G23B-1277 Reduction of Influences of the Earth's Surface Fluid Loads on GPS Site Coordinate Time Series and Global Satellite Laser Ranging Analysis

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Abstract

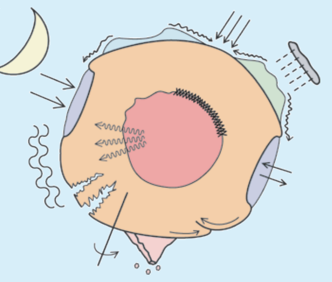
Temporal change of surface loadings due to the mass redistribution of the fluid envelope of the Earth, deform the Earth and cause the coordinate changes of the observation sites. We estimated the crustal displacements due to the atmospheric load (***AL***), the non-tidal ocean load (***NTOL***), the continental water load (***CWL***) and the snow load (***SL***) influences using the several meteorological data and model. And then, we tried to eliminate the load influences from the GPS site coordinate time series and global Satellite Laser Ranging (SLR) analysis.

As the time series of GPS site coordinates, we employed a solution of IGS which was calculated by using GIPSY-OASIS II (Heflin *et al*., 2002) by the Jet Propulsion Laboratory (JPL) and the routine solution of GEONET called F2 solution which was calculated by Bernese version 4.2 software (Hatanaka *et al*., 2003) by the Geographical Survey Institute. To eliminate periodic signals of the loading effects, we calculated

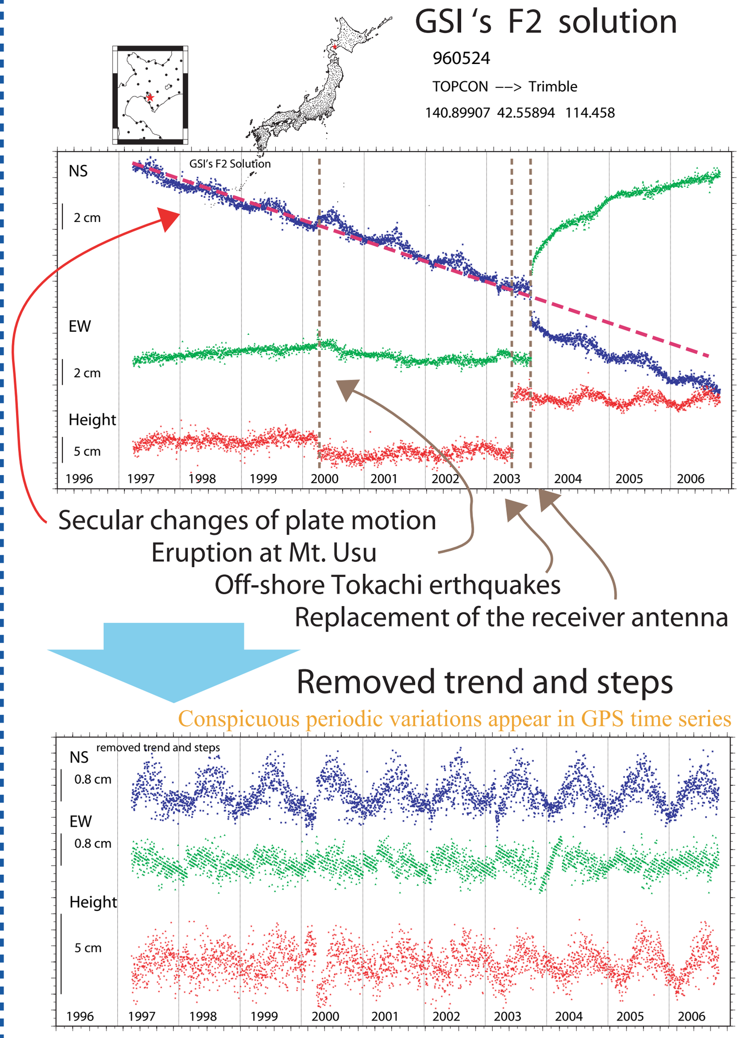
$$\textit{Corrected GPS} = \textit{GPS} - (\textit{Load}_1 + \textit{Load}_2 + \ldots\ldots + \textit{Load}_n).$$

The results show that a combination of atmospheric, non-tidal ocean, continental water, and snow loads can eliminate about **20%** of the annual signal in the coordinate time series for vertical components. We applied the loading correction to the data of the 1997 Bungo channel slow slip event and showed that the correction can benefit the analysis of such a non-periodic event.

Next, we applied the time series of NTOL and CWL to precise SLR analysis that used the '***concerto***' program version 4 developed by the National Institute of Information and Communications Technology (NICT). The LAGEOS orbit analysis reveals that the Estimating the Circulation and Climate of the Ocean (ECCO) model makes the root mean square (RMS) of the range residual **0.2%** smaller, and that the CWL makes it **0.8%** smaller, compared with the case where loading displacement is neglected. On the other hand, with the NTOL derived from Topex/Poseidon altimetry data, the SLR orbit fit is not improved.



Introduction



Temporal change of surface loadings due to the **mass redistribution** of the fluid envelope of the Earth, i.e., atmosphere, hydrosphere, and cryosphere deform the Earth, and cause the coordinate changes of the observation sites.

The coordinate changes can be measured by space geodetic techniques such as VLBI and GPS. From the viewpoint of crustal movements, such displacements due to these noises ***should be eliminated***, and several studies have been trying to estimate the loading influences [van Dam *et al*. (1998, 2001), Mangiarotti (2001), Dong *et al*. (2002), Heki (2001, 2003, and 2004) and Munekane *et al*. (2004) etc.].

In this study,

We first ***create the time series of displacements*** caused by loads using their global data sets.

Then we ***correct the IGS and GEONET site coordinate time series*** to evaluate the results.

And, also we ***applied these time series to the global SLR analysis***.

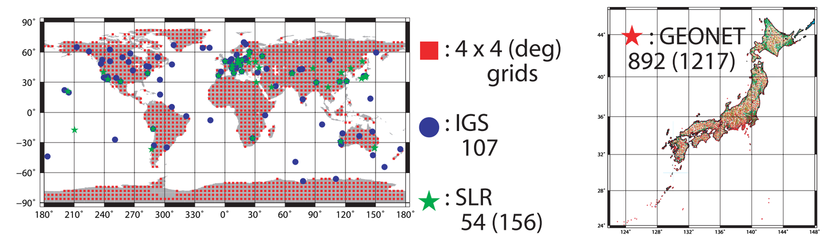
Calculation of the Loading Influences

The deformation of the Earth' s surface due to loading can be estimated by convolution integral with the Farrell's Green function (Farrell, 1972). The radial elastic deformation is given by a global integral:

$$L(\theta', \lambda') = \rho \iint H(\theta, \lambda)\, G_L(\phi)\, T(\alpha)\, dS$$

where ρ is the mean density of the loading material, H is the data of the mass variations, G_L is the mass-loading Green's function of displacements (1066A), and T is a combination of the trigonometric functions of azimuth (α). G_L is a function of the angular distance (ϕ) between the estimation point with coordinates (*colatitude, longitude*) = (θ', λ') and the loading point (θ, λ).

Stations



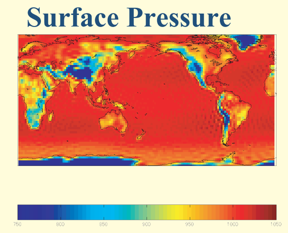
Land-Sea Mask

Global area : 5' x 5' (0.083° x 0.083°)

Japanese area : 2.25" x 1.5"

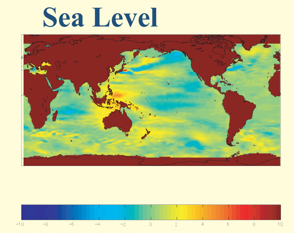
Data

Surface Pressure



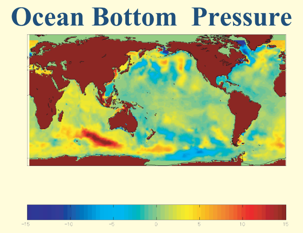
NCEP/NCAR Reanalysis 1
2.5 x 2.5 (deg)
/6 hours
1996/1/1 - 2004/7/31

Sea Level



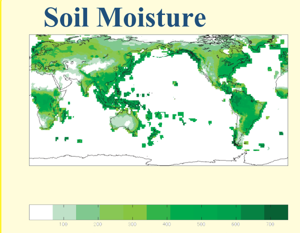
WOCE v3 (Topex/Poseidon)
1.0 x 1.0 (deg), /5 days
1996/1/2 - 2001/12/31
removed the ***thermal steric influences*** (AVHRR, 6 mm/℃)

Ocean Bottom Pressure



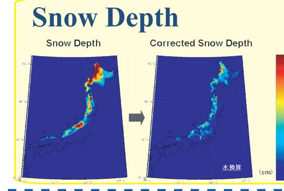
ECCO model
1.0 x 1.0 (deg)
/12 hours
1996/1/1 - 1999/12/31

Soil Moisture

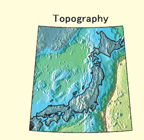


Fan and van den Dool (2004)
0.5 x 0.5 (deg)
/1 month
1996/1/ - 2004/8

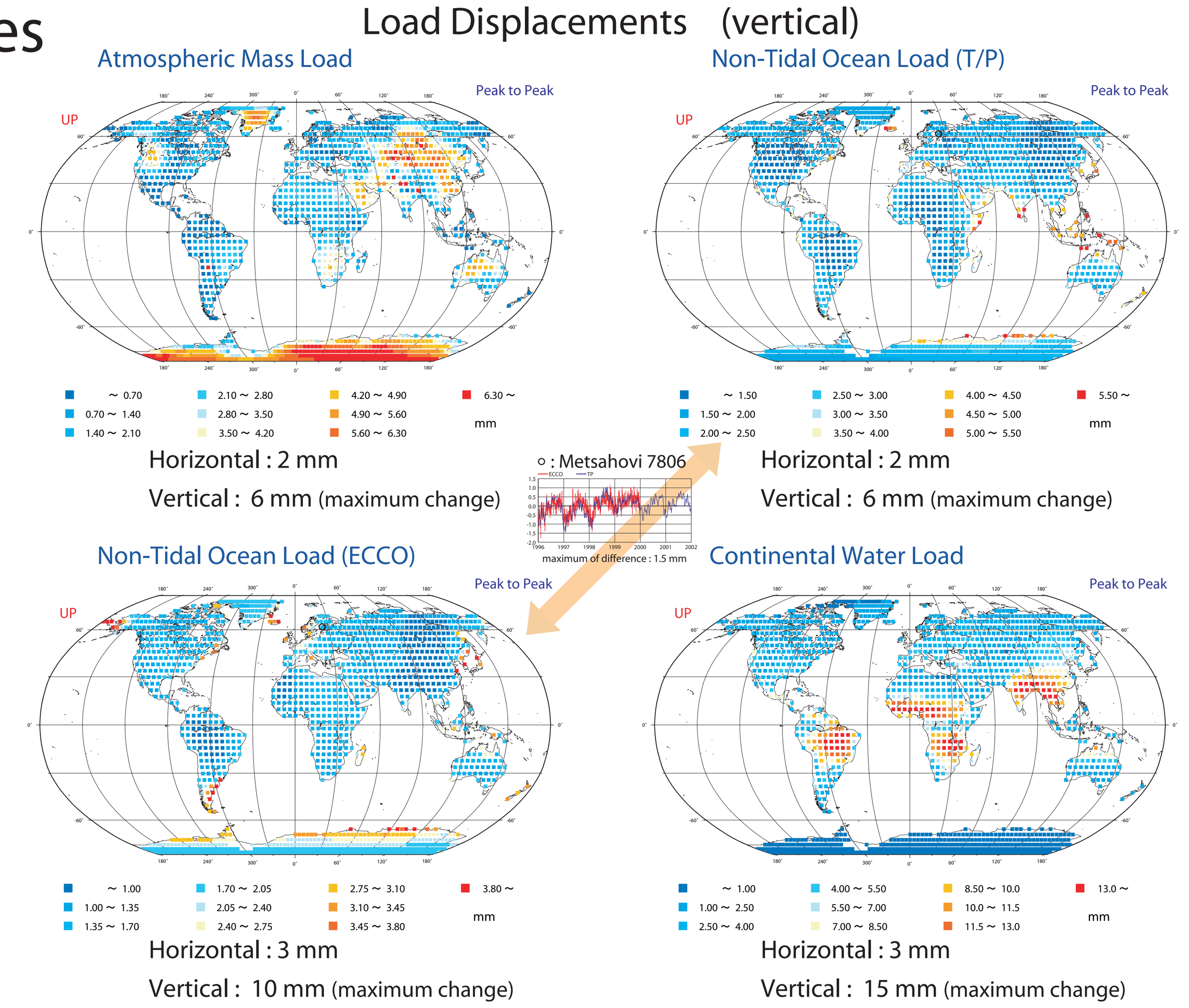
Snow Depth



AMeDAS (only Japanese area)
1997/12 - 2001/12
Altitude correction
Density correction, followed Heki (2004)



Load Displacements (vertical)



Correction of GPS coordinates

We employed a solution of IGS which was calculated by JPL and the routine solution of GEONET. Because the GEONET coordinates suffer the scale errors due to a software bug and the groundwater variations of the IGS station in Tsukuba, we first corrected these errors. Then, we removed trend and steps due to the earthquakes and volcanic activities from the original time series.

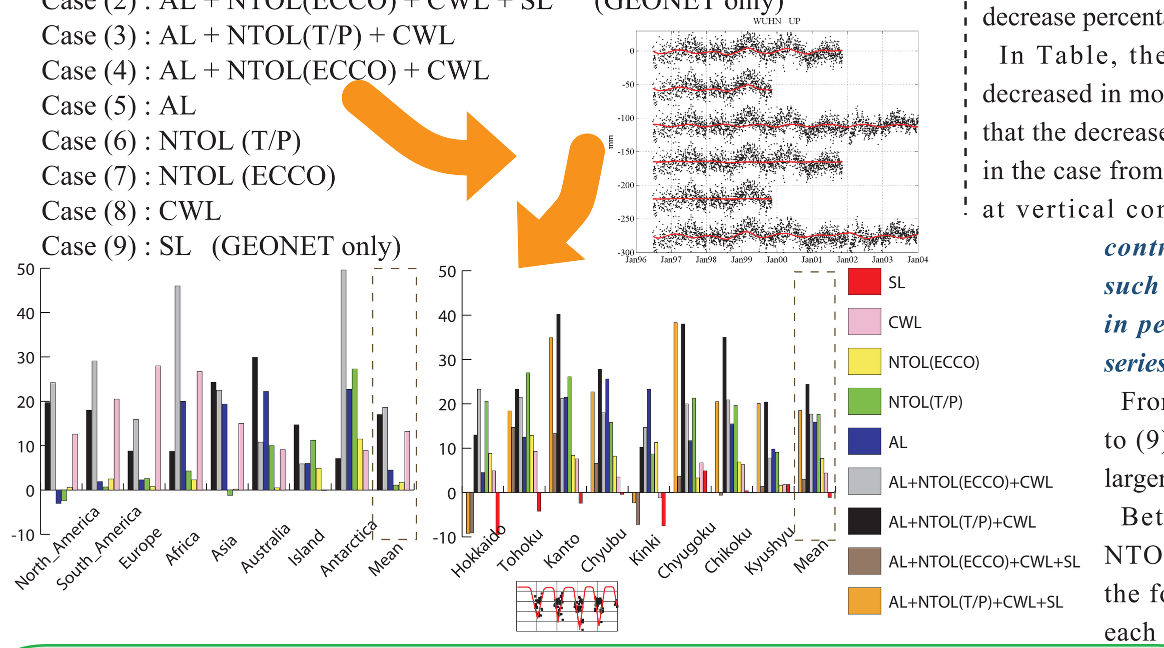
The corrected time series were calculated as follows:

$$\textit{Corrected GPS} = \textit{GPS} - (\textit{Load}_1 + \textit{Load}_2 + \cdots + \textit{Load}_n)$$

Because we employed the data sets of loading masses with time intervals from 12 hours to one month, we first interpolated each of the data sets so that the time intervals became daily. Further we applied a low pass filter to eliminate short period errors in the loading influences time series.

Actually, following combinations of the loading influences were calculated:

Case (1) : AL + NTOL(T/P) + CWL + SL (GEONET only)
Case (2) : AL + NTOL(ECCO) + CWL + SL (GEONET only)
Case (3) : AL + NTOL(T/P) + CWL
Case (4) : AL + NTOL(ECCO) + CWL
Case (5) : AL
Case (6) : NTOL (T/P)
Case (7) : NTOL (ECCO)
Case (8) : CWL
Case (9) : SL (GEONET only)



		IGS			GEONET		
		NS	EW	UP	NS	EW	UP (%)
Case (1) :	*AL + NTOL(T/P) + CWL + SL*	-	-	-	17.5	30.7	18.5
Case (2) :	*AL + NTOL(ECCO) + CWL + SL*	-	-	-	14.7	23.9	3.0
Case (3) :	*AL + NTOL(T/P) + CWL*	4.9	5.1	17.0	15.4	21.1	24.4
Case (4) :	*AL + NTOL(ECCO) + CWL*	1.9	7.5	18.6	14.5	17.8	17.7
Case (5) :	*AL*	-2.6	4.1	4.5	9.0	9.4	15.9
Case (6) :	*NTOL(T/P)*	-0.2	-1.9	1.1	15.1	13.7	17.6
Case (7) :	*NTOL(ECCO)*	-1.6	1.5	1.7	15.5	9.6	7.7
Case (8) :	*CWL*	8.9	4.7	13.2	7.2	8.5	4.4
Case (9) :	*SL*	-	-	-	8.4	15.2	-1.1

In order to assess how far periodic components decreased by the corrections, we estimated annual amplitudes before and after the corrections by using the least squares method. Table shows the ***decrease percentage (%) of annual amplitude*** from before to after at each component. Figure also shows the time series of the displacements caused by the loads and the GPS time series before and after correction. These are examples that the influences due to a local environment change has appeared. It can't be evaluated by the decrease percentage.

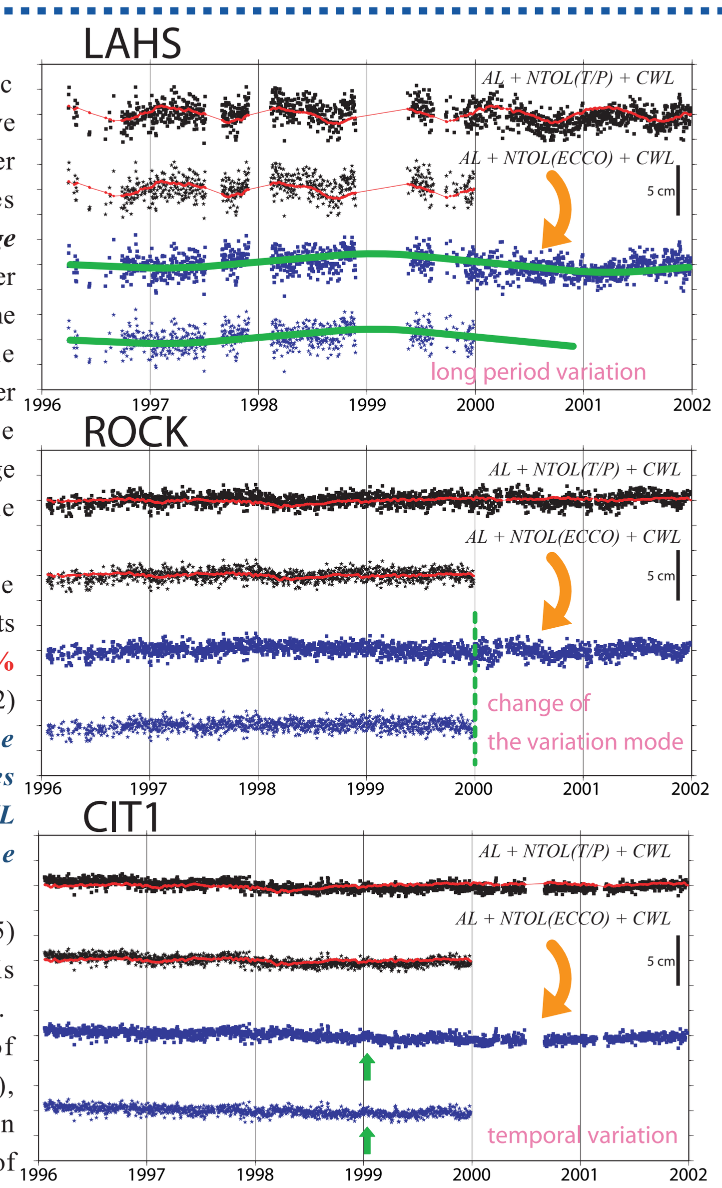
In Table, the annual amplitudes have decreased in most cases. We show the results that the decrease percentage was about **20 %** in the case from (1) to (4) except the case (2) at vertical component. ***This means the contribution of load influences such as AL and NTOL and CWL in periodic source of GPS time series is 20%.***

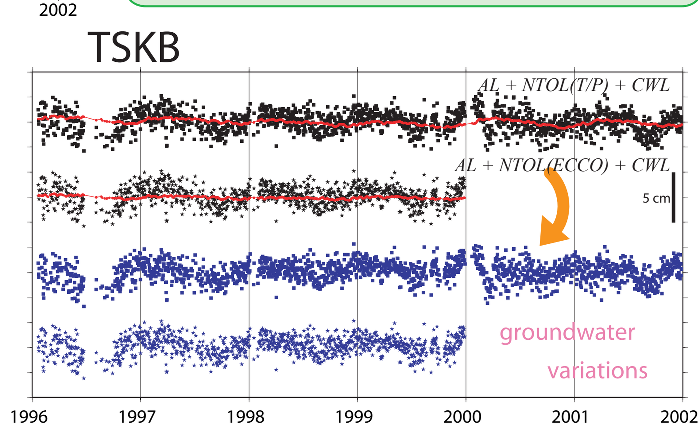
From the result of case from (5) to (9), the influence of NTOL is larger than AL and CWL in Japan.

Between the two different of NTOL(T/P) and NTOL(ECCO), the former gave better results in each area. Generally, the value of the model is smaller than that of observation.

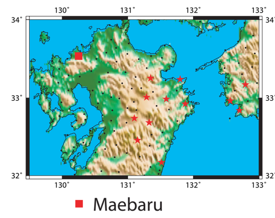
About the SL, the decrease percentage was minus only at vertical component. It might mean the assessment method of the decrease percentage don't function, because of the profiles of SL time series are not smooth curve that peak in winter and flat from spring to autumn.

According to the comparison between the case from (1) to (4) and the case from (5) to (9), the decrease percentage was not increase like additive, even if using plural loads. It might mean that each load has been complex interactive. For example, the common factors might be included in the source data, such as atmospheric pressure and sea level data.



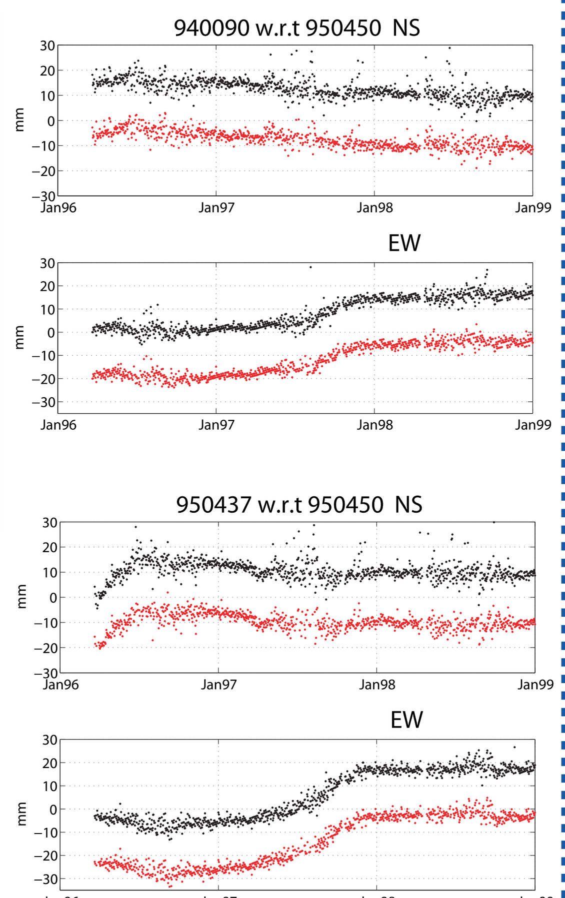


Application to a Slow Slip Event

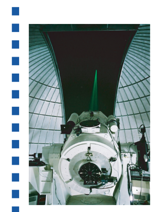


We next checked if the loading correction can improve the qualities of GPS data to study transient crustal deformations. For this purpose we applied the loading corrections to the data set which includes the 1997 slow slip event of the Bungo Channel region. For the analysis, we fixed Maebaru (ID: 950450) following Hirose *et al*. (1999). The secular trend, steps and periodic changes in the time series were estimated as follows. First, we estimated these parameters from the time series just after the end of the event by ***the least squares method***. Second, we removed the changes from the whole period of the data. We compared the obtained time series with the time series ***corrected by loading influences of the case (4)***. Figure shows the comparison of the time series, and RMS differences are summarized in Table. The RMS differences are around **0.4 mm**, and Figure shows that the two time series are very consistent. **This indicates that the correction of the loading influences works well in eliminating the seasonal signals.**

	rms (mm)		
Station ID	NS	EW	Station Name
940090	0.91	0.31	OOITASAIKI
950437	0.41	0.44	MISHOU
950447	0.18	0.37	NISHITOSA
950449	0.27	0.39	KOHCHIOHTSUKI
950466	0.32	0.30	SEIWA
950472	0.35	0.88	YUFUIN
950473	0.25	0.41	SAGANOSEKI
950474	0.40	0.30	KUJUU
950475	0.30	0.25	OOITAMIE
950477	0.82	0.37	HINOKAGE
950478	0.52	0.41	SHIIBA
950480	0.30	0.39	KAWAMINAMI
mean	**0.42**	**0.40**	



Application to the Precise SLR Analysis



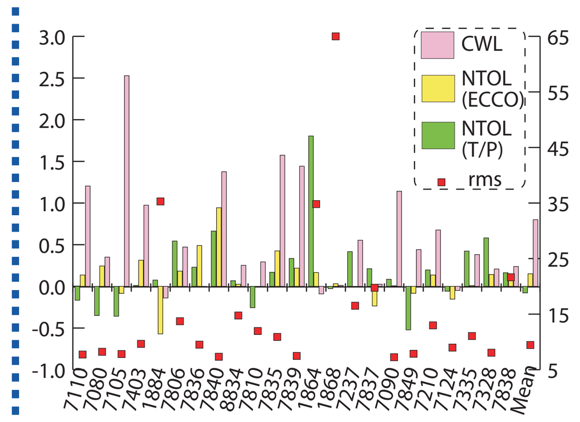
For analysis of the SLR data we used the '***concerto***' v4 and added additional functions to the program to include the effects of **3D LOAD** fluctuations.

For the period of 1997–2001, yearly analyses were carried out for the following four cases:

(1) baseline; without any of these loading effects
(2) baseline plus NTOL(T/P)
(3) baseline plus NTOL(ECCO) (1997–1999)
(4) baseline plus CWL

We used the normal point data of two satellites, LAGEOS-1 and LAGEOS-2, whose orbital parameters were estimated every six days. The coordinates of all SLR stations and the range biases were estimated every year.

	(1) none	(2) NTOL(T/P)		(3) NTOL(ECCO)		(4) CWL	
	rms (mm)	rms (mm)	(%)	rms (mm)	(%)	rms (mm)	(%)
199701	9.535	9.534	0.010	9.519	0.168	9.470	0.682
199801	9.473	9.477	-0.042	9.445	0.296	9.323	1.583
199901	9.205	9.209	-0.043	9.206	-0.011	9.136	0.750
200001	9.738	9.737	0.010	-	-	9.679	0.606
200101	9.249	9.279	-0.324	-	-	9.214	0.378
mean	**9.440**	**9.447**	**-0.078**	**9.390**	**0.151**	**9.364**	**0.800**



We look into the overall post-fit weighted residual RMS of SLR normal point data. We also look into RMS of each station. Since a good model should fit well the observation, the smaller RMS will indicate the usefulness of a model.

With regard to the ***NTOL(T/P)***, the RMS increased on average from the baseline. Considering the fact that the RMS increased in the period of 1998 and 1999, the influence of *El Nino* might not be able to be removed from the altimeter data completely. Moreover, the assumption of 6 mm/℃ might be unreasonable at all over the world.

With regard for the ***NTOL(ECCO)*** and the ***CWL***, the weighted RMS values almost always get smaller. On average, the weighted RMS decreased **0.2%** for mass-loading displacement corrections using the ECCO-NTOL, and **0.8%** for CWL.

We show the percent improvement in the station-by-station RMS values. A large reduction was observed for North American, South American, Europe and Australia stations when using CWL. Compared to the NTOL(ECCO) case, the T/P results behave rather poorly in the island in the Pacific Ocean and the point in the vicinity of North America and the Mediterranean. It is thought that this is a problem of the observation accuracy in the inland sea of the T/P and the problem of the correction of above-mentioned steric height or time resolution of the raw data.

Conclusion

*We calculated the time series of the load displacements at IGS, GEONET and global SLR stations from global data sets of loading masses, and confirmed that an appropriate combination of the loading influences decreased the annual amplitude of GPS site coordinate time series up to **20 %**. The load correction by using plural loads was more effective than using only individual load. However, the effect was not increase like additive, because loads are carrying out the interaction intricately. We also confirmed that the loading correction could well be applied for the analyses of slow slip events. It is possible to eliminate periodic signals empirically. This, however, may cause a danger to eliminate true signals and this is the main reason why we try to calculate the loading influences separately by using independent data sets. We think the correction can be made more precisely when the resolution and accuracy of the loading masses are improved in the future. There satellite gravity mission data will play an important roll to produce a global data set of the loading masses.*

*Furthermore, a precise analysis of SLR has been made using the NTOL and CWL data. The post-fit weighted RMS improved by **0.2%** with the NTOL(ECCO) and by **0.8%** with the CWL, compared to the cases where mass loading effects were ignored*

Acknowledgements

We kindly acknowledge GSI, JPL, NCEP/NCAR, WOCE, NOAA, ECCO, and CPC for providing data used in our analysis. We used the subroutines of GOTIC2 to calculate the load displacements.

Details were given by these papers;
Takiguchi and Fukuda (2006), Takiguchi, Otsubo and Fukuda (2006)

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