A Comparative Study of SBAS Systems for Navigation in Geostationary Orbit

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BIOGRAPHIES

Erin Kahr is currently a PhD candidate in the Position, Location and Navigation group in the University of Calgary's Geomatics Engineering Department, and is co-supervised in the GNSS Technology and Navigation Group at Germany's Space Agency, DLR. Her current research topic is the use of multi-constellation GNSS for relative positioning outside of the main GNSS service volume, and her master's research focused on operating the GPS receiver on board the CanX-2 CubeSat.

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Oliver Montenbruck is head of the GNSS Technology and Navigation Group at DLR's German Space Operations Center. His current research activities comprise space borne GNSS receiver technology, autonomous navigation systems, spacecraft formation flying, precise orbit determination, and multi-constellation GNSS.

ABSTRACT

Real data has been collected from space demonstrating the CanX-2 receiver's ability to track the WAAS, EGNOS, GAGAN, and MSAS systems. Two types of analysis were performed, in order to assess the suitability of SBAS ranging measurements as a source of positioning information for users in geostationary and other higher orbits, in which SBAS satellites may be permanently in view while GPS visibility is severely limited by the shape of the transmit gain patterns.

The first analysis, of the transmit gain patterns of the EGNOS, WAAS, MSAS and GAGAN systems, revealed that all the SBAS satellites transmit enough power to be tracked over the earth's limb. It was revealed that GAGAN has a narrower gain pattern than the other SBAS systems. WAAS and EGNOS appear to have similar gain patterns but WAAS has a higher transmit power by 2-4 dB, and MSAS appears to transmit lower signal power than the other systems but uses an antenna design providing more even global coverage which results in and stronger power transmitted towards the edge of the earth.

The second study determined that the SBAS ranging capability was useable in space, provided that the fast correction data transmitted by the SBAS satellites is applied in addition to the MT9 broadcast ephemeris. The SBAS ranging residuals were assessed compared to GPS single point position solutions in space and on the ground, and were found to agree to within +/- 10 m in most cases for WAAS and +/- 20 m for MSAS and GAGAN. EGNOS does not support ranging.

Provided the lower accuracy compared to GPS is taken into account, the SBAS systems could be used to provide positioning and timing information to users in GEO or other orbits above the MEO GNSS constellations.

INTRODUCTION

GNSS positioning above the GNSS constellations, for satellites in geostationary (GEO) and highly elliptical (HEO) orbits is a growing field of research. The crowding in the geostationary orbit in particular is leading to tighter positioning requirements for station keeping, which is a driving reason for the renewed interest in putting GNSS receivers on geostationary satellites. Another important reason for the revived interest in GNSS based HEO navigation is electric propulsion orbit transfer from LEO to HEO. Autonomous GNSS navigation can help to reduce the costly ground infrastructure and operations during this time consuming mission phase. In keeping with these trends, a space service volume has been defined for the first time for the GPS Block III satellites (IS-GPS-200H) and results have recently been published for a dual frequency GPS receiver flying on board the SBIRS-1 GEO satellite (Barker and Frey 2012), for the

SGR-GEO L1 C/A GPS receiver flying on board GIOVE-A (Unwin et al 2014), and for the HEO Magnetosphere Multiscale Mission (Bauer 2015). Test flights of the Chinese Chang'E-5T moon probe and of NASA's Orion vehicle were also both recently launched carrying GPS receivers outside the standard service volume, but detailed GNSS results have yet to be published.

The main challenges of positioning in GEO and HEO stem from the fact that all GNSS systems have directional transmit antennas, which limit the number and strength of visible signals above the constellations as shown in Figure 1. Typically only signals spilling over the earth's limb from GNSS satellites on the far side, and occasionally side lobe signals, are strong enough to acquire and track. The positioning geometry is weak and there are rarely enough measurements for a position solution.

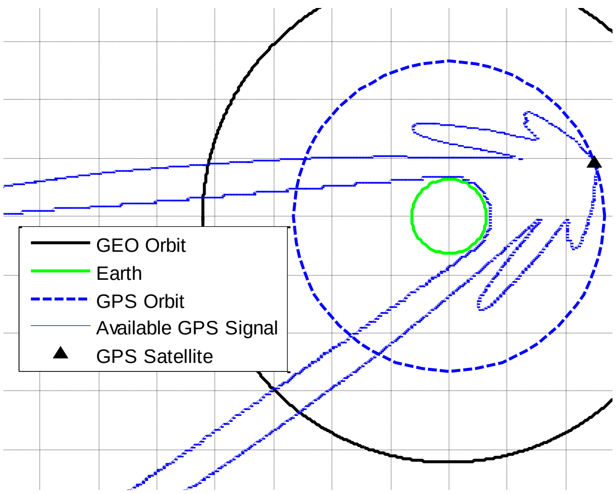

Figure 1: Typical visibility of a GNSS satellite to a user in GEO, based on a 33 dB-Hz availability threshold and the GPS transmit gain pattern from Czopek and Schollenberger (1993)

While the defined space service volume and hardware with space flight heritage are GPS-only, making use of the other constellations has already been shown to have significant benefits for GEO and HEO navigation (Kahr 2013, Lorga et al 2010, Qiao et al 2009). One possible source of navigation signals that has yet to be explored for use in HEO and GEO are the Satellite Based Augmentation Systems (SBAS). There are currently five SBAS operating or under development: American WAAS, European EGNOS, Indian GAGAN, Russian SDCM and Japanese MSAS. The Japanese Quazi-Zenith Satellite System (QZSS) also transmits SBAS signals.

Each system consists of two or three geostationary satellites, which broadcast clock, orbit and atmospheric corrections as well as integrity data to GPS users on the GPS L1 and, in the future L5, frequencies. Previous studies have assessed the use of SBAS transmitted corrections for space users in low earth orbit (Kim and Lee 2015, Kim and Kim 2015), but aside from a few studies assessing the measurement quality (Wanninger 2008, Rho and Langley 2008) and a preliminary study of the SBAS orbit determination capability (Pogorelc et al 1997) the ranging function of the SBAS satellites has largely been ignored.

Unlike GNSS, the SBAS satellites do not carry atomic clocks but are actively monitored and controlled by a network of ground stations, with their broadcast messages being generated on the ground and retransmitted to users from the satellites in a bent-pipe transponder design. The data rate is 250 bits/second, five times faster than GPS L1 C/A navigation data. With the exception of EGNOS system (EGN-SDD SoL, V1.0) the SBAS also support ranging, which means that their measurements can be integrated into GPS positions solutions as additional GPS-like measurements. Each system provides corrections and integrity data valid in a limited country or region, but the end result is a fairly even global availability of SBAS ranging signals which are not service area specific. The current locations of the SBAS satellites, based on NORAD two line elements, are shown in Figure 2. Note the SDCM system is still under development and testing, and the PRN assignments may change.

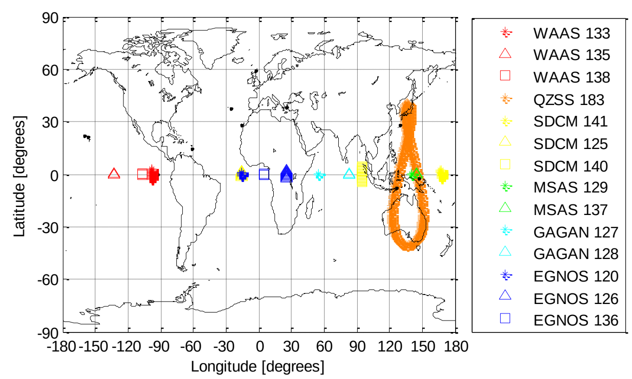

Figure 2: Distribution of SBAS satellites globally

Depending on its longitude, a geostationary satellite attempting to use GNSS for positioning could gain a significant benefit from tracking inter-visible SBAS satellites over the earth's limb, because they are in the same orbital plane and would therefore be permanently in view. The benefit is demonstrated in Figure 3, which shows the number of visible GPS and SBAS satellites from a GEO satellite in a longitude slot of 60 degrees west, where both MSAS satellites are visible.

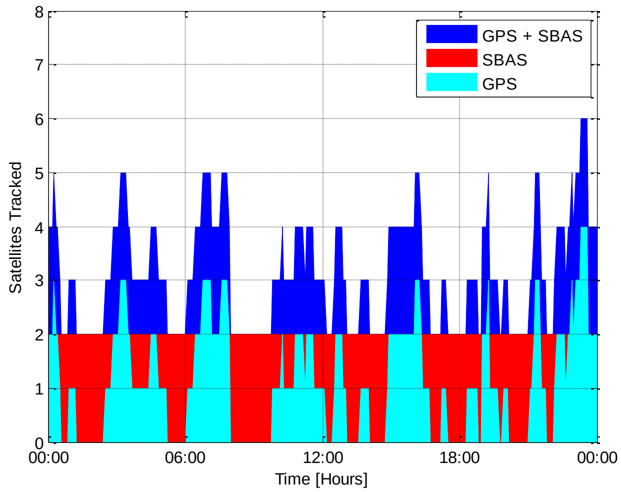

Figure 3: Theoretical visibility of GPS, SBAS, and both from GEO satellite at 60 degrees west, assuming a downward pointing hemispheric gain antenna, an acquisition threshold of 37 dB-Hz, a tracking threshold of 30 dB-Hz, and the WAAS prototype transmit gain pattern from Figure 7 for all SBAS

However, for the SBAS satellites to be considered as a viable source of above-the-constellation positioning information, several important questions come up:

- Does their bent-pipe transponder design prevent a useable level of signal accuracy outside of their specified service areas?
- What do the transmit antenna gain patterns look like? Do they transmit directionally towards their service areas, or are they designed to maintain a constant power by compensating for the earth's curvature similar to the GPS antenna designs?
- Does any signal power spill over the earth's limb? Is the spill-over concentrated over the northern hemisphere? Does it offer sufficient power for acquisition and tracking?
- Does the higher rate navigation data make acquisition or tracking from space more challenging?

The GPS payload onboard the CanX-2 CubeSat has offered a unique opportunity to study the SBAS systems. Because they are geostationary, it is impossible to get a uniform global comparison between the systems, particularly in terms of signal power, from the earth's surface. No two antenna and receiver combinations have exactly the same link budget, because of subtle differences in the antenna, LNA, cables, front end design and internal processing algorithms. A direct comparison of data collected with different user hardware is therefore unlikely to produce meaningful results. Additionally, studying SBAS signal power from fixed receivers on the earth's surface has the disadvantage of fixed viewing geometry, with the SBAS satellite remaining at the same elevation in the receiver's field of view. Mapping the gain patterns from the earth would therefore require a significant level of international cooperation, and even data coverage over the earth's surface would be unlikely.

In contrast, CanX-2's low earth orbit allows for a single unchanging receiver and antenna pair to circle the earth, tracking arcs of SBAS data that are well distributed spatially, in order to consistently map the signal strengths of the SBAS navigation signals. It also allows for an initial assessment of the ranging accuracy from a space borne receiver.

The remainder of this paper has been divided into three main sections. The first section is a brief overview of the CanX-2 mission, the hardware it carries, and the SBAS tracking experiment. The second section presents the transmit gain pattern study, and the third section presents the achieved SBAS ranging accuracy on the earth and in space. Finally, the conclusions about the suitability of SBAS as a source of positioning information above the GNSS constellations are presented.

THE CANX-2 MISSION AND SBAS EXPERIMENT

CanX-2 is a three unit CubeSat measuring 35 x 10 x 10 cm. It was designed and built at the University of Toronto's Space Flight Laboratory, and launched into a near polar, 630 km orbit on April 28, 2008. Its orbit is sun-synchronous with a 9:30 am descending node, and a 98^{o} inclination (Sarda et al 2009).

CanX-2 carries a commercial, geodetic grade NovAtel OEM4-G2L dual frequency L1/L2 GPS receiver as a scientific payload. The antenna is a dual frequency AeroAntenna AT2775-103 patch antenna, with a roughly hemispheric gain pattern. While the GPS receiver and antenna were originally intended for a radio-occultation experiment, the design of the commercial receiver allowed for SBAS tracking functionality to be unlocked years after its launch. In September 2013, the receiver was therefore upgraded to an SBAS capable receiver, and the focus of the GPS experiment changed.

Two channels, previously dedicated to tracking L1 and L2 signals from a GPS satellite, were converted to SBAS L1 channels by applying a new software license code. At the time that the receiver's original firmware was released in 2004 only the American WAAS was formally supported, but thanks to a forward thinking design PRNs 120-139 are all defined in the receiver, making it possible to track WAAS, EGNOS, GAGAN, and MSAS satellites which all share an identical L1 signal and data structure.

While the receiver's performance on CanX-2 was already been well documented prior to the SBAS capability being turned on one important point to reiterate is that the GPS payload suffers from a lower than expected signal power level which was only diagnosed after launch (Kahr et al 2011). The result is that the reported carrier to noise density ratios are roughly 10 dB lower than would normally be expected for a geodetic grade receiver in the same setting, and the measurements experience a corresponding increase in noise, both of which impact the results of the current study.

Another aspect of the mission design which impacts the current study is the CubeSat's attitude determination and control system (ADCS). The satellite benefits from a system based on sun-sensors, magnetometers and a dynamics wheel. The long axis of the satellite is aligned with orbit normal, and the pitch angle can be actively controlled such that the GPS antenna, which is mounted on the +z face of the satellite, can be pointed in a desired direction in the orbital plane. During GPS data collections the antenna is typically pointed either to zenith or rearward, depending on the experiment goals. While the attitude control was previously accurate to 5 degrees (Sarda et al 2009), recent analysis shows that it has degraded over CanX-2's seven years in orbit. While the nominal attitude is still achieved some of the time, logged attitude data suggests that sudden rotations and drifts on the order of tens of degrees can occur.

The GPS payload is operated on a rotating experiment schedule, and is limited to arcs of approximately 85 minutes in duration due to power, data volume and attitude control system constraints of the CubeSat. The result is that approximately every third month is dedicated to GPS experiments, with a few data sets collected each week during GPS data campaigns.

A total of 61 data takes demonstrating successful SBAS tracking have been collected since October 2013, the majority of which were collected with a zenith pointing GPS antenna for more reliable tracking, while ten were collected with a rear pointing antenna in an attempt to better assess the signals tracked over the earth's limb.

All of the fully operational WAAS, EGNOS, MSAS and GAGAN satellites were successfully tracked, as well as one of the newer EGNOS satellites, PRN 136. Several attempts were also made to track the Russian SDCM system's PRN 125 satellite (SDCM also consists of PRNs 140 and 141 which are outside of the NovAtel receiver's defined range), but either SDCM was not yet fully operational at the time of the attempts (supported by Stupak 2015) or the data structure was not sufficiently similar to the other SBAS systems to be tracked by the CanX-2 receiver. The Japanese QZSS system also transmits SBAS signals on PRNs not defined in CanX-2's receiver. Both SDCM and QZSS have therefore been excluded from the remainder of the study.

SBAS SIGNAL POWER

The first goal of the CanX-2 SBAS experiment was to map the transmit gain patterns of the SBAS satellites, which is of particular interest for potential users in GEO and HEO orbits. The SBAS transmit gain patterns are largely unknown because unlike GNSS satellites which are mass produced in blocks, each SBAS system and possibly also each satellite has a unique design, and very little is ever published about them. No assumptions can be made about SBAS satellites having similar transmit signal power or gain characteristics over the earth's limb, which is a significant drawback when attempting to analyze the performance in GEO with simulation studies. This section of the paper attempts to shed light on the similarities or differences in the SBAS transmit patterns based on real tracking data from CanX-2, and compares the findings to the few gain patterns found in literature.

While CanX-2's low earth orbit is not ideal for this study, it allows for an understanding of the centers of the transmit antenna gain patters, which are a good indication of how different the designs of the SBAS transmit antennas are. It also provides a first indication of whether tracking off the edge of the earth is possible. A sample map showing the tracking results for GAGAN PRN 127 is shown in Figure 4. Each line is a CanX-2 tracking arc, colored based on the measured C/N_0 value. The signal powers of the other active SBAS satellites have likewise been mapped from CanX-2's low earth orbit.

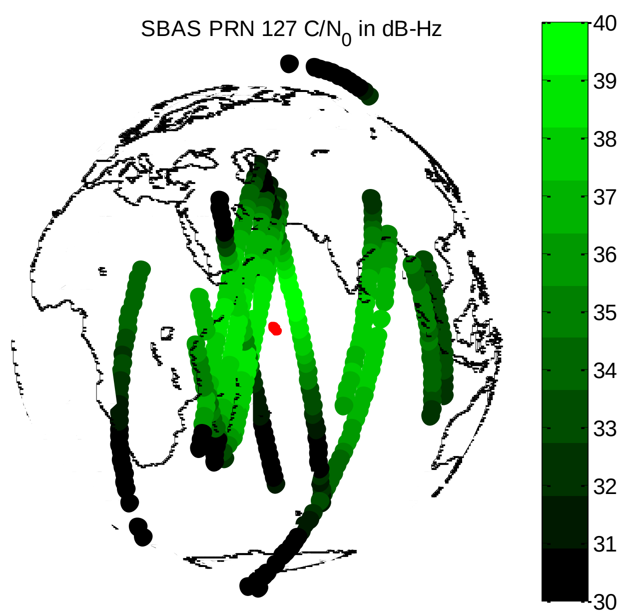

Figure 4: GAGAN PRN 127 (red) and CanX-2 tracking arcs colored by C/N_0

From the figure, several of the results of this study are immediately apparent. First, it's clear that the high rate

SBAS data in no way prevented acquisition or tracking of the signals from a receiver in space, which is in keeping with the earlier ENEIDE mission results (Zin et al 2007). The SBAS signal strength is in fact centered at the equator, and sufficient power spills over the earth that CanX-2 was able to track at least one satellite from each of the four studied SBAS systems over the earth's limb both in the northern and southern hemispheres. CanX-2's orbit and attitude profile unfortunately make the collection of East/West data arcs, which would be more relevant to GEO tracking, impossible.

Approximately 10 dB lower carrier-to-noise-density ratios (C/N_0) are observed from CanX-2 compared to typical values observed on the earth's surface, which are in keeping with the equipment onboard the CubeSat, and not a difficulty in tracking SBAS. Given the additional free space path loss to a receiver in GEO or HEO, this is also an early indication that the signal power would still be sufficient to track the SBAS satellites in higher orbits if more favorable hardware (and a more favorable attitude profile) was used.

The link budget equation describing the carrier to noise density ratio (C/N_0) in dB-Hz at a GNSS receiver is shown below, where EIRP is the equivalent isotropically radiated power in dB-W, G_{Tx} and G_{Rx} are the transmit and receive antenna gains in the direction of the line of sight in dB, L_{path} and L_{atm} are the free space path loss and atmospheric loss in dB respectively, K_B is Boltzmann's constant in dBW/kHz, and T_{sys} is the system noise temperature in dBK. (Van Dierendonck 1997) The first five terms describe the signal strength, while the final two terms describe the noise.

$$C/N_0 = EIRP + G_{Tx} - L_{path} - L_{atm} + G_{Rx} - K_B - T_{sys}$$

In order to better analyze systematic differences, the observed C/N_0 values were adjusted to remove Boltzmann's constant K_B, free space path loss, L_{path}, and the CanX-2 receive antenna's gain pattern, G_{Rx}. CanX-2's gain was measured in an anechoic chamber with a mock-up of the satellite before launch, and validated against the flight results in Kahr et al 2011. Atmospheric loss, L_{atm}, is assumed to be zero. Data points collected when the CanX-2 nominal and measured attitudes differed by more than 10 degrees were rejected in order to overcome the attitude determination difficulties, resulting in only half of the roughly 3000 data points collected across all satellites, all systems being included in the gain pattern analysis.

The remaining quantity, EIRP + G_{Tx} - T_{sys}, was plotted for each SBAS satellite as a function of angle off-boresight, assuming rotationally symmetrical gain patterns and nadir pointing transmit antennas for the SBAS satellites. A mean value of was calculated for each 1 degree bin. A sample figure for GAGAN PRN 128 is shown in Figure 5 below, where the points are colored based on whether they were collected in the northern or southern hemisphere in order to highlight systematic differences.

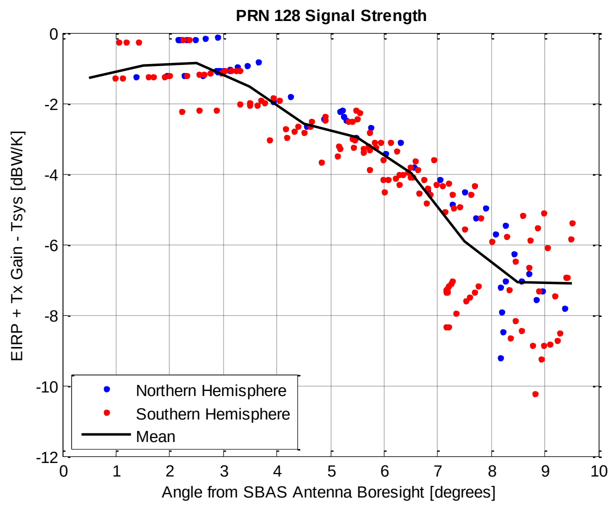

Figure 5: Corrected Signal Strength on GAGAN PRN 128, reflecting the transmit antenna gain pattern

The greater noise in the data after roughly 8.5 degrees off-boresight is a result of the fact that CanX-2 is beyond the edge of the earth. Some signals are tracked at low positive elevations while CanX-2 is still on the same side of the earth as the SBAS satellite, while others are tracked over the earth's limb at negative elevations in the receiver's field of view. The receive antenna gain characteristics at negative elevations are poorly understood, as the signals are either passing through or refracting around the body of the CubeSat.

It is not possible to separate out the remaining three quantities in the figure: system noise temperature, EIRP and transmission gain. System noise temperature is dependent on the environment and hardware onboard CanX-2. A typically value for a geodetic receiver would be ~23 dB-K (Lachapelle 2009), but it is higher for CanX-2's setup. It is assumed that T_{sys} is a constant value common to all CanX-2 tracking, and does not significantly influence the comparison of SBAS systems with each other. EIRP is the total power transmitted by the SBAS payload on a particular satellite. The MSAS MTSAT-1R satellite, for example, has an EIRP of 31 dB–W (Kramer 2015) and the other SBAS systems are expected to transmit power on the same order of magnitude. The actual value however is not known for every system and satellite, therefore could not be calibrated out. The systematic differences in the curves of Figure 6 are therefore a combination of differences in the transmit gain patterns and EIRPs of the SBAS satellites.

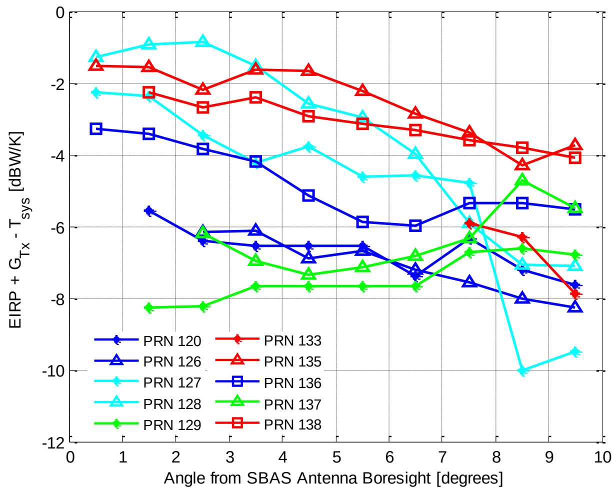

Figure 6: Comparison of the signal strength among SBAS satellites. WAAS is red, EGNOS is blue, GAGAN is cyan and MSAS is green.

It is possible to draw several conclusions from Figure 6. First, it appears that satellites from the same system share a similar antenna design, but have slight offsets in the power level on the order of 1 dB. The WAAS system has the highest overall power level, and seems to have a transmit antenna pattern with the peak power at boresight and only a moderate drop off of about 2 dB in the first 10 degrees off-boresight. The signal is still strong enough to track past the edge of the earth. WAAS PRN 133 appears to have weaker power than PRNs 135 and 138 by 2-3 dB, which may explain why it was tracked so rarely in spite of dedicated efforts to acquire it. It also has a greater inclination than the other WAAS satellites, and therefore its orbit is not as well described by the SBAS almanac format over the time intervals between CanX-2 data takes, which may also have made acquisition less likely.

EGNOS seems to have a similarly shaped gain pattern to WAAS, but a lower power by roughly 4 dB on the two fully operational satellites, PRN 120 and 126. The newer satellite, PRN 136, appears to have a roughly 2 dB higher power than the older EGNOS satellites. The PRN 136 results are however less reliable than the other curves, because the satellite began transmitting later than the others, resulting in a limited number of CanX-2 data arcs during which it was tracked. The limited available data is likely the cause of the dip in signal power at 6 degrees off-boresight.

The GAGAN gain pattern appears to be narrower than WAAS or EGNOS, with a steep drop off of roughly 6 dB at 10 degrees off-boresight, as compared to the center of the pattern. This is an indication that GAGAN is less suitable for space users in GEO, and is probably visible in a narrower window near the earth's surface unless the narrow main beam is accompanied by strong side-lobes.

Finally, the MSAS system pattern shows a completely different trend than the others. While it has the weakest signal levels overall, it also appears to have an antenna design which curves around the earth in order to mitigate free-space path loss for users anywhere on the earth's surface, in spite of its smaller service area. This is a similar design concept to the MEO navigation satellites.

One interesting feature of the MSAS system is that for continuity of service, both satellites can transmit either or both of the assigned MSAS PRNs (Montenbruck et al 2014). For the assessment here it has been assumed that each PRN was transmitted from its own satellite, as depicted in the map in Figure 2. However, both signals appear to have been transmitted from the same satellite over the course of several days in the spring of 2015, and it is possible that other such periods have had a minor influence in the result of this gain pattern study.

For comparison with the observation data, three transmit gain patterns from literature have been plotted from 0 to 10 degrees off-boresight and are shown in Figure 7. Interestingly, the literature pattern for QZSS (Noda et al 2010) is the only gain pattern for a geosynchronous satellite which follows the earth's curvature, and like MSAS is also a Japanese system. The observed MSAS pattern however appears to be wider than the documented QZSS gain pattern, with a peak gain at roughly 10 degrees off-boresight, as opposed to the QZSS pattern's peak at 5 degrees off-boresight. The EGNOS and WAAS patterns agree reasonably well with the literature pattern for GAGAN (Jyoti et al 2005), while the actual GAGAN gain pattern appears to be much narrower, matching the WAAS prototype patch antenna pattern (Iriarte et al 2009). In spite of a long search, no further SBAS gain patterns were found in literature.

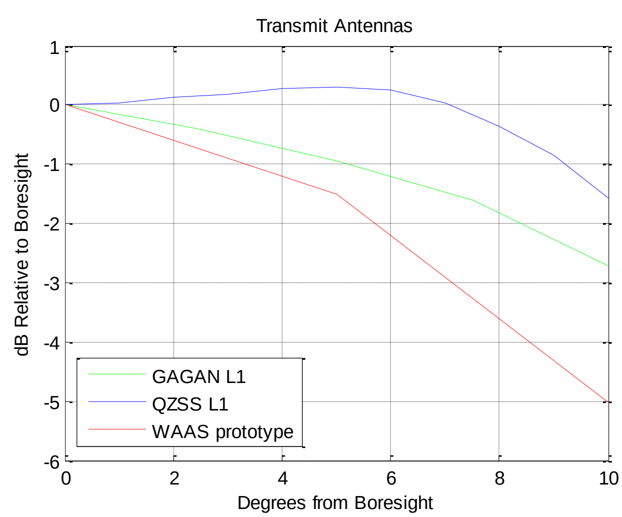

Figure 7: Transmit gain patterns found in literature, for GAGAN, QZSS and a prototype patch antenna design suggested for the WAAS system.

Finally, a last interesting result was discovered when the points for the WAAS system were colored based on hemisphere. It appears that the WAAS system transmits roughly 1-2 dB higher power to users in its service area in the northern hemisphere than towards the southern hemisphere. A sample plot for PRN 135 is shown in Figure 8, and the PRN 138 results (not shown) reveal an equally strong trend. While this may impact space users, as a result of the higher noise level in the CanX-2 data it is not possible to see a significant difference in signal power spilling over the earth in the northern versus southern hemispheres. The only non-WAAS satellite to exhibit a similar trend is the newer MSAS satellite, MTSAT-2, although the trend was not as pronounced as it is for the WAAS satellites.

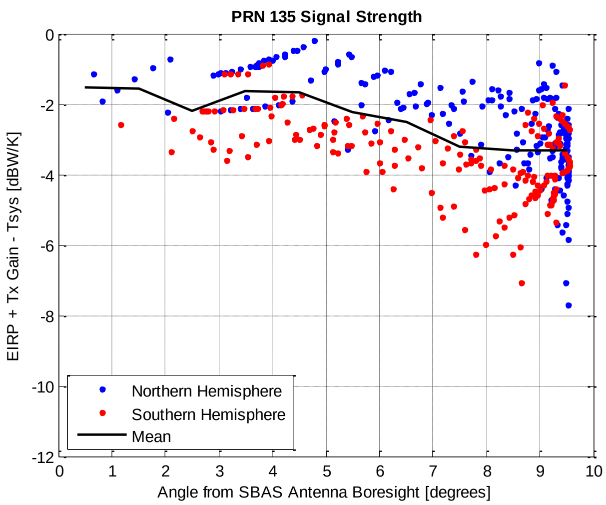

Figure 8: WAAS prn 138 signal power colored by hemisphere. The northern hemisphere appears to benefit from 1-2 dB more gain than the southern hemisphere.

RANGING DATA ACCURACY

While the CanX-2 flight results indicate that SBAS tracking off the edge of the earth is possible, in order to make use of the ranging signals for positioning in HEO they must also be adequately accurate. Ranging accuracy is particularly important to a HEO or GEO user, because the weak geometry and minimum signal level can make the position solution particularly susceptible to bad measurements. Because each SBAS system is monitored and actively controlled by a network of ground based stations in a somewhat limited geographical area, there is no guaranteed level of service for a user in space or even outside the specified coverage area. It is important to understand whether the SBAS signals outside of their service area suffer from different atmospheric effects or residual clock effects requiring special handling.

Because EGNOS officially does not support ranging, and does not transmit sufficiently accurate broadcast ephemeris information for positioning (EGN-SDD SoL, V1.0), this part of the study has been limited to WAAS, GAGAN and MSAS. A previous study assessing the accuracy of the WAAS L1 and L5 signals was published in 2008, which characterized signal noise and biases, and found that the WAAS signals were predictably noisier than GPS (roughly 4 m, as compared to 1 m for GPS), in keeping with the narrower transmitted bandwidth (Rho and Langley 2008). Similar conclusions were drawn by Wanninger (2008). Unlike the previous studies, this section of the paper presents an assessment of SBAS absolute ranging accuracy based on positioning residuals, and also investigates the ranging accuracy beyond the SBAS service areas, which is of particular importance for space users attempting to position over the earth's limb.

Because CanX-2 offers only short data arcs and suffers from significant measurement noise, even a reduced dynamic orbit solution is limited to a few meters of accuracy at best (Kahr et al 2011). Due to the lack of a reliable truth solution for comparison, ranging data from the global network of MGEX IGS stations has been used for the majority of the SBAS ranging accuracy study rather than the CanX-2 data. In addition to the benefits of static setups, the MGEX stations provide longer data arcs for a more thorough assessment.

In order to calculate SBAS range residuals, single point position solutions were calculated making use of GPS and SBAS measurements. At each data epoch, three position unknowns, GPS system time, and a GPS-SBAS inter-system time bias were estimated. The amount of input data was limited such that only one SBAS satellite was included in the positioning solution. As a result, the inter-system bias is minimally constrained, and is essentially the residual of the SBAS measurement as compared to the single point GPS solution. It reflects both any actual timing differences between the SBAS satellite time and GPS system time, as well as any other errors on the SBAS range measurement and model.

For a consistent handling of the systems, single frequency data was used for all GPS and SBAS measurements. Ionospheric corrections were applied from the Ionex files available from the University of Bern's Center of Orbit Determination in Europe (CODE), and both tropospheric corrections and differential code biases were also applied. For the GPS constellation, precise orbit and clock products from the IGS were used. For the SBAS systems no precise products are published, so the SBAS Message Type 9 broadcast ephemerides were used.

The SBAS broadcast ephemerides alone are not sufficiently accurate to use for ranging, because the data suffers from large residual clock errors on the order of 100 m. To get sufficiently accurate ranging information, the fast corrections must be applied to the ranging data in addition to the clock term in the broadcast ephemerides

(RTCA DO-229D), while the slow corrections should not be applied.

Insufficient data was originally logged to properly correct the SBAS ranges, either from the MGEX ground network or onboard CanX-2. In order to continue the study, three Septentrio receivers, including the MGEX stations in Yellowknife, Canada, and Sydney, Australia, as well as a receiver at DLR's Oberpfaffenhofen location in Germany, were configured to log the SBAS corrections of all SBAS satellites and systems for several weeks. Ultimately two sources of historical SBAS corrections are also publicly available, containing data for a few months after they are transmitted: the William J. Hughs FAA Technical Center website for WAAS and the CNES SERENAD server for all systems. The University of New Brunswick also has an archive of WAAS corrections from one satellite of more than 10 years, available to interested parties.

The dramatic improvement offered by the fast corrections over a week of GAGAN tracking is shown in Figure 9. Without the corrections, the SBAS ranging measurements are subject to clock errors of potentially a few hundred meters. These errors are present in all three SBAS systems, but appear to occur less frequently in the WAAS measurements.

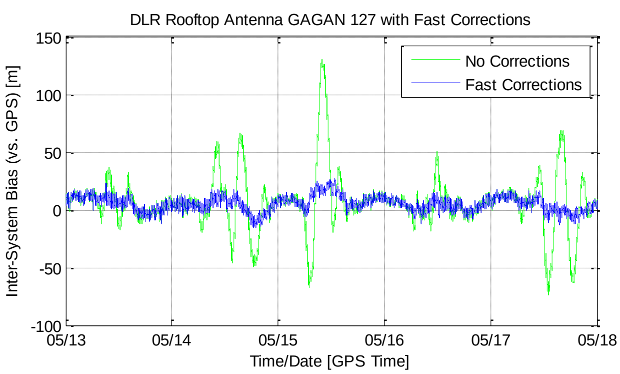

Figure 9: The PRN 127 residual/inter-system bias with and without applying fast corrections

The fast corrections are broadcast in messages 2-5 every six seconds, however to interpret them the PRN mask, which is transmitted in message 1 approximately every five minutes, is also required. The PRN mask is only expected to change when GNSS satellites are launched or reach the end of service. Message 7 also complements the fast corrections, by providing information about the duration of their validity.

The stability and absolute accuracy of the SBAS ranging measurements, with fast corrections applied, for both MSAS satellites are show in Figure 11, for both GAGAN satellites in Figure 12 and for all three WAAS satellites in Figure 13. In all three figures, the stations depicted with black inter-system bias curves are within the defined service areas, while the stations with the colorful curves are far outside the service areas. For reference, the locations of the MGEX stations used for the ranging data assessment are shown on the world map in Figure 10.

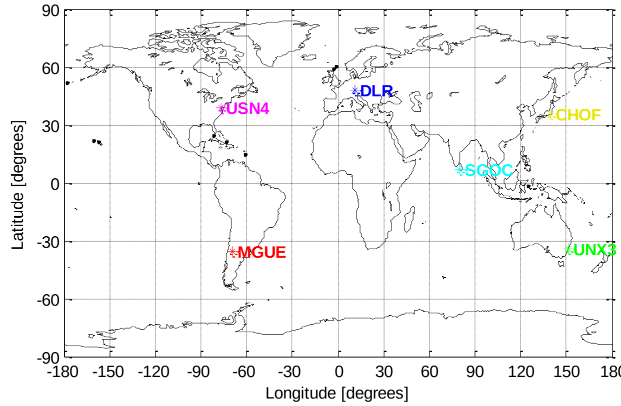

Figure 10: Locations of MGEX stations and receivers used in this study

From Figure 11, it can be seen that a residual timing bias is present in the data from the MSAS system, on the order of +/- 10 m. This timing offset compared to GPS system time is however consistent on both MSAS satellites (over this period each PRN was transmitted from its own satellite), and at both stations, in spite of a substantial geographic distance between them. This consistency suggests that the majority of the error could be eliminated by differencing measurements. Aside from a slight bias, which may be receiver hardware dependent, the ranging quality at the Sydney station, UNX3, was comparable to the quality at the Japanese station, CHOF, in the center of the MSAS service area.

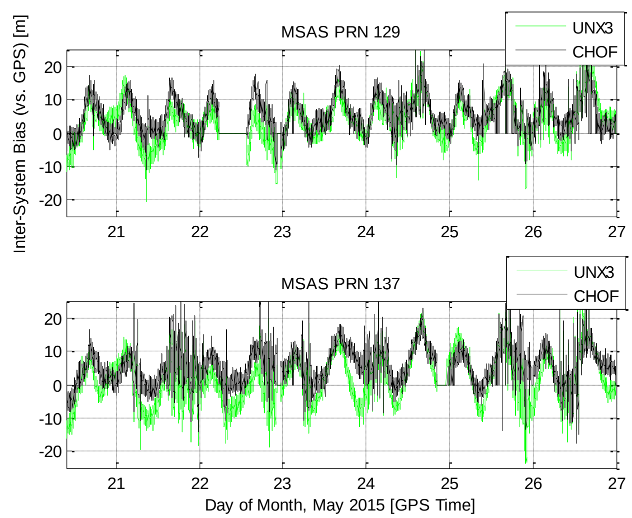

Figure 11: MSAS ranging errors compared to a GPS single point solution

A far more significant difference was revealed for the GAGAN measurement quality, in Figure 12. A very good ranging accuracy was obtained from the SGOC station in

Sri Lanka, off the southern tip of India, from mid-day May 21st until the end of the test period, with noisier measurements being obtained initially on the 20th and 21st. The combined time-varying and systematic ranging errors observed at SGOC were on the order of 5 m. On the contrary, the out-of-service-area receivers in Germany (DLR, PRN 127) and Sydney (UNX3, PRN 128) have much higher noise. Given the narrower GAGAN gain pattern and the extremely low elevations of the GAGAN satellites from DLR and Sydney, this higher noise is likely explained by difficult to model low elevation atmospheric effects and lower carrier to noise densities. Both the DLR and Sydney stations observed time-varying errors as well, which appear to be quite station dependent and inconsistent. Coupled with the lower signal power near the edge of the earth, GAGAN is less likely to provide good quality ranging information to geostationary satellites over the earth's limb than the other SBAS.

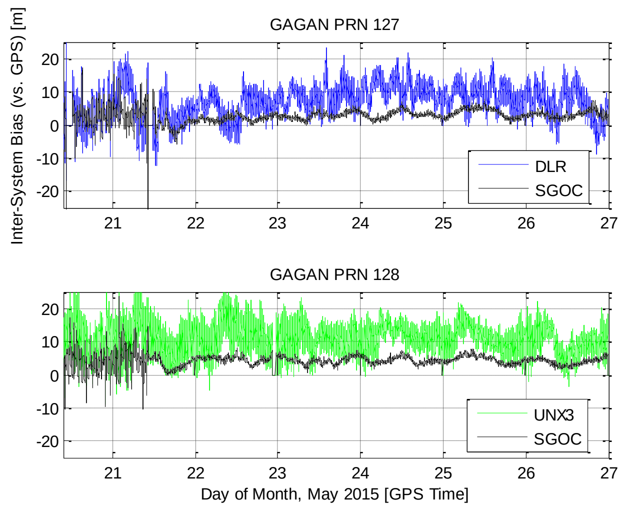

Figure 12: GAGAN ranging errors compared to a GPS single point solution

The WAAS system consistently provided the best performance, with lower time-varying errors and systematic biases, shown in Figure 13. This result is consistent with its larger ground monitoring network and service area. The performance from the MGUE station in South America is however noticeably worse than the performance at the US Naval Observatory's USN4 MGEX station in the continental US. At MGUE PRN 135 is subject to rapidly fluctuating range errors, and PRN 138 shows errors larger than those at USN4 but with the same frequency. The difference in the nature of the errors between the PRNs suggests that the effects are caused by remaining un-modelled atmospheric effects. Clock errors would be common to the station if they were caused by the receiver clock, common to the PRN if they were caused by the satellite clock, or common to both if they were caused by a system time offset as is the case with GAGAN. Because the satellites are geostationary, multipath and orbit errors would vary much more slowly with time if at all. PRN 133 had very consistent performance, but higher noise than the other WAAS satellites consistent with its lower observed signal power.

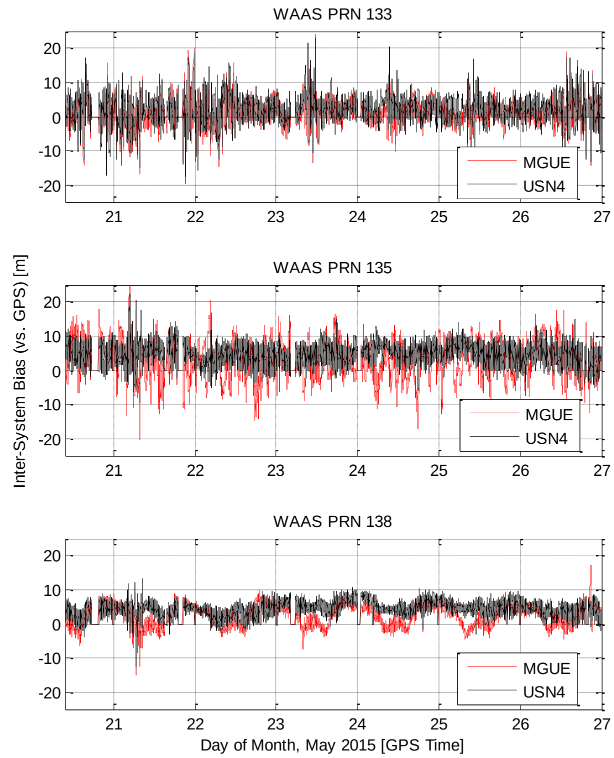

Figure 13: WAAS ranging errors compared to a GPS single point solution

As a final step, the most recent CanX-2 data sets for WAAS and GAGAN, corresponding to fast correction data collected simultaneously on the ground, were processed using the same technique as the ground based data. The results for WAAS PRN 138 are shown in Figure 14, overlaid on a world map to get a sense of the geographic dependence of the ranging accuracy. The figure demonstrates that a ranging accuracy of better than 10 m was generally achieved when the satellite was passing through the WAAS service area. Higher positioning residuals of up to 30 m can be observed when CanX-2 passes over the pole, particularly after CanX-2 begins to set and the WAAS satellite is tracked over the earth's limb. This result is not at all surprizing, as the WAAS satellite is being tracked at negative elevation through the body of the CanX-2 CubeSat, and the signal is passing through layers of increasing ionospheric density as the line of sight approaches the surface of the earth.

In order to mitigate these increased atmospheric effects over the earth's limb, dual frequency measurements could be used. The SBAS systems are being upgraded to transmit L5 as well as L1 signals, with L5 already transmitted from the WAAS and GAGAN satellites. Although it is not yet fully operational even on these systems, L5 will eventually be part of a modernized SBAS service for the aviation community (Walter et al

2013). Because neither CanX-2's receiver nor antenna are L5 capable, a study of the second SBAS frequency remains as a potential area of future work for a different satellite mission.

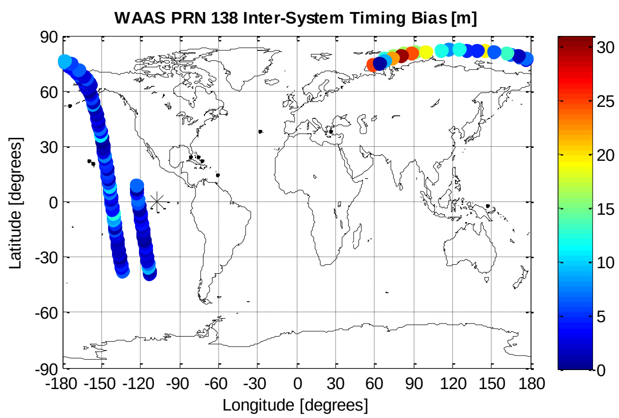

Figure 14: Geographic dependence of WAAS PRN 138 ranging errors compared to a GPS single point solution. The SBAS satellite position is marked by a star.

RESULTS AND CONCLUSIONS

MSAS, GAGAN, EGNOS and WAAS L1 signals were all successfully tracked from orbit using the CanX-2 CubeSat's commercial NovAtel GPS receiver. It was demonstrated that sufficient SBAS signal power spills over the edge of the earth in both the northern and southern hemispheres to make signal acquisition and tracking possible for users in higher orbits, in spite of the higher SBAS data rate.

Although a higher platform than CanX-2 would allow for a wider mapping of the SBAS gain patterns, these early results from low earth orbit already indicate that SBAS satellites have significant differences in their transmit antenna designs and available signal power, which suggests that they have substantially different side lobes as well.

The ranging measurements were assessed, and it was found that being able to decode the SBAS messages will be essential for any space receiver taking advantage of the SBAS signals, not only for the broadcast ephemeris but also in order to apply the fast corrections to the ranging measurements, and avoid significant clock errors. While the higher rate data did not prevent acquisition or tracking, it could present a problem for weak signal tracking applications, because it would limit coherent integration time at 4 s rather than the 20 s achievable with the GPS L1 C/A code.

Of the three systems which support ranging measurements, WAAS is the most suitable for tracking in GEO and HEO, with the highest signal power, a wide main beam, and the best ranging accuracy. MSAS has a transmit gain pattern well suited to tracking over the earth's limb, but transmitted lower power overall and had a significant and non-constant intersystem timing bias compared to GPS, varying by +/- 10 m. In order to get the best performance from the MSAS measurements both satellites should therefore be tracked, making it possible to either solve for or difference out this bias. GAGAN was less suited to GEO or HEO use, having a narrower beam width than the other systems and the largest ranging errors, potentially as a result of the system's monitoring network being over the magnetic equator. Finally, EGNOS has a similar transmit gain pattern to GPS, but weaker transmitted power, and in its current state it does not support ranging. It is therefore unsuitable for use as a source of GEO or HEO positioning information.

In conclusion, the work presented in this study confirms that SBAS tracking from GEO and HEO orbits is possible, and that properly handled, the measurements from WAAS, MSAS, and possibly GAGAN can provide useful ranging information to space users.

ACKNOWLEDGEMENTS

The authors would like to acknowledge NovAtel for their original in-kind donation of the GPS receiver flying on board CanX-2, and their support in upgrading the receiver to unlock its SBAS functionality so many years after the launch. The ongoing support of the operations team at University of Toronto is also gratefully acknowledged; without them no CanX-2 data would be collected. Likewise, the scholarship support over the duration of the CanX-2 mission from NSERC, AITF, Engineers Canada, Zonta International, and University of Calgary is gratefully acknowledged. Finally, the analysis of the CanX-2 data has been supplemented with data from the IGS and in particular the Multi-GNSS Experiment (MGEX) network.

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