THE JOURNAL OF NAVIGATION (2003), **56**, 137–142.
DOI: 10.1017/S0373463302002059 Printed in the United Kingdom

Estimation of Minimum Separation of Geostationary Satellites for Satellite-Based Augmentation System (SBAS) from Equatorial Ionospheric Scintillation Observations

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In Satellite-Based Augmentation Systems (SBAS), the correction messages are transmitted to the users' receivers via geostationary communication satellites (GEOS) at GPS L1 (1575·42 MHz) frequency. Severe scintillations in the equatorial zone disrupt geostationary satellite links even at L-band. Observations of scintillations at 1·5 GHz from Calcutta (22·58°N, 88·38°E geographic, 32°N magnetic dip), located near the crest of the equatorial anomaly in the Indian zone, show that scintillations occur in patches of duration varying from a few minutes to several hours. During the solar maximum years 1998–2000, severe scintillations (Scintillation Index $\geqslant$15 dB) were recorded for 48 hr 55 min (1·27%) out of the total observation time of 3868 hr 9 min in the local time interval 19 to 00 hrs. In order to have a fail-safe system, it is suggested that more than one geostationary satellite be used in SBAS so that, if one link is disrupted, the other can be used for transmission of correction messages to the GPS users. The minimum longitudinal separation between two GEOS required for reliable operation of SBAS has been estimated, from the cumulative distribution of scintillation patch duration, to be 57° in the Indian longitude zone.

KEY WORDS

1. GNSS. 2. SBAS. 3. Satellites.

1. INTRODUCTION. A Satellite-Based Augmentation System (SBAS), like the Wide Area Augmentation System (WAAS) in the United States, European Geostationary Navigation Overlay System (EGNOS) in Europe, Multi-functional Transport Satellite (MTSAT) Satellite-based Augmentation System (MSAS) in Japan and SATNAV in India, will provide precision guidance to aircraft at a large number of airports distributed over extended areas. The area to be covered is divided into $5^{\circ} \times 5^{\circ}$ grids. Precisely surveyed ground reference stations that will be linked to form a SBAS network will receive signals from GPS satellites and estimate errors due to propagation effects over individual grids. Each station will relay

the data to Wide Area Master Stations (WMS) where corrections for a specific geographical area will be computed and uplinked to a GEOS via a Ground Uplink Station (GUS). This message will be broadcast on the same frequency as GPS L1 (1575·42 MHz) to the GPS receivers onboard the aircraft flying within the service area of SBAS. Through the use of GEOS carrying navigation payloads, SBAS will improve the basic GPS accuracy, system availability and provide integrity information about the entire GPS constellation.

The main constraint on the use of SBAS arises from the medium of propagation, particularly the ionosphere. According to ionospheric conditions, the globe may be divided into equatorial, mid-latitude and high-latitude zones. The equatorial region extends from the magnetic equator to $\pm 30^{\circ}$ dip, the mid-latitudes from 30°–60° dip and the high latitudes above 60° dip. The equatorial region is characterised by the equatorial anomaly and an intense form of density irregularities. The equatorial anomaly is the latitudinal variation of the high ambient *F*-region electron density, with a trough over the magnetic equator and two crests around $\pm 30^{\circ}$ dip, during the afternoon and early evening hours. A major part of the Indian subcontinent and South America belongs to the equatorial zone. Radio waves, even in the microwave L-band are subject to severe fluctuations, popularly known as scintillations, both in amplitude and phase, in the equatorial region during certain time intervals. Amplitude scintillations induce signal fading and when the depth of fading exceeds the fade margin of a receiving system, message errors in satellite communication systems are encountered. Scintillations cause degradation in the accuracy of position fixing by standalone GPS receivers (Bandyopadhyay *et al.*, 1997), data loss and cycle slips (Kelly *et al.*, 1996).

Equatorial scintillations have dramatic solar activity dependence, with very minor scintillations in solar minimum years. During post-sunset hours of equinoctial months in solar maximum years (high sunspot activity), scintillation is practically a daily phenomenon. Under extreme conditions of amplitude and phase scintillations, the radio links from geostationary as well as GPS satellites can become completely unusable, and position fixing by GPS may become uncertain. In SBAS, the GEOS link carrying the correction message at L1 (1·6 GHz) will be subject to disruptions during periods of severe scintillations. Non-availability of the GEOS downlink may disable the entire SBAS over a large area in the equatorial zone. Fortunately, the equatorial irregularities that cause scintillations, occur in patches of varying horizontal extent and drift across the ray path of a satellite. In order to have a fail-safe system, it is suggested that at least two geostationary satellites, well separated in space, be used for downlinking so that when one link exhibits scintillations, another may remain free of the phenomenon. This paper estimates the minimum separation between two such geostationary satellites for SBAS in the Indian longitude sector from the distribution of patch duration of scintillations observed from Calcutta.

2. DATA.

Amplitude of the L-band carrier signal (1537·528 MHz) from the geostationary satellite INMARSAT (65°E) (350 km-subionospheric point: 21·08°N, 86·59°E geographic; 28·73°N magnetic dip) has regularly been recorded at Calcutta (22·58°N, 88·38°E geographic; 32°N magnetic dip) since 1990. The receiver used is an ICOM R7100 Wide-Band Communication Receiver, and the detected output is recorded simultaneously on a Strip Chart Recorder and Digital Data Acquisition System with a sampling rate of 20 Hz. The receiver is calibrated at least once a

https://doi.org/10.1017/S0373463302002059 Published online by Cambridge University Press

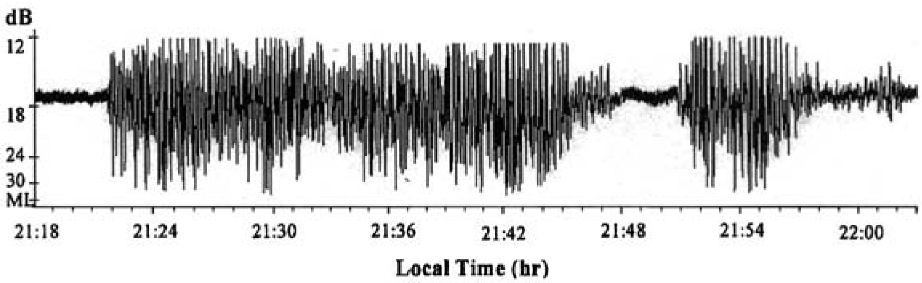

Figure 1. Sample of geostationary INMARSAT (1·5 GHz) signal scintillations recorded at Calcutta on 6th October 1999, showing distinct patches.

week using a HP Signal Generator HP8648C, following Basu and Basu (1989). The dynamic range of the receiver is 28 dB. Scintillations have been scaled every 3 minutes and the Scintillation Index [SI (dB)] is computed by the third-peak method of Whitney *et al*. (1969). According to scattering theory, an SI of 15 dB corresponds to a signal fade of 12 dB (Basu, 2002). A fade of more than 10 dB may cause loss of receiver lock on the SBAS correction systems. Assuming that the SBAS receiver has a fade margin of less than 12 dB (Klobuchar, 2002), the link will be disrupted under the chosen intensity of scintillations. An increase in the amplitude fade margin may be achieved by narrowing the receiver loop bandwidth, but this would make the receiver vulnerable to phase fluctuations. Cumulative distribution of patches with SI $\geqslant$ 15 dB only during solar maximum years 1998–2000 have been used to estimate the minimum separation between two GEOS for uninterrupted SBAS operation.

3. RESULTS. From multi-technique observations (Basu and Basu, 1981) like radar, in-situ and airglow, it is established that within the equatorial zone the irregularities show distinct variations with latitude. Near the magnetic equator, the irregularities have horizontal extents ranging from tens to hundreds of kilometres. As one moves away from the equator, the irregularity clouds become narrower and stream out into distinct patches with clear gaps in between (Weber *et al*., 1980). From GEOS observations, it has been established that scintillations occur over longer time intervals near the magnetic equator than at locations near the anomaly crest. However, scintillations at L-band rarely exceed 10 dB near the equator. On the contrary, scintillations in excess of 25 dB are very common in solar maximum years at locations like Calcutta, Hong Kong and Ascension Island situated around the anomaly crest (Aarons *et al*., 1981; Groves *et al*., 1997). In a SBAS, when the ray path from an aircraft to a GEOS passes through the ionospheric height around the anomaly crest ($\pm 25^\circ$–35° dip) in the post-sunset hours of equinoctial months in high solar activity years, intense scintillations are likely to disrupt the downlink and disable the systems over a large area. Fortunately, the disruptions will not be continuous. It may be assumed that if two geostationary satellites are used with sufficient separation in longitudes, the probability of simultaneous failure of both GEOS downlinks in a SBAS may be practically eliminated. An estimate of longitudinal separation may be obtained from the statistics of patch and gap duration observed in the latitude interval where scintillations are most severe. The station Calcutta near the anomaly crest offers a unique platform for a worst case

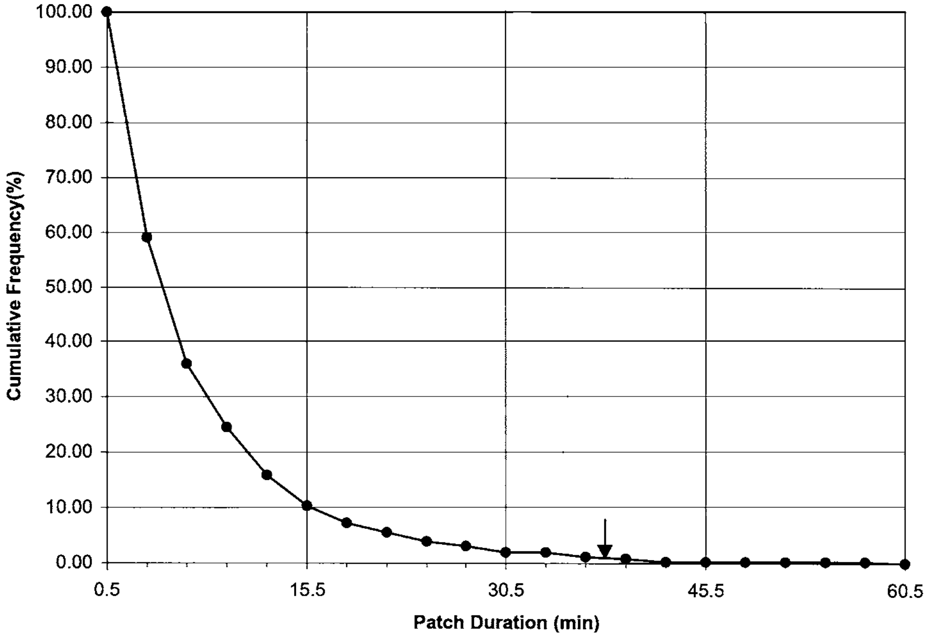

Figure 2. Cumulative distribution of duration of scintillation patches with SI ⩾ 15 dB recorded during 1998–2000. The total number of patches recorded is 359. The arrow indicates the 99th percentile value of the distribution, which is equal to 37·73 mins.

study of scintillations, as the phenomenon is most intense near the crest. Figure 1 shows an example of the patchy nature of scintillations at L-band (1537·528 MHz) observed at Calcutta on 6th October, 1999. In Figure 1, two patches with SI ⩾ 3 dB are observed for 26 min (2122–2148LT) and 11 min (2151–2202LT) with a gap of 3 min (2148–2151LT) in between. The patches have been scaled at 3 min intervals and, considering only those intervals which have SI ⩾ 15 dB, there are three smaller patches of duration 6 min (2126–2132LT), 9 min (2138–2147LT) and 3 min (2155–2158LT) within the above intervals. During 1998–2000, duration of patches with SI ⩾ 15 dB totalled 48 hr 55 min out of a total observational period of 3868 hr 09 min (1·27%) in the post-sunset hours (19–00LT). For 1998, the disruption was for 1 hr 36 min out of 1094 hr 23 min observation time (0·15%). In 1999 and 2000, the figures were 14 hr 57 min out of 1359 hr 28 min (1·10%) and 32 hr 22 min out of 1414 hr 18 min (2·29%), respectively.

Figure 2 shows the cumulative distribution of patch duration recorded during 1998–2000 at Calcutta with geostationary INMARSAT. A total number of 359 patches with SI ⩾ 15 dB were recorded during the three years. The 99th percentile value of patch duration (shown with an arrow) is observed to be 37·73 min. The worst-case scintillation events normally occur during 2000–2100LT. From spaced receiver observations, it was established that the equatorial irregularities move eastward with an initially high velocity, approximately 200 ms^{-1}, in the post sunset hours 2000–2100LT (Bhattacharya *et al.*, 1989). The velocity decreases and attains an average value of about 100 ms^{-1} in the late evening hours. Thus to estimate the longitude separation, the initial value of 200 ms^{-1} has been chosen for the worst-case analysis, which implies the maximum probable patch length. The 99th percentile value of patch duration, 37·73 min multiplied by the drift velocity of 200 ms^{-1} yields a patch length of 452·76 km at the 350 km ionospheric height. This patch length subtends an angle of 3·86° at the centre of the earth. If a receiver establishes links with two geostationary satellites through the two edges of the patch, at least one of them is expected to be unperturbed by scintillations of more than 15 dB. The angle subtended by the two satellites at the centre of the earth is 56·86°. In other words, the minimum separation between two geostationary satellites for reliable SBAS operation with a Scintillation Index of 15 dB or more at L1 is approximately 57°.

4. DISCUSSION.

From observations of intense L-band scintillations at a location situated near the crest of the equatorial anomaly in the Indian zone, the minimum separation between two geostationary satellites required for reliable operation of the proposed SBAS is obtained. The total time of disruption with SI $\geqslant$ 15 dB for which a geostationary satellite link may become unusable has been obtained for the years 1998, 1999 and 2000 individually, and for the solar maximum epoch 1998–2000. The remarkable increase in both intensity and frequency is clearly evident from observations. The present estimate of GEOS longitude separation is based on an assumed SI of 15 dB. However the separation will be determined by the choice of fade margin of GPS receivers onboard with GEOS overlay. A smaller fade margin will correspond to a larger GEOS longitudinal separation. For example, with the present observations in the Indian zone, if the chosen SI is greater than or equal to 10 dB, which corresponds to a fade margin of 7·5 dB, the 99th percentile value of patch duration is 49·29 min corresponding to a longitudinal separation of 70·11°.

To avoid multi-path effects and other interferences, GPS receiving antennas will normally have an elevation mask angle of 15°. This limits the central angle over which a geostationary satellite may be visible on or near the surface of the earth to 66·6°. If the estimated separation exceeds 66·6°, an additional consideration has to be taken into account. With SI $\geqslant$ 10 dB, to accommodate two GEOS simultaneously from the same receiver, one edge of the SBAS coverage area should be $70{\cdot}11^\circ - 66{\cdot}6^\circ = 3{\cdot}51^\circ$ away from one GEOS longitude. In other words, there should be a 3·5° wide skirt in longitude on either side of the operational area. Thus, for every 63° longitude of service area, two geostationary satellites longitudinally separated by 70° may be suitably disposed.

ACKNOWLEDGEMENTS

This research has been sponsored in part by the Ministry of Information Technology (MIT), Government of India and the Indian Space Research Organization (ISRO) through research grants. The authors are grateful to Santimay Basu, J. A. Klobuchar and M. Bakry El-Arini for discussions.

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