Incorporating WAAS Data Into an Ionospheric Model for Correcting Satellite Radar Observations

Carl Toews, Anthea Coster, Lori Thornton, Eric Phelps, Susan Shulman
MIT Lincoln Laboratory

BIOGRAPHY

Carl Toews received his Ph.D. in pure mathematics from the University of Virginia in 2002. His research interests include operator theory and orbital mechanics. He has recently joined the technical staff of the Massachusetts Institute of Technology (MIT) Lincoln Laboratory.

Anthea Coster is a 20-year member of the technical staff at MIT Lincoln Laboratory, where she has served as the atmospheric scientist at the Millstone Hill Satellite Tracking Radar. She currently holds a joint appointment with the Atmospheric Science Group at the MIT Haystack Observatory. She has a Ph.D. in space physics and astronomy from Rice University in Houston, Texas

Ms. Thornton graduated from Mount Holyoke College with a BA in Mathematics and Physics. Since joining Lincoln Laboratory in 1985, her research has been focused on sensor calibration and high-precision orbit determination.

Eric Phelps received his Ph.D. in applied mathematics from the University of Colorado at Denver in 1996. His professional interests include computer science, signal processing, and orbital mechanics. Before joining MIT Lincoln Laboratory in 2000, he worked under contract at Motorola SATCOM.

Ms. Shulman has a bachelors degree from Mount Holyoke College where she majored both in Mathematics and in Russian Language and Literature, with a Computer Science minor. She has been with Lincoln Laboratory since 1999.

ABSTRACT

The GPS Real-Time Ionospheric Monitoring System (GRIMS) has been operational at the Millstone Hill radar in Massachusetts since 1991 and at the FPS-85 radar in Florida since 1994. GRIMS employs GPS derived estimates of the total electron content (TEC) to provide real-time ionospheric corrections to radar measurements, incorporating data from a single receiver to generate TEC estimates for the entire visible sky. Comparisons with range residuals on laser calibration spheres have shown that the GRIMS ionospheric model degenerates during times of sharp spatial TEC gradients, e.g. during geomagnetic storms and day/night transitions. To render the system more robust, we upgraded to a new GPS receiver capable of decoding the signal from the FAA's Wide Area Augmentation System (WAAS). The WAAS signal, culled from over 25 ground reference stations, communicates the vertical ionospheric delays and the associated confidence bounds at grid points regularly spaced in longitude and latitude. Preliminary results suggest that the WAAS model compares favorably to the model currently employed by GRIMS; the improvement in the radar metric data is verified via range residuals on calibration satellites.

1. INTRODUCTION

The MIT Radar Calibration System (MRCS) maintains real time models of both the troposphere and the ionosphere and employs these models to correct radar range measurements. Although the full MRCS system has been in use at both the Millstone and FPS-85 radars since 1994, GRIMS, the subsystem responsible for the ionosphere correction, has been in continuous operation at the Millstone site since 1991[3]. GRIMS employs dual frequency GPS data to calculate TEC delays along line-of-sight paths from the radar to visible GPS satellites. These delays, along with the positions of the relevant GPS satellites, are input to a Kalman-type filter and used to update a local ionospheric model.

Implementing GRIMS considerably improved the metric accuracy of both Millstone and FPS-85. This improvement was demonstrated by analyzing range residuals on calibration satellites: all of the sensors in the SSN routinely track several (~10) calibration satellites, each of which is equipped with corner cube reflectors. These satellites, which have perigee heights ranging from approximately 800 km to almost 20,000 km, are also tracked by the NASA and international laser ranging stations, using lasers that can measure ranges from the ground stations to the satellite borne retro-reflectors with millimeter level accuracy. Independent truth orbits (with an accuracy of tens of centimeters) can be derived from the laser data, and metric residuals can be computed by comparing these "truth" orbits to the sensor observations. Figure 1 depicts a representative comparison of the calibration satellite range residuals collected by the Millstone radar before and after the implementation of the GRIMS model. The improved standard deviation (5.94 TEC units with the GRIMS model versus 22.2 TEC units with the slab model) clearly illustrates the effectiveness of the GRIMS system.

Nonetheless, there are geomagnetic conditions that continue to induce large range residuals. Specifically, exaggerated range residuals tend to be observed during the rapidly changing ionospheric conditions associated with large geomagnetic storms or day/night transitions. The range errors are worse on low elevation tracks, suggesting inherent limitations of a model based purely on local observations.

To remedy this problem, we acquired a GPS Silicon Valley GISTM receiver, capable of decoding all GPS signals as well as the signals from the FAA WAAS Satellite-Based Augmentation Systems [1]. These distinct

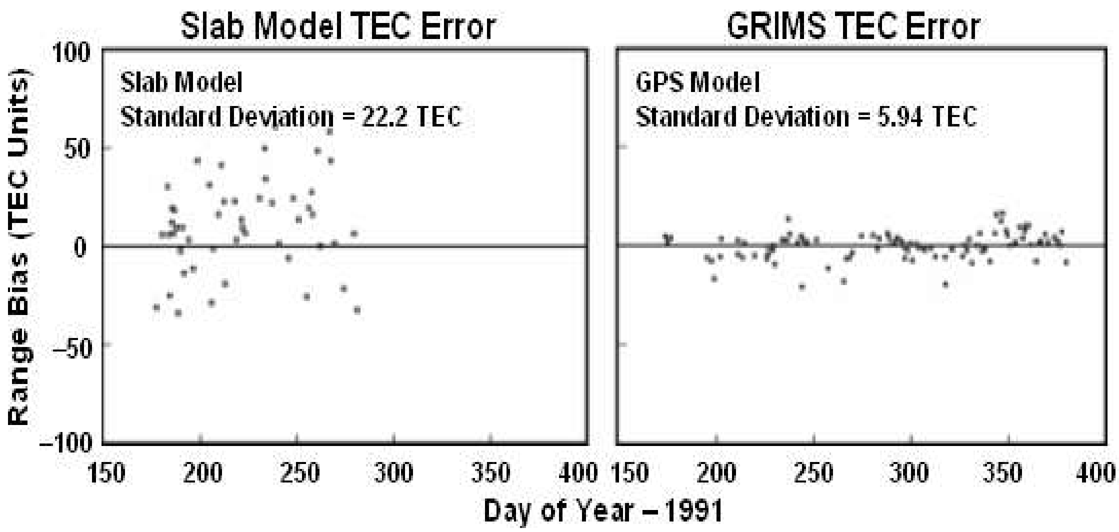

Figure 1. Illustration of the improvement in ionospheric modeling after the GPS model was installed at the Millstone Hill Radar in 1991.

signal sources furnish us with two independent ionospheric models: first, GPS signals can be directly processed by GRIMS, as before, and second, the TEC corrections of the WAAS messages can be interpolated to provide an alternative ionospheric correction. Because the WAAS message is derived from numerous receivers strategically distributed over the United States, the WAAS model, at least in theory, offers the hope of a more robust response to perturbed ionospheric conditions. The purpose of this paper is to present preliminary evidence that this assumption is justified.

The paper is organized as follows. Section 2 presents background information on MRCS. Section 3 focuses exclusively on the GRIMS subsystem, detailing our current ionospheric model and describing the Kalman filter. Section 4 describes the WAAS ionospheric model and discusses issues pertinent to its use at Millstone. Section 5 quantitatively compares the performance of the two models, and, finally, Section 6 contains conclusions and suggestions for further research.

2. MRCS BACKGROUND

Both the ionosphere and the troposphere delay the propagation of radio waves. These delays cause objects in space, when observed by radars on the ground, to appear farther away than in fact they are. The ionospheric correction increases as the satellite elevation decreases and also depends upon the radar's operating frequency. At the operating frequency of the Millstone L-Band radar (1295 MHz), the ionospheric correction to the radar range measurement can be on the order of 30 meters at 20° of elevation. For UHF systems such as the FPS-85 radar, the correction is much larger -- approximately 280 meters at the same elevation. The tropospheric correction does not depend upon frequency, but does depend on elevation and meteorological conditions. Below 5° of elevation, the tropospheric correction to the range measurement can be on the order of 100 meters. The troposphere also bends the radar wave causing distortions in the perceived elevation angle. At the horizon, this elevation correction can be as much as 1°. Both the ionospheric and tropospheric delays change dynamically as functions of position and time.

The MRCS was designed to monitor these dynamic changes and use them to determine real-time refraction corrections for radar measurements. The MRCS ionospheric model is based on a Kalman filter, and will be described in greater detail in the next section. The MRCS tropospheric models differ somewhat according to site: at Millstone Hill, the tropospheric model is based on inputs of site temperature, barometric pressure, and humidity, all derived from an on-site weather station, while the FPS-85 radar employs a standard tropospheric model based on averaged meteorological conditions near the site. Utilizing these models, MRCS calculates real-time refraction estimates and transmits these estimates to the radar tracking system.

In addition to furnishing real time range corrections, MRCS serves two other important functions: the first is to provide a quick-look sensor calibration assessment, and the second is to perform sensor bias model regression. The quick-look sensor calibration assessment is accomplished by comparing predicted calibration satellite positions to observations. This assessment can be done as soon as observations from the tracking system are transferred to the MRCS. The intention of this assessment is to quickly identify any gross errors in the tracking system before metric tracking data are sent to the Space Control Center (SCC).

The sensor bias model is entirely radar-specific. Whenever significant hardware changes are implemented and/or data quality is suspect, regression analysis of the sensor's observation residuals is warranted. The regression analysis requires much higher precision orbits than the quick-look. Sensor bias models are available for both the Millstone Hill and the FPS-85 radars.

3. GRIMS and the Kalman Filter

The MRCS ionospheric model GRIMS is based on real-time ionospheric measurements derived from GPS signals. The GPS receiver can track up to twelve satellites simultaneously. Each satellite broadcasts at two frequencies, L1 (1575.42 MHz) and L2 (1227.6 MHz). Line of sight TEC measurements can be computed for each tracked satellite by comparing the arrival time and phase of the two signals. The TEC delay and satellite position are input to a Kalman filter sequential estimator, which uses the input to update a state vector representing local ionospheric conditions.

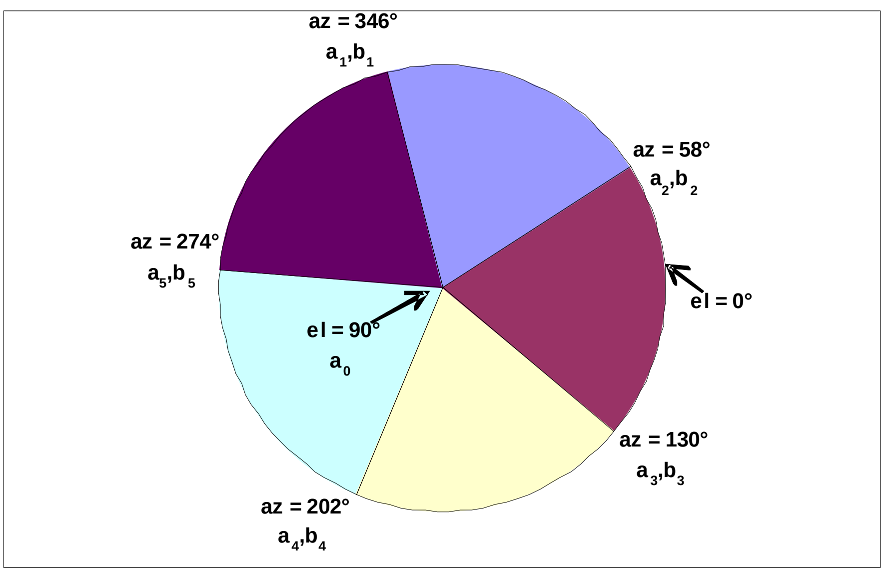

Figure 2. MRCS Circus Tent Ionosphere Model.

The definition of the GRIMS Kalman state vector requires an elevation dependent `mapping function' and the notion of an `ionospheric pierce point', i.e. the latitude and longitude of the point on the wave path where electron density is maximal. An assumption of the model is that the TEC along the radar path is an elevation dependent multiple of the vertical TEC at the pierce point. The mapping function provides this multiple. (A standard rule of thumb for ionospheric mapping functions is that their values vary between one at zenith and approximately three at elevations below 10°.) The actual Kalman state consists of eleven coefficients that, together with the mapping function, describe the (vertical) ionospheric delays around the site. The first term a_0 is the estimate for the TEC delay through the pole directly above the site. The area around the pole is then divided in azimuth into quintets, where the line that separates quintet 1 from quintet 5 aligns with geomagnetic North (see Figure 3). The lines separating each quintet represent look angles of fixed azimuth, with elevation angles ranging linearly from 90° at the center down to 0° at the edge. The TEC corrections along these lines are modeled by the equations:

TEC

where,

a_0 = Zenith correction term

a_i,b_i = polynomial coefficients for each of the five azimuth quintets

EL = elevation.

The TEC correction for any interior point is obtained by linear interpolation.

4. WAAS Overview

GPS navigation is used extensively to determine the position of commercial and military aircraft. However, the sharp TEC gradients induced by excessive solar activity introduce unacceptable levels of error to the GPS navigation position estimate. To mitigate this error, the FAA has developed a Wide-Area Augmentation System (WAAS).

The WAAS system consists of a series of WAAS Reference Stations (WRSs), which relay GPS data to WAAS Master Stations (WMSs). The Phase 1 plan for WAAS includes 25 precisely calibrated WRSs across the United States and two WMSs [7]. Additional WRSs are under consideration. At the WMSs, the data from the multiple WRSs are combined to compute the vertical TEC at specific points in space, called ionospheric grid points (IGPs). Error bounds on these TEC measurements are also computed. The density of the IGPs vary according to latitude; over the United States, they are located at intervals of 5° in latitude and longitude [2]. A subset of the grid point locations are depicted on a map of the continental United States, marked by red squares in Figure 3. (The Millstone and FPS-85 radar positions are denoted on the figure with blue diamonds.) Once computed, the grid point data are uploaded to geostationary satellites that broadcast this information back to GPS receivers on the ground. Nominally, these data are updated every five minutes.

Given TEC corrections at the IGP's, the user can approximate the ionospheric delay at an arbitrary look angle by first calculating the pierce point, then interpolating a vertical TEC delay at the pierce point from the vertical TEC delay of the nearest IGP's, and finally multiplying this delay by an appropriate slant factor (cf. Section 3 on mapping functions). Figure 4 depicts an example of the interpolated WAAS data at a time near sunset on March 31, 2003. The purple circles represent projections of pierce points corresponding to level elevation curves at Millstone; note that the interpolated WAAS data does not completely fill the field of view.

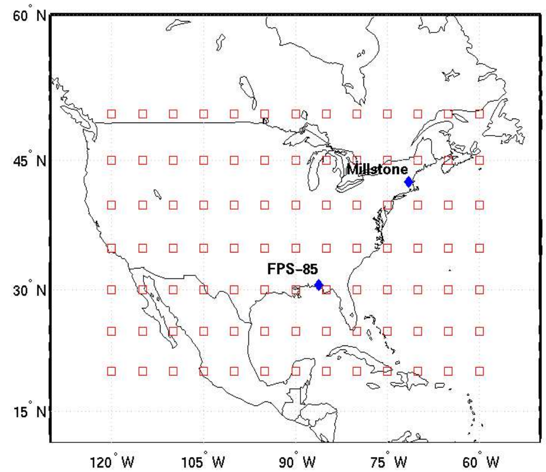

Figure 3. Partial Display of Locations of WAAS Ionospheric Grid Points.

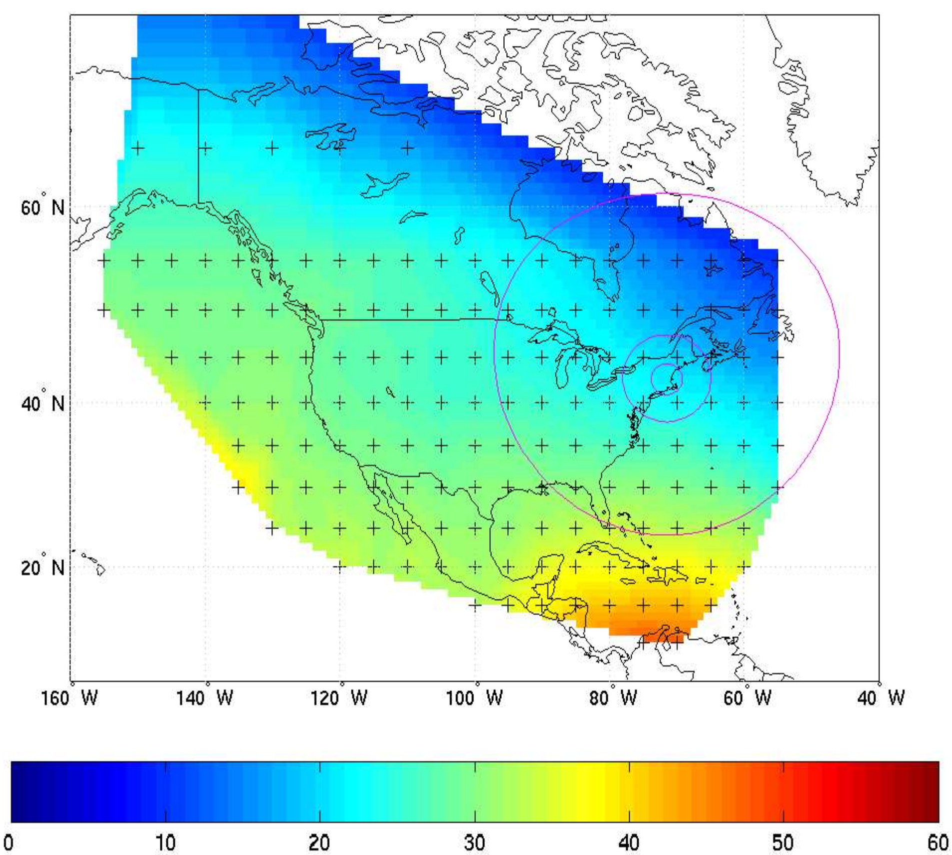

Figure 4. Availability of WAAS Ionospheric Grid Point Data.

5. WAAS vs. GRIMS: Preliminary Results

Figure 5 depicts an example of a direct comparison between GRIMS and WAAS based local TEC predictions near sunset on January 15 2003. The same data used to generate Figure 4 generated the right hand side of Figure 5, where the white band to the north east reflects the incomplete WAAS coverage. The left hand plot depicts the local TEC corrections predicted by the GRIMS model. Note that since the sun is setting, there should be larger TEC levels to the southwest, a phenomenon captured broadly by both models. However, the MRCS model still seems saddled with an unduly high zenith coefficient, while the WAAS model seems to have responded to the shifting electron densities quickly and gracefully. This behavior is consistent with the hope expressed in the Introduction.

In order to quantitatively compare the GRIMS and WAAS models, we compared range residuals on calibration spheres. Since the position of calibration spheres is known with centimeter accuracy, it is possible to calculate very exactly the true range from the radar to the sphere at any given time. The magnitude of the difference between this true range and the range observed provides an excellent measure of the quality of the calibration model.

The calibration data included time, azimuth, elevation, and range, as well as residuals for all three quantities. The range residuals were those obtained with the GRIMS model. The ionospheric correction that had generated these residuals could be reproduced by finding the Kalman state at the time of the observation. The correction predicted by the WAAS model could be obtained by reconstructing the WAAS grid that was valid at that time and interpolating the TEC correction for the pierce point corresponding to the relevant azimuth and elevation. Finally, the WAAS residual could be obtained by simply adding the MRCS correction and subtracting the WAAS correction from the original residual.

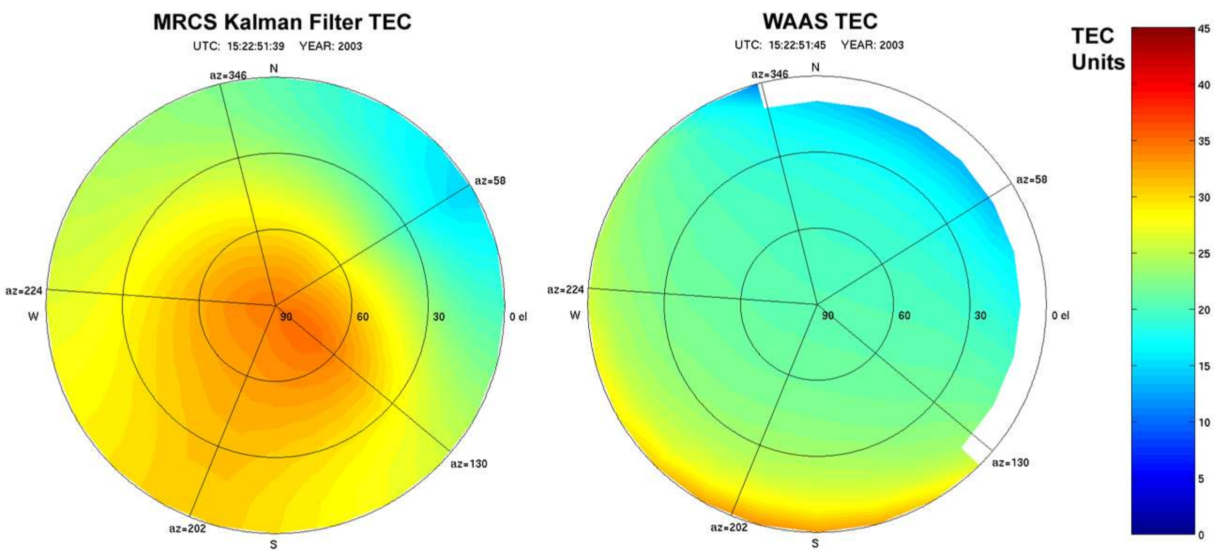

Figure 5. Estimation of TEC from the MRCS Kalman Filter versus the WAAS.

The comparison shown in Figure 6 is of range residuals from the FPS-85 UHF radar on the Eglin AFB in Florida for the day 31 March 2003. The second part of this day was moderately disturbed with the geomagnetic index, Kp, reaching a value of 6. The upper plot contains residual statistics based on the GRIMS model, while the lower plot contains residual statistics calculated from the WAAS model. Each vertical bar in the plots contains statistics for a single calibration pass, with the bar centered at the average residual and extending as far as the standard deviation of the residuals.

It is important to note that for the majority of the passes, the range residuals show very little difference, suggesting that, for the most part, the two models are comparable. However, one pass (indicated with an arrow in Figure 6) showed considerable improvement in shifting from the MRCS model to the WAAS model, with the mean passing from -32 to -4 and the standard deviation from 29 to 13. It is telling that this pass occurred during the day/night transition, which is typically when the MRCS performance suffers and we would hope for superior results from the WAAS.

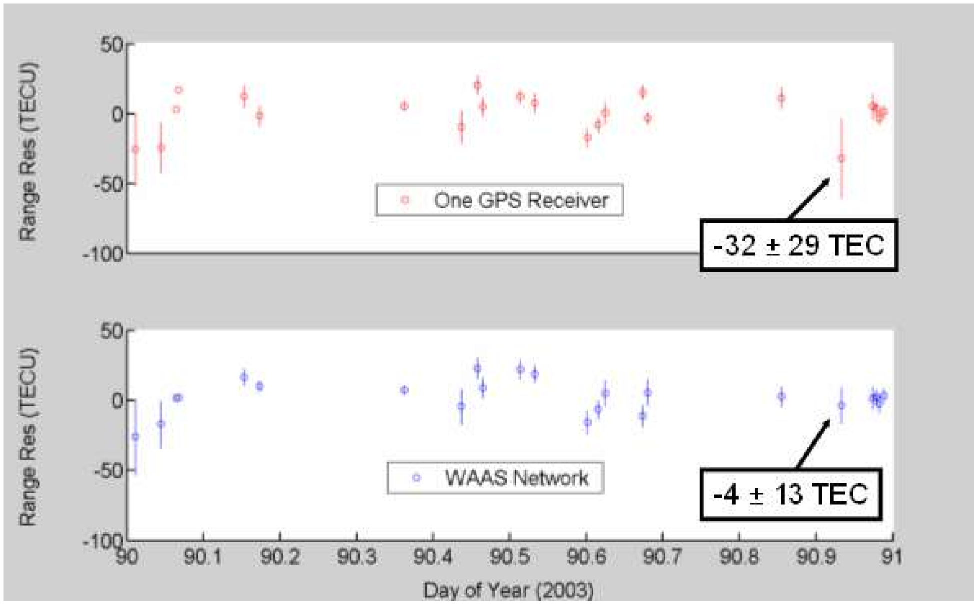

Figure 6. Comparison of FPS-85 EGLIN Radar residuals with MRCS and WAAS ionospheric corrections.

For a more in-depth analysis of the improvement of the WAAS ionospheric model, range residuals from the Millstone radar were examined for the full month of July 2003. In comparing models, we looked only at those calibration observations for which we could produce valid ionospheric corrections from both models. Since we keep complete records of the GRIMS Kalman state and this state generates a correction for every azimuth and elevation, we could always generate a GRIMS correction; as noted above, however, the field of view of the radar extends beyond the scope of the WAAS grid, so WAAS corrections thus could not be calculated for observations at certain look angles. Moreover, there were scattered periods during which the WAAS receiver was either down, elsewhere, or not collecting relevant data. Ultimately, we were able to process 853 observations dispersed over seven different days.

Some of the essential results of this analysis are displayed in Figure 7, which compares the two models by displaying range residuals as a function of elevation. The values for both the mean and the standard deviation were calculated from the entire data set. Note that in both categories, the WAAS model outperforms the GRIMS model. Pass-wise analysis confirms this assessment, with WAAS residuals consistently showing lower mean and lower standard deviation. The difference between the two models is especially marked at low elevations, where the GRIMS model is clearly suffering a positive bias. As elevation increases, the two models yield increasingly similar results. This trend is consistent with the idea that lower elevation pierce points are farther from the site and should be more difficult to model with only local data. Numerical support for elevation dependent correlation is illustrated in Figure 8, which was generated by grouping residuals into elevation classes of ten degrees and calculating correlation coefficients; as the plot indicates, correlation seems to increase as elevation increases, which, together with Figure 7, suggests that the real contribution of the WAAS data will be in estimating TEC at pierce points far from the site.

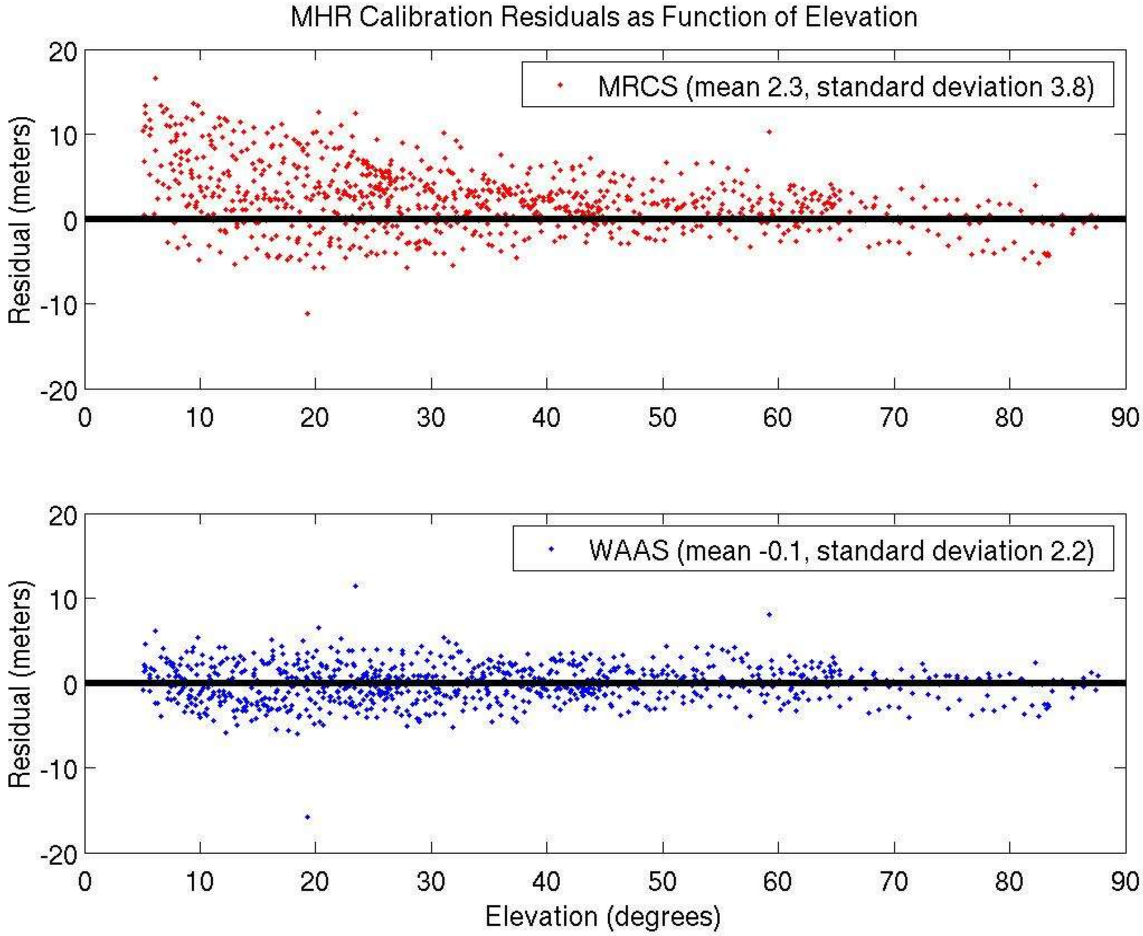

Figure 7. Calibration residuals as a function of elevation.

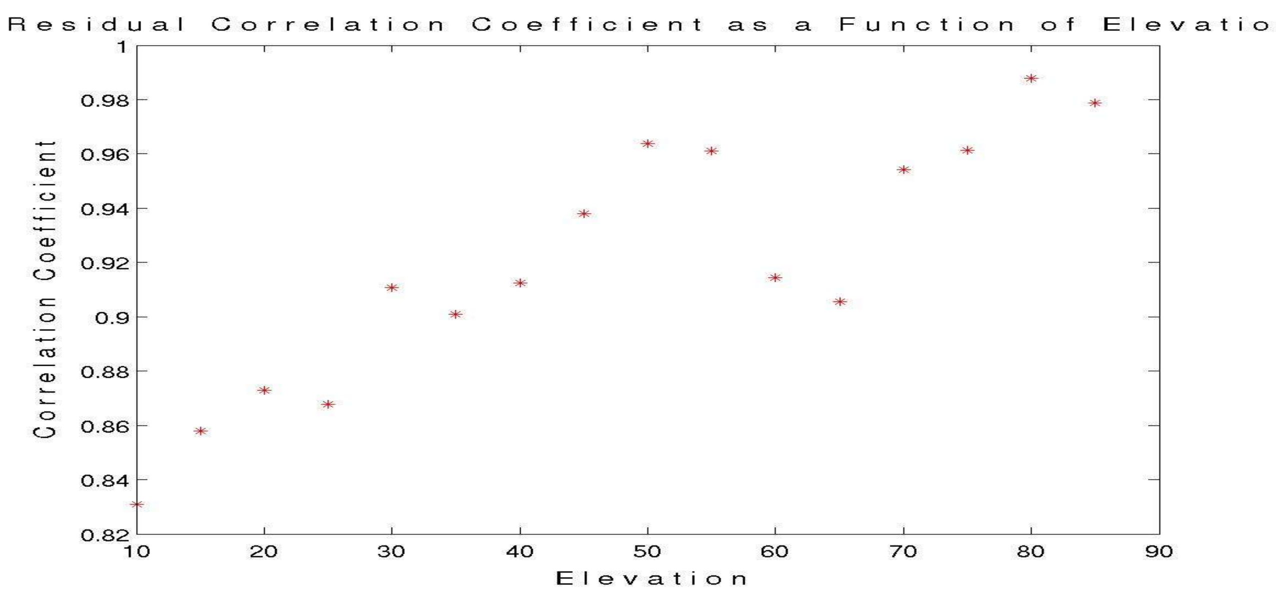

Figure 8. Correlation coefficients as a function of elevation class.

6. Conclusions

Preliminary data analysis strongly supports the utility of the WAAS ionospheric model as an aid in radar calibration. We have speculated that one of the reasons GRIMS performance suffers during periods of high geomagnetic activity is that observations from a single receiver are inadequate to keep pace with a rapidly changing ionosphere. In contrast, the TEC corrections of the WAAS model are derived from a broad network of strategically positioned GPS receivers. This gives WAAS data an a priori advantage.

On the other hand, there are several reasons to maintain at least some variant of the GRIMS model. Firstly, as Figures 4 and 5 illustrate, the WAAS grid points fail to fill the entire field of view of the Millstone Radar. Accordingly, any supplementary ionospheric data we can generate for this region has the potential to be of use. More generally, the presence of a receiver directly at the radar site is itself a great asset, since, after all, we are interested in TEC corrections as functions of look angle from the site. It thus seems that the local receiver can and should be put to use in concert with the WAAS data. Future tasks willl center on finding an optimal method to fuse WAAS data with the data generated from our local receiver.

This work was sponsored by the Air Force under contract F19628-00-C-0002. Opinions, interpretations, conclusions, and recommendations are those of the authors and are not necessarily endorsed by the United States Government.

1. *OEM4 Family of Receivers User Manual-Installation and Operation*, NovAtel, Incorporated, 21 June 2001.
2. *Minimum Operational Performance Standards for Global Positioning System/Wide Area Augmentation System Airborne Equipment*, Document No. RTCA/DO-229C, Prepared by SC-159, RTCA, Inc., Washington, DC, November 28, 2001.
3. Coster, Anthea J., Edward M. Gaposchkin, and Lorraine E. Thornton, "Real-Time Ionospheric Monitoring System Using GPS", Navigation: Journal of the Institute of Navigation, Vol. 39, No. 2, 1992.
4. Ashtech Z-12 Receiver Operating Manual, Ashtech, Incorporated, May 1994.
5. Brannon, private communication, 2003.
6. Walker, Matt, private communication, 2002.
7. El-Arini, M. B.; Poor, W.; Lejeune, R; Conker, R., "An Introduction to WAAS and Its Predicted Performance", Radio Science, vol. 36, no. 5, p. 1233-40, Sept.-Oct. 2001.
8. *Fact Sheets - WAAS*, http://gps.faa.gov/Library/waas-f-text.htm, WAAS Product Team, 1 September 2001.
9. *GSV4004 GPS Ionospheric Scintillation & TEC Monitor (GISTM) User's Manual*, GSV GPS Silicon Valley, 1.