Assessment of Atmospheric Delay Correction Models for the Japanese MSAS

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BIOGRAPHY

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Sunil Bisnath received an Honours B.Sc. in 1993 and an M.Sc. in 1995 in Surveying Science from the University of Toronto. For the past five years he has been a Ph.D. candidate in the Department of Geodesy and Geomatics Engineering at the University of New Brunswick. During this time he has worked on a variety of GPS-related research and development projects, the majority of which have focused on the use of GPS for space applications.

ABSTRACT

This paper aims to evaluate the potential error involved in the application of the recommended algorithms and the consequent effects on the positioning errors, under typical atmospheric conditions for MSAS (Multi-Functional Transport Satellite Satellite-based Augmentation System). The results and analysis presented in this paper will serve as benchmark for further development of MSAS.

In order to assess the accuracy of Wide Area Augmentation System (WAAS) atmospheric models and their applicability to the Japanese MSAS, different analyses were carried out. Japan has different climates according to the region because of the North-South length. Airport locations and the weather in Japan were first studied. Tropospheric delay corrections obtained

from the SBAS model were compared with Saastamoinen and Hopfield models that use temperature, air and vapor pressures as their input. The normal values for such meteorological parameters were taken from the *Rika Nempyo (Chronological Scientific Tables)* published by the National Astronomical Observatory of Japan.

The data from flight tests conducted in the summer and winter as well as data for a week collected at 2 control stations were processed and analyzed. The stations located near Sendai and Naha airports were selected. Relative comparisons for positioning using different atmospheric correction models were made and preliminary results were obtained.

The differences in height (vertical component of position) brought using different tropospheric correction models were less than 50 cm from our results. The SBAS troposheric model would be applicable to Japanese MSAS. The use of different ionospheric correction models (Klobuchar and dual frequency) provided the difference of 2.5 m in vertical component. Development of a correcion model for the ionosphere would be necessary. Some areas occasionally have poor satellite geometry. A ranging capability of MTSAT would be important in some areas over Japan.

INTRODUCTION

The Japanese Civil Aviation Bureau is implementing the MTSAT Satellite-based Augmentation System (MSAS), which will cover the Flight Information Region associated with Japan. MSAS will broadcast information to suitably equipped users via one or more geostationary satellites called Multi-Functional Transport Satellites (MTSATs). MSAS will be interoperable with the U.S. Wide Area Augmentation System (WAAS) and the European Geostationary Navigation Overlay System (EGNOS) – satellite-based augmentations to GPS currently under development.

Differential corrections broadcast via MTSAT would improve positioning accuracy to the order of 5 m. The propagation errors caused by the atmosphere (ionosphere and troposphere) must be modeled properly to achieve full accuracy, in particular in the vertical component, using the corrections.

In order to assess the accuracy of WAAS atmospheric models and their applicability to the Japanese MSAS, different analyses were carried out using the data from flight tests, as well as the data for a week collected at 2 control stations.

Ionosphere

The ionosphere, extending in various layers from about 50 km to more than 1000 km above the earth, releases free electrons since a fraction of the gas molecules has been ionized by the ultra-violet radiation from the sun. GPS signals, like any radio-electric signal propagating through an ionized medium are affected by the nonlinear dispersion characteristics of this medium. The effect is normally 5-15 m in the zenith direction, the error can reach 100 m at sunspot maximum periods, midday, near the equator, satellite near horizon. The dual-frequency correction removes most of the ionospheric effect. Doherty *et al.* (1999) examined position errors for single frequency GPS receivers. Standard errors without Selective Availability for single and dual frequency receivers are 5.1 m and 3.3 m (quoted in RMS values for filtered UERE). One of the important error sources is the ionosphere, in particular for single frequency receivers, contributing 4.0 m (constituting about 40% of errors). On the other hand, the residual dual-frequency ionospheric error is about 0.01 m and thus negligible (NRCC 1995, Hay & Wong 2000). The error sources are discussed in Langley (1997).

Dual-frequency receivers can eliminate most of the ionospheric effects with a first approximation inversely proportional to the square of the carrier frequency. The pseudorage corrected for ionospheric effects (P) is:

$$P = \frac{P_2 - \left(\frac{f_1}{f_2}\right)^2 P_1}{1 - \left(\frac{f_1}{f_2}\right)^2}$$

where P_i is pseudorange measured by the L_i-band channel.

GPS receivers on board aircraft, however, are typically single frequency units and are therefore not capable of correcting for the ionospheric effects with the dual-frequency technique. The GPS satellites send the values of eight parameters of the Klobuchar model in the navigation message so that single frequency users can calibrate the ionospheric delay to a certain extent. WAAS and EGNOS use a grid of ionospheric delay values to provide single-frequency users with a means to correct for ionospheric effects with a higher accuracy than typically obtained from the data in the navigation message. It is anticipated that the ionosphere activity near Japan is different from that observed in North America. The accuracy of such single-frequency techniques needs to be evaluated before developing a new model for MSAS.

Troposphere

Tropospheric delay is one of the major error sources in satellite navigation. The signal transmission delay caused by the troposphere can be over 2 m at the zenith and 20 m at lower elevation angles (*e.g.* below 10°). If the tropospheric delay is not properly modeled, resulting positioning errors can be in excess of 10 m.

Tropospheric models developed for air navigation are significantly less accurate than the more sophisticated models commonly used in space geodesy where meteorological measurements are available to help quantify the state of the neutral atmosphere. The ICAO Standard and Recommended Practices (SARPS) recommend the application of an empirical correction algorithm, based on a receiver's height and estimates of five meteorological parameters (pressure, temperature, water vapor pressure, and temperature and water vapor lapse rates) using average and seasonal variation data related to the receiver's latituide and day-of-year (Collins 1999, Collins & Langley 1998). However, such a simple average and seasonal variation model is unlikely to model exactly the temporal weather changes. Although this model is globally applicable, most of the meteorological data used to generate the model originated in North America. The delay at different elevation angles is obtained by multiplying the zenith delay by a given mapping function.

Dodson et al. (1999) assessed SARPS recommended tropospheric models for SBAS in Sunbury near London and Nottingham, UK, for EGNOS. They estimated the total tropospheric delay above a receiver using a Kalman filter approach. They concluded that the SBAS model represents mean tropospheric delay with maximum zenith delay differences of 16 cm between the model and GPS estimates.

Some models explicitly use meteorological data taken at the ground station and others use the coordinates (latitude and height) of the observation site. Saastamoinen and Hopfield models are representative of the former group. Mendes and Langley (1998) assessed a great number of zenith delay prediction models using a one-year data set of radiosonde profiles from 50 stations distributed worldwide (including Tateno, Japan, North of Narita, latitude 36.05°, longitude 140.13°, altitude 27 m). The results of their assessment are the following. The Saastamoinen model had outstanding performance with submillimeter bias and RMS scatter for hydrostatic zenith delay with respect to the benchmark values from ray tracing of the radiosonde data. Saastamoinen was ranked among the best for wet zenith delay, and had a better match with radiosonde ray tracing results, less than 1 cm of bias and a few centimeters of RMS scatter for total zenith delay. The Hopfield model tends to over-predict the zenith delay except for the equatorial region. Hopfield bias at Tateno was about 3 mm.

In this paper, the SPS positioning results using the SBAS model are compared with those using the Saastamoinen model as well as those using the Hopfield model. The formulae of the troposheric models are found in the Appendix.

WEATHER AND TROPOSHERIC DELAYS AT AIRPORTS IN JAPAN

Japan is an archipelago lying to the east of China. The latitude of the northernmost city is about 45°30'N and the southern part of Japan is located at about 26°N, having a sub-tropical climate. There are 4 main international airports into Japan: Tokyo, Osaka, Fukuoka and Nagoya. There are 5 more international airports: Naha, Hiroshima, Takamatsu, Niigata, Sapporo, but they are mostly serviced from the Asian countries (Korea, China and Russia) and there are only a few flights into them in a week. Sendai Airport is considered as international, having a few flights to Russia. Table 1 summarizes some of the airport locations.

Table 1. Major airport locations in Japan

Airports	Latitude	Longitude	Altitude
Sapporo	43°07' N	141°23' E	11 m
Sendai	38°08' N	140°55' E	4 m
Niigata	37°57' N	139°07' E	4 m
Narita	35°46' N	140°23' E	44 m
Nagoya	35°15' N	136°56' E	17 m
Osaka	34°47' N	135°27' E	15 m
Takamatsu	34°13' N	134°01' E	188 m
Fukuoka	33°35' N	130°27' E	12 m
Naha	26°11' N	127°39' E	6 m

Because of the North-South length, Japan has different climate according to the region. Monthly average of the temperature in Sapporo, in the northern island, is -4.6°C in January and 21.7°C in August. In Naha, Okinawa, the lowest normal temperature is 16.0°C in January and the highest is 28.3°C in July. For other cities where airports are located, the temperature varies midway between those for Sapporo and Naha. The lowest and highest values of relative humidity in Naha are respectively 69% and 85% in January and in June. Sapporo has the lowest relative humidity 64% in April and the highest 78% in August. Sendai has about 70% humidity (annual average) like most Japanese cities. In the summer season, it exceeds 80% in many cities.

Before evaluating the performance of the SBAS model, the behavior of the model itself needed to be examined. The wet component of tropospeheric delay is affected by the meteorological conditions. Tropospheric delays at the airport locations were computed using the SBAS model. The wet component varied from 10 cm to 22.5 cm with a variation of 12.5 cm in Sendai. The hydrostatic component varied around 2.3 m with a variation about 1.5 cm for 9 sites listed on Table 1. Difference in the total zenith delay between the originally proposed UNB model based on mapping functions developed by Niell (1996) and the SBAS model in ICAO SARPS was negligible: about 2 mm in the zenith delay, and 1-2 cm at the elevation angle of 15° at all of major airport locations in Japan.

Tropospheric delay corrections obtained from the SBAS model were compared with Saastamoinen and Hopfield models that use temperature, air and vapor pressures as their inputs. The delays were also computed at the ground level of each airport using the monthly average of the dry temperature, humidity and air pressure of the city where the airport was located. The normal values for such meteorological parameters were taken from the *Rika Nempyo (Chronological Scientific Tables)* published by the National Astronomical Observatory of Japan. The values were of numerical averages over a 30-year period, between 1961 and 1990 inclusive.

Figure 1 shows the difference in computed tropospheric delays using Saastamoinen and SBAS models for a satellite at the zenith. The difference in tropospheric delay between SBAS and Saastamoinen models at Sendai Airport in December was -7 cm at the zenith. The differences were smaller in the summer period. The differences in the zenith delays at Sendai were -5 cm and +7 mm in June and August, respectively. Figure 2 shows the same computation for the difference in tropospheric delays but with Hopfield and SBAS models. The curves are similar to the ones in the previous figure.

Figure 3 shows the difference in tropospheric delays between Saastamoinen and SBAS models but for the satellite elevation angles at 15°. In Sendai, the differences in delays at 15° were -22 cm and +1 cm in June and August. The SARPS recommended SBAS model had a better fit with the Saastamoinen model in Naha all the year around. Figure 4 shows the same computation between Hopfield and SBAS models for the satellite elevation angles at 15°. Similar values were obtained for the difference in the delay between SBAS and Hopfield models at Sendai Airport in December: -7 cm in the zenith delay, -25 cm at 15° elevation angle. In Sendai, the differences in the delay between Saastamoinen and SBAS models were 4 mm for the satellite at the zenith in August. The same differences for the satellite at 10° elevation angle were 1.5 cm in August and -47 cm in December.

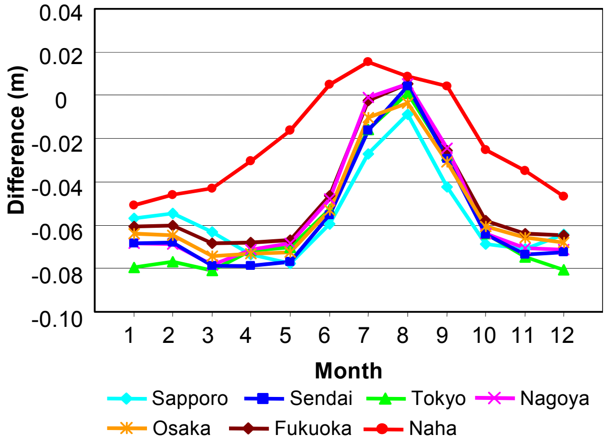

Figure 1. Difference in tropospheric corrections between Saastamoinen and SBAS models for a satellite at the zenith

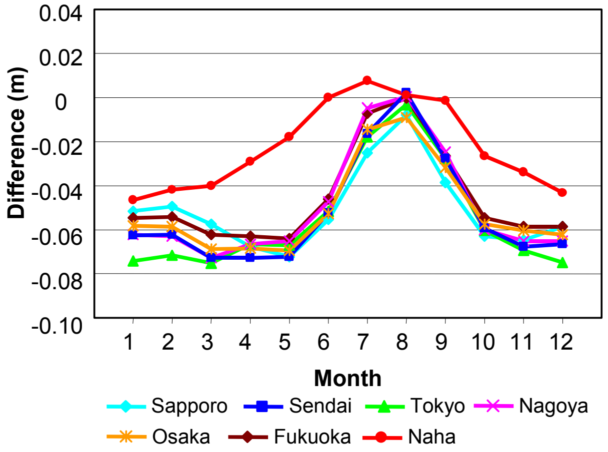

Figure 2. Difference in tropospheric corrections between Hopfield and SBAS models for a satellite at the zenith

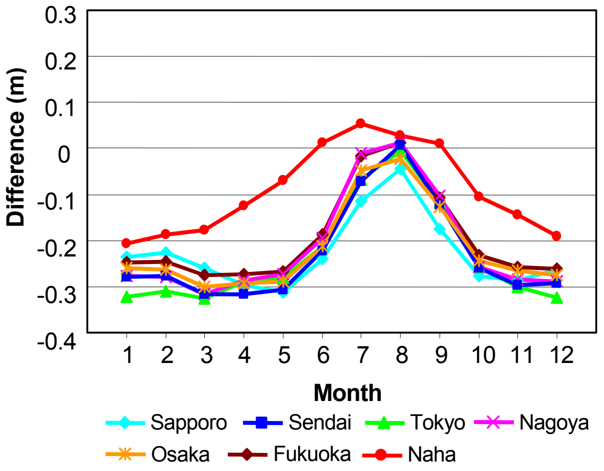

Figure 3. Difference in tropospheric corrections between Saastamoinen and SBAS models for a satellite at 15° elevation angle

Due to the differences in mapping functions, the difference of delay computation between Hopfield and Saastamoinen was larger in the winter period for lower elevation-angle satellites. In January, in Sendai, there are differences of 4 cm in the delay at the elevation of 15° and 12 cm at 10°, respectively. The differences between Saastamoinen and SBAS models were more important in Tokyo, in particular during the winter period. The differences in the total zenith delays were about 8 cm between December and March. In January, the differences were of 30 cm at 15° and 45 cm at 10°. During the winter period, in the area around Tokyo, it is relatively dry with average humidity around 50% while other parts of Japan have average humidity more than 65% during the same period.

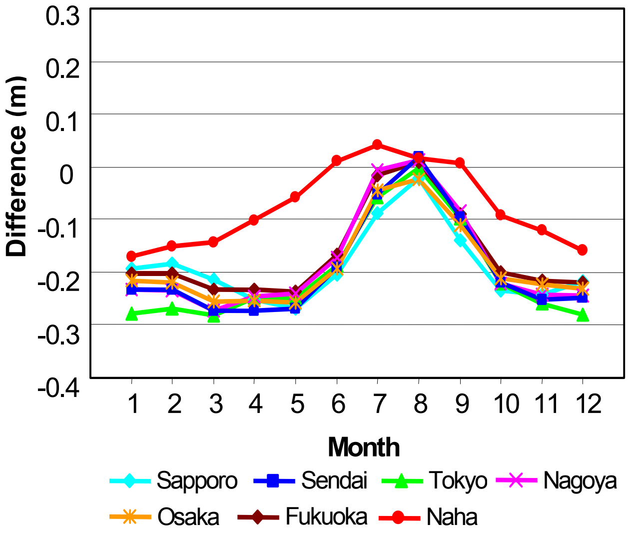

Figure 4. Difference in tropospheric corrections between Hopfield and SBAS models for a satellite at 15°

FLIGHT TESTS IN SENDAI

In order to assess the accuracy of WAAS atmospheric models and their applicability to the Japanese MSAS, different analyses were carried out using the data from flight tests.

Furuno has been developing a prototype GPS/SBAS receiver under a research contract with the subsidiary of Nippon Foundation supported by Japan Civil Aviation Bureau and ENRI. The details of the prototype SBAS receiver were in Nakao *et al.* (1999). Three flight tests were conducted to verify the performance of software to receive a WAAS pseudorange and correction signal. The first test was conducted in August 1999. The second and the third ones were conducted in January and December 2000, respectively. The details of the first and second tests were in Kawai *et al*. (2000).

The Japanese prototype single-frequency GPS/SBAS receiver was installed on board the plane B99 owned by ENRI. The SBAS corrections provided by the Inmarsat POR satellite were available during the test. A Trimble dual-frequency receiver operating as a reference station at Sendai Airport (a few hundred kilometres north of Tokyo) simultaneously collected GPS data. The antenna was installed on the tower of ENRI's branch office in Sendai. The antenna position was determined by professional surveyors beforehand. Another dual-frequency unit was also installed on board the plane for kinematic positioning to provide a truth reference. The data were post-processed using Trimble software and our original software.

The data collected at the airport was first processed. Different atmospheric correction models were used to assess the possible errors in positioning. Two tropospheric correction models (Hopfield and Saastamoinen) that explicitly use the values of atomospheric pressure, temperature and relative humidity, were used to compare the results with the SARPS recommended model. The meteorological data were obtained from the records of the aviation observatory located at Sendai Airport. The meteorological data observed hourly at Sendai Airport was interpolated for every epoch and used as input for the Saastamoinen and Hopfield models. The data at the reference station were processed and the results were compared with the known coordinates of the station. Table 2 summarizes the results during 2000-m level flights in August 1999 (08.99) and December 2000 (12.00). Both the flights lasted about 2 hours. The results of static data observed at the reference station in the airport were compared with the known coordinates of the antenna location. Selective Availability (SA) existed when the first test was conducted. The effect of SA would appear with the same magnitude to the computed result even when different models were used. The comparison was rather to see the difference between the models. The number of available satellites was 5-9 and the PDOP value varied from 1.48-3.89 during the test. The number of available satellites was 4-7, and the PDOP value varied between 1.89-5.44 during the level flight in December. The characters H, S and U in Table 2 denote the Hopfield, Saastamoinen and UNB (SBAS SARPS recommended) models. The symbols μ and σ are the mean and standard deviation of the component, respectively. The units used in Tables 2, 3, 4 and 6 are all meters.

Table 2 Comparison of positioning using different models

			Dual Frequency			Klobuchar		
			ϕ	λ	h	ϕ	λ	h
08.99	H	μ	-1.48	0.88	3.53	0.68	1.35	-0.62
		σ	±24.03	±18.59	±52.75	±24.23	±18.64	±53.07
	S	μ	-1.48	0.88	3.61	0.68	1.35	-0.51
		σ	±24.03	±18.59	±52.75	±24.23	±18.64	±53.07
	U	μ	-1.48	0.88	3.76	0.68	1.35	-0.38
		σ	±24.03	±18.59	±52.75	±24.23	±18.64	±53.07
12.00	H	μ	-1.75	0.13	2.82	-0.05	0.23	0.38
		σ	±2.71	±1.88	±4.34	±2.46	±2.05	±3.23
	S	μ	-1.75	0.13	2.84	-0.05	0.23	0.39
		σ	±2.71	±1.88	±4.34	±2.46	±2.05	±3.23
	U	μ	-1.75	0.13	2.65	-0.05	0.23	0.20
		σ	±2.71	±1.88	±4.34	±2.46	±2.05	±3.23

The meteorological data obtained from the observations differed somewhat from the normal values. When the meteorological data collected from the aviation observatory located at the airport were used, the differences in tropospheric delays between the Saastamoinen and UNB models were about 35 cm for the satellite at lower elevation angle, and about 10 cm at higher elevation angle. The mean of the difference in height (vertical component of position) was about 20 cm (19 cm between Saastamoinen and UNB, and 18 cm between Hopfiled and UNB) in December. The differences were about 15 cm between Saastamoinen and UNB in August. The differences in the horizontal position were less than 5 cm. When dual frequency ionospheric corrections were used, the position got worse during the test. It is probably due to the reception and quality of L2 signals during the session. The height offset from the true coordinate was about 2.5 m using the dual frequency method and 0.5 m with the Klobuchar model in December. The mean height was, however, estimated within the error range of SPS positioning. The results show that the accuracy of SPS was significantly improved after SA was turned off. The accuracy of height determination was better than 10 m at 95% during the flight in December. The major source of errors was the ionosphere, which provides 2.5 m of difference between different corrections.

The data collected on board the aircraft was compared with the kinematic positioning results. Table 3 summarizes the height determination during the level flight. The results of kinematic GPS positioning served as a “true” reference. The mean difference in height between two models (Saastamoinen and UNB) was about 15 cm during the test in 1999 and about 25 cm during the test in 2000.

Table 3 Comparison of height with different correction models during the level flight

		Dual Frequency			Klobuchar		
		H	S	U	H	S	U
08.99	μ	7.65	7.72	7.87	10.61	10.67	10.83
	σ	±60.37	±60.37	±60.37	±60.00	±60.00	±60.00
12.00	μ	-2.84	-2.82	-3.08	-6.17	-6.16	-6.41
	σ	±6.52	±6.52	±6.52	±4.60	±4.60	±4.60

Table 4 summarizes the comparison of positioning results in different mode. The true reference was obtained from double difference kinematic solutions using a linear combination of carrier phase without ionospheric effect (with an average RMS value about 5 cm). The headings of the columns in Table 4 signify the results of the following. SPS represents the results of stand-alone positioning of the Japanese GPS/SBAS receiver. POR is the results of the same receiver using the POR WAAS corrections. DGPS shows the results of relative positioning with Trimble receivers and DGPSF is for the filtered results. UNB denotes the results obtained with precise point positioning software developed at UNB (Bisnath & Langley 2001). The use of corrections from POR does not show the improvement in positioning. The visibility of the POR is not that poor in Japan. The elevation angles and azimuth of the POR observed in Sendai area was 29.7° and 121.7°, respectively. The GPS satellites tracked by WAAS are mostly seen in the north-eastern part of the sky. In addition, there are no WAAS ionospheric corrections available around Japan. This is probably why the accuracy improvement cannot be seen and therefore the results are not good. It would be interesting to see what would happen with MTSAT that will be launched in the spring of 2003.

Table 4 Comparison of height computation with kinematic GPS during the level flight

		SPS	POR	DGPS	DGPSF	UNB
08.99	μ	-8.65	-10.28	-3.01	-3.01	N/A
	σ	±83.94	±77.52	±3.35	±3.31	N/A
12.00	μ	-10.24	-12.13	-5.32	-5.32	-3.98
	σ	±4.56	±6.60	±1.33	±0.97	±0.83

STATIC DATA PROCESSING

The previous analysis provided some insight for the short-term variation in positioning. In order to assess the impact of the use of different correction models on positioning, in particular, on the vertical component of position for a longer period, data collected at GPS stations operated by the Geographical Survey Institute of Japan were used. Two observation sites selected for the evaluation were Rifu about 20 km from the Sendai airport and Tamaki about 13 km from the Naha airport. The week of 10-16 June 2001 (GPS Week 1118) was used for the evaluation. The normal values for meteorological data taken from the *Rika Nempyo (Chronological Scientific Tables)* were used as the input for Saastamoinen and Hopfield tropospheric delay models. Table 5 shows the normal values for June.

Table 5. Normal meteorological values in Sendai and Naha in June

	Sendai	Naha
Air Pressure (hPa)	1010.1	1008.6
Temperature (°C)	18.3	26.2
Relative Humidity (%)	80	85

The data collected by the Geographical Survey Institute of Japan had particular features. The data were provided with dual frequency carrier and pseudorange observations for a period of 24 hours. The observations were made at an interval of 30 seconds and elevation mask angles were set to 15°. The results may be somehow limited due to the granularity of the data. The coordinates of the stations were in the ITRF94 frame. Broadcast orbit data were used for the processing to see what happens in the real world. The data at the two sites were processed using different correction models in the same manner as in the previous section. Hopfield, Saastamoinen and SBAS models were used for the troposphere and the Klobuchar model with broadcast ionospheric parameters and dual frequency corrections were used for the ionosphere. The results were compared to the coordinates of the observation sites.

The PDOP values varied between 1.6 and 9.6 at Tamaki, and 1.5-45 at Rifu. The epochs with the PDOP values more than 10 were removed from the analysis. Due to the fact that the elevation cut-off angle was 15°, there were epochs with insufficient numbers of satellites available for positioning at Rifu. The number of satellites available for most of the time was 6 at Rifu and 7 at Tamaki. Figure 5 shows the difference in height estimation between the Hopfiled and SBAS models. The Klobuchar ionospheric model was used. The mean of the difference between the two models was about 16 cm. The figure shows some periodical repeatability.

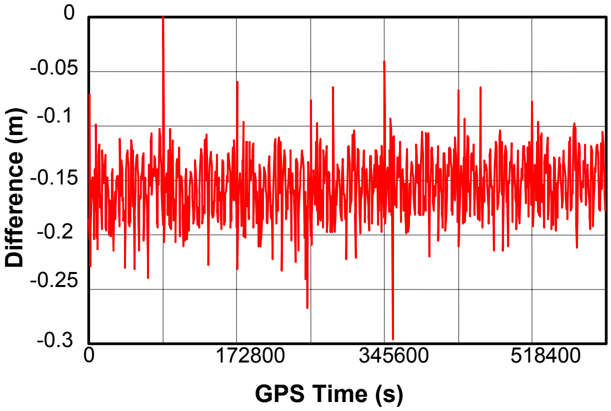

Figure 5. Difference in height estimation between Hopfield and SBAS models with Klobuchar ionospheric correction model at Rifu (GPS Week 1118)

Table 6 summarizes the results of the difference in positioning using different correction models. The symbols are the same as Table 2. The acharacters H, S and U denote the Hopfield, Saastamoinen and UNB (SBAS SARPS recommended) models. The symbols μ and σ are the mean and standard deviation of the component, respectively. The units are meters. The ID numbers for the observation sites are listed on the table: 37 for Rifu and 100 for Tamaki.

Table 6. Comparison of positioning results using different atmospheric correction models

			Dual Frequency			Klobuchar		
			ϕ	λ	h	ϕ	λ	h
37	H	μ	-0.59	-2.01	-2.27	0.58	-0.73	1.50
		σ	±8.75	±5.80	±16.89	±6.39	±4.26	±10.74
	S	μ	-0.59	-2.01	-2.23	0.58	-0.73	1.54
		σ	±8.75	±5.80	±16.89	±6.39	±4.26	±10.74
	U	μ	-0.59	-2.01	-2.43	0.58	-0.73	1.35
		σ	±8.75	±5.80	±16.89	±6.39	±4.26	±10.74
100	H	μ	-1.35	-0.99	0.99	1.39	0.24	3.46
		σ	±1.81	±1.99	±4.45	±3.32	±2.53	±4.96
	S	μ	-1.35	-0.99	0.91	1.39	0.24	3.38
		σ	±1.81	±1.99	±4.45	±3.32	±2.53	±4.96
	U	μ	-1.35	-0.99	0.93	1.39	0.24	3.40
		σ	±1.81	±1.99	±4.45	±3.32	±2.53	±4.96

In Tamaki, the mean value for the vertical component using the Hopfiled model and dual frequency ionospheric correction was 0.99 m and the same component with SBAS model was 0.93 m. Tamaki had 6 cm of mean difference in the vertical component between the Hopfield and SBAS models. Rifu had 16 cm of mean difference between the two models. The differences for the same component were 19-20 cm (Rifu) and 2 cm

(Tamaki) with Saastamoinen models. Sendai area has larger difference than Naha area. It may be partly because of poorer satellite geometry. It would also be considered as poorer representation of the weather used in the tropospheric delay models. Dual frequency corrections for the ionosphere worked better for Tamaki. The diffence caused by the use of different models is about 2.5 m.

Increasing the elevation cut-off angle could reduce the positioning errors caused by the SBAS model errors. However, some epochs were rejected at higher elevation cut-off angles. In week 1118, for example, about 18 minutes of data were rejected every day due to poor satellite geometry at an elevation cut-off angle of 15°. Ranging capability of MTSAT would be important in some areas over Japan.

CONCLUSIONS AND FUTURE WORK

This paper aimed to evaluate the potential error involved in the application of the recommended algorithms and the consequent effects on the positioning errors, under typical atmospheric conditions for MSAS. Airport locations and the weather in Japan were first studied.

In order to assess the accuracy of SBAS atmospheric models and their applicability to the Japanese MSAS, different analyses were carried out using the data from flight tests conducted in the summer and winter as well as data for a week collected at 2 control stations. Two sites selected for the evaluation were Rifu and Tamaki located near Sendai and Naha airports. The effect of using different atmospheric correction models on positioning was analyzed and preliminary results were obtained.

The differences in the trpospheric delay were computed. In Sendai, the differences in the delay between Saastamoinen and SBAS models were 4 mm for the satellite at the zenith in August. The same differences for the satellite at 10° elevation angle were 1.5 cm in August and -47 cm in December.

The normal values for meteorological data taken from the *Rika Nempyo (Chronological Scientific Tables)* were used as the input for the Saastamoinen tropospheric delay model. The differences between Saastamoinen and SBAS models were more important in Tokyo, in particular during the winter period. The differences in the total zenith delays were about 8 cm between December and March. In January, the differences were of 30 cm at 15° and 45 cm at 10°. The SARPS recommended SBAS model had a better fit with the Saastamoinen model in Naha all the year around.

From our data processing, the differences appeared in height due to the use of different tropospheric models were about 25 cm between Saastamoinen and SBAS, in December, about 15 cm between Saastamoinen and SBAS in August.

Increasing the elevation mask angle could reduce the positioning errors caused by the SBAS model errors. However, some epochs were rejected at higher elevation cut-off angles. During GPS Week 1118, for example, about 18 minutes of data were rejected every day due to poor satellite geometry (number of satellites and PDOP) at an elevation mask angle of 15°. A ranging capability of MTSAT would be important in some areas over Japan.

Rifu and Tamaki respectively had about 20 cm and 2 cm of mean difference in the vertical component between the Saastamoinen and SBAS models during GPS Week 1118. Although, the Sendai area has larger difference than Naha area, the differences by the use of various troposheric models were minor and therefore, SBAS models would be applicable to MSAS.

The results show that accuracy of SPS was significantly improved after SA was turned off. The accuracy of height determination was better than 10 m at 95% during the flight in December. The major source of errors was the ionosphere, which provides 2.5 m of difference between different corrections. Corrections for the ionosphere would be more important than those for the troposphere and we expect further study on the development of the correction model for the ionosphere.

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REFERENCES

Bisnath, S.B. & R.B. Langley (2001); Precise Orbit Determination of Low Earth Orbiters with GPS Point Positioning, Proceedings of the ION National Technical Meeting, Long Beach, California, U.S.A., January, pp. 725-733.

Collins, J.P. (1999); Assessment and Development of a Tropospheric Delay Model for Aircraft Users of the Global Positioning System, Department of Geodesy and Geomatics Engineering, Technical Report No. 203, University of New Brunswick, Fredericton, N.B., Canada, 174 p.

Collins, J.P. & R.B. Langley (1998); The Residual Tropospheric Propagation Delay: How Bad Can it Get?, Proceedings of GPS'99, the 11th International Technical Meeting of Satellite Division of the U.S. Institute of Navigation, Nashville, Tennessee, U.S.A., September, pp. 729-738.

Dodson, A.H., W. Chen, H.C. Baker, N.T.Penna, G.W. Roberts, R.J. Jeans & J. Westbrook (1999); Assessment of EGNOS Tropospheric Correction Model, Proceedings of GPS'99, the 12th International Technical Meeting of Satellite Division of the U.S. Institute of Navigation, Nashville, Tennessee, U.S.A. pp.1401-1407.

Doherty, P.H., Smithan, M.C., Delay, S.H. & G.J. Bishop (1999); Determination of Position Errors for Single Frequency GPS Receivers, Proceedings of the 55th Annual Meeting of the U.S. Institute of Navigation, Cambridge, Massachusetts, U.S.A., June, pp. 355-362.

Hay, C. and J. Wong (2000); Enhancing GPS: Tropospsheric Delay Prediction at the Master Control Station, GPS World, Vol. 11, No. 1, January, pp. 56-61.

Hofmman-Wellenhof, B., Lichtenegger, H. & Collins J. (1994); Global Positioning System: Theory and Practice, Third edition, Springer-Verlag Wein and New York, 355 p.

ICD-GPS-200C (1999); Navstar GPS Space Segment/Navigation User Interface Control Document, GPS Navstar JPO, 138 p.

Kawai, M. Nakao, H. Wakasa, K. Hoshinoo, K. & M. Ito (2000); GPS/SBAS Receiver Flight Test in Japan, Proceedings of GPS'2000, The 13th International Technical Meeting of Satellite Division of the U.S. Institute of Navigation, Salt Lake City, Utah, U.S.A., pp. 266-276.

Langley, R. (1997); The GPS Error Budget, GPS World, Vol. 8, No. 3, March, pp. 51-56.

Leick, A. (1995); GPS Satellite Surveying-Second Edition, John Wiley & Sons, Inc., New York, U.S.A., 560 p.

Mendes, V.B. & R.B. Langley (1998); Tropospheric Zenith Delay Prediction Accuracy for Airborne GPS High-Precision Positioning, Proceedings of the 54th Annual Meeting of the U.S. Institute of Navigation, Denver, Colorado, U.S.A., June, pp. 337-347.

Nakao, H. Kawai, M. & K. Wakasa (1999); The First Prototype GPS/WAAS Receiver in Japan, Proceedings of GPS'99, the 12th International Technical Meeting of Satellite Division of the U.S. Institute of Navigation, Nashville, Tennessee, U.S.A., September, pp. 189-197.

Niell, A.E. (1996); Global Mapping Functions for the Atmosphere Delay at Radio Wavelengths, Journal of Geophysical Research, Vol. 101, No. B2, pp 3227-3246.

NRCC - National Research Council Committee on the Future of the Global Positioning System (1995); The Global Positioning System: A Shared National Asset, National Academy Press, Washington, D.C., 264 p.

RTCA (1999): Minimum Operational Performance Standards for Global Positioning System/Wide Area Augmentation System Airborne Equipment, RTCA/DO-229 B, October, 255 p.

Saastamoinen, J. (1973); Contributions to the Theory of Atmospheric Refraction, Part II Refraction Corrections in Satellite Geodesy, Bulletin Geodesique, pp. 13-34.

APPENDIX

The formulae of the tropospheric models used in the analysis are listed in the following.

Saastamoinen Model

Tropospheric delays for the satellite (the zenith angle z) using Saastamoinen model are computed as:

$$\Delta_{Trop} = \frac{0.002277}{\cos z}\left\{p + \left(\frac{1255}{T} + 0.05\right)\cdot e - B\tan^2 z\right\} + \delta R \quad (1)$$

where p is the atmospheric pressure in millibars, e is the partial pressure of water vapor in millibars, T is the temperature in Kelvins, z is the zenith angle, and B is the correction term for the refined Saastamoinen model and takes values from the table. The values are for example, 1.156 for the height 0 m and 1.079 for 0.5 km. δR is the correction term for the northern latitude over 60°. There is no need for this term for Japan.

Hopfield Model

In the Hopfield model, the total delay is expressed with the sum of the two components.

$$\Delta_d^{Trop}(E)=\frac{10^{-6}}{5}\frac{77.64\frac{p}{T}}{\sin\sqrt{E^2+6.25}}\{40136+148.72(T-273.16)\}$$

$$\Delta_w^{Trop}(E)=\frac{10^{-6}}{5}\frac{-12.96T+3.718\cdot 10^5}{\sin\sqrt{E^2+2.25}}\frac{e}{T^2}\cdot 11000 \qquad (2)$$

Most of the parameters are the same as in the formula of the Saastamoinen model. E is the elevation angle in degrees.

SBAS Correction Models

The ICAO Standard and Recommended Practices (SARPS) recommend the application of an empirical correction algorithm, based on a receiver's height and estimates of five meteorological parameters (pressure, temperature, water vapor pressure, and temperature and water vapor lapse rates) using average and seasonal variation data related to the receiver's latitude and day-of-year (Collins 1999, Collins & Langley 1998).

Each meteorological parameter is computed using the following equation:

$$\xi(\phi,D)=\xi_0(\phi)-\Delta\xi(\phi)\cdot\cos\left(\frac{2\pi(D-D_{\min})}{365.25}\right) \qquad (3)$$

where $D_{min}=28$ for northern latitudes, $D_{min}=211$ for southern latitudes, and ξ_0 and $\Delta\xi$ are the average value and seasonal variation for a particular parameter at the receiver's latitude, obtained through a linear interpolation. ϕ and D are the receiver latitude and day-of-year.

The zenith delays at sea level for the hydrostatic and wet parts are calculated using Equations (4) and (5) respectively.

$$z_{hyd}=\frac{10^{-6}k_1R_d\,p}{g_m} \qquad (4)$$

$$z_{wet}=\frac{10^{-6}k_2R_d}{g_m(\lambda+1)-\beta R_d}\cdot\frac{e}{T} \qquad (5)$$

where p, T, e, λ and β are pressure, temperature, vapor pressure, water vapor lapse rate and temperature lapse rate at the given latitude, and k_1, k_2, R_d, and g_m are constant coefficients.

The zenith delay at a particular height H is computed using Equations (6) and (7).

$$d_{hyd}=\left(1-\frac{\beta H}{T}\right)^{\frac{g}{R_d\beta}}\cdot z_{hyd} \qquad (6)$$

$$d_{wet}=\left(1-\frac{\beta H}{T}\right)^{\frac{(\lambda+1)g}{R_d\beta}-1}\cdot z_{wet} \qquad (7)$$

The tropospheric delay mapping function for satellite elevation, $m(E)$, is calculated as:

$$m(E)=\frac{1.001}{\sqrt{0.002001+\sin^2 E}} \qquad (8)$$

This mapping function is valid for satellite elevation angles of not less than 5°.

The tropospheric delay d_α at a particular elevation angle is then calculated as:

$$d_\alpha=(d_{hyd}+d_{wet})\,m(E) \qquad (9)$$