NOAA Technical Memorandum OAR GSD-34

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**UNITED STATES DEPARTMENT OF COMMERCE**

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# Contents

## Abstract

The National Environmental Satellite Data and Information Service (NESDIS) Geostationary Observational Environmental Satellite (GOES)-derived, total precipitable water (TPW) vapor product is routinely produced at NESDIS for Advanced Weather Interactive Processing System (AWIPS) users, primarily for National Weather Service (NWS) forecast offices. Global Positioning System (GPS) signal delay due to atmospheric water vapor has been shown to provide accurate, real-time, measurement of TPW. Until GPS data came on the scene, there had been no way to validate GOES product data at asynoptic times (other than the occasional field experiment or limited regions such as the ARM CART sites), and therefore routine rawinsonde (RAOB) data have the largest influence on calibration, and these are constrained to fundamental synoptic times and frequency (every 12 hours).

This paper examines asynoptic satellite product performance and explores corrections to GOES product differences based on GPS measurements. The derived correction scheme is useful not only for applying to satellite data before use, but for studying error characterization as well. It becomes apparent that GOES 12 data error characteristics, measuring the eastern continental U.S. (CONUS) are also present in GOES 10, even though GOES 10 data are far drier (measuring the western CONUS) and from a completely different set of optics and satellite acquisition systems. This suggests that the observed product bias may be due to elements common to both satellite data products, e.g., model first guess, cloud clearing, tuning to only synoptic data, or some other unknown issue.

The development of the satellite product correction algorithm is detailed and coefficients for correction to GOES 12 and GOES 10 product data are presented.

## 1. Introduction

The investigation of the GOES 12 TPW product data and the coinciding GPS IPW record for the past year and a half have revealed that the moist bias in GOES 12 sounder-derived products has remained virtually unchanged. This is in spite of a concerted effort during FY 2007 in which nearly 100 case study scenarios were gleaned and scrutinized by the product developers at the University of Wisconsin – Madison (UW) and NESDIS. Despite these efforts, essentially no progress was achieved at improving asynoptic bias error; in effect, the data from the operational GOES 12 shared almost identical error characteristics with the data sets garnered during the 2002 International H2O Project (IHOP) from GOES 8 and GOES 11. So the compelling question for us at the Earth System Research Laboratory (ESRL) was just how we can best use the GPS asynoptic data to improve the satellite operational products. The result is work summarized by this paper in which we established a means to characterize the GOES error based on past data and applied the correction in real time to new product data. Furthermore, we examined the characteristics of the correction algorithm for clues as to the cause of the error.

Another concern is how the error from other GOES platforms compares with the highly studied GOES 12. We compared archived data for GOES 10 between the two satellites to ascertain whether there were any similarities in error structure. We viewed this information as useful in determining the source of the error. If the nature of the error from the two instruments was different, one could speculate that the errors were instrument related. On the other hand, error similarities might well indicate some kind of common thread between the systems; perhaps in the retrieval algorithm, model first guess moisture processes, or types of data assimilated and used for first-guess model initialization.

## 2. The GOES 12 and GPS Datasets

GOES 12 data were acquired from the NESDIS Center for Satellite Applications and Research (STAR) and the development and testing group that prepared the product prior to releasing it to NESDIS operations in support of National Weather Service activities. Typically, the data were garnered in the second step of a three-step process designed to get the data products to the field. The first step was the algorithm development at the University of Wisconsin, the second was initial product testing on a routine basis at NESDIS (the data used in this study), and the third was the actual data production. We chose to assess the data in the second level of development since it was one step ahead of operational status (somewhat improved) and perhaps not as volatile in change of attributes that would be produced by developers. It could potentially be modified if we discovered some kind of issue that could be corrected. The data used here were fairly close to what was operationally produced by NESDIS. GOES sounder data were used to solve a retrieval of thermal and moisture profiles. The moisture profile was integrated to compute total precipitable water fundamentally equivalent to that measured by GPS.

GPS TPW data were produced at ESRL using techniques for production that are now routine after about a decade of development. The system is planned to be transferred to the National Weather Service for operational management. The acquisition of water vapor from GPS satellites is tantamount to discerning the change in the speed of light through the atmosphere due to the presence of water vapor (Wolf and Gutman 2000). The determination of water vapor-induced "signal delay" is used to derive a value for the zenith "equivalent" integrated water. Unlike satellite sounder retrievals, the distribution or profile of the water vapor in the vertical is not measured; only the sum total can be computed, however there is a good match in the asynoptic measuring abilities of both GPS and GOES systems.

Even though the satellite and GPS are totally different systems, and use different techniques to compute TPW, the end result should be the same. The GPS system is known to be more accurate, comparable to ground-based, passive microwave measurements and much better than traditional radiosonde data. In fact, GPS measurements have been used to identify bad "batches" of radiosonde instruments. The typical precision of GPS water measurements is on the order of 0.2 to 0.3 mm liquid water equivalent. What GPS lacks is the ability to reveal the vertical distribution of moisture. Also GPS measurements are essentially point data where there are working ground stations. GPS data therefore overlap GOES data in geographic location and measurement time, enabling a fair comparison of the two systems.

The GOES 12 data used in this statistical assessment were archived coinciding with GPS IPW data (Birkenheuer and Gutman, 2005) over the course of about two years. Pairs of data were identified satisfying the criteria that the distance between the GPS and satellite locations were within 10km and both data samples were collected within 20 minutes of each other. We did not discriminate whether the GPS or GOES data were obtained first or second. This was similar to the criteria used in the IHOP data comparison effort.

No attempt was made to "clean up data." Both GOES and GPS TPW were essentially in their rawest operational form. It became evident after assessment (refer to the points in the upper portion of Fig. 1) that some comparisons were indeed outliers. However, these are relatively few in number, and given the enormous size of the overall dataset (nearly 1.8 million pairs) were deemed insignificant and any affect they may have is ignored.

Of course, one motivation for this work was to not only characterize the GOES bias (differences between GOES and GPS), but also to see if applying a correction based on this characterization would be useful on real-time data acquired after this sample was evaluated. Furthermore, another point of interest was a comparison of this evaluation to that of GOES 10 data with GPS. GOES 10 data were acquired at roughly the same time as the GOES 12 data set, but the GOES 10 acquisition was begun at a later date, so that the sample was not as large. Also, there were not as many matches between GPS sites and GOES 10 because there are fewer GPS sites in the western CONUS.

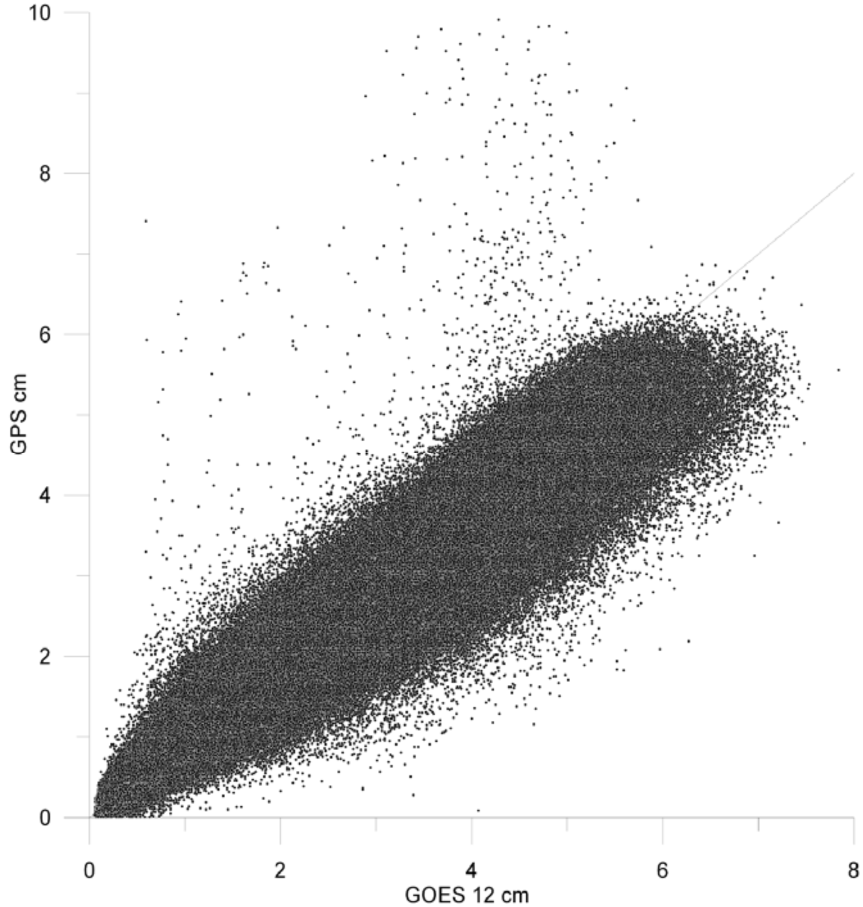



**Figure 1 above shows the scatter plot of roughly 1.8 million GPS-GOES 12-derived total moisture comparisons for approximately 1.5 years, ending January 2007. A 1:1 line is plotted from 0.0 to 8.0 cm. This exhibits a GOES moist bias similar to what we observed during IHOP 2002; as the moisture amount increases, the GOES bias increases. We refer to this as the "rooster tail" effect since the moist bias appears to curve toward a greater bias at higher moisture levels. The above plot represents data pairs from all times of the day and represents all observations.**

We decided to further examine the hourly bias at asynoptic times in a similar fashion to the one we used during the IHOP data analysis, Birkenheuer and Gutman 2005. That study revealed a strikingly similar pattern (Fig. 2) in which minima are seen near 00 UTC and 12 UTC while intervening times show the bias figures climbing. The overall moist GOES bias is computed to be near 0.19 cm for the entire data set. The hourly values lay on either side of this value.

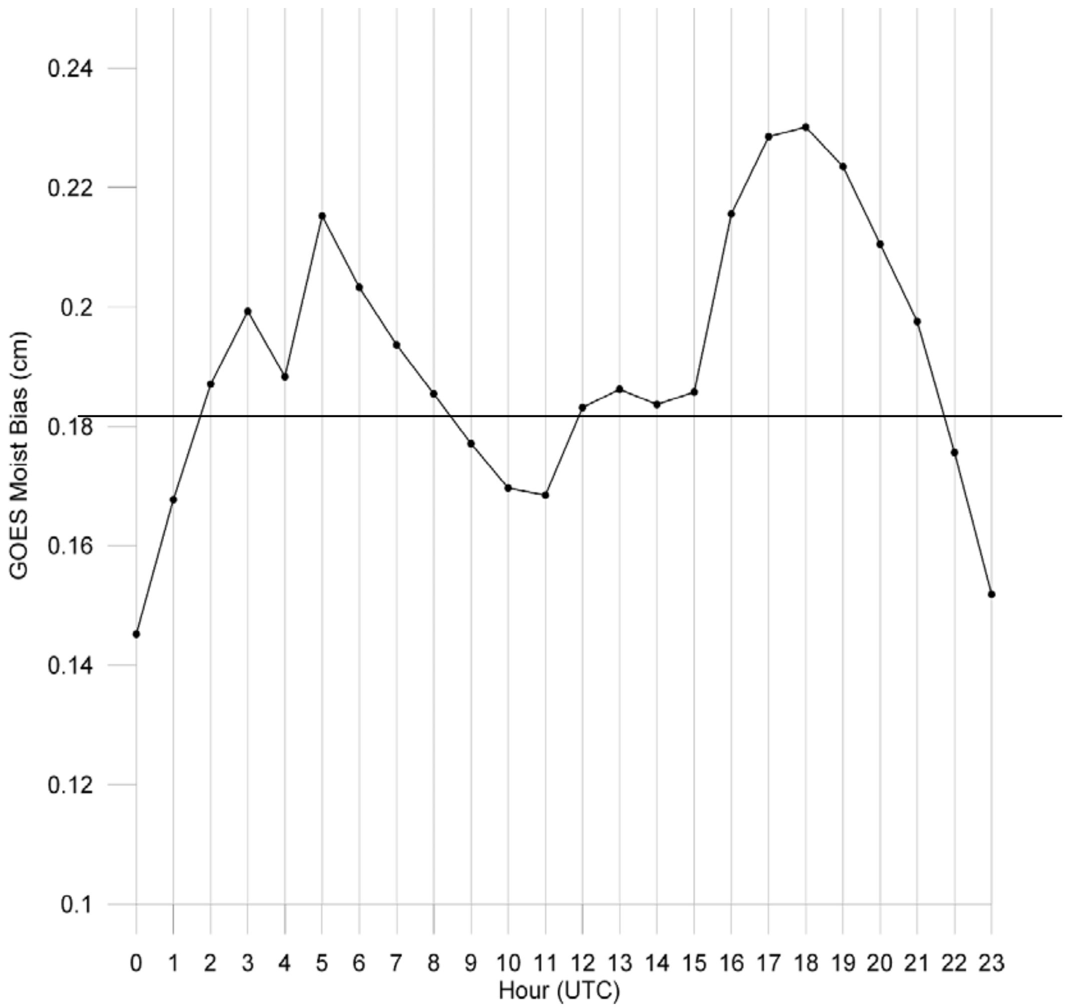



**Figure 2 shows the hourly bias observed in the data set acquired for GOES 12 and GPS-paired comparisons from June 2005 to January 2007. The essence of the bias characteristics for this data set emulates the observations made during IHOP 2002. Again the lowest bias is seen at 00 UTC and a secondary minimum is seen at 11 UTC, *identical* to the IHOP results.**

Our next obvious question is just how we can affect operations in a positive way with the above information. Clearly, the case studies generated in 2006 focused on major discrepancies between GOES and GPS TPW, and were not effective in finding solutions to correct problems. It was apparent that these cases could not reveal a systematic asynoptic bias as shown by long-term statistics; rather they were effective for examining outliers.

To better utilize the archived data as a whole, we decided to provide UW and NESDIS with bias correction algorithms for each hour. Not only could we produce these correction algorithms from the data we have archived, we could both test the effectiveness on past data and offer them as 24-bias correction algorithms unique to each hour; making them easy to incorporate on the operational product computation for GOES 12.

The basic formulation of the bias correction was decided to be a power law relationship that would guarantee zero change for zero moisture (no imposed linear bias). It can be seen in Fig. 1 that bias does tend to 1:1 as we near the zero point on the plot. Therefore, the overall correction strategy is:

$$G_c = aG^b \tag{1}$$

where $G_c$ is the corrected GOES moisture values, $G$ is the initial product values as received from NESDIS, $a$ is a scaling term and $b$ is a power term, both dimensionless. The $b$ term removes curvature from the paired measurements, while the scaling term helps to move the linear agreement to the 1:1 line. The selection of this fitting equation was made such that no absolute bias offset was defined.

The method of solution for (1) was variational analysis. This was chosen because it has an advantage over traditional linear least squares determination of coefficients $a$ and $b$. In traditional least squares fitting of (1), the corrected GOES measurement $G_c$ would be replaced with the corresponding set of GPS measurements. The log of the equation would be first taken rendering a linear form. The log of the GOES moisture and log of GPS data would be terms used in computation of coefficients. The absolute values of very small (near zero) numbers would be very large, as well as numbers that were naturally large; however, the upper limit to the moisture values would typically be near 7 to 8 cm. For example, the log of 8 is 0.9 while the log of 0.003 is -2.522. Thus, very small and very large values drive the solution for the least squares since the absolute value of the log terms is largest at both extremes. If one only focuses on very tiny and very large numbers, the resulting correction becomes potentially highly unrepresentative.

Instead, the variational method was used as the following simple functional:

$$J = \sum_{i=1}^{N} (G_{ci} - GPS_i)^2 \quad (2)$$

where *J* was minimized via iteration using the Powell (1962) method by modifying coefficients *a* and *b* from (1) and summed over all of the data (*N* points) consisting of paired (*i*) GOES and GPS data. The "best fit" (and lowest *J* value) therefore forced all of the corrected GOES measurements to be as close as possible in magnitude to GPS. The variational method puts direct linear weight on the water amount differences. Thus, small differences (less than one, even if they described large amounts of water) would likely carry almost insignificant weight in determining the result, while ever increasing values of moisture discrepancies would proportionally influence the correction terms.

Table 1 enumerates the tabulated statistical data for each hour and summarizes the plotted data in Fig 1.

**Table 1. Overall Statistics of the GOES 12 Compared with GPS TPW**

| Sample Size | Difference mean (cm) | Difference sigma (cm) |
|---|---|---|
| 1846382 | 0.189954087(~0.2) | 0.340749055 |

Hourly statistics:

| | | | Hour |
|---|---|---|---|
| 77149 | 0.1451841 | 0.326997399 | 0 |
| 79163 | 0.167799324 | 0.333233804 | 1 |
| 79677 | 0.187112406 | 0.340882629 | 2 |
| 79633 | 0.199308515 | 0.34721899 | 3 |
| 64712 | 0.188389182 | 0.354360223 | 4 |
| 55388 | 0.215271473 | 0.366844922 | 5 |
| 63340 | 0.203290358 | 0.363681376 | 6 |
| 78400 | 0.193654135 | 0.354441524 | 7 |
| 78478 | 0.185493708 | 0.355892688 | 8 |
| 79518 | 0.177166924 | 0.354920417 | 9 |
| 78712 | 0.169746995 | 0.360813648 | 10 |
| 78860 | 0.168546513 | 0.351962864 | 11 |
| 80721 | 0.183212727 | 0.349612921 | 12 |
| 83206 | 0.186258167 | 0.332360089 | 13 |
| 84387 | 0.183728412 | 0.319724947 | 14 |
| 81874 | 0.18580541 | 0.323772699 | 15 |
| 78148 | 0.21556583 | 0.324803203 | 16 |
| 74347 | 0.228538767 | 0.327521175 | 17 |
| 76359 | 0.230120406 | 0.33018446 | 18 |
| 76794 | 0.223517194 | 0.336179137 | 19 |
| 78273 | 0.210550457 | 0.330599844 | 20 |
| 80293 | 0.197571233 | 0.332213998 | 21 |
| 81052 | 0.175653189 | 0.325276226 | 22 |
| 77922 | 0.151863873 | 0.329036385 | 23 |

Referring to Table 1, we see that the hourly sigma in many cases is less than the overall sigma for the entire population. It was not surprising to discover that the bias corrected sigma as a whole population is reduced.

Table 2 summarizes the terms *a* and *b* for each hour followed and Table 3 enumerates GOES-GPS differences and standard deviation (sigma) on an hourly basis. There are many interesting highlights that can be gleaned from this information. The simple algorithm appears to work well providing a robust correction algorithm that is a function of hour. The hourly corrections after 16 UTC are interesting in that the *b* term, or power term, is near unity, which indicates that at these times there was minimal curvature in the bias, and the bias correction was more of a simple linear scaling function. On the other hand, hours 0 and 11 had the lowest initial bias requiring more curvature correction.

**Table 2: Hourly Correction Coefficients for GOES 12**

| *a* | *b* | Hour |
|---|---|---|
| 0.979470611 | 0.952045858 | 0 |
| 0.96386236 | 0.958807886 | 1 |
| 0.951016307 | 0.962379932 | 2 |
| 0.932851493 | 0.974993765 | 3 |
| 0.938412488 | 0.973992229 | 4 |
| 0.928518832 | 0.971161544 | 5 |
| 0.932472348 | 0.975237787 | 6 |
| 0.936737478 | 0.97503674 | 7 |
| 0.943030536 | 0.971995413 | 8 |
| 0.945574582 | 0.972088754 | 9 |
| 0.953864217 | 0.967487574 | 10 |
| 0.952823639 | 0.967738211 | 11 |
| 0.944226384 | 0.970142543 | 12 |
| 0.934683204 | 0.977410853 | 13 |
| 0.928368866 | 0.98369354 | 14 |
| 0.923411667 | 0.988313854 | 15 |
| 0.90421778 | 0.997356713 | 16 |
| 0.896550059 | 1.00138319 | 17 |
| 0.896099865 | 1.00216639 | 18 |
| 0.900296807 | 1.00008261 | 19 |
| 0.905209124 | 1.00010216 | 20 |
| 0.923843801 | 0.986412048 | 21 |
| 0.942986071 | 0.975428104 | 22 |
| 0.970267594 | 0.958948851 | 23 |

The following shows a summary similar to the first table after applying the GOES correction algorithms. Bias results are near zero at all hours and we see a reduction in the GOES variance overall.

**Table 3: Statistics after Applying Bias Corrections**

| Num | Bias (cm) | Sigma (cm) | Hour |
|---|---|---|---|
| 77149 | 0.00177616451 | 0.292245328 | 0 |
| 79163 | 0.00261056516 | 0.297694743 | 1 |
| 79677 | 0.00169990247 | 0.302271068 | 2 |
| 79633 | -0.000553681341 | 0.310711473 | 3 |
| 64712 | 0.000401427213 | 0.319695294 | 4 |
| 55388 | -0.000414054375 | 0.322597355 | 5 |
| 63340 | -0.00131554063 | 0.325285763 | 6 |
| 78400 | -1.90824721E-05 | 0.319985747 | 7 |
| 78478 | 9.41948019E-05 | 0.321559876 | 8 |
| 79518 | -0.000290779368 | 0.322418272 | 9 |
| 78712 | 0.000494285661 | 0.329654783 | 10 |
| 78860 | -0.000135583352 | 0.31978035 | 11 |
| 80721 | -0.000470061059 | 0.31356591 | 12 |
| 83206 | -0.00125479081 | 0.29614839 | 13 |
| 84387 | -0.00253195036 | 0.284297198 | 14 |
| 81874 | -0.00316451443 | 0.289983094 | 15 |
| 78148 | -0.00477298256 | 0.285934418 | 16 |
| 74347 | -0.00472133886 | 0.289746225 | 17 |
| 76359 | -0.00413449015 | 0.293306589 | 18 |
| 76794 | -0.00375525164 | 0.300256968 | 19 |
| 78273 | -0.00458336901 | 0.297615409 | 20 |
| 80293 | -0.0032954677 | 0.298026621 | 21 |
| 81052 | -0.0024598802 | 0.291823328 | 22 |
| 77922 | 0.00016256237 | 0.296616346 | 23 |

| | Overall Bias (cm) | Overall Sigma (cm) |
|---|---|---|
| | -0.00129276153 | 0.30450815 |

The hourly corrections were applied to all data and then the overall statistics were recomputed at the end of Table 3. The results show very little bias and an overall reduction in sigma by 0.0362 cm.

Figure 3 shows the GOES corrected data when broken down by hour, similar to Fig. 2.

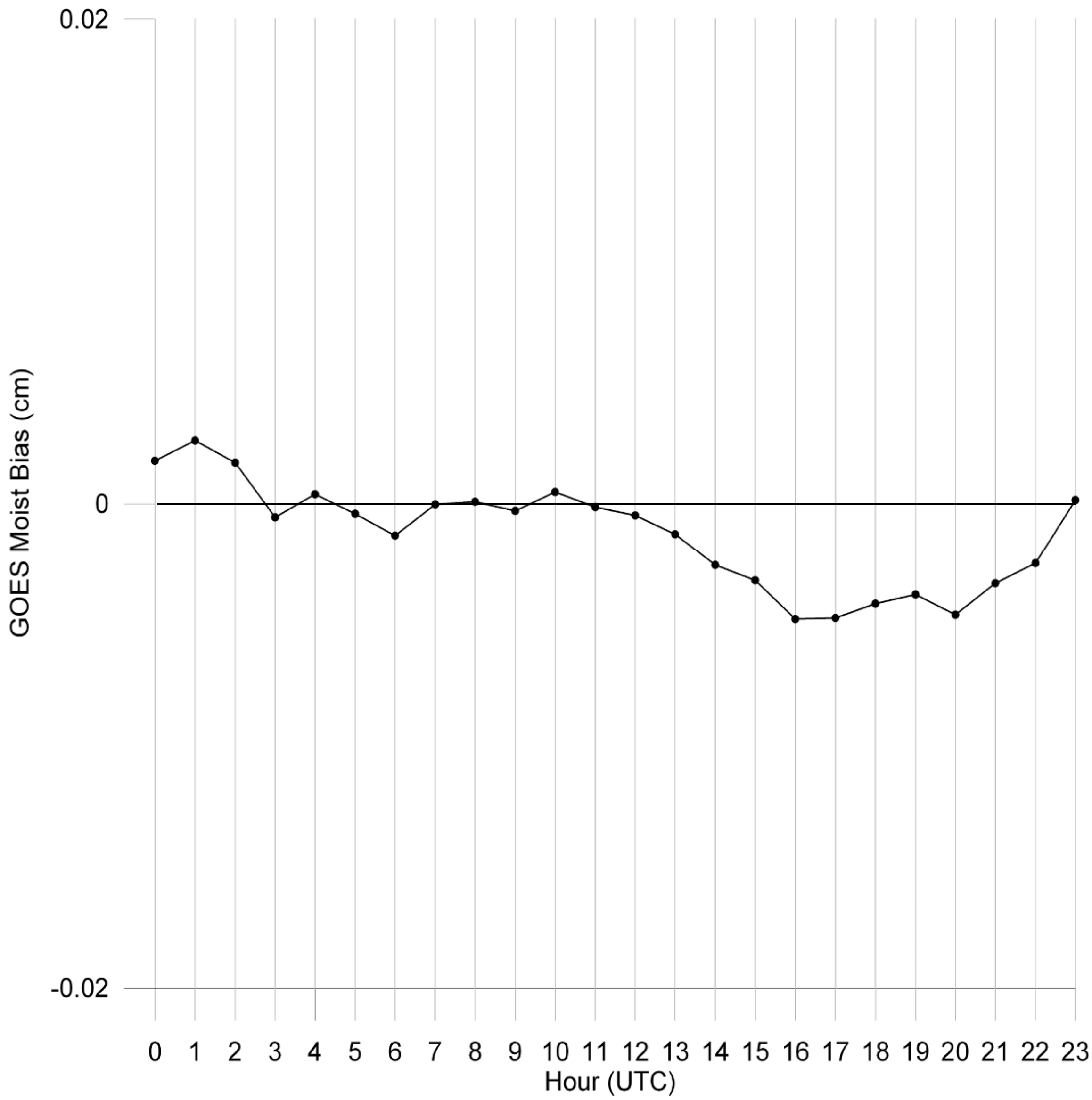



**Figure 3. Hourly bias (GOES-GPS differences) modified by one of 24 unique algorithms. Bias values are all near zero cm.**

Figure 4 is the recomputed scatter plot similar to Fig. 1 that shows the comparison of GPS and GOES TPW data after the correction has been applied to each data point.

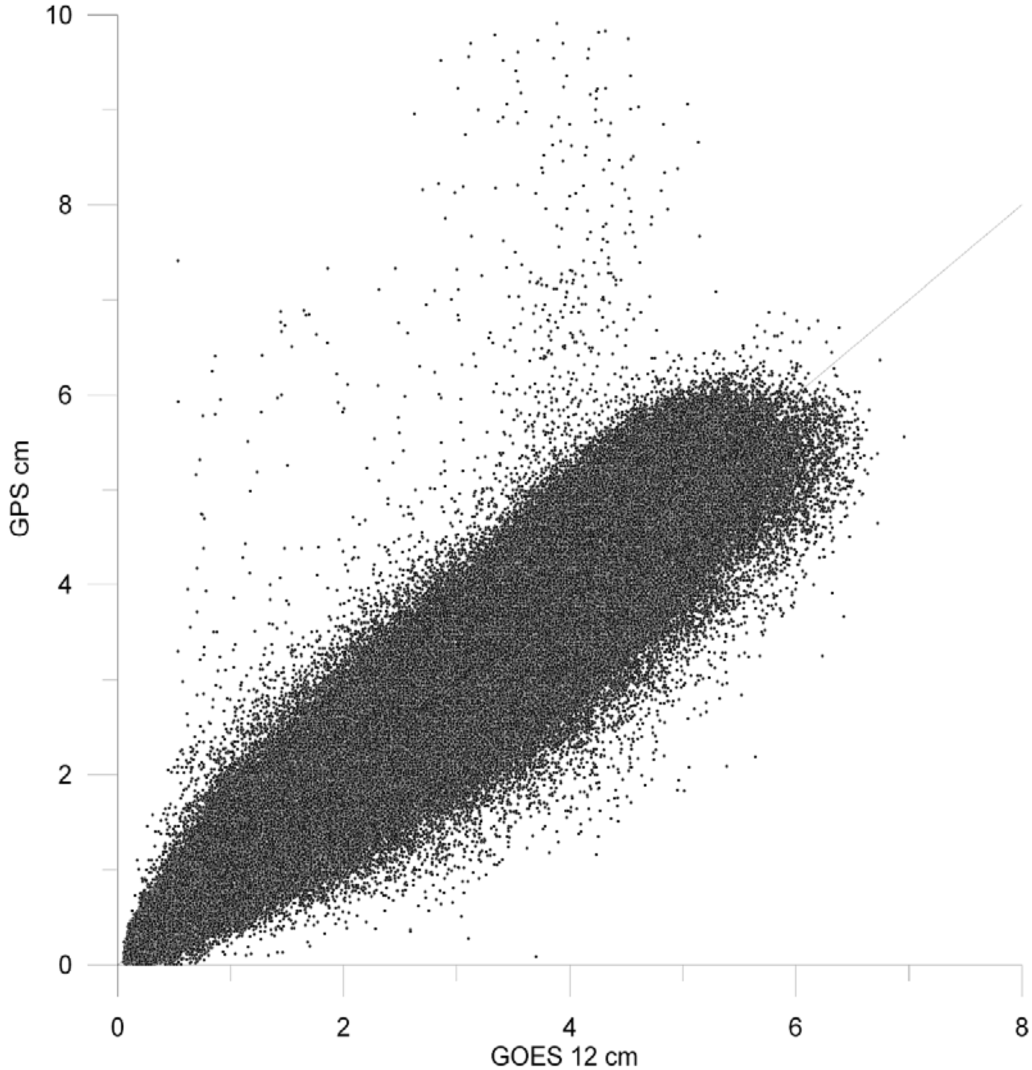



**Figure 4. Scatter plot of corrected GOES data compared with GPS values.**

Noteworthy is that the data now line up with the diagonal 1:1 line and the spread in the data appears to be improved near 2 cm and at the high moist end of the plot.

### 3. GOES 10 Evaluation

GOES 10 was paired with GPS TPW data in a similar fashion as just described for GOES 12 data, but fewer data pairs were studied since roughly a half year (June 2006-January 2007) were archived. GOES 10 was scanning the drier western CONUS and generally measured differences were less than what was seen for GOES 12. The lower differences did not surprise us given that GOES 12 scatterplots showed better agreement at low vapor totals. Somewhat more surprising was that the bias-corrected technique applied to GOES 10 data using the same correction relationship (1) performed just about as well as GOES 12. Applying the same variational scheme as used for GOES 12, the correction coefficients were worked out for GOES 10 and shown in Table 4.

**Table 4: Bias Correction Coefficients for GOES 10**

| *a* | *b* | Hour (UTC) |
|---|---|---|
| n/a* | n/a | 0 |
| 0.996533394 | 0.95236516 | 1 |
| 0.996538579 | 0.946112096 | 2 |
| 0.989015937 | 0.951574981 | 3 |
| 0.983487904 | 0.952166796 | 4 |
| 0.988218307 | 0.950105309 | 5 |
| 0.986881852 | 0.944489419 | 6 |
| 0.987462819 | 0.942130029 | 7 |
| 0.982085943 | 0.954229712 | 8 |
| 0.977829933 | 0.967253745 | 9 |
| 0.977529407 | 0.956604183 | 10 |
| 0.982349575 | 0.9490183 | 11 |
| 0.981856227 | 0.955889702 | 12 |
| 0.975823998 | 0.963789642 | 13 |
| 0.982822776 | 0.962480724 | 14 |
| 0.988664567 | 0.972649038 | 15 |
| 0.985295117 | 0.980493426 | 16 |
| 0.975872576 | 0.987788618 | 17 |
| 0.964276195 | 0.994780362 | 18 |
| 0.963219404 | 0.993331313 | 19 |
| 0.959865749 | 1.00000048 | 20 |
| 0.952994823 | 0.996276438 | 21 |
| 0.970916569 | 0.983162522 | 22 |
| 0.973964751 | 0.969606757 | 23 |

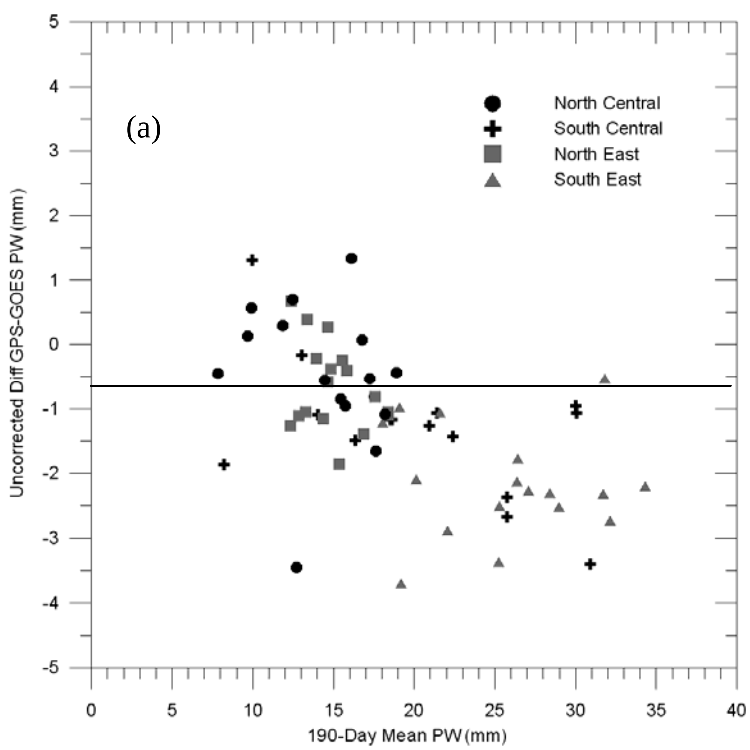
***Coefficients are not available at 00 UTC in the western US due to the lack of continuous surface data for GPS computations. As the stations in the**

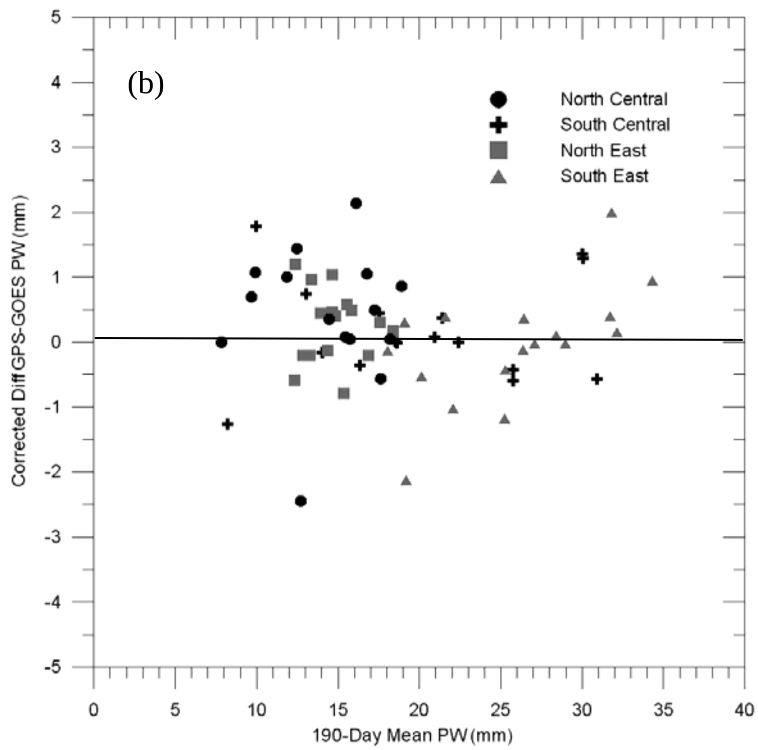
**western CONUS mature, 00 UTC data will eventually become routine as they are with the eastern CONUS.**

As can be seen in Table 4, the nature of the correction terms is similar to GOES 12. This was surprising since the initial bias values did not appear to be that significant, but as mentioned, the water vapor levels out west are typically lower than those measured by GOES 12. However, these results indicate that the nature of the bias for GOES 10 is strikingly similar to GOES 12. We note the very similar "*b*" term result near 20 UTC when it is very near unity. This indicates, as in the case of GOES 12, that in the local afternoon time frame the bias lacks curvature and needs simple scaling to remove the bias. At other times, however, especially near synoptic times, the bias correction requires more of a curvature correction. Though the magnitude of the coefficients for GOES 12 and GOES 10 are not identical, they are similar enough to suggest a fundamental commonality.

## 4. Real-Time Application of Correction Coefficients

During the summer months of 2007, the coefficients derived from earlier GOES 12 and GPS measurements were used to correct GOES 12 real-time data, and compare these corrected results to simultaneous GPS measurements. The object was to discern whether the correction algorithm based on earlier data would effectively improve subsequent data. Various comparisons were made. Initially, single stations were examined and found to be vastly improved by the correction algorithm. We then examined specific geographic regions to see if there were any latitudinal differences in correction or possibly optical path preferences (i.e., would we see better results in the south where there were higher water vapor amounts?).






**Figures 5(a) and 5(b). Two scatter plots showing the improvement to 2007 GOES 12 data before and after applying the correction algorithm based on earlier data. Fig. 5(a) shows the uncorrected data identified by region, indicating the southeast CONUS (triangles) contained the greatest moist bias; Fig. 5(b) shows the same data after application of the bias correction algorithm. Data are clustered closer to the zero bias line with the most improvement seen in the southeast.**

## 5. Differences Observed Between GOES 10 and GOES 12 Correction Coefficients

Near the end of this study we explored the tabulated correction coefficients (Tables 2 and 4) and decided to plot the coefficients as a function of hour. This was initially done to better visualize how they compared; as noted in the text they appeared similar. When plotted, a potentially much more important feature becomes apparent. Figure 6 shows the *a* and *b* correction terms for each satellite. As we anticipated, they are similar, but what was not apparent until plotted was that they appear to be phase shifted.

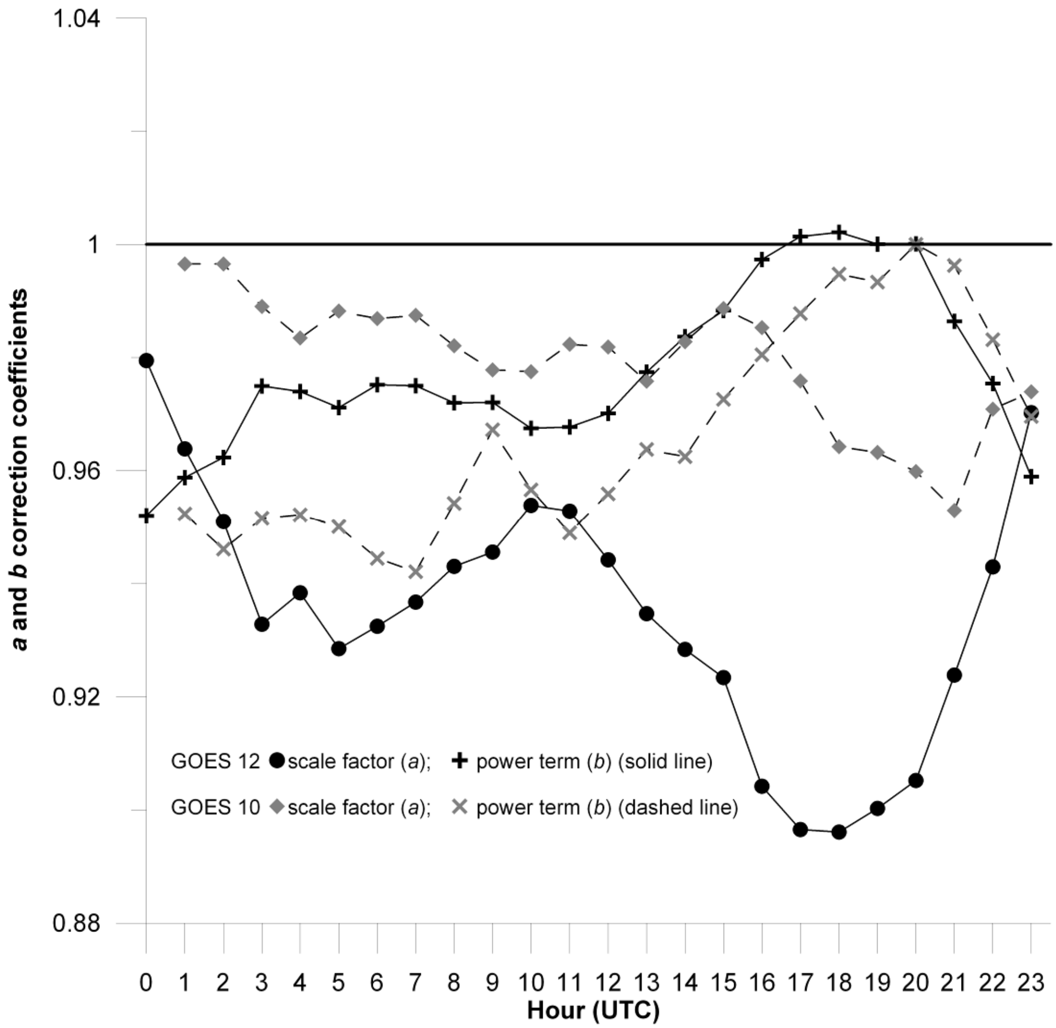



**Figure 6. Correction coefficients for both satellites plotted as a function of hour (UTC). Apparent is the temporal phase shift in the sunny part of the day (between 12 and 00 UTC).**

Figure 6 clearly shows a phase shift relationship between both the *a* and *b* terms from the correction equation with about a 3-hr offset. One can see that the *b* power term for GOES 10 is shifted to the right about 3 hours later especially between 12-18 UTC. Furthermore, the shift in the minima of both *a* terms occurs at 17 UTC for GOES 12 and about 21 UTC for GOES 10 is roughly a 3-hr difference, similar to the *b* term. Could this have something to do with the apparent solar or "time zone" difference between the two satellites? GOES 12 is stationed at a subpoint near 75 west longitude and GOES 10 was positioned at 135 west longitude, a difference of 60 degrees or 4 time zones. This would translate to an approximate solar time of day shift between each satellite of about 4 hours, on the order of what we observe in Fig. 6. So what is responsible for what appears to be a “solar effect” in the correction coefficients between the two moisture products from GOES? The algorithms for both spacecraft and channels are the same, all in the infrared and presumably at wavelengths deemed far enough away from the solar spectrum to be effectively insensitive to sunlight. Though they use the same a-priori guess model profile in the retrieval algorithm, there appears to be a solar component to the bias correction. At this time we can only present the observation here and have no established explanation, only speculation that the phase shift appears to be solar related (it does not appear during dark hours and the phase shift is seemingly well correlated to the spacecraft’s longitudinal separation or possibly the CONUS solar separation of the ground locations used in this study).

## 6. Summary

The primary outcome of this study is a technique to correct satellite TPW product bias. Even more important, the study shows that the correction technique is valuable for real-time correction when based on prior data. The correction algorithm was devised using variational methods and has shown similar correction coefficients for both GOES 10 and 12. Individual station data have been assessed both as a long-term and real-time trend (not shown here). It was also shown that the previously derived coefficients were useful in different geographic regions. These tests were only performed for GOES 12 for which there was the largest database for coefficient computation, but also consisted of the data set with the greatest variations in total water amount (the western CONUS being climatologically drier).

The fact that correction coefficients for both satellites studied are so similar suggests that the nature of the observed bias is not specific to hardware, i.e., the particular satellite, but instead is related to some aspect common to both data sets – namely the retrieval system or design of the instruments. The algorithms used in the retrieval system, including the model first guess (model initialization or influence by synoptic data) the forward radiance model, or some other aspect in deriving water profiles from radiometric data common to both GOES 12 and 10 has a non-random behavior that can be characterized. One would never have surmised this relationship by looking at the raw data (scatterplots), since the data for GOES 10 is far drier and the synoptic curvature effect is not that noticeable when plotted. It was shown (Fig. 3) that overall bias can be reduced to very close to zero with the algorithm. It is probably more useful to take from this study not so much that we now have an algorithm to correct GOES water vapor values, but instead to draw our attention to improving the product generation from GOES, since there seems to be something germane to the nature of the bias in both satellites.

Finally, the fact that we have a clear solar-related signal in the correction terms suggests that either sunlight is playing a role in the satellite measurement, or the retrieval algorithm is somehow sensitive to solar effects. Given that the satellite channels used for moisture and thermal retrievals are theoretically not influenced by solar effects, one can only rationalize that this phase difference is coming into play in the retrieval system by way of the raw measurement in a way we don't understand, or some other means that is not fully accounted for such as the model first guess. Certainly the results illustrated in Fig. 6 deserve attention, and future study should focus on solar dependence in the forecast model and any aspect of the GOES TPW generation that might relate to observed solar influence.

## References


Birkenheuer, D., and S. Gutman, 2005: A comparison of the GOES moisture-derived product and GPS-IPW during IHOP. *J. Atmos. Oceanic Tech.* **22**, 1840-1847.

Powell, M.J.D., 1962: An iterative method for finding stationary values of a function of several variables. *Computer J.*, **5**, 147-151.

Wolfe, D. E., and S. I. Gutman, 2000: Developing an operational, surface-based, GPS, water vapor observing system for NOAA: Network design and results. *J. Atmos. Oceanic Technol.*, **17,** 426–440.