Longitudinal Differences in Ionospheric Scintillation Characteristics

K. Groves, C. S. Carrano, C. Bridgwood, R. G. Caton, ISR/Boston College,
AFRL/RVB, USA

This paper was prepared for presentation at the 13th International Congress of the Brazilian Geophysical Society, held in Rio de Janeiro, Brazil, August 26-29, 2013.

Abstract

Extensive efforts to expand the global coverage of low-latitude scintillation observations over the past decade have resulted in the development of more than 100 monitoring stations distributed on all the equatorial continents and numerous available landmasses to achieve relatively good longitudinal coverage. Furthermore, satellite missions such as ROCSAT (1999-2004), DMSP (1989-present) and C/NOFS (2008-present) provide in situ observations of electron density at all longitudes for a range of altitudes. Many aspects of irregularity climatology have been reported from investigations exploiting these data sets, yet much more information remains to be extracted, including features that may be of great value from a practical perspective. Parameters considered in the current study include variations of occurrence variability, irregularity strength, and spatial extent as a function of longitude and solar flux. Principal data sources include ROCSAT, C/NOFS and the SCINDA network. Findings reported in the presentation may suggest potential approaches for the development of new and improved scintillation products for users.

Introduction

Because it causes deleterious effects on radio wave propagation and thus impacts the performance of communication and navigation systems, ionospheric scintillation has been a topic of interest for more than four decades. The severity and frequency of scintillations associated with equatorial Spread F have drawn special attention from both the research and operational communities. The basic morphology of such scintillation, resulting from km-scale irregularities cascading from large-scale post-sunset instabilities, has been well established along with an understanding of diurnal, seasonal and longitudinal variability [see, e.g., *Aarons, 1982*]. But information from low-inclination satellites within the past decade and the recent expansion of ground-based sensors around the world has enabled a more detailed characterization of low-latitude scintillation that has revealed new aspects of the nature of scintillation occurrence, severity and the physical processes responsible for its generation. Specifically we address deviations in previously accepted longitudinal variations of scintillation occurrence and strength, particularly in the under sampled African sector, and striking differences in the true day-to-day variability as a function of longitude. The consideration of variability has practical implications for the development of long term scintillation forecasts. The results suggest that the role of specific physical drivers of irregularity formation is strongly influenced by the declination of the earth's magnetic field.

Data

Magnetic field declination is the principal determinant of the observed longitudinal variability of scintillation occurrence [*Tsunoda*, 1985]. Burke et al. (2004) used data from the Republic of China Satellite (ROCSAT) to quantify the seasonal dependence of equatorial plasma bubbles and demonstrated the general consistency of the magnetic declination-solar terminal alignment theory, though the results also showed considerable deviations in occurrence, particularly in the African sector (see Figure 1). This can be seen perhaps more clearly in the work of Su et al. [2006] where the longitudinal occurrence is broken out by season; activity can be seen to peak over the African continent during about nine months of the year (see Figure 2), not predicted by magnetic declination considerations alone. One possible explanation is the modulation of the declination pattern by non-migrating tides which have been shown to have a clear effect on TEC production and anomaly characteristics [*Immel et al.,* 2006], but a better understanding of the seasonal and longitudinal variations of such tides is needed to address this question with any certainty. A review of ground-based scintillation observations reveals even more curious details about the nature of irregularity formation over Africa.

Figure 3 shows the occurrence of VHF (250 MHz) scintillations over Nairobi, Kenya (1.27°S, 36.81°E) in 2011 as a function of day of year and local time relative to sunset. The data show high levels of activity throughout most of the year, but also exhibit a marked change in the diurnal pattern during the June-July period when the scintillation onset is delayed two or more hours relative to the usual post-sunset development. Electric field data from the Communication/Navigation Outage Forecast System (C/NOFS) satellite shows upward drifts in the African longitude sector during these periods consistent with the appearance of the observed scintillations, but no mechanism to explain why the drifts during the June solstice period are upward at these local times has been proposed at this time [*Yizengaw, et al.*, 2013].

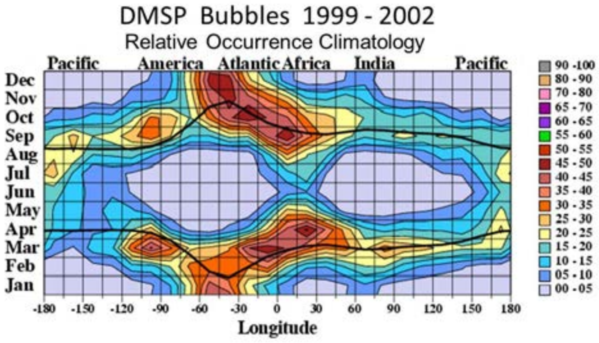

Figure 1. Equatorial plasma bubble occurrence climatology from the DMSP satellites. The solid black lines show the day when the solar terminator is aligned with the magnetic declination, a condition considered most favorable for bubble generation [*Burke et al.,* 2004]

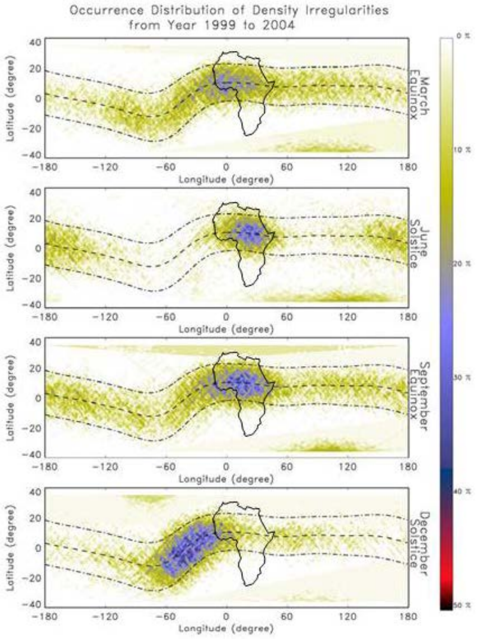

Figure 2. Seasonal irregularity occurrence percentage derived from ROCSAT data from 1999-2004. Africa shows maximum activity during 3 of the 4 seasons in the analysis. Adapted from *Su et al*., [2006].

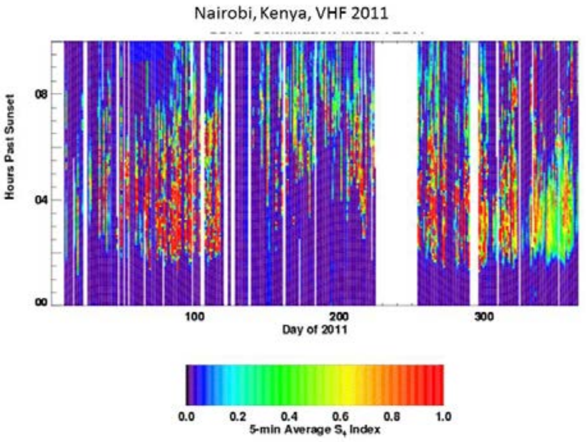

Figure 3. VHF scintillation observed at Nairobi, Kenya in 2011. The location is active throughout the year, though the delayed onset time in June and July is a peculiar feature that remains unexplained.

A comparison of the Nairobi scintillation data with data from the American longitude sector presents an even more puzzling result. Data from Cuiabá, Brazil (15.07°S, 303.93°E) is presented in Figure 4. While both sites show a lot of scintillation activity, note that Cuiabá exhibits very well-defined seasonal patterns relative to Nairobi. In fact seasonal modulation exerts greater control over scintillation activity at Cuiabá than daily variability. Scintillation activity persistence for both sites is plotted in Figure 5a (Nairobi) & b (Cuiabá). In these plots persistence is calculated by assigning each day a “1” or a “0” depending on whether a specific S4 scintillation index was exceeded for at least an hour or not. Results were summed over a running 15 day window and then normalized by the number of days and multiplied by 100 to form a percentage of scintillation activity. Thus, if scintillation exceeded the threshold for every day in the sample window the persistence index would equal 100, and it would equal zero if no days exceeded the threshold, etc.; values close to 100 or 0 indicate little change in activity over the sampling period (low variability), whereas a value of 50 suggests that half the days in the sample had activity and half did not, which is the least persistent (most variable) outcome. As can be seen in Figure 5b, this measure of variability shows a clear seasonal pattern at Cuiabá; indeed, with the exception of the brief transition periods, the data show an astounding day-to-day persistence. During the same period in Nairobi persistence fluctuates significantly within a range of 20-80% for most of the year.

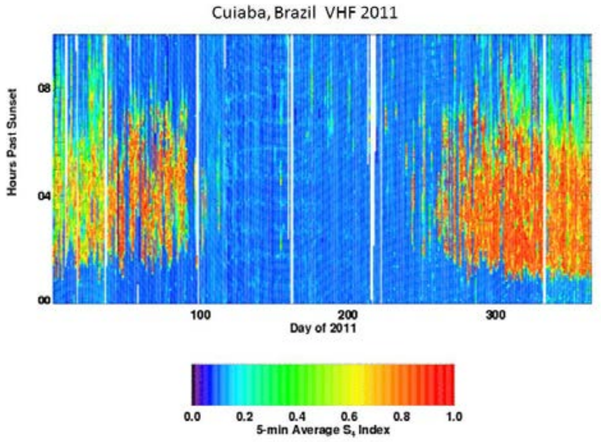

Figure 4. VHF scintillation observed at Cuiabá, Brazil in 2011. A strong seasonal pattern dominates activity. The marked increase in activity in the 2nd half of the year is due to an increase in solar flux.

The implication is that persistence, a concept similar to climatology, can provide a robust forecast at Cuiabá throughout most of the year while the same approach would yield poor results in Nairobi. We extended the investigation to include additional sites at different longitudes to include Cape Verde (16.73°N, 337.06°E), Kwajalein Atoll (9.40°SN, 167.47°E) and Christmas Island (2.00°N, 202.60°E). The results for Cape Verde, off the west coast of Africa approximately 35° east of Cuiabá, are surprisingly similar to the Brazilian station. Kwajalein and Christmas, conversely, are much more like Nairobi in terms of scintillation variability.

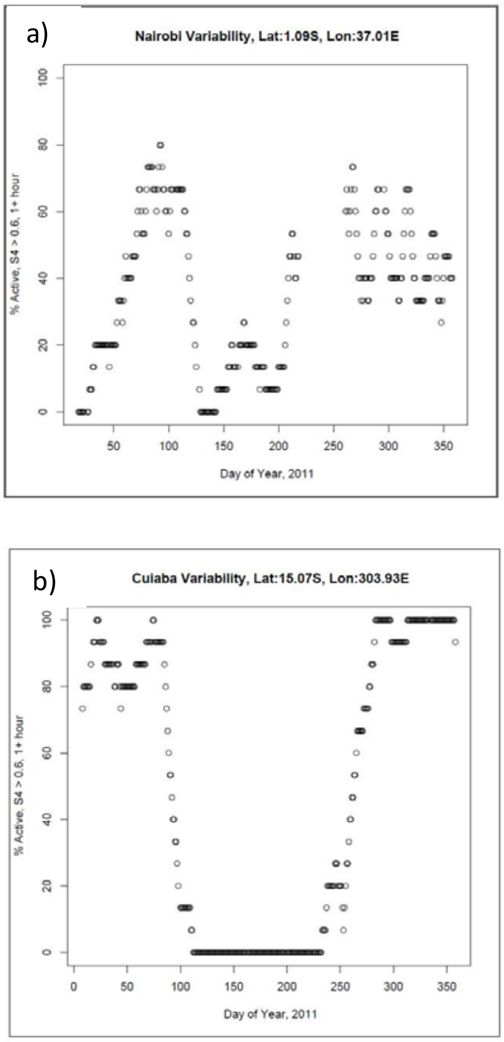

Figure 5. Scintillation persistence measured as a percentage of days within a 15 day window that exceeded S4=0.6 for at least one hour from a) Nairobi and b) Cuiabá in 2011.

Results

From the data it is clear that there is much that remains to be learned about the climatology of equatorial scintillation occurrence. While the gross features can be be explained largely in terms of the alignment of the solar terminator and the magnetic declination angle, other physical processes are also playing a role. The variability of scintillation occurrence also shows a substantial dependence on longitude. Neutral atmosphere influences in the form of gravity waves and tidal forces have been linked to low-latitude irregularity formation, but it is unclear why these processes would differ substantially as a function of longitude, particularly regarding disparate behavior in Africa and South America which are both regions of maxima in the non-migrating tide. And if gravity waves are invoked to explain variability in Africa, why are similar variable effects not observed in South America? A common though not necessarily causative association between sites with high variability (Nairobi, Kwajalein, Christmas Island) and those with low variability (Cuiabá, Cape Verde) is magnetic declination. The sites with low variability have strongly westward declination (-15.2°, -10.2°) while those with high variability have eastward or nearly zero declination (~0°, 7.3°, 9.3°). If magnetic declination is the key parameter, the data suggest that strong westward declination and solar terminator angle are overriding factors, both positive and negative, in determining scintillation occurrence. Where declination is eastward or perhaps small, the role of other processes increases and, accordingly, so does the day-to-day variability of scintillation.

Conclusion

Data from additional sites and time periods is needed to verify these results and guide us in developing a physical framework to explain the observed effects. This is an important study to undertake because it will help unravel the roles various processes play in the development of equatorial irregularities and scintillation at different longitudes.

From a practical perspective the results have significant implications for the limits of long-term forecasts or outlooks as a function of longitude. In the American to West African sectors it appears that during periods of moderate to high solar flux it should be possible to “predict” VHF scintillation activity with nominal accuracies of 85-90% days or even weeks in advance for about 10 months of the year. Advance forecasts in other longitudes would be restricted to much smaller time periods during the year. And it should be noted that the results cannot yet be applied to L-band (GPS) frequencies; though data exist to carry out such an investigation. Based on our experience with GPS we would not expect the results to be as well ordered as the current findings suggest, due to the greater variability in space and time of L-band scintillations.

References

Aarons, J. (1982). Global morphology of ionospheric scintillations. *Proceedings of the IEEE*, *70*(4), 360-378.

Burke, W. J., L. C. Gentile, C. Y. Huang, C. E. Valladares, and S. Y. Su (2004), Longitudinal variability of equatorial plasma bubbles observed by DMSP and.ROCSAT-1, J Geophys. Res., 109, A12301, doi:10.1029/2004JA010583.

Immel, T. J., E. Sagawa, S. L. England, S. B. Henderson, M. E. Hagan, S. B. Mende, H. U. Frey, C. M. Swenson, and L. J. Paxton (2006), Control of equatorial ionospheric morphology by atmospheric tides, Geophys. Res. Lett., 33, LXXXXX, doi:10.1029/2006GL026161.

Su, S. Y., Liu, C. H., Ho, H. H., & Chao, C. K. (2006). Distribution characteristics of topside ionospheric density irregularities: Equatorial versus midlatitude regions. *Journal of Geophysical Research: Space Physics (1978–2012)*, *111*(A6).

Tsunoda, R. T. (1985). Control of the seasonal and longitudinal occurrence of equatorial scintillations by the longitudinal gradient in integrated E region Pedersen conductivity. *Journal of Geophysical Research: Space Physics (1978–2012)*, *90*(A1), 447-456.

Yizengaw, E., J. Retterer, E. E. Pacheco, P. Roddy, K. Groves, R. Caton, and P. Baki, Post-midnight bubbles and scintillations in the quiet-time June solstice, *Geophys. Res. Lett*., submitted 2013.