, 2002.

## 1. Introduction

[2] Changes in gravitational and surface forces due to seasonal inter-hemispheric mass exchange have been shown to cause a degree-1 spherical harmonic mode of elastic deformation that is observable in GPS measurements [*Blewitt et al.*, 2001a]. This mode is described by the load moment vector [*Blewitt et al.*, 2001a], and should be observable using any space geodetic technique. Seasonal mass exchange also causes variations in the geocenter, the translation of the origin between terrestrial frames located at the center of the solid earth and the center of mass of the entire Earth system (Earth, oceans and atmosphere). The load moment is directly related to the geocenter via the elastic properties of the Earth (Blewitt, Self-Consistency in Reference Frames for Solid Earth Dynamics, submitted to Journal of Geophysical Research, 2002). Prior to *Blewitt et al.* [2001a] the deformation of the Earth's surface that accompanies geocenter motions was not emphasized or investigated. The analysis of degree-1 deformations using satellite techniques is complex since coordinate displacements are highly frame dependent [*Blewitt et al.*, 2001b] and could be biased by seasonal satellite orbit error or the procedure for estimating geocenter motions.

[3] The methods for determining degree-1 deformation and geocenter motions can be independent; the latter relies on observations of the center of mass of the Earth system through satellite orbit models and the former purely on observing strain at the Earth's surface. VLBI is not a satellite technique and is not sensitive to geocenter motions. VLBI can observe degree-1 deformation as it affects baseline lengths and can therefore indirectly observe geocenter motions. Thus VLBI may provide important validation of estimated variations in load moment and geocenter estimates from other techniques. Here the presence of degree-1 Earth deformation in VLBI measurements is investigated for the first time. Estimation of the degree-1 signal from VLBI measurements is difficult due to the relatively poor spatial coverage of the global VLBI network and the limited number of common observing sessions. The GPS load moment was estimated from a network of 66 sites (at most 2145 baselines) with on average 1300 baselines being observed weekly. In contrast the VLBI solution covers a network of 33 sites and 110 baselines (out of a possible 528) and on average estimates 13 baselines each week. To investigate the presence of degree-1 deformation in VLBI observations, we compare the VLBI baseline length measurements with the deformation field predicted using the GPS determined load moment of *Blewitt et al.* [2001a].

## 2. The Degree-1 Deformation Field

[4] The degree-1 mode deforms the Earth from one sphere to another of identical radius but with a strained surface. The coordinate displacement field however varies greatly between different frames. *Blewitt et al.* [2001a] show that the load moment vector **m** can be used to predict the surface displacement vector $\Delta\tilde{\mathbf{s}}$ (East, North and Up) at any location in the center of surface figure (CF), no-net translation frame using:

$$\Delta\tilde{\mathbf{s}} = \tilde{l}_1{}' \, diag[+1 \quad +1 \quad -2]\mathbf{Gm}/M_{\oplus} \qquad (1)$$

Where $\tilde{l}_1{}'$ is the lateral degree-1 load Love number [e.g. *Farrell*, 1972] transformed to the CF frame [*Blewitt et al.*, 2001a]. **G** is the 3 × 3 matrix that rotates geocentric into topocentric displacements (east, north and up) and $M_{\oplus} = 6.0 \times 10^{24}$ kg is the total Earth system's mass.

[5] *Blewitt et al.* [2001a] estimated a weekly load moment series from 5 years of data (1996–2001) acquired

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[1] Also at Department of Geomatics, University of Newcastle upon Tyne, UK.

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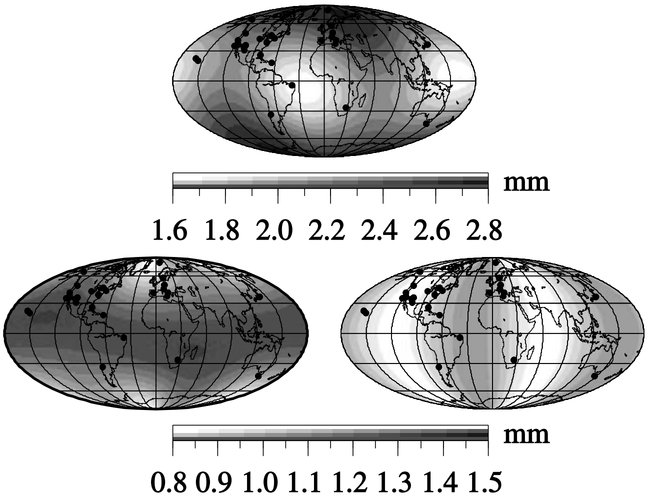

**Figure 1.** RMS of the predicted degree-1 deformation signal in the up (top) North and East (bottom). Also shown are all VLBI sites used in this analysis.

by 66 sites of the International GPS Service (IGS) network. The load moment series is dominated by seasonal inter-hemispheric mass exchange; the largest signal is seen in the z (polar) component with 70% of the variance accounted for by annual variation. This load moment series is used to predict the displacement time series in the CF frame at all surface locations using (1) for the period 1996–2001. The root mean square (RMS) of the predicted displacement time series at each surface location is plotted in Figure 1.

## 3. Comparison with VLBI Baseline Length Series

[6] We compare the predicted degree-1 baseline series with estimated baseline series from NASA's Goddard Space flight Center 2001 VLBI Terrestrial reference frame solution 2001a_bas [NASA Goddard Space Flight Center VLBI group, 2001].

[7] Baseline length rates are estimated and removed from the VLBI baseline series as an initial step to remove tectonic motion. If a time series contains significant periodicity then the estimated rate will be in error, particularly at short data spans [*Blewitt and Lavallée*, 2002]. This effect also biases the residuals and will cause a subsequent underestimate of any signal present [*Black and Scargle*, 1982; *Blewitt and Lavallée*, 2002].

[8] The degree-1 load moment predicts significant annual periodic variation in the baseline series with amplitudes on average ~2 mm and up to ~5 mm. Seasonal variation within VLBI baseline series has also been previously observed [*MacMillan and Ma*, 1994; *Argus and Gordon*, 1996; *Titov and Yakovleva*, 2000]. *Titov and Yakovleva* [2000] estimate annual signals from 35 VLBI baseline length series with amplitudes on average ~6 mm and up to ~13 mm.

[9] To avoid an erroneous rate estimate and subsequent reduction in the size of the loading signal both annual and semi-annual sinusoidal parameters are estimated simultaneously with the linear baseline rate. Only the baseline rate however is later subtracted from the VLBI baseline series. The mean correlation coefficient between the degree-1 and VLBI baseline time series is increased by 4% when this procedure is followed.

[10] We compare two sets of series, first we compare the degree-1 baseline series predicted by the weekly load moment estimates of *Blewitt et al.* [2001a] to the VLBI baseline series for the period 1996–2001. We divide the VLBI measurements into weekly bins centered on the GPS week intervals of the load moment series. The mean number of measurements in each bin is 1.15, 89% of bins have only one measurement, 9% have two and the most is five. Where more than one measurement is available in each bin the weighted mean is taken.

[11] The VLBI solution includes measurements taken as early as 1981 so in a second analysis we compare baseline series predicted by an annual and semi-annual sinusoidal fit to the load moment series [*Blewitt et al.*, 2001a]. This allows predicted values to be extrapolated to epochs outside of the 1996–2001 period.

[12] Only baseline series that have greater than 50 corresponding points are considered. In the first analysis 35 baselines amongst 11 sites fit this criteria. In the second analysis 110 baselines amongst 33 sites are available. The available sites are plotted in Figure 1, the majority (76%) of these sites are in continental N America or mainland Europe.

## 4. Results

[13] The linear correlation coefficient, $r$ [*Press et al.*, 1992] is calculated for each baseline comparison and is shown in Figure 2 versus the number of matching data points. Figure 3 displays three individual sets of baseline series that show a large correlation coefficient. Figure 2 shows that the VLBI baseline series are clearly correlated with the GPS estimated degree-1 deformation field. In both

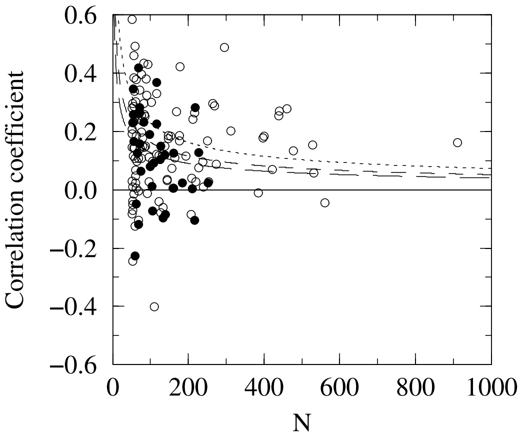

**Figure 2.** Correlation coefficient $r$ versus number of points $N$ in individual baseline series comparisons. Filled circles are points resulting from the first analysis comparing 35 VLBI baseline series to predicted degree-1 deformation series (from 1996–2001). Open circles result from the second analysis comparing 110 VLBI baseline length series to a deformation field predicted using a seasonal annual and semi-annual fit to the load moment series (from 1981–2001). The long dashed line represents the 10%, the dashed line the 5% and the dotted line the 1% significance level (one-tailed test).

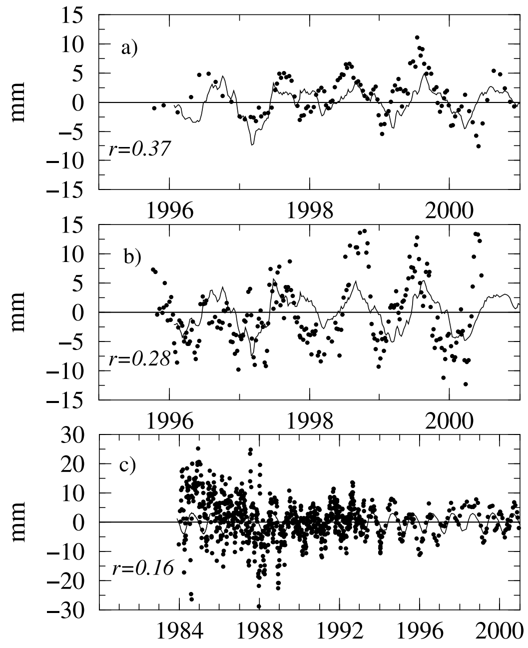

**Figure 3.** VLBI baseline series (points) compared to predicted degree-1 loading series (line). From the first analysis (1996–2001) the baselines Gilcreek-Westford (a) and Nrao20-Wettzell (b) are shown; from the second analysis (1981–2001) the baseline Westford-Wettzell (c) is shown. For the period 1996–2001 VLBI formal uncertainties are in the range 1–7 mm, formal uncertainties for the degree-1 series are in the range 0.5–1 mm. For clarity of the figure only, the series are smoothed with a four point running average. Values of the correlation coefficient $r$ are also shown; all values are significant at 1% probability.

analyses over 80% of baselines have a correlation coefficient larger than zero. Table 1 gives the results of two one-sided hypothesis tests [*Press et al.*, 1992], with the null hypothesis that the two series are uncorrelated and the alternative hypotheses, that the two series are positively correlated or negatively correlated. Also given in Table 1 are the numbers of baselines expected to pass these tests by random chance. These numbers are exceeded in both analyses when testing for positive correlation, the VLBI and degree-1 baseline sets of series are significantly positively correlated at 10%, 5% and 1% in both analyses. They are not negatively correlated at 10%, 5% or 1%, ruling out the possibility that random annual signals in the data just happen to correlate with the degree-1 series. If this were the case we would expect an equal proportion of positive and negative correlations by random chance.

[14] The power spectra of the 110 VLBI baseline series indicate that 15 baseline series have power at the annual frequency significant at 1% [*Press and Teukolsky*, 1988]. All of these VLBI baseline series are amongst those significantly correlated with the degree-1 deformation model at 1%. Annual and semi-annual signals are estimated from the VLBI baselines. By doing so we are not estimating degree-1 variation and do not expect the degree-1 predictions to account for all the power at the annual frequency. The annual estimates will additionally incorporate loading from higher degrees. Since the two "raw" series are so correlated however we do expect the degree-1 component to be a major part. An atmospheric pressure loading model [*Macmillan and Gipson*, 1994] was subtracted from the VLBI measurements (Leonid Petrov, personal communication, 2002). The model consists of loading coefficients calculated from a

**Table 1.** VLBI Baselines Correlated With Predicted Degree-1 Deformation

| Test | $r > 0$ | | | $r < 0$ | | |
|---|---|---|---|---|---|---|
| Significance level | 10% | 5% | 1% | 10% | 5% | 1% |
| First analysis $N$ = 35 | | | | | | |
| Data | 17 | 14 | 6 | 2 | 1 | 0 |
| Random chance | 3.5 | 1.8 | 0.4 | 3.5 | 1.8 | 0.4 |
| Second analysis, $N$ = 110 | | | | | | |
| Data | 66 | 49 | 36 | 2 | 2 | 1 |
| Random chance | 11 | 5.5 | 1.1 | 11 | 5.5 | 1.1 |

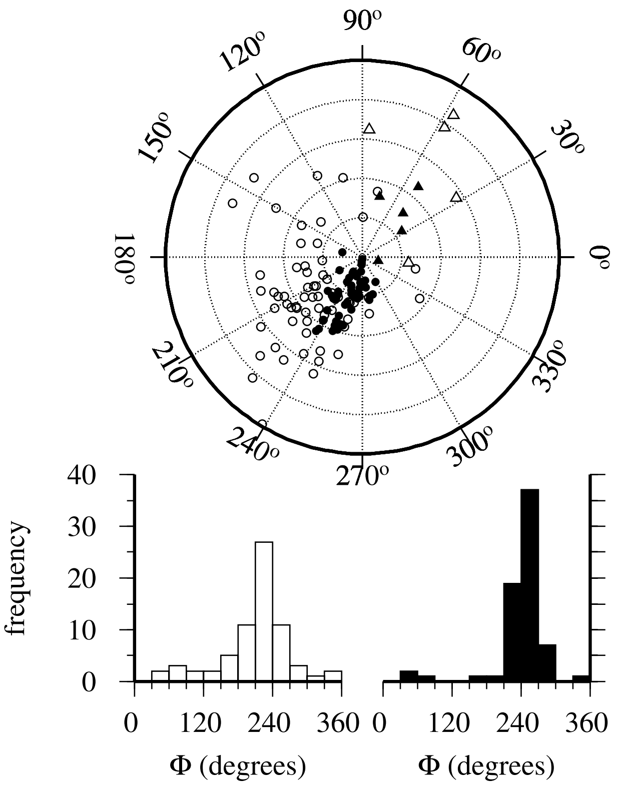

**Figure 4.** Polar plot of annual signal and histograms of annual phase estimated from VLBI baseline series (open symbols and bars) and predicted by the degree-1 loading model (filled symbols and bars). Annual amplitude $A$ and phase $\Phi$ are defined by $A\cos[2\pi f(t - t_0) - \Phi]$ where $t_0$ is January 1 and $f$ is frequency ($f = 1$) in cycles per year. Only VLBI baseline series with estimated annual signal amplitude $A > 2$ mm and their matching degree-1 predicted signals are plotted. Triangles are used to represent signals along all available baselines between sites only in the southern hemisphere. All other signals are plotted as circles. Circular gridlines indicate amplitude and are spaced at 2 mm. For clarity of the plot only, two outlying VLBI points at amplitude and phase 13 mm 273° and 15 mm 221° are omitted from the polar plot.

regression between local pressure and VLBI determined height changes. Such a local model is not expected to remove a global degree-1 deformation and its influence is likely confined to the local higher degree deformations.

[15] Amplitudes and phases of annual signals estimated from the VLBI baseline series have a mean formal error of 0.9 mm. Figure 4 plots the estimated amplitudes and phase in polar form when the amplitude is >2 mm, the corresponding degree-1 amplitudes and phases are also plotted. A 2 mm floor is used since at low amplitudes the estimated phase becomes less meaningful. Figure 4 shows that both amplitude and phase of the VLBI annual signals are consistent with the degree-1 predictions. The phase and amplitude of the degree-1 baseline series is dominated by the seasonal nature of the GPS-determined load moment series. Maximum contraction within the northern hemisphere and maximum extension within the southern hemisphere occurs during northern hemisphere winter (Feb–March). The opposite occurs during southern hemisphere winter (Aug–Sep). This causes a shift in phase of the predicted annual degree-1 signal approximately along the division of the hemispheres. All four VLBI baseline series between sites only in the southern hemisphere have a phase in agreement with the degree-1 series and within the opposite quadrant to the majority of the northern hemisphere located VLBI baselines. Such a distribution of phase could only be due to a degree-1 type of deformation and given the agreement of phase in the northern hemisphere it is likely that degree-1 dominates the phase of the VLBI annual signals.

[16] Histograms of annual phase are also plotted in Figure 4; they indicate a strong agreement between the degree-1 and VLBI series. Both histograms are dominated by peaks centered around 240°. There is however a difference, the peak occurs in August for the VLBI series and September for the GPS predicted degree-1 series. Since annual signals and not degree-1 deformation are estimated from VLBI, this could be caused by higher degree loading signals in which case the overall phase difference would depend on how the particular VLBI network samples the higher degrees. To test this possibility we estimated annual signals from GPS results along the same baselines, the GPS network would observe the same sampling effect due to a real higher degree deformation. It is possible to match 73% of the VLBI network by assuming VLBI and GPS sites <∼100 km apart have the same loading signal. We emphasize that these estimates come from standard GPS time series along selected lines that match the smaller VLBI network and are not the degree-1 predictions. A histogram of phase (not shown) does not have a similar early peak in phase suggesting that the earlier phase in some VLBI baselines compared to the degree-1 predictions may not be due to higher degree loading but differences between GPS and VLBI.

[17] The annual amplitude of the VLBI baselines is also on average larger than the degree-1 series with a mean of 4.5 mm compared to a mean of 2.3 mm from the degree-1 series. Possible explanations for the phase and amplitude differences are: a) an atmospheric loading model was used in the VLBI analysis and b) no model for thermal deformation of the VLBI antennae was used. *Titov and Skurikhina* [2002] calculate seasonal signals for six VLBI baselines due to thermal effects; on average this accounts for ∼30% of the seasonal amplitude.

## 5. Conclusions

[18] A significant correlation between VLBI baselines and the deformation field predicted by the GPS determined load moment vector has been shown. Estimates of VLBI baseline series annual phase have a pattern of phase reversal between opposing hemispheres consistent with degree-1 deformation. These are important results since they confirm the findings of *Blewitt et al.* [2001a] that the degree-1 spherical harmonic response of the Earth to seasonal mass exchange involves a deformation of the Earth's surface (in addition to the more well known phenomena of geocenter motion). Since VLBI cannot directly observe an Earth fixed frame these results unambiguously show that the Earth deforms in a degree-1 mode. They also demonstrate the potential of VLBI to indirectly infer changes in the solid Earth center of mass (geocenter motions) using knowledge of the Earth's elastic properties. Currently the relatively small number of baselines observed per session limits the potential for robust estimation of the load moment vector from VLBI measurements.

[19] **Acknowledgments.** We thank Chopo Ma, Leonid Petrov and the VLBI group at NASA's Goddard Space flight center for the VLBI solution and comments on the manuscript. We are grateful to D. Dong for comments on the manuscript. This work was supported by the National Science Foundation Geophysics Program, grant EAR-0125575.

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D. Lavallée and G. Blewitt, Nevada Bureau of Mines and Geology, University of Nevada, Reno, Mail Stop 178, Reno, NV 89557-0088, USA. (lavallee@unr.edu; gblewitt@unr.edu)