Atmospheric Pressure Loading and its Effects on Precise Point Positioning

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BIOGRAPHY

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ABSTRACT

As the precision of space geodetic techniques improve many trends or unwanted noise can be observed in the geodetic time series that were at one time considered negligible. The first users to be affected by these trends in the time series are those using the most precise techniques such as VLBI and SLR. With the improvement of GNSS technology, as well as precise orbit and clock products from the IGS, many of these same errors have become visible in GNSS time series derived using the technique of PPP.

Atmospheric pressure loading is the displacement of the earth's crust as a result of the movement of pressure systems over the Earth. While this effect has been known for a long time, it is only recently that it can be detected using space geodetic techniques. Occasionally, these displacements can reach 2-3 centimeters in the vertical direction due to the movement of pressure systems over the earth. Since this is within the realm of precision for PPP it is hypothesized that the atmospheric loading signal will be visible in the PPP time series.

A global set of 8 stations were selected and processed for one year using the PPP technique. These time series were then corrected for atmospheric loading using both the *geophysical approach* and the *empirical approach* to model the crustal displacement. For the empirical approach the local pressure values were obtained from site VMF1 data as suggested by Kouba [2008].

The variance of the PPP solutions was in most cases several orders of magnitude larger than the variance of the atmospheric loading corrections. In total, six out of the eight stations saw a reduction in the RMS after the geophysical model was applied while only five stations saw a reduction when the empirical model was used. The reductions were small for all stations, approximately 3.6 and 5.9 percent for the geophysical and empirical model respectively. On average this translates into approximately 2-3 mm reduction in scatter for the time series.

As PPP techniques improve the benefits of applying the atmospheric loading correction should become more pronounced. At this time, the inclusion of atmospheric pressure loading corrections into routine PPP processing does not seem necessary. However, for studies that examine other pressure related parameters, atmospheric pressure loading corrections should be considered.

INTRODUCTION

Space geodetic techniques allow for the determination of station positions at the millimeter level. These techniques typically include Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR) and network Global Navigation Satellite System (GNSS) positioning. As the precision of space geodetic techniques improve many trends or unwanted noise can be observed in the geodetic time series which were at one time thought to be insignificant. The first users to be affected by these trends are those using the most precise techniques such as VLBI and SLR. With the improvement of GNSS technology as well as precise orbit and clock products from the International GNSS Service (IGS) many of these same errors have appeared in GNSS time series derived using the Precise Point Positioning (PPP) technique [Zumberge et al., 1997].

PPP involves the processing of both pseudorange and carrier phase measurements using precise ephemeris and clock information in order to obtain a position of a single point without the need of a reference station. Typically, users employ dual frequency receivers allowing the formation of the ionosphere free combination along with estimating real valued carrier phase ambiguities. Over the last decade, PPP methods have improved substantially and now with the use of precise IGS products it is possible to obtain centimeter level accuracies for 24 hour static positioning [Bisnath and Gao, 2007].

Atmospheric pressure loading is the displacement of the earth's crust as a result of the movement of pressure systems over the Earth. While this effect has been known for over a century, it is only within the last two decades that it has been possible to identify the atmospheric pressure loading signal in space geodetic data, typically using VLBI or global GPS networks. Although the effect has been identified, there are no IGS Analysis Centers that routinely account for non-tidal atmospheric loading effects in their daily processing schemes, at this present time. Due to the of the improvements over the past decade in achievable accuracy using a single GPS receiver, it is postulated that we will soon see the effect of atmospheric pressure loading in time series derived using PPP.

BACKGROUND

Unlike other types of loading, such as snow, soil moisture and ocean bottom pressure, atmospheric loading has received a lot of attention in the geodetic community. This is most likely a result of the readily available gridded atmospheric pressure values which are provided by numerous metrological centers around the world.

The idea that the atmosphere could deform the Earth's crust was originally published by Darwin [1882]. Much of the modern theory on surface loading has followed from Longman [1962;1963] and Farrell [1972] who studied the effect of surface loads on an elastic, self-gravitating earth.

Early attempts at modeling the Earth's response to atmospheric loading assumed that the pressure systems follow a Gaussian distribution, with the highest or lowest pressure located in the middle and then dissipating as you move out from the site [Rabbel & Zschau, 1985].

vanDam and Wahr [1987] were the first to use global pressure models in order to obtain a more realistic representation of the pressure system around the site of interest. This eventually led to the identification of an atmospheric pressure loading signal in station time series through the use of VLBI techniques [vanDam and Herring, 1994; MacMillan and Gipson, 1994] and for a global GPS network [vanDam et al., 1994a]. However, this did not lead to a standard model for routine data processing due to difficulties in modeling the oceans response and difficulty in validating models and the various approaches [vanDam et al., 2003].

There are two approaches which can be used to account for atmospheric pressure loading: the *empirical approach* and the *geophysical approach*.

The empirical approach, which was used in MacMillan and Gipson [1994], assumes that the stations displacement in the up direction, u_h, as measured through geodetic techniques, is directly related to the pressure above the site:

$$u_h=\alpha(P-P_0) \qquad (1.0)$$

where

- α is the site pressure loading regression coefficient
- P is the surface pressure at the site
- P_0 is a reference pressure for the site

With this approach it is not possible to determine the horizontal displacement of the site. An additional method of the empirical approach is to determine the predicted station displacement using the geophysical approach and then fit the corrections to the local pressure data. This prevents the coefficients from absorbing other pressure related errors in the geodetic station time series.

The geophysical approach, used for example in vanDam and Herring [1994], employs a convolution of Green's Functions with a global gridded atmospheric pressure model to determine the displacement of the site:

$$u_{(r,t)} = \int\int \Delta P(\theta,t) G_\theta cos\phi d\lambda d\phi \qquad (2.0)$$

where G_θ are the Green's Functions, ΔP is the change in pressure at radial distance θ from the site and time t. λ and ϕ are the geocentric longitude and latitude respectively. The approach used to compute the displacement is very similar to that of the ocean loading problem as described in Scherneck [1991]. For a complete description of the geophysical approach see Farrell, [1972] and Petrov and Boy, [2004].

Both methods have several advantages and disadvantages as shown in Table 1. Although the geophysical model itself may not be convenient for real-time processing it is possible to use a combined approach as described above whereby the geophysical approach is used to derive site specific coefficients.

The pressure data required to compute the displacements can come from several sources. For the geophysical approach a global pressure field is required. These

Table 1. Comparison of Geophysical and Empirical Approach

	Geophysical Approach	***Empirical Approach***
Advantages	- Computed for any location on earth. - Validation using other models - Standard computations can be used.	- Available in real-time - Less complex
Disadvantages	- Require a global pressure data set - Latency of 24 hr for global data sets. - Resolution of data; both spatial and temporal. - Difficulty in modeling the Earth, oceans and pressure field.	- Coefficients cannot be extrapolated. - Only compute vertical displacement. - Coefficients typically vary with technique, time and seasons. - May absorb other pressure correlated signals

pressure fields are a product of Numeric Weather Models (NWM) which have become an important tool for weather forecasting as well as the development of accurate mapping functions for tropospheric delay modeling [Boehm et al., 2006].

For the empirical or combined approach only local pressure measurements are required. Barometers are an obvious option as they provide the local pressure at the site. However, Kouba [2008] proposes the use of pressure values obtained from NWM data. These pressure values are provided along with the site and gridded Vienna Mapping Function 1(VMF1). With these values Kouba [2008] derived PPP based site regression coefficients which were comparable to the more rigorously derived values from the International Earth Rotation Service (IERS) and those obtained through the use of VLBI. A similar comparison is performed here to show the time and technique dependence of the empirical method.

Due to the need of a more unified approach to surface loading, the IERS created the Special Bureau on Loading (SBL) in 2002. Following the SBL's suggestions Petrov and Boy [2004], through the *Goddard VLBI group,* now provide an efficient and standard algorithm for computing pressure loading time series for over 600 geodetic stations dating back to 1976. These corrections are now available for download from: http://vlbi.gsfc.nasa.gov/aplo/.

ERROR SOURCES IN APL TIMES SERIES

Modeling the Earth's response to surface loads is very complex and includes assumptions and simplifications about the composition, rheology and the interaction with dynamic systems such as the ocean and atmosphere. Although there is some error in the formulation of the Green's Functions [Petrov and Boy, 2004], we focus on the physical parameters rather than the algorithm used in evaluating the deformation. We do not intend to provide an in-depth coverage of the potential error sources involved in modeling the earth's response to atmospheric pressure. For this the reader is asked to view the references at the end of the paper.

The atmospheric pressure field is one potential source of error. While comparing the gridded pressure field published by the National Centers for Environment Prediction (NCEP) and the European Center for Mid-range Weather Forecasting (ECMWF), Velicogna et al. [2001] found good agreement although many of the same measurements are used to produce these models. Additionally, observed surface values were compared but the observed values were not independent as they were assimilated into the NWMs themselves. Even within one analysis center the difference between models can vary due to outputs relying more heavily on model atmospheres rather than on observations [Kalnay et al., 1996]. Therefore users of these products must have a full understanding of their development.

The earth model is another potential error source. Although simplifications regarding the shape of the earth, (e.g. spherical vs elliptical), and its composition, simplify the Green's Functions computations they can lead to errors larger than 1mm [vanDam et al., 2003]. In order to model the atmospheric pressure loading for applications requiring sub-millimeter precision it will be necessary to consider the anisotropy, lateral heterogeneities and the non-elastic nature of the earth [*ibid*]. This means that the earth most likely does not respond instantaneously to loads and may not return to its previous state once the load is removed. This can be seen in the effects on glacial rebound on the Canadian Shield, although this is on a much longer time scale.

The response of the oceans to pressure fields may be the largest potential error source. Studies have shown that for deep water oceans as well as enclosed basins the Inverted Barometer Ocean (IBO) model could be insufficient [Bock et al., 2005]. The pure IBO model assumes that for every mbar increase in the pressure above the ocean, the ocean surface level depresses a centimeter [vanDam and Herring (1994)]. This response ensures that the total mass

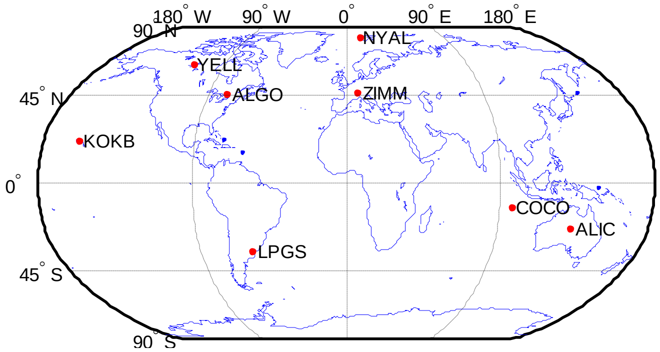


Figure 1. World Map Showing GPS Station Locations

of the atmosphere and the ocean is conserved and there is no net change of pressure on the ocean bottom [*ibid*]. Additionally, vanDam and Wahr [1987] found that the effect of the mass redistribution of the ocean and deformed crust on the local gravity should also be accounted for and can have a typical effect of 2-4 mm on stations located within 1000 km of the coast.

There is also difficulty in defining a reliable reference pressure for each station. One possibility is to use climate models to provide standard atmosphere parameters but these can be insufficient for highly variable areas such as high latitudes or where local conditions cause anomalies. Other possibilities include using average pressure values over a set period of time, as done in Petrov and Boy [2004] where the pressure was averaged for a 22 year period [Petrov, 2008].

METHODOLOGY

Currently, the achievable accuracy of PPP is several centimeters in static mode, once the solution is able to converge [Bisnath and Gao, 2007]. Although the magnitude of the horizontal displacement due to atmospheric loading is only several millimeters, the vertical displacement may reach 2 centimeters [Petrov and Boy, 2004]. While on the day-to-day basis the contribution of atmospheric pressure loading to the PPP error budget may be quite small there is a possibility that atmospheric pressure loading could have a significant impact on PPP results, especially at high-latitudes which are frequented with large scale disturbances. Since the contribution of the pressure loading to the horizontal displacement is so small the focus of this work is on the vertical displacement.

In order to identify the atmospheric pressure loading signal within the PPP solutions a global set of 8 stations was chosen. Figure 1 shows the locations of the stations

Table 2. Location of GPS Stations

Stations	*Location*	*Distance from Coast, km*
ALGO	Algonquin,CAN	700
ALIC	Alice Springs, AUS	1000
COCO	Cocos, AUS	<10
KOKB	Kokee Park, USA	<10
LGPS	La Plata, ARG	<10
NYAL	Ny-Alesund, NOR	<10
YELL	Yellowknife, CAN	1000
ZIMM	Zimmerwald, CHE	400

involved in the analysis. The stations were chosen to provide a good distribution geographically, as well as an equal distribution of continental and coastal stations (see Table 2).

The daily RINEX observation files obtained from the IGS were processed using the GPS Analysis and Positioning Software (GAPS) [Leandro et al., 2007]. A first attempt was to process each station in kinematic mode to obtain 30-second solutions in order to observe crustal displacements on very short time scales, but the precision of the solutions were much too large. Instead, the static processing mode was used which provided a daily solution for each station. GAPS implements the standard PPP model described in Kouba [2003], the elevation angle was set to 7 degrees and the non-hydrostatic tropospheric delay was estimated allowing it to vary at a rate of 5 mm^2 per hour. GAPS was modified to accept the site Vienna Mapping Functions 1 (VMF1) which are based on ray-traced observations through NWMs. The zenith hydrostatic delay was initialized using the ray-traced zenith delay provided along with the VMF1.

Currently, GAPS does not implement an ocean loading correction. Since we are computing a solution over a 24 hour period, the majority of this effect should be removed. However, it may introduce some error into the results.

Both the geophysical approach and the empirical approach were considered in this analysis. The atmospheric pressure loading time series, for the geophysical approach, were provided by the Goddard VLBI group and are available on the Web at *http://gemini.gsfc.nasa.gov/aplo*. These time series use the algorithm described in Petrov and Boy [2004] whereby the Green's Functions are convolved with atmospheric pressure fields obtained from NCEP. The pressure field has a resolution of 2.5° X 2.5° and are provided every 6-hours. A SNREI earth model was used adopting PREM elastic parameters (see Dziewonski and Anderson [1981]) and the oceans were assumed to behave as an inverted barometer.

For the empirical approach the site regression coefficients were obtained from:
ftp://maia.usno.navy.mil/conv2000/chapter7/atmospheric.regr. The regression coefficients were computed from the convulsion of a 2.5° x 2.5° global pressure grid with Farrell's [1972] Green's Functions for a Gutenberg-Bullen A Earth model [McCarthy et al., 2003]. Following the approach of Kouba [2008] the local pressure at the sites were obtained from the site VMF1 data.

To apply the atmospheric loading corrections care must be taken to ensure that the PPP solutions and the atmospheric loading corrections are in the same reference frame. The atmospheric pressure loading corrections obtained from the Atmospheric Pressure Loading Service are with respect to the center-of-mass (CM) of the earth, including the oceans and atmosphere. The origin of the PPP solution will vary depending on which precise products are used (e.g. rapid vs. final). Since only precise IGS final clock and orbit products were used with the PPP software the solutions will be with respect to the CM [Ferland et al., 2004]. Therefore no transformation was needed before applying the atmospheric loading corrections.

Both the empirical and the geophysical approach are assessed based on the improved repeatability of the PPP height solution with the atmospheric pressure loading modeled versus the un-modeled time series. Each PPP height time series was first de-trended by fitting a linear model to the height estimates. Next the weighted root-mean square (WRMS) was computed, using the inverse weights of the PPP solutions, before and after the pressure loading corrections were applied.

RESULTS AND ANALYSIS

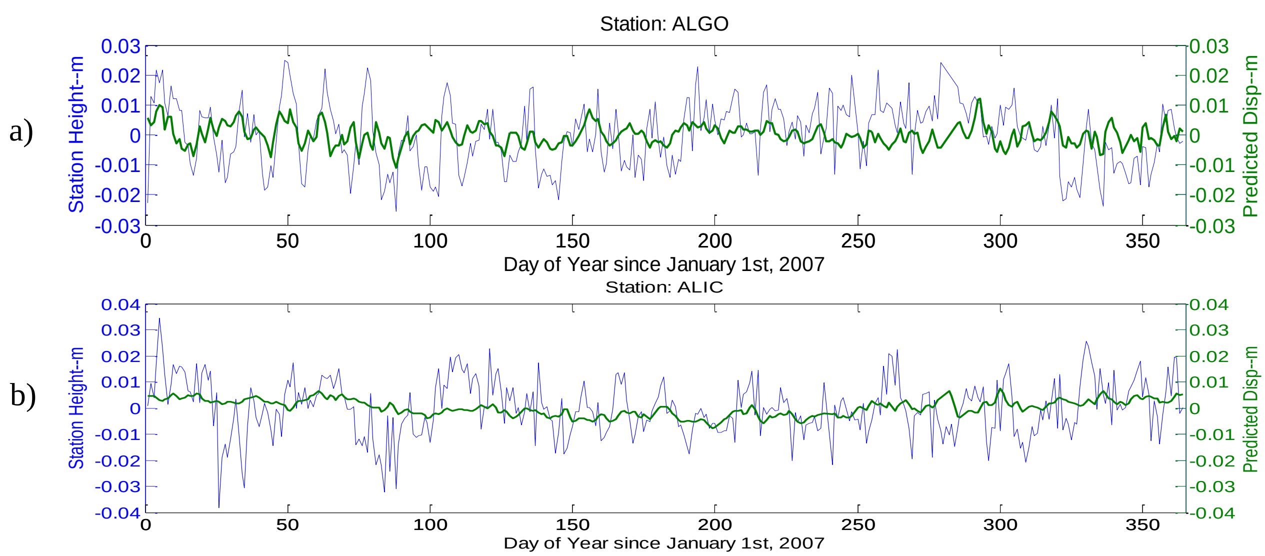
Figure 3 shows the time series of the PPP height estimates (blue) and the predicted station displacements resulting from atmospheric pressure loading (green) along with their statistics in Table 3. As expected the magnitude of the corrections are much smaller than the PPP height repeatability and it is not expected to drastically reduce the variance of the PPP time series.

Table 3. RMS of Station Heights, Atmospheric Pressure Loading and Variation of Site Pressure

	Height mm^2	APL, mm^2	Δ Pres., $mbar^2$
Stations			
ALGO	111.608	12.681	49.879
ALIC	115.334	9.837	23.241
COCO	206.347	0.403	3.213
KOKB	177.833	0.876	6.183
LPGS	331.779	8.248	38.353
NYAL	139.714	3.735	148.580
YELL	204.075	27.930	100.272
ZIMM	135.620	15.266	37.619
Avg.	**177.789**	**9.872**	**50.918**

A common trend can be seen between the magnitude of the corrections and the distance of the station from the coast. The cause of this is the response of the ocean as an inverted barometer which absorbs much of the effect of the atmospheric load. For example, although NYAL has the largest pressure RMS, the predicted displacement remains quite small.

The largest peak-to-peak variations are seen at YELL and ZIMM where over a period of several weeks the corrections vary by approximately 20 mm. This is typical to other studies.



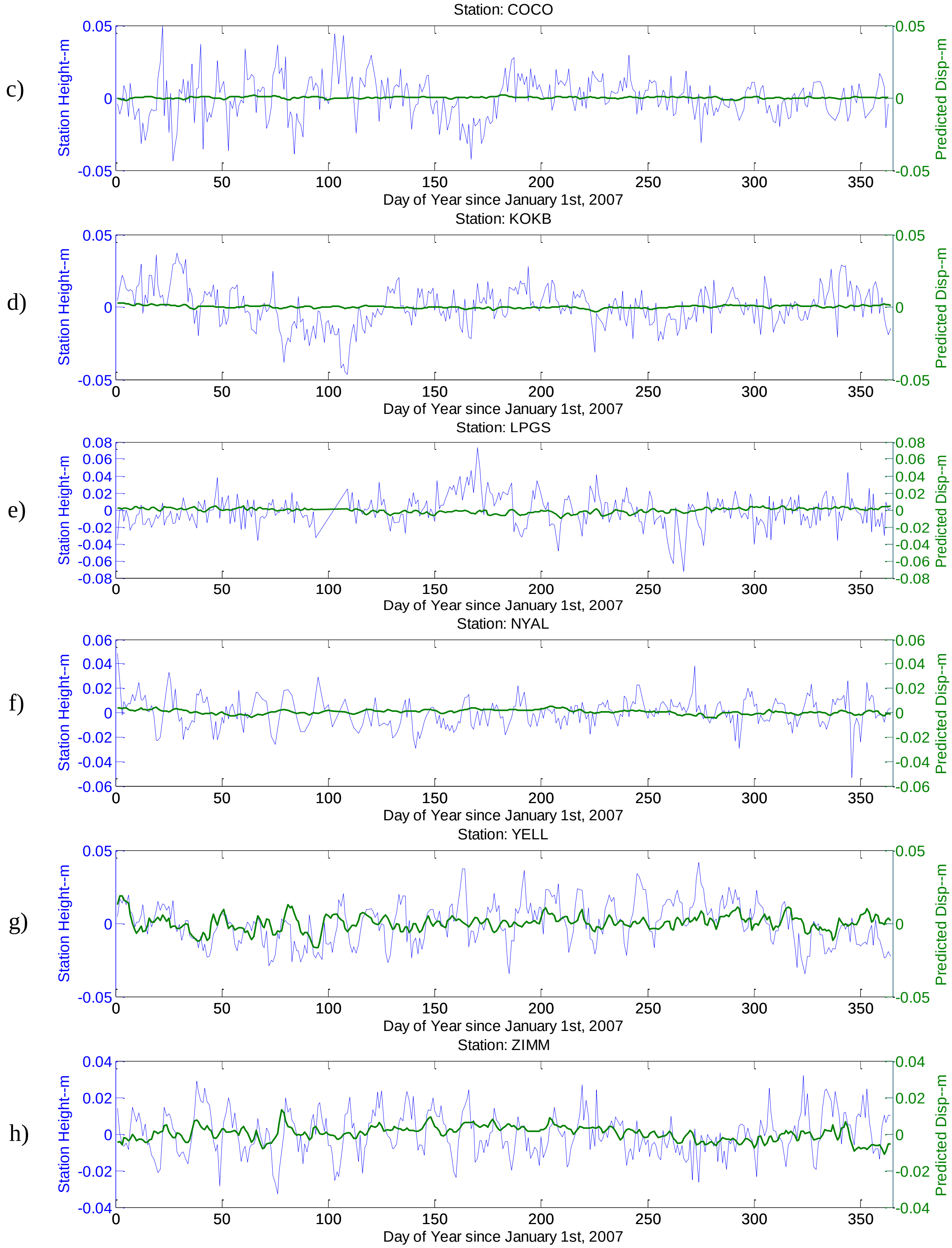


Figure 3(a-h). GPS Height Time Series (blue) and Predicted APL Crustal Displacement (green) [displacements computed using the geophysical approach].

Table 4 shows the results after the geophysical and empirical models were applied to the time series. The first column for each approach shows the RMS of the times series after the correction has been applied. The second column shows the percent change in RMS where a negative change is a reduction in the scatter of the time series, i.e. an improvement in the results.

Table 4. RMS of GPS Time Series After Corrections Applied

	Geophysical		***VMF1/IERS03***	
	Height mm²	***% Chg***	***Height mm²***	***%Chg***
Stations				
ALGO	100.755	-9.72	102.591	-8.07
ALIC	109.096	-5.40	N/A	N/A
COCO	205.480	-0.42	206.771	0.21
KOKB	173.448	-2.47	175.298	-1.43
LPGS	348.705	5.10	336.452	1.41
NYAL	142.128	1.73	125.017	-10.52
YELL	173.977	-14.75	175.342	-14.08
ZIMM	132.120	-2.58	123.165	-9.18
Avg	**173.214**	**-3.56**	**177.805**	**-5.95**

The empirical result for ALIC was not available since the site regression coefficient was not published. The largest improvements were experienced at YELL and ALGO for the geophysical approach. However, the empirical approach showed an improvement of over ten percent at station NYAL while the RMS increased for the geophysical approach.

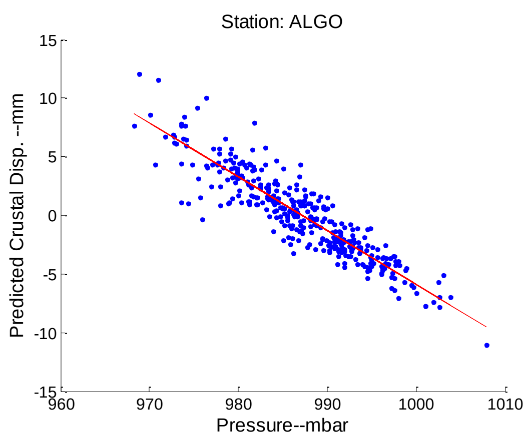


Figure 5. Correlation Between Pressure and Predicted Crustal Displacement

Some disparities between the geophysical approach and the empirical approach can be seen. The empirical approach assumes that the atmospheric pressure loading correction at the site is directly related to the local pressure at the site. From Figure 5 it seems that this assumption is valid. As we have an increase in pressure, the crust would be depressed. The two values are highly anti-correlated, and can be approximated well by a linear model. Table 5 shows the correlation coefficient between the predicted crustal displacements and the local pressure obtained from the site VMF1 data. From this we can see that the correlation is not as high in some cases. Typically this occurs for coastal sites, while sites such as ALGO, ALIC and YELL, which are all over 700 kilometers from the coast, have a high correlation between local pressure and predicted displacement. So although the empirical approach may be sufficient for continental sites, care must be taken when using the empirical approach for coastal sites. One possibility is that as a large pressure system moves over a coastal site, if the center of the pressure system is partly over the ocean the loading effect would displace the water, as predicted by the IBO model, rather than the site itself. If that same pressure system had passed inland of the site, although the largest change in pressure may have occurred tens of kilometers inland of the site we could see a larger crustal displacement since the ocean would not be displaced.

Table 5. Correlation Coefficients for Site Pressure and Expected APL Displacement

	Correlation coefficient
Stations	
ALGO	-0.91
ALIC	-0.98
COCO	-0.14
KOKB	-0.18
LPGS	-0.88
NYAL	-0.02
YELL	-0.95
ZIMM	-0.79
Avg.	**-0.61**

An example of how the local pressure may not correlate with the expected displacement is shown during an extreme weather event known as the "weather bomb" which occurred in Atlantic Canada during February 2004 [Santos, et al., 2005]. A "weather bomb" is a low pressure system which can produce extreme meteorological conditions in the region. Figure 6 shows the local pressure versus the predicted station displacement for station STJO, located in St. John's, Nfld. The second highlighted area shows that shortly after the time of the extreme change in pressure (DOY 48 to 50) the predicted displacement was decreasing at the same time the pressure was decreasing. From analyzing the time series involved in this study, this phenomenon is not totally uncommon. Although the period of these phenomenons are typically short, they may cause some difficulties when using the empirical approach for modeling site displacements.

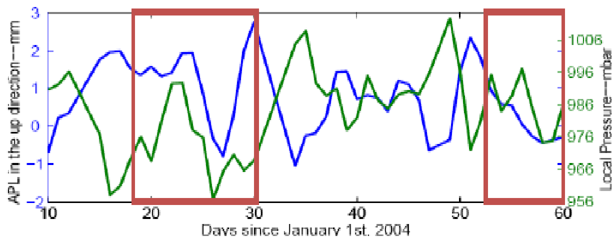


Figure 6. Local Pressure and Expected APL Displacement During "Weather Bomb" for Station STJO.

Overall the difference between the geophysical approach and the empirical approach in terms of reduction of time series scatter is quite small. The two approaches only account for a reduction of RMS on average of 7 and 10 mm^2 respectively which is well below the PPP noise level. Although this is quite small in comparison to the PPP solution noise level there does seem to be a consistent improvement in the RMS when the atmospheric loading corrections are applied.

A final comparison was performed that considered the regression coefficients derived from various sources to see how the results varied over technique and length of time series. Following Kouba [2008], the loading regression coefficients were computed by performing a linear fit of PPP station height to the local pressure obtained from the site VMF1 data. Table 6 shows the results of the PPP approach using GAPS and compares it to the IERS regression coefficients as well as those obtained from other sources such as Kouba [2008], vanDam et al. [1994] and MacMillan and Gipson [1994] (Column VLBI) .

Table 6. Comparison of Height Regression Coefficients Derived from Various Methods (1σ)

Stations	IERS	PPP		Koubda, 2008		VLBI	
	α	α	Std. dev	α	Std. dev	α	Std. dev
ALGO	-0.398	-0.417	0.016	-0.27	0.04	-0.35	0.17
ALIC	N/A	-0.552	0.022				
COCO	-0.127	0.527	0.083				
KOK B	-0.175	-1.260	0.055	-0.46	0.17	-0.49	0.35
LPGS	-0.411	-0.042	0.023				
NYAL	-0.196	-0.341	0.019	-0.19	0.16	-0.19	0.16
YELL	-0.456	-0.538	0.016	-0.35	0.03	-0.37	0.13
ZIMM	-0.413	-0.621	0.019				
Avg.	**-0.311**	**-0.406**	**-0.032**	**-0.3175**	**0.1**	**-0.35**	**0.2**

Various approaches and time series lengths were used to derive the coefficients including VLBI, a global network GPS solution and PPP. The results of Kouba [2008] match extremely well with those derived using VLBI. For stations ZIMM, YELL, NYAL and ALGO the resultant atmospheric coefficients obtained from the PPP solutions are similar to those obtained from the IERS conventions, when the standard deviations are considered while several stations such as COCO and KOKB show rather unrealistic values. It should be noted that both of these stations are located on islands so this could be a result of other pressure correlated biases. LPGS also falls in this unrealistic category. From the time series for station LPGS we can see that the PPP solution has several large displacements at DOY 170 and DOY 267. Additionally, DOY 95 to DOY 108 were unavailable. This may have contributed to the unrealistic results for this station.

CONCLUSIONS AND RECCOMENDATIONS

As the precision of geodetic space techniques continue to improve correcting for site displacement effects due to loading, including atmospheric loading will become more important. Through the creation of the SBL, there is now a unified approach to correcting for pressure loading which can be applied in post-processing or in real-time through the use of regression coefficients based on geophysical models.

Although the theory of crustal displacement is basically agreed upon there are still many issues to be addressed in the implementation of atmospheric loading corrections. This includes the response of the oceans to pressure loading, the accuracy of global gridded pressure fields, structure of the earth, and accuracy of the Green's Functions.

The results presented show that the difference between the geophysical and empirical approach is very small. For the empirical approach there is some concern about the decorrelation of the local pressure and the displacement in the case of large scale, large gradient pressure systems. This is typically more of a concern for coastal and high latitude sites as these types of pressure systems are more common than for continental sites.

The variance of the PPP solutions were in most cases several orders or magnitude larger than the variance of the atmospheric loading correction. However, a correlation could be seen between the PPP solutions and the predicted pressure loading displacements. In total, six out of the eight stations saw a reduction in the RMS after the geophysical model was applied while only five stations saw a reduction for the empirical model. This reduction was small for all stations, on average about 3.6 and 5.9 percent for the geophysical and empirical model respectively.

As PPP techniques improve the benefits of applying the atmospheric loading correction should become more apparent. Additionally, for studies which examine other pressure related parameters atmospheric pressure loading corrections should be employed.

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