Parametric Ionospheric Characterization Using Automatic Dependent Surveillance Broadcast Signals

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I: Abstract

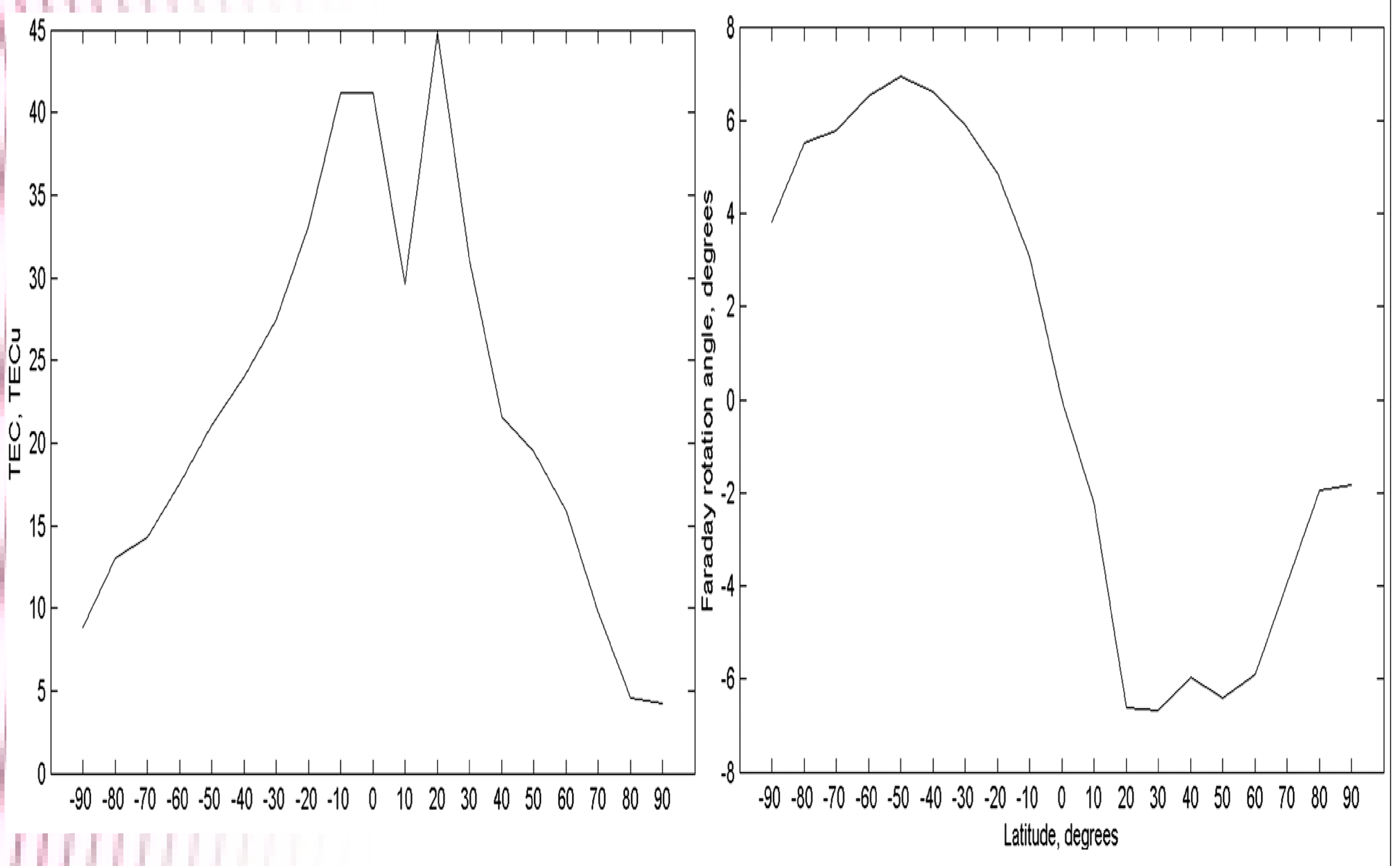
Radio waves propagating through plasma in the Earth's ambient magnetic field experience Faraday rotation (FR); the plane of the electric field of a linearly polarized wave changes as a function of the distance travelled through a plasma. Linearly polarized radio waves at 1090 MHz frequency are emitted by Automatic Dependent Surveillance Broadcast (ADS-B) devices that are installed on most commercial aircraft. These radio waves can be detected by satellites in low Earth orbits, and the change of the polarization angle caused by propagation through the terrestrial ionosphere can be measured. In this manuscript we discuss how these measurements can be used to characterize the ionospheric conditions. In the present study, we compute the amount of Faraday rotation from a prescribed total electron content (TEC) value and two of the profile parameters of the NeQuick ionospheric model.

II: Introduction

In this study, we compute the amount of FR from a prescribed ionospheric electron density profile, specified by the parameters used in the NeQuick model, based on the Epstein layer [Rawer,1963]. **We study the sensitivity of FR angle to ionospheric parameters such as layer thickness and the altitude of the peak density. By considering the FR in addition to the TEC, we show that the ionospheric characterization can be improved [Cushley et a. 2017].** The total TEC along the raypath of unit cross-section is given by:

$$TEC = \int_0^{z_{max}} n_e(z)dz$$

where n_e is the electron density and z is the path length. TEC is usually expressed in TEC units (TECu) equal to 10^{16} electrons m^{-2}, with typical values ranging from 1 to 100 TECu. The upper limit of integration, z_{max} in this definition is somewhat arbitrary, as long as it is well above the altitude of the peak ionospheric density. Usually values of at least 1,000 km are used [Klobuchar et al.,1973].



Left: the VTEC as a function of geographic latitude for 15 January 2015 along the Greenwich Meridian at 12 UTC. Although TEC is highly variable, the daily global maximum is typically found over equatorial regions at solar maximum conditions and generally decreases with latitude. The peak occurs between 15 and 20° on either side of the equator with an ionization trough at the geomagnetic equator. Right: the FR as a function of latitude. The maximum amount of FR occurs at midlatitudes, which shows that the technique presented would work best in the midlatitude region [Cushley et al., 2017].

ADS-B is a technology developed to track the position and movement of aircraft through intermittent broadcasts containing information about their identity, itinerary, and position state vectors to ground-based receivers and other aircraft within range. ADS-B coverage will be particularly useful for oceanic and polar regions, where coverage from another source is otherwise unavailable. These regions also correspond to the largest errors for TEC maps [Jakowski et al.,2011]. Therefore, using ADS-B measurements in those areas can improve the accuracy of the TEC maps.

One of the main benefits of considering ADS-B signals is that ADS-B receivers are able to distinguish and identify signals from different aircraft,which results in potentially hundreds or even up to a couple of thousand independent FR measurements along different propagation paths. The ADS-B signals, currently produced by aircraft, offer a unique opportunity to be used for ionospheric sounding in addition to their operational purpose. This is similar to how GNSS systems have been used for ionospheric science in addition to their intended purpose of geospatial positioning. A relatively simple method is presented that can be used to characterize the ionosphere using two parameters that can be adjusted in order to produce an electron density profile that agrees with FR and TEC observations.

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III: Theory

Linearly polarized waves propagating through the ionosphere undergo FR of the polarization plane. The angle of this rotation is given by Kraus (1966) among others:

$$\Omega = \frac{e^3}{8\pi^2\epsilon_0 m_e^2 c}\frac{1}{f^2}\int n_e(z)B_{||}(z)dz$$

By assuming that $B_{||} = B_r$ we restrict our analysis to the case when the satellite is directly overhead. We further assume that the magnitude of the parallel component of the magnetic field can be described by the dipole approximation.

$$B_{||} = B_r = B_{eq}\frac{2R_E^3\sin\lambda}{(z+R_E)^3}$$

where B_{eq} = 3.1×10⁴ nT is the equatorial dipole strength at the surface of the Earth and λ is the latitude of the point in consideration.

The electron density is given by

$$n_e(z) = \frac{4n_m\alpha}{(1+\alpha)^2} \quad \text{Where} \quad \alpha = exp\left(\frac{z-z_0}{H}\right)$$

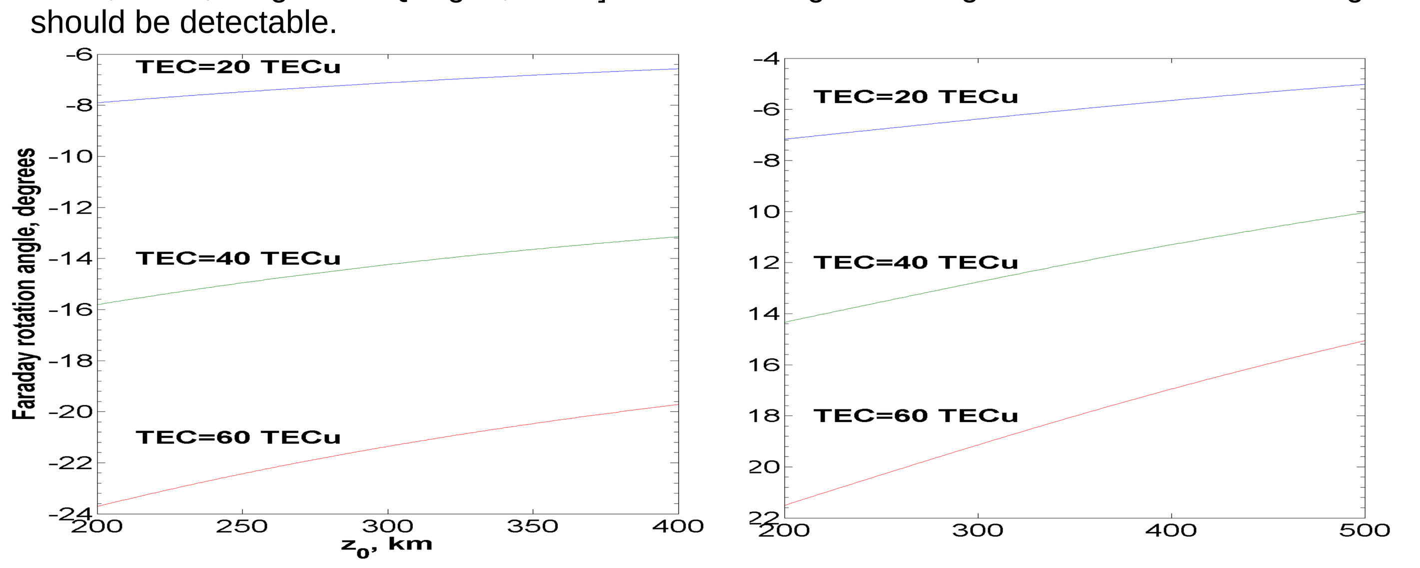
Here n_m is the maximum density of electrons in the ionosphere, z_0 is the altitude of the density peak, and H is the layer thickness parameter. TEC can be computed analytically for the profile as

$$TEC = 4n_m\int_0^{\infty}\frac{exp\left(\frac{z-z_0}{H}\right)}{\left(1+exp\left(\frac{z-z_0}{H}\right)\right)^2}dz = \frac{4n_mH}{1+exp\left(-\frac{z_0}{H}\right)}$$

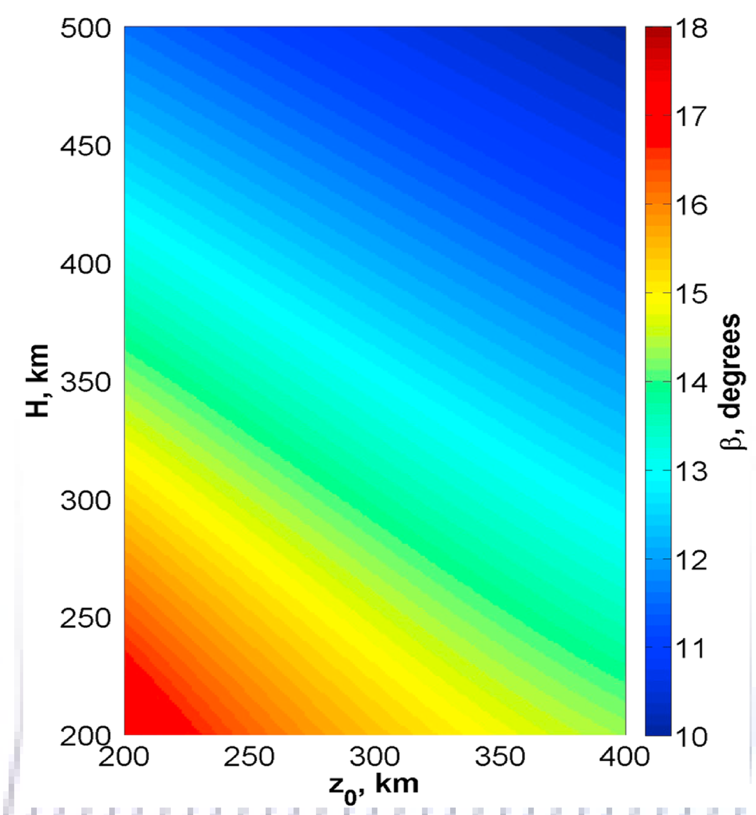
We assume that the TEC of the ionosphere is a known quantity. The peak density is inferred from the TEC and is not an independent variable. The NeQuick model has three adjustable parameters, namely, n_m, z_0, and H that can be adjusted in order to produce an electron density profile that agrees with FR and TEC observations.

IV: Results

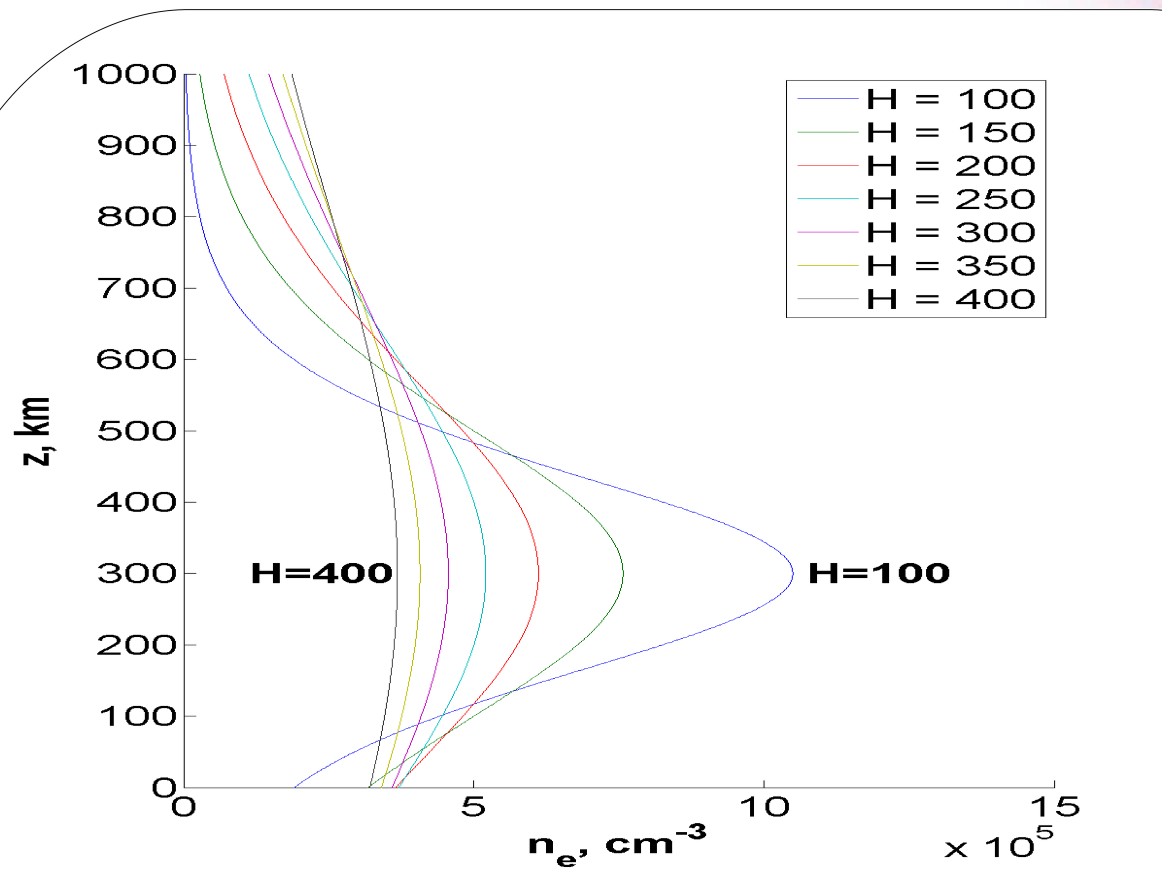
We deliberately explored a 100–500 km range of slab thickness values, which is beyond that typically observed for the midlatitude ionosphere. The change in FR is near the 1° threshold that can be detected by instruments on board an orbiting satellite [Dhar et al.,1977; Anderson et al., 2011; Rogers & Quegan, 2014]. These changes in magnitude of the rotation angle should be detectable.



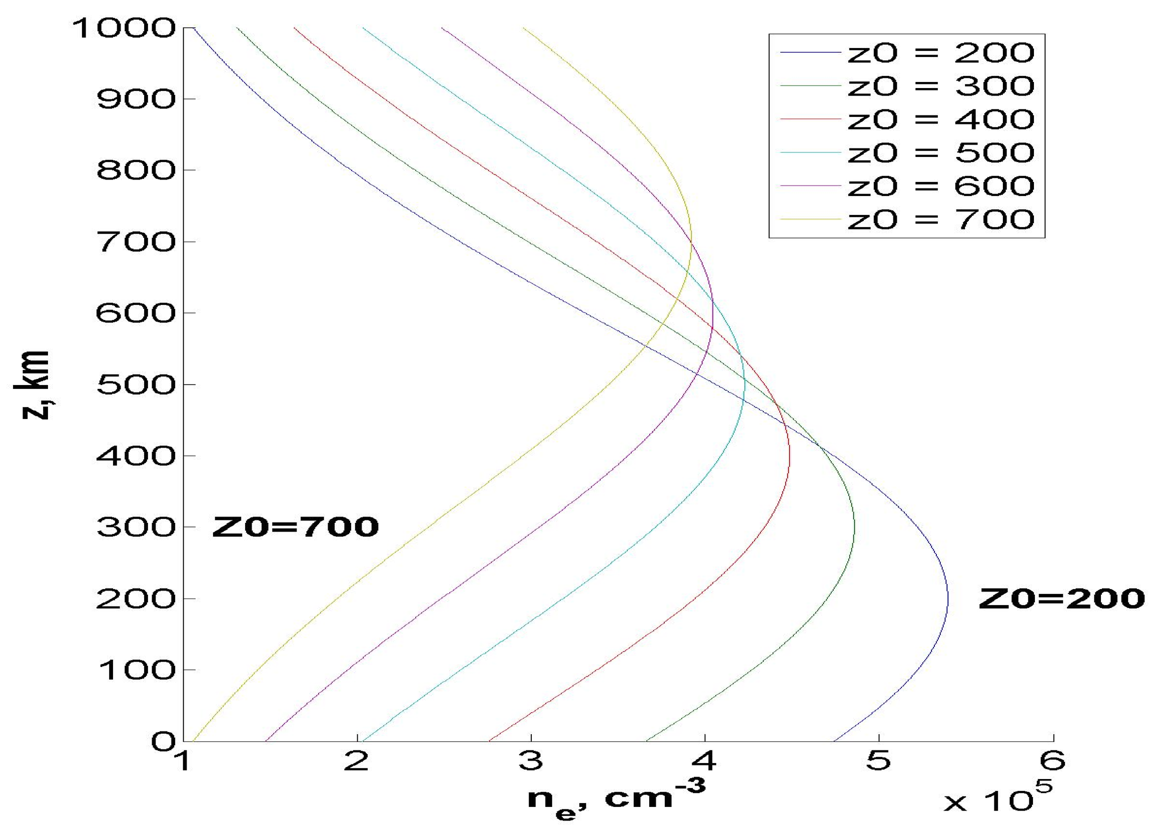
Left: FR angle as a function of peak density z_0 for H = 275 km for constant TEC (20 TECu blue line, 40 TECu green line, and 60 TECu red line). Right: FR angle as a function of H for z_0 = 300 km for constant TEC. The amount of FR expected for the ADS-B transmission, even for elevated values of TEC, is less than 180°, so we do not need to be concerned with phase ambiguity.



The FR angle as a function of z_0 and H for TEC = 40 TECu [Cushley et al., 2017].



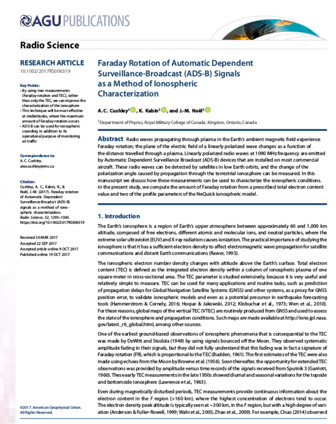
Electron number density, n_e, profile for peak density z_0 = 300 km, TEC = 40 TECu and different values for the layer thickness H



Electron number density profile for H = 275 km, TEC = 40 TECu and different altitudes for the z_0 [Cushley et al., 2017].

V: Conclusion

- A simple model using three adjustable parameters can be used to produce an electron density profile that agrees with FR and TEC observations.
- Using FR and TEC rather than only TEC can improve the ionospheric characterization.
- This technique works best at midlatitudes, where the FR effect is largest.
- Variations in the FR smaller than 1° may not be detectable using current instruments but could present an engineering problem for future application.
- Useful for distributing the electron density vertically and may be improved with data ingestion from another source. For example, the peak density and corresponding altitude from a nearby ionosonde may be used to constrain the problem further, leaving only the layer thickness to be calculated. If both n_m and z_0 are measured, then the problem becomes overdetermined and will probably require some version of a least squares computation.
- Useful for applications such as computerized ionospheric tomography as an a priori estimate for reconstruction of the ionospheric electron content over regions where information from other instrumentation is otherwise unavailable (Cushley, 2013; Cushley & Noël, 2014; Siefring et al., 2015).
- Application of this technique will be the inverse problem; using FR and TEC measurements to determine the profile parameters.
- The inverse problem is underdetermined—we have only two constraints and three parameters. Determination of the ionospheric parameters will require additional measurements, for example, z_0 from ionosonde data (Kersley et al., 1993; Stankov et al., 2003).
- More detailed studies are needed to investigate other more general propagation geometries as well as multiple ionospheric layers.



For complete details please refer to:

Cushley, A. C., Kabin, K., & Noël, J.-M. (2017). Faraday rotation of Automatic Dependent Surveillance-Broadcst (ADS-B) signals as a method of ionospheric characterization. Radio Science, 52, 1293–1300. https://doi.org/10.1002/2017RS006319