Analysis of trends between solar wind velocity and energetic electron fluxes at geostationary orbit using the reverse arrangement test

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Abstract
A correlation between solar wind velocity (VSW) and energetic electron fluxes (EEF) at geostationary orbit was first identified more than thirty years ago. However, recent studies have shown that the relation between VSW and EEF is considerably more complex than was previously suggested. Application of process identification technique to the evolution of electron fluxes in the range 1.8 - 3.5 MeV has also revealed peculiarities in the relation between VSW and EEF at geostationary orbit. It has been revealed that for constant solar wind density EEF increases with VSW until a saturation velocity is reached. Beyond the saturation velocity an increase in VSW is statistically not accompanied with EEF enhancement. The present study is devoted to the investigation of the saturation velocity and its dependency upon solar wind density using the reverse arrangement test. In general, the results indicate that the saturation velocity increases as solar wind density decreases. This implies that solar wind density plays an important role in defining the relationship between VSW and EEF at geostationary orbit.

Introduction
Energetic electron fluxes (EEF) at geostationary orbit represent a serious hazard to the satellites and other space-based systems. The severity of the hazard is determined by the level of EEF (Baker et al., 1987; Baker, 2002). Therefore, accurate prediction of EEF at geostationary orbit could help to mitigate the damage caused to the satellites and other space-based systems. The solar wind controls the population of the energetic electrons at geostationary orbit. Thus, an understanding of how EEF depends upon the main solar wind parameters will lead to better predictions of EEF at geostationary orbit.

Results and discussions
The reverse arrangement test was applied to electron fluxes measured in the energy range 1.8 - 3.5 MeV and solar wind density measured in the range 2.2 ≤ n < 2.3 cm\(^{-3}\) as presented in Figure 1 in order to estimate the saturation velocity.

![Figure 1. Energetic electron fluxes and solar wind velocity for electron fluxes measured in the energy range 1.8 - 3.5 MeV and solar wind density measured in the range 2.2 ≤ n < 2.3 cm\(^{-3}\).](image)

The saturation velocity was estimated to be 586 km/s with 95% confidence as indicated in Figure 2. Here a 95% confidence level was preferred solely because lower confidence level would provide less accurate estimation and higher confidence level would make the reverse arrangement test less tolerant to small expected variations in the data. Figure 3 shows the saturation velocity as a function of solar wind density for all electron fluxes measured in the fixed energy range 1.8 - 3.5 MeV and solar wind densities of 0.03329 cm\(^{-3}\). It clearly illustrates that the saturation velocity decreases with the solar wind density increases. This implies that the range of VSW that is correlated to the EEF decreases as solar wind density increases. Density controls the efficiency with which solar wind velocity drives energetic electron fluxes. Low densities indicate electron loss which may be due to magnetopause shadowing or EMIC waves. For solar wind density in the range 1.8 ≤ n < 1.6 cm\(^{-3}\), the saturation velocity appears to be curiously lower than expected as indicated by circle in Figure 3. This anomaly may be due to the relatively larger solar wind density range which is obscuring information leading to inaccurate interpretation of the results. The most appropriate solution to this problem would be to reduce the bin size. However, reducing the bin size leads to considerably fewer number of data points in each data subset which is likely to produce unreliable results due to inaccurate representation of data.

![Figure 2. Saturation velocity as a function of solar wind density.](image)

Conclusion
From the results obtained in this study, it can be concluded that solar wind density plays an important role in defining the relationship between EEF and VSW at geostationary orbit. Clearly the EEF have a distinct velocity-dependent lower limit separated from the velocity-independent upper limit by some saturation velocity. The reverse arrangement test is employed to estimate the saturation velocity with 95% accuracy. The results in Figure 3 demonstrates that the solar wind density that determines the saturation velocity. The saturation velocity decreases as the solar wind density increases. This implies that the range of VSW that is correlated to the EEF decreases as solar wind density increases. The result of such a trend is that the loss from the outer radiation belt through wave-particle interactions and drift loss through the dayside magnetopause due to both outward diffusion and magnetopause shadowing (Matsumura et al., 2011). The latter is where the electron path takes electrons outside the magnetosphere which is magnetopause is significantly compressed on the dayside due to high solar wind dynamic pressure (Ohtani et al., 2006). This knowledge of the saturation velocity and its dependency upon solar wind density will not only provide better understanding of the physical processes within the geosynchronous orbit but also lead to improved modelling and forecasting of fluxes of high energy electrons in the outer terrestrial radiation belt. This can potentially help mitigate the damage to the satellites and other space-based systems. The study was based on one day averages of electron fluxes measured between 1.8 - 3.5 MeV and solar wind densities less than 0.6 cm\(^{-3}\). The relationship between solar wind velocity and solar wind density may be different with shorter or longer time scales. Also, determination of the relationship between the saturation velocity and solar wind density for electron fluxes measured in other energy ranges and for solar wind densities larger than 6 cm\(^{-3}\) is highly beneficial for modelling and forecasting of fluxes of high energy electrons. This will be at the centre of future investigations into EEF at geostationary orbit.

Methodology
The saturation velocity can be estimated mathematically using the reverse arrangement test which is a widely used methodology to identify whether there is a significant correlation in a set of observation data in an increasing solar wind velocity (Bendat and Pinson, 2000; Berk et al., 2006). In general, large enhancements in the electron fluxes occur during fast solar wind conditions. Hence, the saturation velocity is estimated using a modified reverse arrangement test with the assumption that there is no correlation between EEF and VSW for solar wind velocities larger than the saturation velocity. The analysis is based on one day averages of electron fluxes measured in the energy range 1.8 - 3.5 MeV and for solar wind densities 60 cm\(^{-3}\).

![Figure 3. Energetic electron fluxes as a function of solar wind velocity for electron fluxes measured in the energy range 1.8 - 3.5 MeV and solar wind density measured in the range 2.2 ≤ n < 2.3 cm\(^{-3}\).](image)

References
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Appendix
[If any additional information is provided in an appendix, it is listed here.]