Preliminary Analysis of the Effects of Ionospheric Scintillation on the MTSAT Satellite-based Augmentation System (MSAS)

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Abstract

MSAS (Multi-functional Transport Satellite [MTSAT] Satellite-based Augmentation System) is under development to aid GPS enroute to non-precision approach and eventually precision approach in Japan. Like all satellite-based augmentation systems (SBASs), it requires GPS L1 and L2 signals in order to compute and broadcast ionospheric, clock, and ephemeris corrections. Ionospheric scintillation, along with other factors, can cause a loss of lock on L2, the weaker signal. This study is a first look at an initial set of data collected in Japan in order to assess the potential for loss of lock of L2 and determine the extent to which ionospheric scintillation is responsible.

Introduction

MSAS is one of at least three Satellite-Based Augmentation Systems to the Global Positioning System (GPS) that are under development. These augmentation systems are planned to be used by aircraft for air navigation in en route, terminal, and non-precision approaches as well as instrument approaches. MSAS has three components: 1) extra ranging sources using geostationary earth orbiting (GEO) communications satellites (called Multi-functional Transport SATellite (MTSAT)), 2) a vector of corrections to the GPS signal-in-space, including components for ionosphere, clock, and ephemeris, and 3) an integrity monitoring function to alert users of out-of-tolerance operations. In order to provide these services, MSAS has Ground Monitoring Stations (GMSs), Monitor and Ranging Stations (MRSs), Master Control Stations (MCSs) and a Network Communication System (NCS). The MTSAT system is composed of one or two GEOs, depending on the timeframe; up to two Ground Earth Stations (GESs) for each MTSAT; and two Tracking, Telemetry, and Command (TT/Cs) Stations [1].

The GPS L1 and L2 pseudoranges and carrier phase measurements at the GMSs and MRSs are required for the operation of MSAS in order to calculate and broadcast ionospheric, clock, and ephemeris corrections (and error bounds) during various phases of flight. Loss of lock on either L1 or L2 can prevent these corrections from being calculated during the time period that lock is lost and for a few seconds after lock is regained. A satellite is declared “not monitored” in the MSAS broadcast message unless a sufficient number of GMSs/MRSs have L1 and L2 measurements on that satellite. Because the received signal of L2 is much weaker than L1, receivers may lose lock on the L2 signal more often than on the L1 signal. The main purpose of this study was to examine data collected during and after the peak of solar cycle from two sites in Japan and derive a preliminary estimate of the frequency of occurrence of loss of lock on L2 due to ionospheric scintillation. Since the magnetic equator extends above the geodetic equator in the Eastern Hemisphere, areas in southern Japan are close to the northern equatorial scintillation anomaly region as shown in Figure 1. This figure depicts the amplitude scintillation index S_4 and was constructed by the Wideband Ionospheric Scintillation Model (WBMOD) for a day in the Fall equinox time period (September 15) at 9:00 PM local time everywhere. Solar activity is elevated (SSN = 150), but it is a quiet geomagnetic day (Kp = 1). Given these conditions, it is apparent that significant equatorial scintillation becomes possible in the southern parts of Japan as satellites are tracked to the south.

Data Analyzed

All of the data associated with this study was collected by the Electronic Navigation Research Institute (ENRI). Figure 2 shows the amplitude and phase scintillation that occurred at Naha, Japan during 2000-2001 [2]. The diurnal and seasonal effects are clearly portrayed. A smaller set of this data consisting of eight days was analyzed. The data was collected during October 3-5, 13, and 29, 2000, and February 16-18, 2001 from two sites in Japan -- Naha and Mitaka/Tokyo. The data at each site was of two types: (1.) GPS 1-sec reports of L1 and L2 code and carrier phase and (2.) Ionospheric Scintillation Monitor (ISM) 1-min reports of amplitude and phase scintillation at L1. The GPS data originated from dual-frequency NovAtel WAAS receivers and the ISM data originated from single frequency GSV4000 receivers. At each site, the estimates of amplitude and phase scintillation at L1 from the ISM receiver were compared with the loss of lock on L2 from the GPS receiver. The ISM and GPS antennas were 10’s of meters apart at Naha. For the second site, the ISM receiver was located at Mitaka about 20 km away from the Tokyo GPS receiver.

Charts for all eight days were constructed depicting $S_4(L2)$, $\sigma_\phi(L2)$, and percent loss of lock of L2 with respect to L1. The ISM receiver estimates total $S_4(L1)$, designated S_{4T} along with the contribution from ambient noise designated S_{4N}. The *corrected* S_4 at L1 is determined by removing the noise as follows [3]: $S_4 = \sqrt{S_{4T}^2 - S_{4N}^2}$.

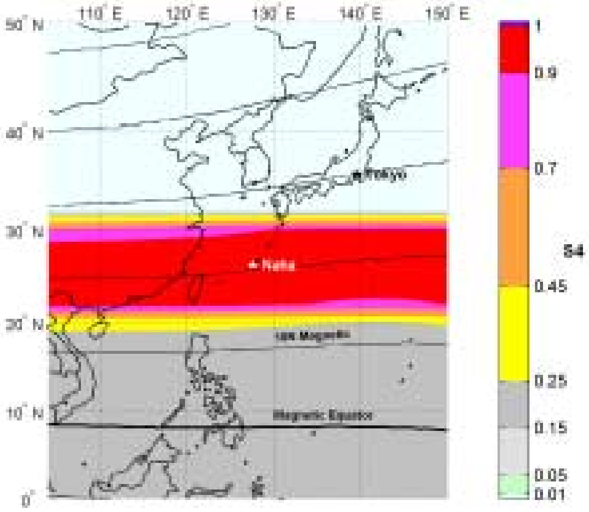

Figure 1. S_4 **Scintillation Index in Region Surrounding Japan (September 15, local time = 9pm everywhere)**

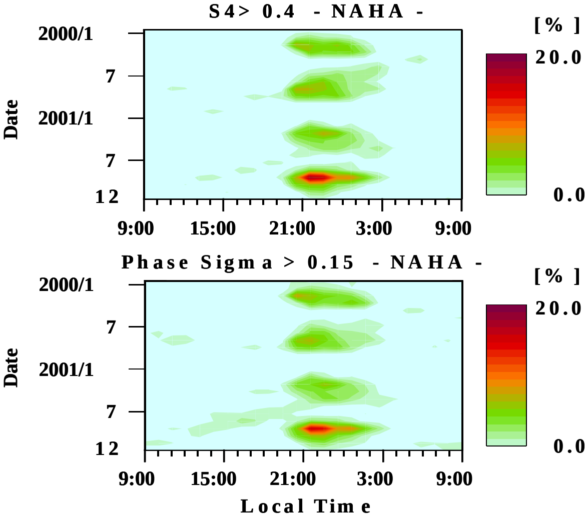

Figure 2. Amplitude and Phase Scintillation for Naha, Japan (2000–2001) [2]

Since the ISM receiver only tracks L1, all receiver estimates of S_4 are for L1. Estimates of $S_4(L1)$ can be scaled to the L2 frequency using the relationship [3]: $S_4(L2) = S_4(L1)\left(f_{L1}/f_{L2}\right)^{1.5} = 1.454 \cdot S_4(L1)$, where f_{L1} is the frequency of L1 and f_{L2} is the frequency of L2. Values for the carrier phase standard deviation can also be scaled to the L2 frequency using the relationship [3]: $\sigma_\phi(L2) = \sigma_\phi(L1)\left(f_{L1}/f_{L2}\right) = 1.283 \cdot \sigma_\phi(L1)$. In all cases, the ISM carrier phase standard deviation for 60-second intervals was used. A mask angle of 5 degrees was also used.

Naha and Mitaka/Tokyo experienced significant scintillation activity (resulting in loss of L2) for 4 days and 2 days respectively in the 8-day period. Figures 3-4 show a time-based picture of scintillation activity at Naha for February 17th, 2001, the place and date of maximum scintillation activity during this 8-day period. The x-axis is Local Time ranging between 9 and 33 hours which is 9 hours ahead of UTC. (Data was collected over 24 hours between 0 and 24 UTC.) The green curves are $S_4(L2)$ for each PRN with a range of [0 2] between PRNs, however, the values of $S_4(L2)$ are limited to $\sqrt{2}$ which is believed to be the theoretical limit. The red curve is the percent loss of lock of L2 calculated on a per-minute basis using the 1-sec GPS data in order to correlate it with ISM data that is reported once per minute. The percent loss of lock is related to the reporting of L1 for the GPS receiver. Thus it is the percent of time that L2 has lost lock given that L1 is locked. If L1 is not locked and is missing from the data, this percent will be underestimated. The range for loss of lock is [0 1] between PRNs (where 1 corresponds to 100%). The blue curve is $\sigma_\phi(L2)$ for a 60-second period. The range is [0 1] radians, however, the values of $\sigma_\phi(L2)$ are limited to 0.8 radians. The blue squares that occasionally appear below a PRN line indicate that there was no information reported by the ISM for that minute. It is clear that when there is severe scintillation, the ISM receiver frequently fails to report, although fortunately it does report enough so that usually a clear indication of scintillation activity can be determined. On February 17th, Naha experiences severe scintillation after local sunset and loses lock on L2 for PRNs 4, 7, 8, 13, 24, 26, and 27. Even worse, this loss of lock was simultaneously experienced for four satellites (PRNs 4, 7, 26, 27) for approximately 30 minutes. (The event around 21:00 local time at Naha for PRN 19 is the result of a brief rise of the satellite above the mask angle of 5 degrees.)

To verify that the elevated levels of S_4 were caused by satellites tracking through the equatorial region, a map was constructed based on ionospheric pierce point (IPP) tracks using a thin-shell representation of the ionosphere with peak density at a height of 350 km as shown in Figures 5-6.

It is possible to get a very broad view of the amount of scintillation present by, for example, determining the number of times $S_4 > .4$, and ascribing scintillation or multipath to those times when the elevation angle is respectively above or below 15 degrees. Part of the purpose of this study, however, was to evaluate a more direct means of discriminating between scintillation and multipath by examining the scintillation/multipath discrimination test in references [4,5]. This test is summarized as follows: For any 1-minute ISM epoch, if $\sigma(CCD)/S_{4T} > 5$, then it is a multipath, otherwise it is an amplitude scintillation, where CCD = code carrier divergence, and S_{4T} = total S_4 as defined above. Both CCD and S_{4T} are measured parameters by the ISM receiver. The discrimination test uses the 1-minute ISM data and was applied to all eight days of data at both sites and evaluated according to how well it appeared to function compared to the time-based scintillation graphs. Figures 7 and 8 show the results of applying this test for an unambiguous scintillation for PRN 13, and unambiguous multipath for PRN 31. Each figure depicts percent loss of L2, if any, $S_4(L1)$, $\sigma(CCD)/S_{4T(L1)}$, and elevation angle vs. local time. Any gaps in the data within the charts represent time periods when there was no data from the ISM receiver. Considering the time (after local sunset) and place (equatorial region) when satellites lost lock on L2 on this date, PRN 13 is a good example of unambiguous scintillation. The graph of $\sigma(CCD)/S_{4T(L1)}$ (Figure 7) shows that for PRN 13, the group of points marked scintillation (below the threshold) are generally quite separated from those identified as multipath which are located above the threshold. The percent loss of lock of L2 from all sources is shown in Table 1.

Figure 3. Time-based Scintillation Activity (PRN1 – PRN17) (Naha, February 17, 2001)

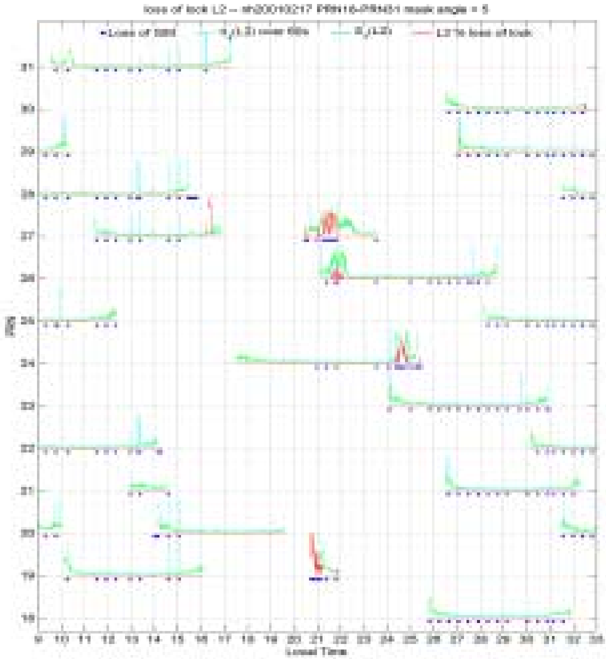

Figure 4. Time-based Scintillation Activity (PRN18 – PRN31) (Naha, February 17, 2001)

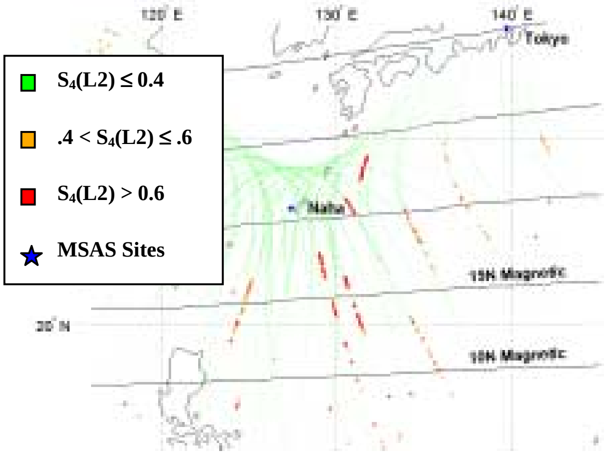

Figure 5. $S_4(L2)$ Mapped Onto IPPs for Naha (February 17, 2001)

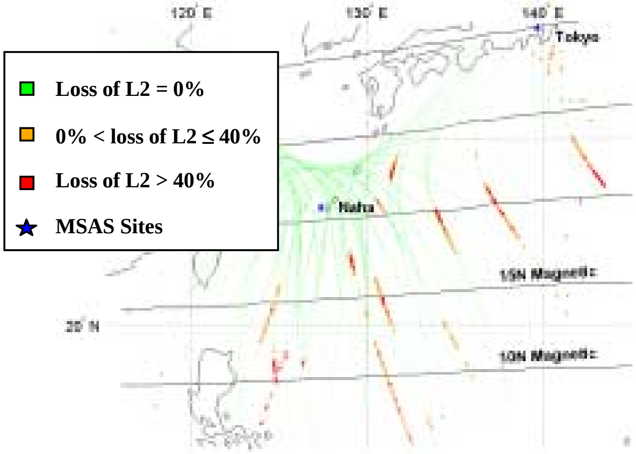

Figure 6. L2 Percent Loss of Lock Mapped Onto IPPs for Naha (February 17, 2001)

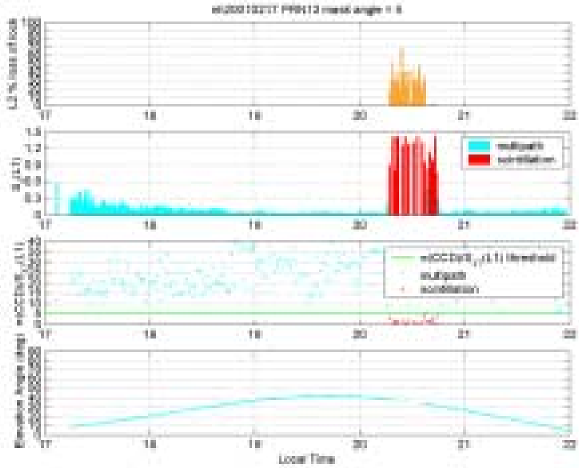

Figure 7. Scintillation/Multipath Test Applied to Unambiguous Scintillation (PRN 13, Naha, February 17, 2001)

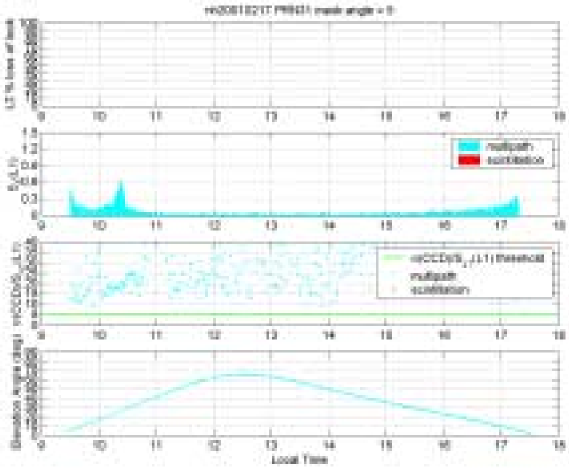

Figure 8. Scintillation/Multipath Test Applied to Unambiguous Multipath (PRN 31, Naha, February 17, 2001)

Table 1. Percentage of Loss of Lock for L2

	5 degree mask angle		*10 degree mask angle*		*15 degree mask angle*	
	Naha	***Mitaka/Tokyo***	***Naha***	***Mitaka/Tokyo***	***Naha***	***Mitaka/Tokyo***
October 3, 2000	**3.3%**	**.16%**	**.98%**	**.05%**	**.09%**	**0%**
October 4, 2000	**4.3**	**.04**	**.84**	**.005**	**.18**	**.004**
October 5, 2000	**8.4**	**1.03**	**3.53**	**1.11**	**1.44**	**1.24**
October 13, 2000	**7.0**	**.03**	**2.41**	**.006**	**.22**	**.002**
October 29, 2000	**6.0**	**10.6**	**2.41**	**8.71**	**.18**	**7.3**
February 16, 2001	**.48**	**.15**	**.45**	**.006**	**.33**	**.006**
February 17, 2001	**.59**	**.31**	**.52**	**.12**	**.44**	**.093**
February 18, 2001	**.33**	**.09**	**.23**	**.0006**	**.13**	**0**

Observations

Ionospheric scintillation is significantly elevated in the southern region of Japan after sunset during the peak of solar cycle. Of the eight days of data in this study, four days experienced severe scintillation at Naha and two days were severe at Mitaka/Tokyo. This was responsible for a noticeable loss of the GPS L2 in addition to that caused by multipath. On February 17, at Naha, loss of lock of L2 was simultaneously experienced for four satellites for approximately 30 minutes. The scintillation/multipath discrimination test seemed to perform reasonably well and will be tested further on additional data.

References

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