The Effect of Tropospheric Propagation Delay Errors in Airborne GPS Precision Positioning[1]

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BIOGRAPHIES

Virgílio Mendes received his Diploma in Geographic Engineering from the Faculty of Sciences of the University of Lisbon, Portugal, in 1987. Since then, he has been working as a teaching assistant at this university. In 1990, he completed the Specialization Course in Hydrography at the Hydrographic Institute, Lisbon. In 1991, he enrolled as a Ph. D. student at the University of New Brunswick (UNB). He is involved in tropospheric delay modeling of radio signals and application of the Global Positioning System (GPS) to the monitoring of crustal deformation.

Paul Collins graduated from the University of East London in 1993 with a B.Sc. (Hons) in Surveying and Mapping Sciences. He is currently enrolled in the M.Sc.E. degree program in the Department of Geodesy and Geomatics Engineering at UNB, where he is investigating the effect of the troposphere on kinematic GPS positioning.

Richard Langley is a professor in the Department of Geodesy and Geomatics Engineering at the UNB, where he has been teaching since 1981. He has a B.Sc. in applied physics from the University of Waterloo and a Ph.D. in experimental space science from York University, Toronto. After obtaining his Ph.D., Dr. Langley spent two years with the Department of Earth and Planetary Sciences of the Massachusetts Institute of Technology where he carried out research involving lunar laser ranging and very long baseline interferometry.

Dr. Langley has worked extensively with GPS. He is a co-author of the best-selling Guide to GPS Positioning published by Canadian GPS Associates and is a columnist for GPS World magazine. He has helped develop and present a number of seminar courses on GPS for both Canadian GPS Associates and the American-based Navtech Seminars Inc. Dr. Langley has consulted extensively in the field of GPS with private companies and government agencies both in Canada and abroad.

ABSTRACT

When operating in an airborne environment, test results have shown that ambiguity resolution is particularly sensitive to errors in the tropospheric delay models applied to the carrier phase observations. Since the aircraft is at a higher altitude than the ground-based reference station, the model must accurately represent the relative tropospheric delay caused by the altitude difference. In kinematic applications, the zenith tropospheric delay can be determined with prediction models such as Saastamoinen's using pressure, temperature, and humidity measurements. This zenith delay is then mapped to other elevation angles using mapping functions such as those of Ifadis or Niell.

This paper highlights the performance of several widely used tropospheric delay models, including the model currently proposed for the FAA's WAAS. The accuracy of this model is assessed by (1) comparisons with ray tracing through an extensive set of radiosonde data, covering different latitudes, and (2) analyzing position solutions and the carrier phase observation residuals of GPS flight tests. We conclude that (1) the tropospheric delay error is mainly due to the inaccuracy of the zenith delay determination, and (2) a combination of a zenith delay model with the Niell or Ifadis mapping functions yields improved solutions, as compared to the currently proposed WAAS model.

INTRODUCTION

The need for accurate navigation with GPS lead to the implementation of various differential GPS (DGPS) techniques. In DGPS, corrections are broadcast to a user from a known reference station or stations, in order to eliminate or minimize different range measurement errors. Different implementations of DGPS techniques are mainly conditioned by the area over which the system is intended to cover. Local area differential GPS (LADGPS) and wide area differential GPS (WADGPS) are the two general categories under which most systems fall.

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The Wide Area Augmentation System (WAAS), proposed by the Federal Aviation Administration (FAA), is perhaps the most important WADGPS currently planned. It is intended to provide GPS navigation for aircraft across North America and, eventually, worldwide. Recent literature (e.g. Shaw et al., [1995]) indicates that WAAS will be used for in-flight navigation and CAT-I precision approaches. Additionally, a supplemental LADGPS, possibly using carrier phase positioning, will eventually be used for CAT-II and CAT-III precision approaches. The system contract has recently been awarded with the intention of having WAAS fully operational by the year 2001 [Johns, 1995].

Actually WAAS is more than just a GPS differential correction service because of the planned employment of INMARSAT geostationary satellites to not only broadcast differential corrections, but also GPS-like signals on the L1 frequency and integrity data. This augmentation of GPS will help to provide improved positioning accuracy, availability, and integrity.

One important residual error source that will contribute to the overall error budget of WAAS is any mismodeling of the tropospheric delay experienced by the GPS signals propagating through the electrically-neutral atmosphere. In this paper, the accuracy of the proposed WAAS [DeCleene, 1995] tropospheric model is assessed.

TROPOSPHERIC DELAY

A radio signal traveling through the neutral atmosphere suffers a delay (mostly due to the lowest-most region of the atmosphere – the troposphere), which can be defined at the zenith (zenith tropospheric delay) as:

$$d^{z}_{trop} = \int_{r_s}^{r_a} \left[n(r) - 1 \right] \, dr = 10^{-6} \int_{r_s}^{r_a} N \, dr$$

where n is the refractive index, N is the refractivity, r_s is the station geocentric radius and r_a the radius of the top of the neutral atmosphere (for more details, see, for example, Mendes and Langley [1994]). The zenith tropospheric delay is usually divided into two components, designated as hydrostatic (or dry) and wet. The hydrostatic component of the zenith delay can be modeled very accurately provided good station pressure measurements are available. The wet component is spatially and temporally highly variable and poorly predicted by models (see Mendes and Langley [1995]).

The zenith delay can be related to the delay that the signal would experience at other elevation angles through the use of mapping functions. If the mapping functions are determined separately for the hydrostatic and the wet component, the tropospheric delay can be expressed as:

$$d_{trop} = d^{z}_{h} \cdot m_{h}(\varepsilon) + d^{z}_{w} \cdot m_{w}(\varepsilon)$$

where d^{z}_{h} is the zenith delay due to mostly dry gases, d^{z}_{w} is the zenith delay due to water vapor, m_h is the hydrostatic component mapping function, m_w is the wet component mapping function, and ε is the non-refracted elevation angle at the ground station. In the early years of space geodesy, the tropospheric delay models had no explicit separation of zenith delay and mapping function. We will designate such models as tropospheric delay models.

The number of available tropospheric delay models, zenith delay models and mapping functions is very large. The performance of fifteen mapping functions was assessed by Mendes and Langley [1994] and the impact on station coordinates of the use of these mapping functions was analyzed by Santerre et al. [1995]. The assessment of four of “the best” zenith wet delay models can be found in Mendes and Langley [1995]. Besides the WAAS tropospheric delay model, we have selected for comparison purposes: (1) two tropospheric delay models widely used in navigation applications, designated Altshuler [Altshuler and Kalaghan, 1974] and NATO [1993]; (2) the Ifadis [1986] global hydrostatic and wet mapping functions; (3) the Niell [1995] hydrostatic and wet mapping functions, also designated as NMF. The Ifadis and NMF mapping functions are both coupled with the Saastamoinen [1973] zenith hydrostatic delay model and the Ifadis [1986] global zenith wet delay model. For the sake of simplicity we hereafter will designate these combinations as Ifadis and NMF, unless stated otherwise.

Both the Altshuler model and the WAAS model, which is derived from Altshuler’s [DeCleene, 1995] are driven by the station’s height above sea level, station latitude, and day of year. The NATO model uses a reference value for the surface refractivity and the height above sea level for the determination of the zenith total delay. This delay is then mapped using the Chao [1972] dry mapping function. The NMF and Ifadis mapping functions represent different philosophies in modeling the elevation angle dependence of the tropospheric delay. The Ifadis mapping function is parameterized by pressure, temperature and water vapor pressure (both for the hydrostatic and wet mapping functions), whilst the NMF is parameterized by day of year, station latitude and station height (hydrostatic mapping function), and station latitude only (wet mapping function). Despite the different approaches, these mapping functions show comparable accuracy (see Mendes and Langley [1994]).

The Saastamoinen zenith hydrostatic delay model is a function of the surface pressure, station height and latitude, and the Ifadis zenith wet delay model is a function of pressure, temperature and water vapor pressure.

MODEL ASSESSMENT

For the accuracy assessment, we used ray-tracing results as benchmark values, for different sites (for details see Mendes and Langley [1994, 1995]). The results of this comparison are listed in Tables 1 and 2. In general, NMF and Ifadis show a low bias, as compared with the other models, and the scatter about the mean is consistently smaller. The performance of these two models is very similar, as expected. Overall, the WAAS model has a larger bias than the Altshuler model, but a lower scatter. The NATO model performs the worst.

The logical next step in model assessment would be the confirmation of these results in a kinematic environment. The availability of reliable meteorological data is an important issue. If the meteorological data is not available, standard atmospheric profiles to take into account the lapse rate of the meteorological parameters with altitude have to be introduced and may lead to incorrect zenith delay determinations. The models which do not rely on meteorological parameters will apparently have an advantage over the others, unless the modeling of the elevation angle dependence of the delay is poor. From Mendes and Langley [1994] we know that NMF and Ifadis mapping functions have very small biases, and the larger biases seen in the results presented here are nothing other than the amplification of the errors in the zenith delay determination. For the WAAS model, it is difficult to separate the zenith delay error from the mapping function error. Due to the advantage of not relying on meteorological data, we chose NMF as the reference mapping functions for testing against WAAS in the analysis of a set of kinematic GPS data, taken aboard a Convair-580 aircraft. To avoid the propagation of errors in the zenith wet delay determination, due to uncertainties in the measurement of the meteorological parameters, we used the Saastamoinen [1973] zenith wet model, which uses the partial pressure due to water vapor only. In the absence of errors, Ifadis and Saastamoinen zenith wet models have comparable accuracy [Mendes and Langley, 1995].

FLIGHT DATA DESCRIPTION

The flight data processed for our study was part of a data set collected by the National Research Council, Canada, at and around St. John's, Newfoundland, in March 1995. The campaign (denominated *Frizzle '95*) was primarily conducted between the latitudes of 45°N and 52°N and longitudes 57°W to 47°W.

The main objectives of the campaign included:

- studying stratiform drizzle formation, particularly over sea ice;
- studying drizzle formation from frontal lifting;
- measurement of ice accretion and testing of measurement systems;
- testing of a de-icing scheme;
- studying the change in aircraft performance with ice accretion.

The flight paths consisted of repeated horizontal and vertical profiles through cloud layers up to heights of approximately 8 km. Frontal zones and temperature inversions are often associated with potential causes of freezing precipitation and therefore provide highly unpredictable conditions for tropospheric delay modeling.

The GPS data consists of 14 days of dual-frequency pseudorange and carrier phase measurements recorded at two second intervals. Data were simultaneously recorded by an Ashtech Z-12 receiver and NovAtel GPSCard single-frequency receiver, both on the aircraft and at a ground reference station in St. John's. Range corrections were transmitted from the reference station to the aircraft for real-time positioning. The data from each day generally consists of one three-to-five hour flight. Meteorological parameters were recorded at both the ground station and the aircraft. The ground meteorological data is available at one minute intervals and the airborne data every second.

A subset of the data has been analyzed using the Kinematic and Rapid Static (KARS) software developed by Dr. Gerald Mader at the National Geodetic Survey, NOAA. It uses the ambiguity function method [Mader, 1992] for resolving the carrier phase ambiguities. The generous provision of the source code has allowed the implementation of most of the currently available tropospheric delay models. However, due to the nature of the processing software, which requires dual-frequency GPS observations, we have limited our data analysis thus far to the Ashtech Z-12 receiver observations. It is intended to process the single-frequency data in the future, along with similar data provided as part of the Beaufort Arctic Storms Experiment, undertaken at Inuvik, N.W.T., in October, 1994. Because of the geographic location and nature of these projects it is expected that the data will provide a good test of the currently available tropospheric delay models.

STATION	ε (°)	AL	NATO	WAAS	IFADIS	NMF
Alert	15	-7	47	-21	-2	-2
	10	-2	69	-21	-3	-4
	5	9	137	81	-6	-10
Denver	15	-35	-50	-51	-2	-2
	10	-43	-72	-64	-3	-3
	5	-74	-117	15	-4	-4
Frobisher	15	11	45	-6	-3	-3
	10	24	66	1	-5	-5
	5	57	132	126	-9	-12
Grand Junction	15	-59	4	-44	4	4
	10	-79	6	-56	6	6
	5	-127	21	-2	11	11
Guam	15	-57	4	-28	1	1
	10	-75	6	-33	1	1
	5	-119	20	45	3	2
Kotzebue	15	2	39	-15	-3	-3
	10	12	58	-11	-4	-4
	5	35	119	105	-8	-8
Nashville	15	-15	-7	-29	-6	-6
	10	-13	-9	-33	-9	-9
	5	-10	-1	70	-16	-18
Oakland	15	3	12	-14	5	5
	10	14	19	-9	8	8
	5	43	51	117	16	15
San Juan	15	-39	-46	-53	-4	-4
	10	-45	-66	-66	-6	-5
	5	-77	-107	13	-10	-9
St. John’s	15	2	21	-13	-5	-5
	10	12	31	-9	-7	-7
	5	38	72	112	-12	-14
The Pas	15	-5	26	-14	-3	-3
	10	2	38	-10	-5	-5
	5	19	83	106	-9	-10
Whitehorse	15	-29	28	-16	0	0
	10	-34	42	-14	0	0
	5	-47	87	88	-1	0

Table 1 - Mean tropospheric delay error for 15°, 10° and 5° elevation angle. The values represent the mean differences between the tropospheric delay model predictions and ray-trace results, in centimetres. (Note: AL = Altshuler)

STATION	ε (°)	AL	NATO	WAAS	IFADIS	NMF
Alert	15	10	12	9	3	3
	10	14	17	13	5	5
	5	27	28	23	8	10
Denver	15	21	22	21	18	18
	10	31	32	31	26	26
	5	60	60	58	49	48
Frobisher	15	13	16	12	6	6
	10	19	23	18	8	8
	5	33	40	31	15	15
Grand Junction	15	14	17	13	7	7
	10	20	24	19	10	10
	5	38	44	35	20	19
Guam	15	11	13	11	7	7
	10	17	20	16	11	11
	5	31	35	29	20	20
Kotzebue	15	14	17	14	6	6
	10	21	25	20	9	9
	5	39	45	36	16	16
Nashville	15	28	30	27	12	12
	10	41	44	40	18	18
	5	79	81	74	33	33
Oakland	15	13	13	12	10	10
	10	19	19	18	15	15
	5	36	35	34	16	15
San Juan	15	16	16	16	13	13
	10	23	24	23	19	19
	5	45	46	44	35	35
St. John’s	15	21	24	21	13	13
	10	31	34	31	19	19
	5	57	62	55	35	35
The Pas	15	11	14	11	7	7
	10	17	21	16	11	10
	5	31	37	28	19	19
Whitehorse	15	11	14	11	5	5
	10	16	21	15	8	8
	5	30	38	27	14	14

Table 2 - Root-mean-square scatter about the mean of the differences between the tropospheric model predictions and the ray-trace results for 15°, 10° and 5° elevation angle, in centimetres. (Note: AL = Altshuler)

We are using carrier phase data to test the WAAS tropospheric delay model because of the greater accuracy they provide over pseudoranges. The lower noise and multipath components should allow us to more accurately determine any residual tropospheric delay errors induced by the different models. Our use of carrier phase data is also germane to the idea of extending the WAAS concept to a Local Area Augmentation System (LAAS). This concept requires carrier phase positioning and on-the-fly ambiguity resolution to perform precision CAT-II and CAT-III approaches.

FLIGHT DATA TEST RESULTS

An important consideration in this type of study is that a proper comparison be made between models. Several previous studies have shown that the correlation in meteorological parameters degrades very quickly with height [Brown and van Diggelen, 1994; Qin et al., 1995]. Therefore, only where both air and ground meteorological data are concurrently available are comparisons made, rather than using default meteorological data.

As an example of the kind of data we have processed, we present in Figure 1 the carrier phase double difference residuals for one hour's worth of data, processed with the WAAS model and then the Saastamoinen zenith delay models with the Niell mapping function. As we suspected, using the Saastamoinen wet zenith delay model proved slightly superior than using the Ifadis zenith wet model. The elevation cutoff angle used was 10 degrees. The residuals using the WAAS model appear to be more unstable over a longer period of time. This is partly due to the fact that after two separate cycle slip events at approximately 5 and 45 minutes into the data set, the ambiguities are resolved differently (and incorrectly) than in the Saastamoinen/Niell solution. The difference is only one cycle on both L1 and L2, but it is enough to account for the divergence of the residuals after 30 minutes. A cycle slip also occurs on a low elevation angle satellite at approximately 30 minutes but it drops below the cutoff before its ambiguities can be resolved.

Both these plots show some systematic trends in the residuals and by examining Figure 2 we might suggest a closer correlation with the distance between the two receivers, rather than their relative height difference. Over a distance of nearly 200 kilometres, uncorrelated tropospheric effects and orbit errors should be the predominate errors. Hence, for the residuals presented in Figure 3, which are from exactly the same data and tropospheric model combinations as before but processed with International GPS Service for Geodynamics (IGS) precise orbits, almost all the systematic trends have been removed and the cycle slips are still resolved with a one-cycle difference between the two solutions. However, the biases that remain in the WAAS solution stand out more clearly.

Turning to Figure 4, we consider the effect on the formal errors of the position solutions. This plot represents the height, northings and eastings (respectively reading down the y axes) standard deviation using the broadcast orbits. We can immediately see that the precision of the height component of the WAAS solution is more sensitive compared to the Saastamoinen/Niell solution at all times.

Also in Figure 4, one might note the two jumps in the WAAS height standard deviation. The first, at 30 minutes is also in the Saastamoinen/Niell standard deviation, but the latter at 51 minutes, is not. This would suggest that this is purely a consequence of the use of a different tropospheric delay model, however this is only the case in an indirect way. This jump is actually due to the WAAS model solution solving for the second cycle slip three minutes later than the Saastamoinen/Niell solution.

CONCLUSIONS

The ray trace results indicate that either the Niell or Ifadis mapping functions, coupled with a standard zenith delay model will perform better than the proposed WAAS model. However, reliable meteorological data is advisable, particularly the pressure (one mbar error in the pressure introduces about 2 mm error in the zenith hydrostatic delay determination).

The flight data results indicate that the WAAS model can introduce errors into the ambiguity resolution of the carrier phases even over short distances between the receivers, as compared to the Saastamoinen/Niell model. These errors are small (1 cycle) but significant over long time periods. They were also present even when precise orbits were used to compute the solutions.

The WAAS model solution's precision is degraded slightly with respect to the Saastamoinen/Niell solution and especially in the height component.

Further work at UNB will involve processing more of the flight data using different models and with lower elevation angle cutoffs. The advantages of using a different model at the reference station from that used for the aircraft will also be investigated. Any improvements that can be made to the currently proposed WAAS model will be considered and tested.

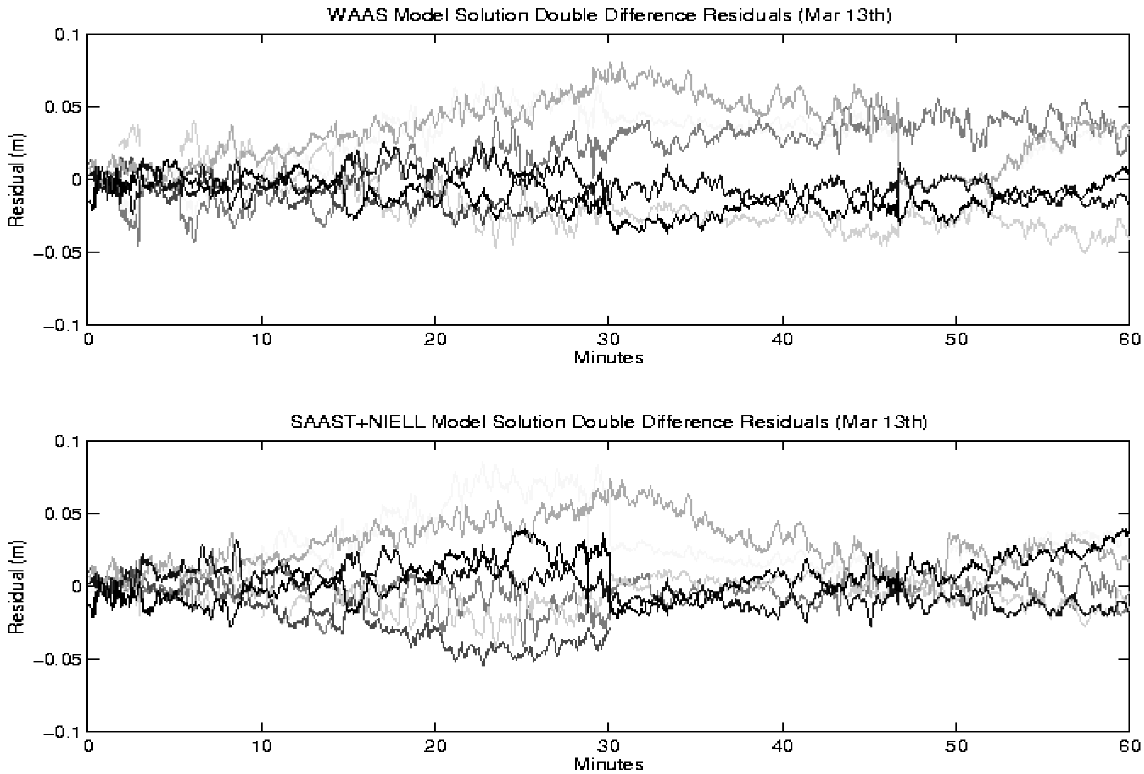

Figure 1. L1 Carrier Phase Double Difference Residuals (Broadcast Orbits)

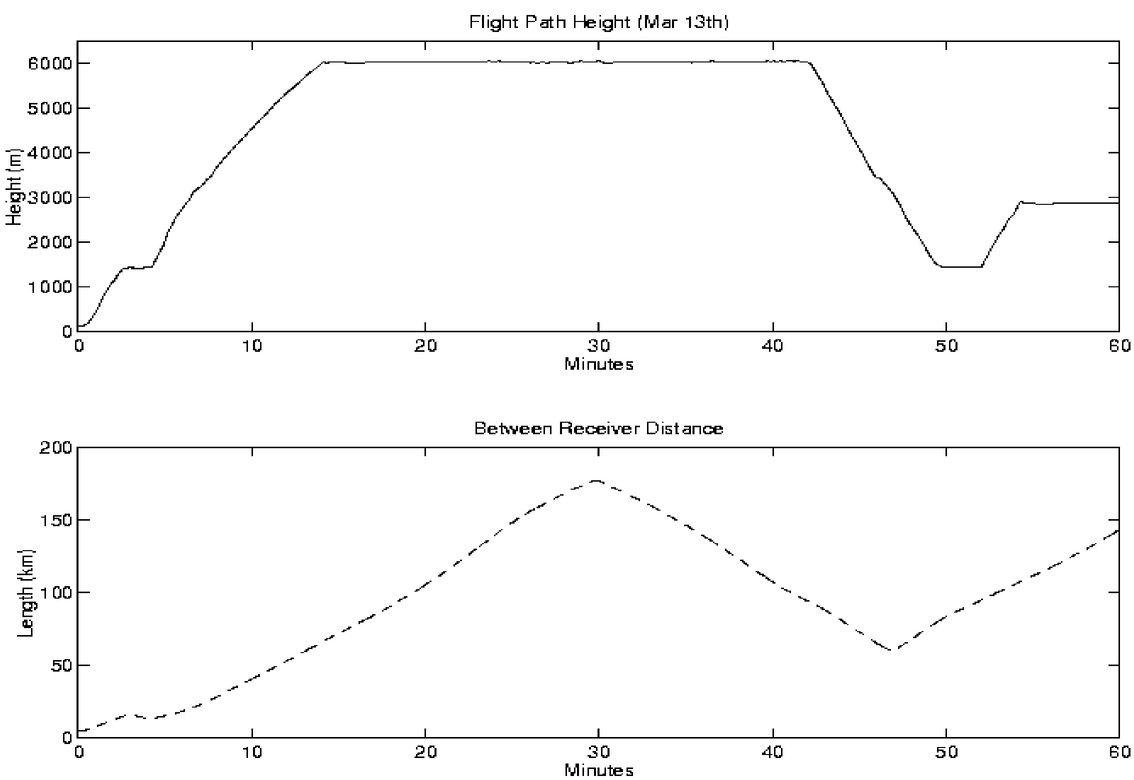

Figure 2. (a) Height of airplane. (b) Distance from reference receiver.

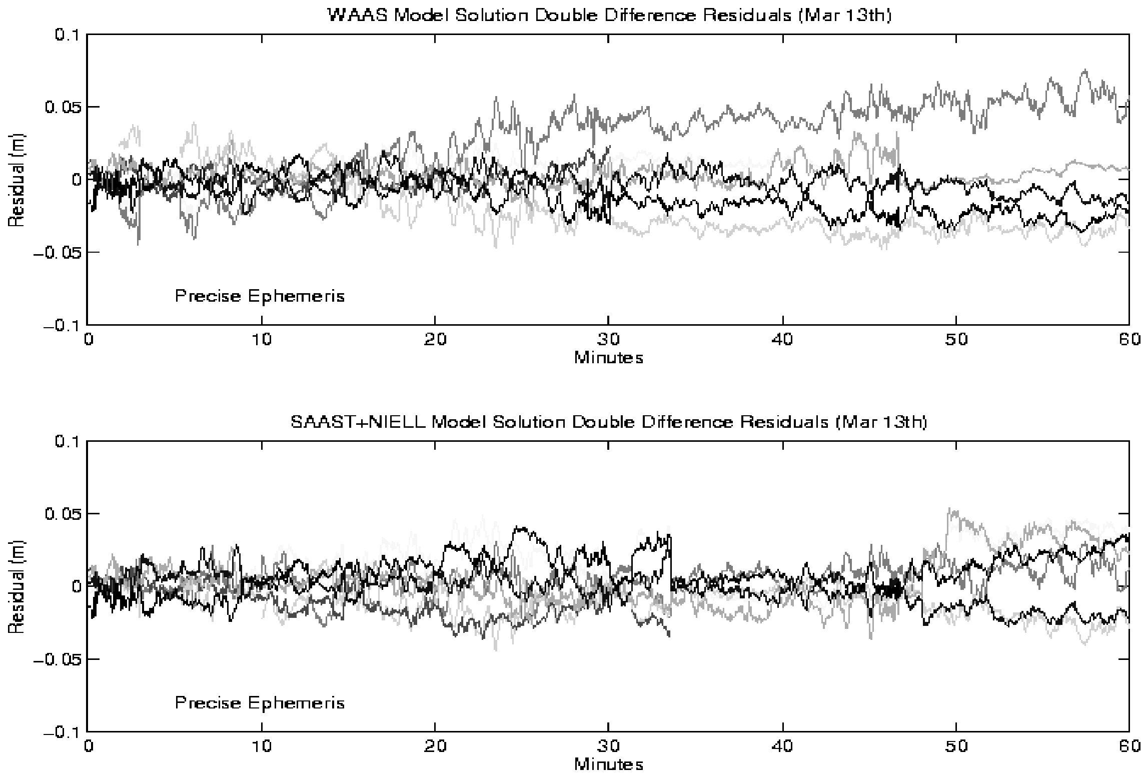

Figure 3. L1 Carrier Phase Double Difference Residuals (Precise Orbits).

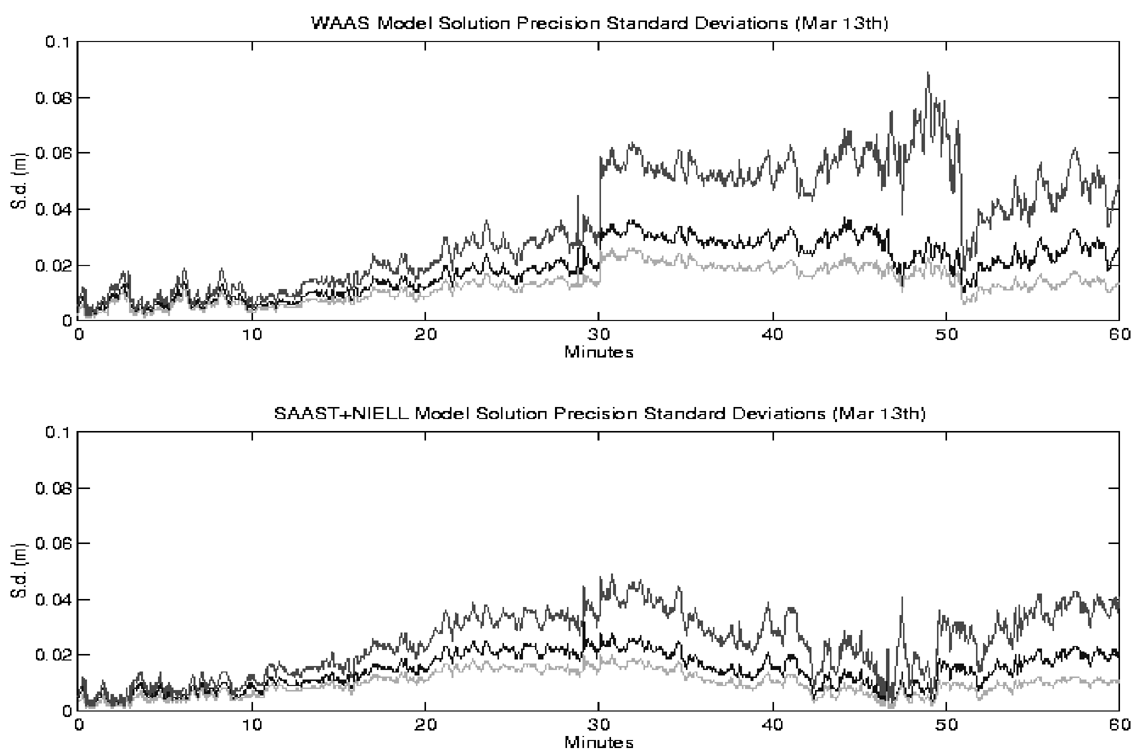

Figure 4. Precision of solutions (standard deviations of height, northings and eastings respectively descending the y axes).

Future work will also involve analysis of the NovAtel data set by our partners at NAVSYS Corp., Colorado Springs, CO, using their own on-the-fly software. This phase of the analysis program will look specifically at the effect of tropospheric delay models on aircraft precision approaches.

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