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Key Points:
- Indian SBAS-GAGAN is commissioned over low-latitude region
- SBAS can be used effectively for large-scale ionospheric studies
- Demonstrates the capability using two case studies

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Satellite-based augmentation systems: A novel and cost-effective tool for ionospheric and space weather studies

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Abstract Satellite-Based Augmentation Systems (SBASes) are designed to provide additional accuracy and robustness to existing satellite-based radio navigation systems for all phases of a flight. However, similar to navigation systems such as GPS which has proven its worth for the investigation of the ionosphere, the SBASes do have certain advantages. In the present paper, we propose and demonstrate SBAS applicability to ionospheric and space weather research in a novel and cost-effective way. The recent commissioning of the Indian SBAS, named GPS Aided Geo Augmented Navigation (GAGAN), covering the equatorial and low-latitude regions centered around the Indian longitudes provides the motivation for this approach. Two case studies involving different ionospheric behavior over low-latitude regions vindicate the potential of SBAS over extended areas.

1. Introduction

Historically, the ionosphere has played an important role in long-range radio communication since its discovery in the early twentieth century. However, it has also turned out to be a hurdle in satellite-based navigation services as it is potentially the largest single most unpredictable and significant sources of positioning error.

Satellite-based radio navigation systems such as the Global Positioning System (GPS) have addressed the ionospheric perturbation by broadcasting at multiple frequencies so that the total electron content (TEC) along the line of sight from the receiver to the GPS satellite can be computed. With this capability, GPS has emerged as a powerful tool for ionospheric research due to the potentially wide spatial and temporal coverage of TEC measurements that can be realized, unlike some of the standard techniques such as Faraday rotation, incoherent scatter, ionosondes, etc. It is worthy to note that 1 TEC unit (1 TECU = 10^{16} el m^{-2}) introduces a delay of ~0.16 m at L1 frequency [*Klobuchar*, 1996]. Notwithstanding, the stated advantages there are some difficulties as well due to the continuous motion of the satellite, especially when there is a requirement of electron density over a fixed location. Data processing techniques that yield average vertical TEC surrounding the receiver location with certain elevation cutoff angles are normally used for this purpose [*Mannucci et al.*, 1998; *Rama Rao et al.*, 2006a, 2006b]. These methods are found to have limitations in the equatorial anomaly region due to the presence of sharp spatial gradients in the plasma densities. Furthermore, it becomes necessary to have a multistation network of GPS receivers to study the ionospheric phenomena, more so during geomagnetic storms and associated space weather conditions. This mandatory requirement invariably puts certain constraints on the availability of data from receivers that have large spatial coverage. In addition, the dual-frequency GPS receivers suited for ionospheric studies that employ semicodeless technique to acquire the P(Y) code at L2 frequency are expensive; and hence, it becomes a difficult proposition to establish a reasonably dense network especially in equatorial/tropical region. Moreover, additional care needs to be taken to account for the interfrequency biases, especially in low-latitude region, before deriving the absolute TEC [*Wilson and Mannucci*, 1993; *Ma and Maruyama*, 2003; *Rama Rao et al.*, 2006a]. In the light of the above limitations, we present below a novel method to make use of the data from the existing Satellite-Based Augmentation Systems (SBAS) in different parts of the globe that have both spatial coverage and temporal resolution making it an ideal tool for ionospheric and space weather related studies. Before providing the details of the method and demonstrating its capability, a brief outline of an SBAS is provided.

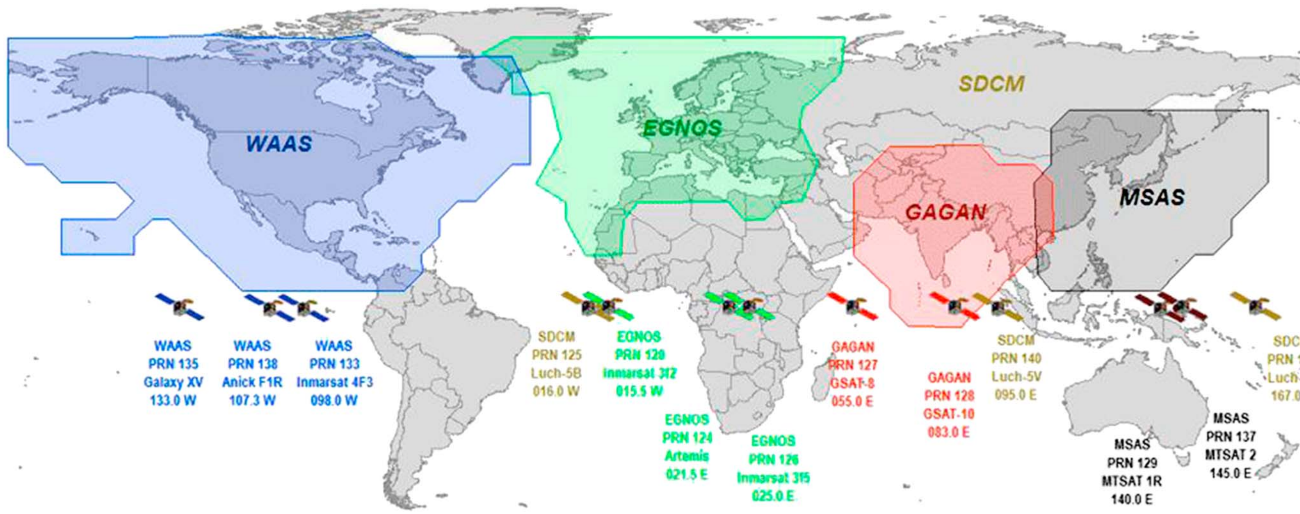

Figure 1. Fleet of operational SBAS-GEO satellites along with marked service area of each SBAS around the globe. The PRN and location of each GEO satellite is also indicated on the map. (Courtesy GENEQ Inc.)

2. SBAS

Satellite-based navigation is gaining importance in lieu of ground-based navigation aids with the emergence of GPS. Safety in air navigation, which is a life critical application, has stringent requirements of accuracy, availability, continuity, and integrity [*Kelly and Davis*, 1994]. However, a standalone GPS cannot meet these requirements due to various error sources like ionospheric delay, ephemeris (orbital), and clock errors, in addition to the absence of warning of the failure of any satellite (or Misleading Hazardous Information). Hence, to overcome these limitations, the concept of Satellite-Based Augmentation System (SBAS) has been formulated which could enhance the capability of GPS by providing error corrections and integrity information through a geostationary satellite to any potential applications like the precision approach of civil aircraft. This concept referred to as Wide Area Augmentation System (WAAS) was first proposed by the Federal Aviation Administration to demonstrate the Category I precision approach over the U.S. [*Enge et al*., 1996].

Currently, there are four operational SBAS systems, viz., (1) the U.S. WAAS, commissioned in July 2003, (2) Japan's Multifunctional Transport Satellite Augmentation System (MSAS) commissioned in 2007, (3) European Geostationary Navigation Overlay Service (EGNOS) commissioned in March 2011, and (4) India's GPS Aided Geo Augmented Navigation (GAGAN) commissioned recently in 2013–2014. Apart from the above, Russia's System for Differential Correction and Monitoring (SDCM) is under development. All these systems together provide almost full coverage of the Northern Hemisphere with their fleet of geostationary satellites as shown in Figure 1.

Figure 2 shows the configuration of Indian SBAS-GAGAN, which consists of 15 Indian Reference Stations (INRES), 2 Indian Master Control Centers (INMCC), and 3 Indian Land Uplink Stations (INLUS)—all the above three components forming the ground segment while the geostationary Earth orbiting (GEO) satellites and GPS satellites form the space segments. The widely separated reference stations collect the GPS dual-frequency measurements and transfer them to master control center through the communication network in real time. The ionosphere, ephemeris, and clock errors are estimated precisely using the suitable algorithms in the master control center. The error corrections along with integrity information are, then, generated in specified message format [*Radio Technical Commission for Aeronautics*, 1999] and sent to the GEO satellite through the uplink station. The user receives the correction messages from GEO at L1 frequency and corrects the GPS-derived position by applying the necessary SBAS corrections. All the SBAS correction and integrity messages are identified by message-type numbers, and each message has its own update interval [*RTCA*, 1999]. The ionospheric-related information is broadcast by message types 18 and 26 with update interval of 300 s. The user receiver is a single-frequency GPS receiver with SBAS functionality.

The ionospheric corrections are broadcast in the form of vertical delay at the predefined ionospheric grid points (IGPs), applicable to a signal on L1. There are numerous algorithms investigated by SBAS system designers, to be incorporated in Master Control Center for estimation of ionospheric vertical delay at the IGPs.

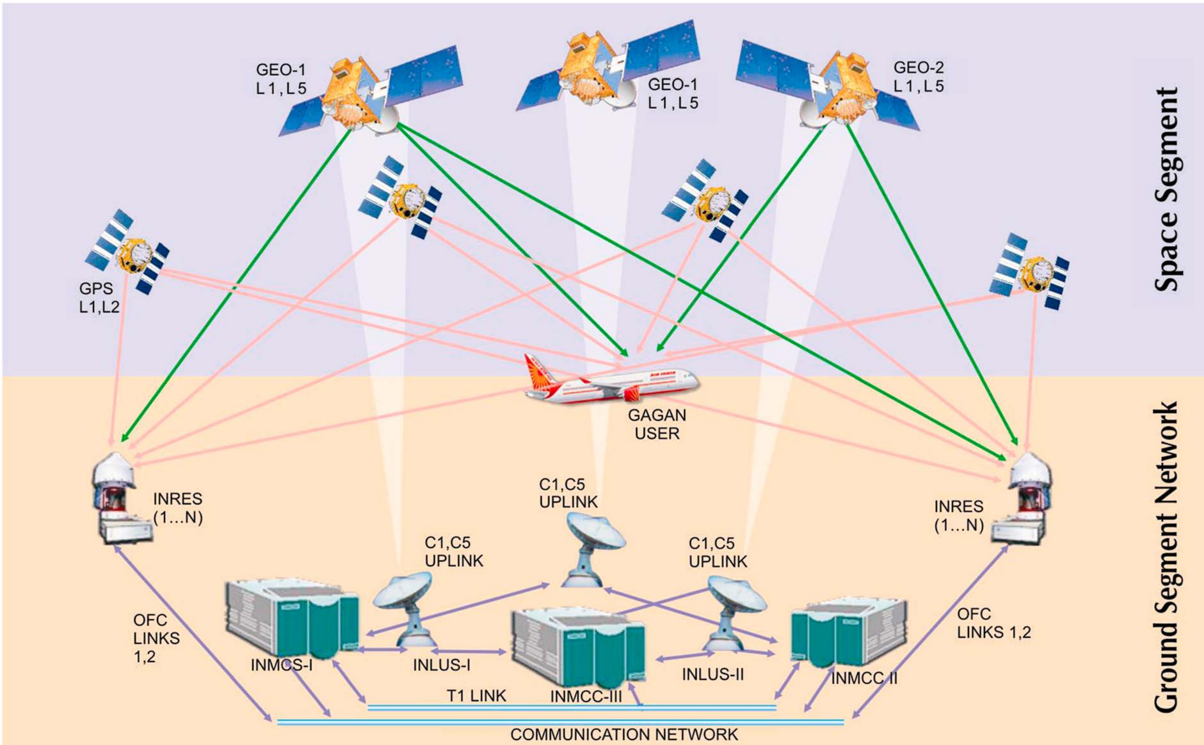

Figure 2. Configuration of Indian SBAS-GAGAN (Courtesy AAI/ISRO). GAGAN consists of 15 reference stations (INRES), 3 Master control centers (INMCC) and 3 Uplink stations (INLUS).

The simplest and widely used by WAAS is a planar fit model which was later on replaced by the kriging technique [*Blanch*, 2002] as it improved the system availability [*Sparks et al*., 2011]. The GAGAN system has employed a uniquely designed Multilayer Data Fusion model for its improved performance over equatorial and low-latitude region. GAGAN became the first SBAS to be commissioned in the equatorial ionization anomaly (EIA) region, paving the way to a new dimension in ionosphere and space weather research. The EIA is considered as one of the most complex systems due to its large day-to-day variability. Large networks of ionospheric sensing equipments (dual-frequency GPS receivers, ionosonde etc.) are required to monitor the development of EIA starting from the magnetic equator to low latitude and midlatitude. However, this can be elegantly accomplished by making use of ionospheric correction data broadcast from SBAS as will be demonstrated below.

The novelty of the proposed method to derive ionospheric parameters lies in the use of continuously available information at intervals as short as 5 min over a wide area of interest. Since the ionospheric error varies spatially, the whole globe is divided into the number of bands (0–8) defined as band number, which are further divided into predefined grid points known as ionospheric grid points (IGPs). The precisely estimated ionospheric vertical delay at the predefined IGPs known as Grid Ionospheric Vertical Delay (GIVD) for L1 is broadcast along with the error bound defined as Grid Ionospheric Vertical Error (GIVE). Since the ionospheric delay, which is frequency dependent, is directly proportional to the TEC (1 m delay at L1 = ~ 6.25 TECU), the former can potentially be used to study the large-scale ionospheric behavior by just using only one SBAS enabled GPS receiver from any location within the region served by the augmentation system. With this background information we proceed to briefly explain the SBAS messages relevant to ionospheric corrections and methodology to decode them.

3. Methodology

3.1. SBAS Message Format

The baseline data rate of the navigation message of the SBAS Signal-In-Space is 250 bits per second. Out of 250 bits, data field is of 212 bits, followed by 6 bit message-type identifier and 8 bit preamble. Remaining

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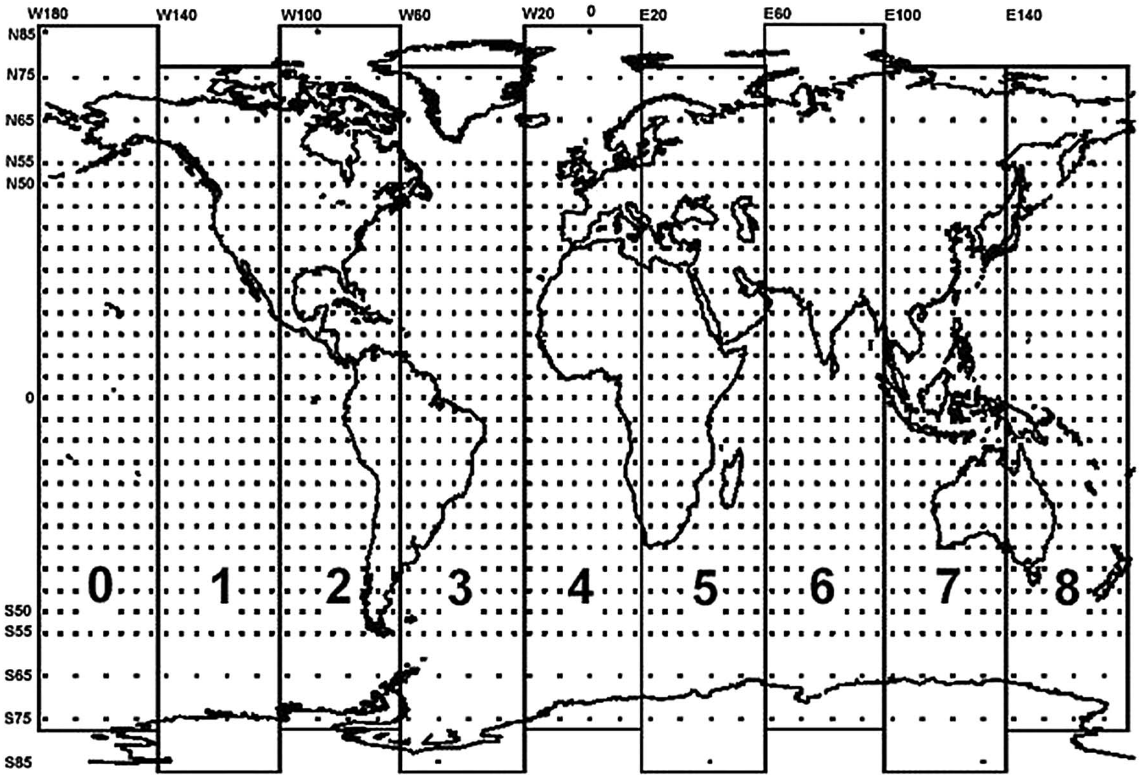

Figure 3. Predefined global ionospheric grid points (IGPs). The bold numbers in rectangular shape denote the band numbers (Courtesy RTCA/DO-229B).

24 bits are used for message parity. The two relevant messages for ionospheric information, viz., message type 18 and message type 26 as defined by *RTCA* [1999] will be discussed below.

3.2. Message Type 18

The message type 18 (MT 18) contains the ionospheric grid point (IGP) masks to define the IGP locations, where ionospheric delays are to be broadcast. Although this message does not contain any SBAS correction or integrity information, it is still very important for applying the ionospheric corrections delivered in message type 26. The ionospheric delay corrections are broadcast as vertical delay estimates at specified IGPs. The predefined IGPs are contained in 11 bands (numbered 0 to 10, each band covering 40° of longitude). The predefined 1808 possible IGP locations in bands 0–8, given in latitude and longitude coordinates, are illustrated in Figure 3. The IGP grid at the equator has 5° spacing, which increases to 10° at north of N55° and south of S55°, and finally has spacing intervals of 30° beyond N85° and S85° around the poles.

The message format of the MT 18 and its contents are given in Figure 4. Each message indicates the Band associated with 201 possible IGPs. It should be noted that the Indian SBAS-GAGAN is providing the service over three bands, i.e., band numbers 5, 6, and 7. Figure 5 shows the IGPs served by GAGAN over Indian flight

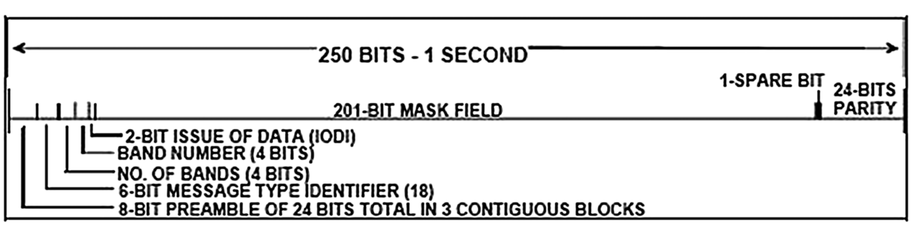

Figure 4. Message Type 18 IGP mask message format (Courtesy RTCA/DO-229B).

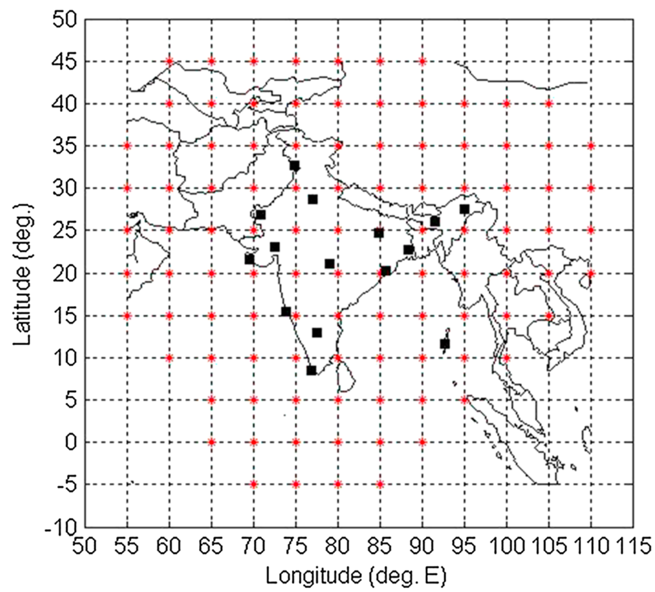

Figure 5. Ionosphere grid points (IGPs) served by GAGAN system (denoted by stars) and the location of 15 GAGAN reference stations marked by squares.

information region. These IGPs were decoded and stored in a text file, since these are permanent for GAGAN service volume.

3.3. Message Type 26

The message type 26 ionospheric delay correction message provides the users with vertical delays (relative to L1 signal) known as Grid Ionospheric Vertical Delay (GIVD) and their accuracy Grid Ionospheric Vertical Error (GIVE) at geographically defined IGPs identified by band number and IGP number. Each message contains a band number and a block ID, which indicates the location of the IGPs in the respective band mask. Each band is divided into a maximum of 14 blocks (numbered 0 to 13). The data content of this message and its format is presented in Figure 6.

The 9 bit GIVD has 0.125 m resolution, for a 0 to 63.750 m valid range. A GIVD of 63.875 m (111111111) will indicate the warning message of *do not use*. Its associated accuracy is broadcast by the index (0 to 15) defined as Grid Ionospheric Vertical Error Index (GIVEI). The GIVEI of 15 indicates the user that particular IGP is *NOT MONITORED*. These vertical delays and the evaluated σ^2_{GIVE}'s will be interpolated by the user to the Ionospheric Pierce Point (IPP) [*Mannucci et al.*, 1998] of the observed satellite for further corrections in the range [*RTCA*, 1999].

Software tools in MATLAB were developed to extract and decode the SBAS message types 18 and 26 from the raw GPS file of Novatel OEM4 receiver. The GIVE is a very important parameter as it provides the integrity information related to ionospheric model and is usually exaggerated in view of the "safety-of-life" application. At the outset it may appear that it may be a worthless parameter for ionospheric research. Nonetheless, it may still be used to study/monitor the spatial variations and plasma density irregularities that cause scintillations. *Sunda et al.* [2013] have demonstrated the effect of scintillation on GIVE. In a nutshell, the GIVD, which is directly proportional to the TEC could well be used to infer the spatial and temporal variation of TEC while the GIVE could be used for gleaning out information on the ionospheric irregularities.

4. Validation

In order to validate the above mentioned method to be potentially used in ionospheric and space weather research, we compared it to the real measurements of TEC from dual-frequency GPS receivers (GSV4004b). The comparison is carried out in two stages. In the first stage, a point-to-point comparison at two different locations using single receiver is performed and in the second stage, a wide network of dual-frequency GPS receivers is used over a large coverage area. The dual-frequency GPS receivers established under

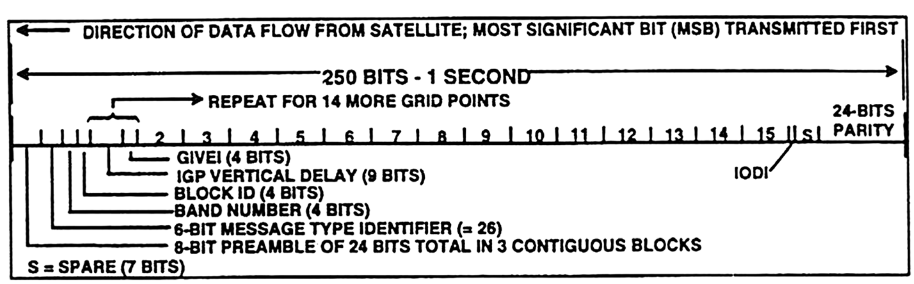

Figure 6. Message type 26 ionospheric delay corrections message format (Courtesy RTCA/DO-229B).

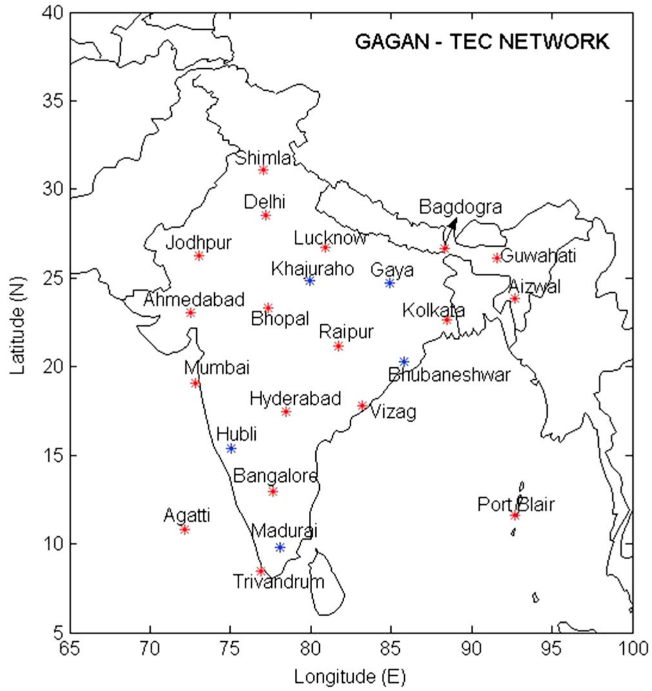

Figure 7. Location of GPS stations operating under the GAGAN-TEC network. Stations marked by red color were installed in 2003–2004 and blue marked ones were installed in 2009–2010.

GAGAN project known as GAGAN-TEC network [*Acharya et al*., 2007] are used for comparison. It is worth mentioning here that the GAGAN-TEC network is independent from the GAGAN reference stations (INRES); however, some of the sites are colocated (see Figure 5, square marks). Figure 7 shows the locations of the 23 receivers under GAGAN-TEC network.

For point-to-point verification, we selected the sites of Gaya (24.75°N, 84.95°E; usually beyond the anomaly crest region) and Hubli (15.3°N, 75.02°E; usually below the anomaly crest region) from the GAGAN-TEC network as they are closer to the IGPs of 25° × 85° and 15° × 75°, respectively (since SBAS broadcast the iono corrections at IGPs), thus providing direct comparison without any interpolation. Figure 8 shows the diurnal variation of vertical TEC derived from the measurements of dual-frequency GPS receiver (dotted line) at Hubli (left panel) and at Gaya (right) and the corresponding vertical TEC derived from the SBAS (GAGAN) corrections (solid line) at respective IGPs on a typical day of 23 November 2012. There is a good agreement in TEC obtained from two different methods at both the locations. We found that the absolute average of the difference between two types of TEC (error) at Gaya is 2.35 TECU with its standard deviation of 2.1; whereas at Hubli, the absolute average error is 2.23 TECU with variance of 1.75. It is worthy to mention that a lot of data processing was carried out in GPS measurements to remove the interfrequency biases [*Acharya et al*., 2007] and to estimate the vertical TEC by averaging the measurements above an elevation cutoff angle of 40° [*Rama Rao et al*., 2006a]. The issues related to elevation cutoff, slant to vertical mapping function [*Langley et al*., 2002] etc. are still wide open and debatable as some workers prefer 50° [*Rama Rao et al*., 2006b], while others put limitation on latitude/longitude of ±2° surrounding the station [*Bagiya et al*., 2009]. On the other hand, it is easier to extract and decode the TEC from SBAS corrections directly.

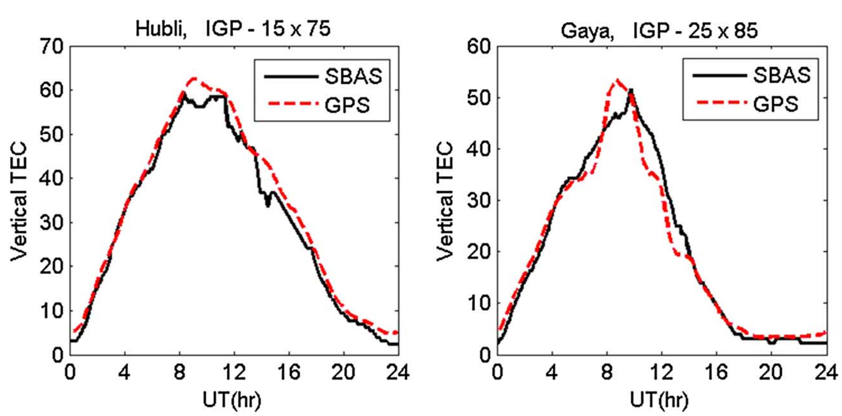

Figure 8. Comparison of vertical TEC derived from GPS measurements (dashed line) and SBAS (GAGAN) corrections (solid line) at two different locations—(left) Hubli (15.3°N, 75°E) and (right) Gaya (24.75°N, 84.95°E) on a typical day of 23 November 2012.

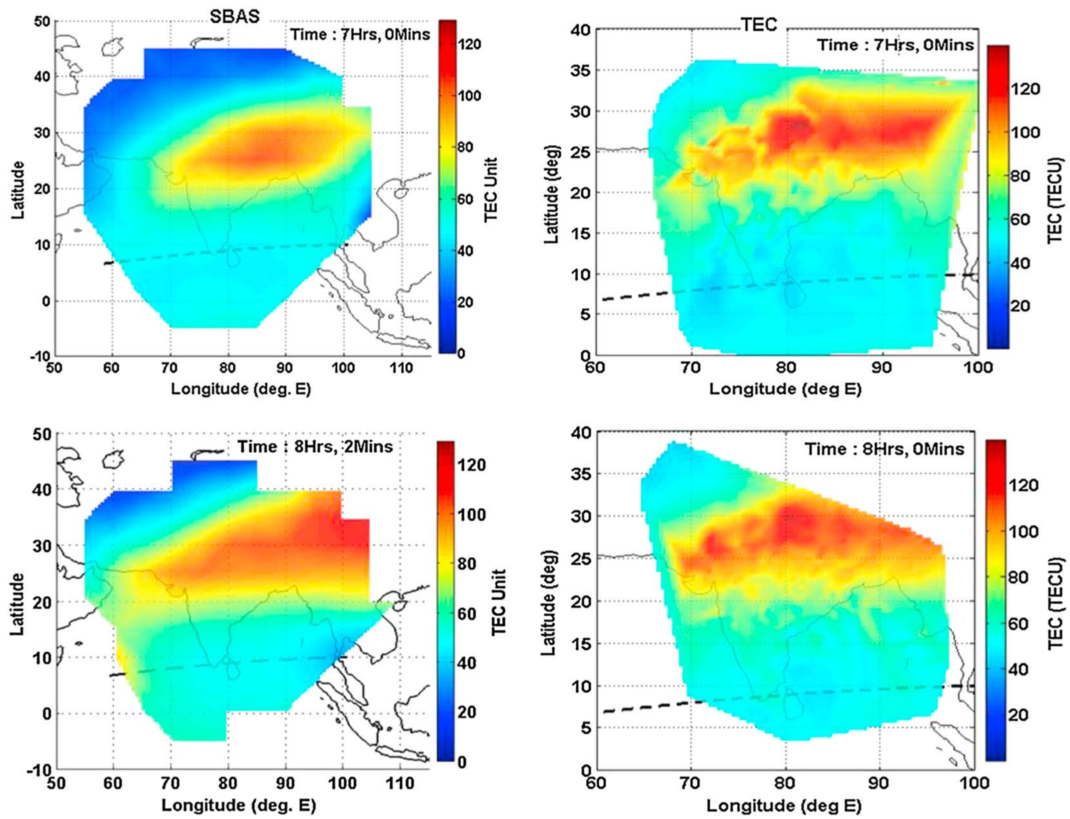

Figure 9. A comparative study of the ionospheric TEC maps generated from (left) SBAS broadcast iono corrections from a single SBAS receiver, and from (right) a dense network of dual-frequency receivers (GAGAN-TEC Network) at different times on 29 September 2012, depicting the development of strong EIA. The horizontal dashed line passing through the southern tip of India is magnetic equator. The fairly good agreement in both contours highlights the potential of using a single-SBAS receiver data.

After the successful validation in the first stage, we performed the second stage verification which involves TEC variations over a large coverage area. Since the vertical TEC, derived from SBAS broadcast, is available continuously at specified grid points of $5° \times 5°$ covering a large area specified by service provider, the regional contour maps of TEC can be developed using suitable interpolation techniques. On the other hand, very fine resolution contour maps of TEC were generated using the dense network of 23 GAGAN-TEC receivers. For this, the whole Indian subcontinent region was divided in the bins of $2° \times 2°$ latitude and longitude. The vertical TEC computed at each Ionospheric Pierce Point (IPP) is grouped in the respective bins at the interval of 5 min. Finally, the linear interpolation technique is used to generate the regional contour maps of TEC.

In order to explore/demonstrate the potential and scope of the proposed method, we carried out case studies involving two different days with totally different ionospheric behavior. For this, we identified one enhanced EIA day, i.e., 29 September 2012 and another day during a geomagnetic storm (16 July 2012). Figure 9 presents the classical example of the development of a strong EIA on 29 September 2012 as perceived by the SBAS broadcast iono delay information (GIVD) converted into TEC contours (left) and the regional TEC contours generated from measurements of GAGAN-TEC network (right). The horizontal dashed line indicates the magnetic equator passing through southern tip of India. Usually the crest of EIA is formed at around ±15° of the magnetic equator [*Balan and Iyer*, 1983], i.e., around 22–23°N (geographic) over Indian longitudes. However, in this case on 29 September 2012, the EIA crest is perceived to be located between 25°N and 30°N at 0700 UT (1230 IST) and has moved further beyond 30°N at 0800 UT (1330 IST). Such unusual behavior of EIA on magnetically quiet day calls for wider network of stations to study and monitor their progress. The general agreement between these two contours developed from different sources of information highlights the potential of the suggested method. While one source of information is a single-GPS receiver with SBAS capability, the other source is the dense network of 23 GPS receivers.

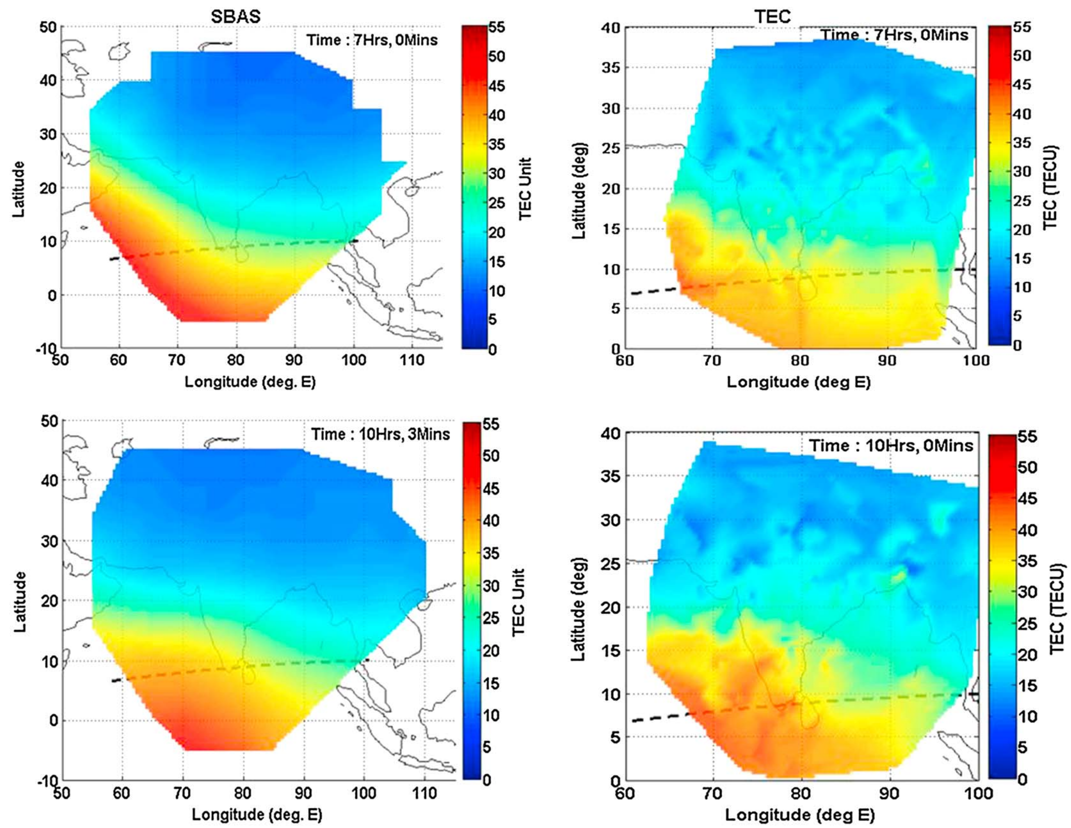

Figure 10. Comparative study of the regional TEC maps developed from (left) SBAS iono corrections and (right) TEC measurements from 23 stations (GAGAN-TEC network) at different times on 16 July 2012 in the wake of a geomagnetic storm, i.e., during the recovery phase of a geomagnetic storm. The horizontal dashed line passing through the southern tip of India is magnetic equator. The behavior of the ionosphere during such dynamic space weather events could be studied with unprecedented spatial and temporal resolution.

The second case of 16 July 2012 is distinctly different from the previous one. An intense geomagnetic storm occurred on 15 July 2012 (minimum $Dst = -133$ and maximun $Kp = 7$) following an X-class solar flare. The interplanetary magnetic field Bz remained southward for unusually longer duration (~33 h) on 15 and 16 July 2012 [*Bagiya et al*., 2014]. During its recovery phase on 16 July 2012, the low-latitude ionosphere in the summer hemisphere experienced an unusually strong negative storm as shown in the regional contour maps in Figure 10 developed from SBAS Iono correction (left) and dual-frequency measurements from GAGAN-TEC network (right). It can be noticed, especially from SBAS generated TEC contours, that the equatorial ionization anomaly in the summer (northern) hemisphere is conspicuously absent, while in the winter (southern) hemisphere it appears to be normal. This contrasting hemispherical response in TEC is due to the combined effects of strong interhemispheric, and solar driven day-night winds as suggested by *Bagiya et al*. [2014] using the multistation, multitechnique data from Northern and Southern Hemispheres. The general agreement in all the large-scale features in both the maps of TEC vindicates the point that the simple SBAS-enabled system from one location is turning out to be an ideal tool for the investigation of large-scale processes in general and also space weather events in particular.

5. Potential Applications of SBAS Data in Ionospheric and Space Weather Research

The successful commissioning of GAGAN, an Indian SBAS providing the service over equatorial and low-latitude region has opened up a new front for ionospheric and space weather research from equatorial latitudes. The capability to use the SBAS iono corrections in studying the various manifestations of EIA and space weather effects on ionosphere has been demonstrated successfully by two case studies. In fact, the proposed method emerges as a low-cost alternative to multiple dual-frequency GPS receivers for large-scale ionospheric studies. With the availability of multiple SBAS systems, one would be able to monitor ionospheric processes eventually enabling the generation of global ionospheric maps during quiet and severe space weather conditions. Studies of phenomena like the equatorial ionization anomaly (EIA) over the magnetic equatorial region and its longitudinal variation could be attempted with a high degree of finesse.

Nonetheless, the use of SBAS in ionospheric research is not limited to this particular application. SBAS, especially WAAS, has been used for calibration of TEC in dual-frequency GPS receivers (GSV4004) before shipment of the latter (GSV4004 receiver manual). However, the interfrequency bias of the receiver, being dynamic in nature, changes with location and time. This necessitates the regular estimation of receiver bias, which itself is a very complex procedure. Now with the existing almost global coverage of SBAS, it can be used directly for estimation of receiver biases by calibrating the TEC against the SBAS ionospheric corrections. Further addition to the broadcast iono corrections, the dual-frequency measurements from SBAS-GEO satellite itself can be used for estimating the TEC independently. The significant advantage of such a GEO-based TEC measurement is the elimination of the problems one faces due to the finite movement of the GPS satellites while deriving the vertical TEC thus enabling precise determination of the TEC at any fixed location. Though some of the older SBAS-GEO satellites have only one frequency of transmission (L1), most of the current and upcoming GEO satellites have dual-frequency transmission (necessary for TEC estimation) at L1 and L5. When it comes to the ionospheric scintillation, the GEO platforms have a distinct advantage and transmission in one frequency itself would suffice. The equatorial nighttime ionospheric irregularities which themselves are highly dynamic are known to move eastward. The velocity determination could be done unequivocally by using a combination of two GEO transmissions received by one SBAS receiver or two SBAS receivers separated by a finite distance with one GEO transmission. The SBAS iono correction information would become extremely useful in nowcasting/forecasting the turbulent phenomena of ionospheric irregularities and also while studying their temporal variations. Since the information is based on actual measurements, on many applications wherever currently ionospheric models like International Reference Ionosphere (IRI) are used to make an assessment of the impact on the near-Earth space, the SBAS-based measurements would provide more credence, more so to the assessment of the space weather impact thus opening up new vistas to space weather science.

6. Summary

Just as GPS has been used extensively for a host of applications beyond its originally intended use of positioning, the SBAS, based on the GPS platform, can also be exploited similarly for several other applications. The ionospheric delay which is proportional to TEC is broadcast at predefined IGPs covering a large area of the service provider and a single-frequency GPS receiver with a SBAS channel is all that is required to receive the correction messages corresponding to all the IGPs. A new method to make use of the SBAS broadcast ionospheric delay (~TEC) for estimating the ionospheric parameters has been demonstrated through case studies to have significant potential. Currently, there are four operational SBAS systems providing almost full coverage of the northern hemisphere, and the commissioning of the Indian SBAS-GAGAN has filled up an important area owing to its location over EIA regions. Since the information is based on actual precise measurements and accessible through a single-SBAS enabled receiver, it can emerge as low-cost alternative for ionosphere and space weather research.

Acknowledgments
The data (SBAS and TEC) used in the study are part of the GAGAN project, a joint collaboration between Airports Authority of India (AAI) and ISRO. While the GAGAN-SBAS data are freely available, the TEC data are restricted under the project. The SBAS data from WAAS and EGNOS are available freely on websites http://www.nstb.tc.faa.gov/index.htm and http://www.gsa.europa.eu/egnos/edas, respectively. Please contact the corresponding author for additional information on how to access the SBAS data. S.S. duly acknowledges the AAI for the support and SAC (ISRO) for hosting his position. R.S. duly acknowledges the National Academy of Sciences Allahabad for the NASI Sr. Scientist position and also PRL for hosting the position.

References

Acharya, R., M. R. Sivaraman, K. Bandyopadhyay, N. Nagori, S. Sunda, and S. Regar (2007), Ionospheric studies for the implementation of GAGAN, *Indian J. Radio Space Phys.*, *36*(5), 394–404.

Bagiya, M. S., H. P. Joshi, K. N. Iyer, M. Aggarwal, S. Ravindran, and B. M. Pathan (2009), TEC variations during low solar activity period (2005–2007) near the equatorial ionospheric anomaly crest region in India, *Ann. Geophys.*, *27*, 1047–1057, doi:10.5194/angeo-27-1047-2009.

Bagiya, M. S., R. Hazarika, F. I. Laskar, S. Sunda, S. Gurubaran, D. Chakrabarty, P. K. Bhuyan, R. Sridharan, B. Veenadhari, and D. Pallamraju (2014), Effects of prolonged southward interplanetary magnetic field on low-latitude ionospheric electron density, *J. Geophys. Res. Space Physics*, *119*, 5764–5776, doi:10.1002/2014JA020156.

Balan, N., and K. N. Iyer (1983), Equatorial anomaly in ionospheric total electron content and its relation to dynamo currents, *J. Geophys. Res.*, *88*, 10,259–10,262, doi:10.1029/JA088iA12p10259.

Blanch, J. (2002), An ionosphere estimation algorithm for WAAS based on kriging, in *Proceedings of 15th International Technical Meeting of the Satellite Division of the US Inst. of Navigation*, pp. 816–823, Portland, Oregon.

Enge, P., T. Walter, S. Pullen, C. Kee, Y. C. Chao, and Y. J. Tsai (1996), Wide area augmentation of the global positioning system, *Proc. IEEE*, *84*(8), 1063–1088.

Kelly, R. J., and J. M. Davis (1994), Required navigation performance (RNP) for precision approach and landing with GNSS application, *Navigation*, *41*(1), 1–30.

Klobuchar, J. A. (1996), Ionospheric effects on GPS, in *Global Positioning System: Theory and Applications*, vol. 1, edited by J. J. Spilker et al., pp. 485–515, Am. Inst. of Aeronaut. and Astronaut. Inc., Washington, D. C.

Langley, R., M. Fedrizzi, E. Paula, M. Santos, and A. Komjathy (2002), Mapping the low latitude ionosphere with GPS, *GPS World*, *13*(2), 41–46.

Ma, G., and T. Maruyama (2003), Derivation of TEC and estimation of instrumental biases from GEONET in Japan, *Ann. Geophys.*, *21*, 2083–2093.

Mannucci, A. J., B. D. Wilson, D. N. Yuan, C. M. Ho, U. J. Lindqwister, and T. F. Runge (1998), A global mapping technique for GPS-derived ionospheric total electron content measurements, *Radio Sci.*, *33*, 565–582, doi:10.1029/97RS02707.

Rama Rao, P. V. S., S. Gopi Krishna, K. Niranjan, and D. Prasad (2006a), Temporal and spatial variations in TEC using simultaneous measurements from Indian GPS network of receivers during low solar activity period of 2004–05, *Ann. Geophys.*, *24*, 3279–3292.

Rama Rao, P. V. S., K. Niranjan, D. S. V. V. D. Prasad, S. Gopi Krishna, and G. Uma (2006b), On the validity of the ionospheric pierce point (IPP) altitude of 350 km in the Indian equatorial and low-latitude sector, *Ann. Geophys.*, *24*, 2159–2168.

Radio Technical Commission for Aeronautics (RTCA) (1999), Minimum operational performance standard for Global Positioning System/Wide Area Augmentation System airborne equipment, *RTCA/DO-229B*, Washington, D. C.

Sparks, L., J. Blanch, and N. Pandya (2011), Estimating ionospheric delay using kriging: 1. Methodology, *Radio Sci.*, *46*, RS0D21, doi:10.1029/2011RS004667.

Sunda, S., B. M. Vyas, S. V. Satish, P. V. Khekale, and K. S. Parikh (2013), Improvement of position accuracy with GAGAN and the impact of scintillation on GNSS, *Positioning*, *4*, 282–288, doi:10.4236/pos.2013.44028.

Wilson, B. D., and A. J. Mannucci (1993), Instrumental biases in ionospheric measurements derived from GPS data, in *Proceedings of ION GPS 93, September 22–24*, pp. 1343–1351, The Inst. of Navig., Salt Lake City, Utah.