



Recommendation ITU-R P.531-13
(09/2016)

**Ionospheric propagation data and
prediction methods required for
the design of satellite services
and systems**

P Series
Radiowave propagation



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SM	Spectrum management
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Note: This ITU-R Recommendation was approved in English under the procedure detailed in Resolution ITU-R 1.

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RECOMMENDATION ITU-R P.531-13

**Ionospheric propagation data and prediction methods required
for the design of satellite services and systems**

(Question ITU-R 218/3)

(1978-1990-1992-1994-1997-1999-2001-2003-2005-2007-2009-2012-2013-2016)

Scope

Recommendation ITU-R P.531 describes a method for evaluating of the ionospheric propagation effects on Earth-space paths at frequencies from 0.1 to 12 GHz. The following effects may take place on an Earth-space path when the signal is passing through the ionosphere:

- rotation of the polarization (Faraday rotation) due to the interaction of the electromagnetic wave with the ionized medium in the Earth's magnetic field along the path;
- group delay and phase advance of the signal due to the total electron content (TEC) accumulated along the path;
- rapid variation of amplitude and phase (scintillations) of the signal due to small-scale irregular structures in the ionosphere;
- a change in the apparent direction of arrival due to refraction;
- Doppler effects due to non-linear polarization rotations and time delays.

The data and methods described in this Recommendation are applicable for planning satellite systems, in respective ranges of validity indicated in Annex 1.

Keywords: Trans-ionospheric propagation, scintillation, group delay

The ITU Radiocommunication Assembly,

considering

- a) that the ionosphere causes significant propagation effects at frequencies up to at least 12 GHz;
- b) that effects may be particularly significant for non-geostationary-satellite orbit services below 3 GHz;
- c) that experimental data have been presented and/or modelling methods have been developed that allow the prediction of the ionospheric propagation parameters needed in planning satellite systems;
- d) that ionospheric effects may influence the design and performance of radio systems involving spacecraft;
- e) that these data and methods have been found to be applicable, within the natural variability of propagation phenomena, for applications in satellite system planning,

recommends

- 1** that the data prepared and methods developed as set out in Annex 1 should be adopted for planning satellite systems, in the respective ranges of validity indicated in Annex 1.

Annex 1

1 Introduction

This annex deals with the ionospheric propagation effects on Earth-space paths. From a system design viewpoint, the impact of ionospheric effects can be summarized as follows:

- a) the total electron content (TEC) accumulated along a mobile-satellite service (MSS) transmission path penetrating the ionosphere causes rotation of the polarization (Faraday rotation) of the MSS carrier, time delay of the signal, and a change in the apparent direction of arrival due to refraction;
- b) localized random ionospheric patches, commonly referred to as ionospheric irregularities, further cause excess and random rotations and time delays, which can only be described in stochastic terms;
- c) because the rotations and time delays relating to electron density are non-linearly frequency dependent, both a) and b) further result in dispersion or group velocity distortion of the MSS carriers;
- d) furthermore, localized ionospheric irregularities also act like convergent and divergent lens which focus and defocus the radio waves. Such effects are commonly referred to as the scintillations which affect amplitude, phase and angle-of-arrival of the MSS signal.

Due to the complex nature of ionospheric physics, system parameters affected by ionospheric effects as noted above cannot always be succinctly summarized in simple analytic formulae. Relevant data edited in terms of tables and/or graphs, supplemented with further descriptive or qualifying statements, are for all practical purposes the best way to present the effects.

In considering propagation effects in the design of MSS at frequencies below 3 GHz, one has to recognize that:

- e) the normally known space-Earth propagation effects caused by hydrometeors are not significant relative to effects of § f) and h);
- f) the near surface multipath effects, in the presence of natural or man-made obstacles and/or at low elevation angles, are always critical;
- g) the near surface multipath effects vary from locality to locality, and therefore they do not dominate the overall design of the MSS system when global scale propagation factors are to be dealt with;
- h) ionospheric effects are the most significant propagation effects to be considered in the MSS system design in global scale considerations.

2 Background

Caused by solar radiation, the Earth's ionosphere consists of several regions of ionization. For all practical communications purposes, regions of the ionosphere, D, E, F and top-side ionization have been identified as contributing to the TEC between satellite and ground terminals.

In each region, the ionized medium is neither homogeneous in space nor stationary in time. Generally speaking, the background ionization has relatively regular diurnal, seasonal and 11-year solar cycle variations, and is dependent strongly on geographical locations and geomagnetic activity. In addition to the background ionization, there are always highly dynamic, small-scale non-stationary structures known as irregularities. Both the background ionization and irregularities degrade radiowaves. Furthermore, the refractive index is frequency dependent, i.e. the medium is dispersive.

3 Prime degradations due to background ionizations

A number of effects, such as refraction, dispersion and group delay, are in magnitude directly proportional to the TEC; Faraday rotation is also approximately proportional to TEC, with the contributions from different parts of the ray path weighted by the longitudinal component of magnetic field. A knowledge of the TEC thus enables many important ionospheric effects to be estimated quantitatively.

3.1 TEC

Denoted as N_T , the TEC can be evaluated by:

$$N_T = \int_s n_e(s) ds \quad (1)$$

where:

s : propagation path (m)

n_e : electron concentration (el/m³).

Even when the precise propagation path is known, the evaluation of N_T is difficult because n_e has diurnal, seasonal and solar cycle variations.

For modelling purposes, the TEC value is usually quoted for a zenith path having a cross-section of 1 m². The TEC of this vertical column can vary between 10¹⁶ and 10¹⁸ el/m² with the peak occurring during the sunlit portion of the day.

For estimating the TEC, either a procedure based on the International Reference Ionosphere (IRI-2012) or a more flexible procedure, also suitable for slant TEC evaluation and based on NeQuick2 v.P531-12, are available. Both procedures are provided below.

3.1.1 IRI-2012-based method

The standard monthly median ionosphere is the COSPAR-URSI IRI-2012. Under conditions of low to moderate solar activity numerical techniques may be used to derive values for any location, time and chosen set of heights up to 2 000 km. Under conditions of high solar activity, problems may arise with values of electron content derived from IRI-2012. For many purposes it is sufficient to estimate electron content by multiplication of the peak electron density with an equivalent slab thickness value of 300 km.

3.1.2 NeQuick2-based method

The electron density distribution given by the model is represented by a continuous function that is also continuous in all spatial first derivatives. It consists of two parts, the bottom-side part (below the peak of the F2-layer) and the top-side part (above the F2-layer peak). The peak height of the F2-layer is calculated from M(3000)F2 and the ratio foF2/foE (see Recommendation ITU-R P.1239).

The bottom-side is described by semi-Epstein layers for representing E, F1 and F2. The top-side F layer is again a semi-Epstein layer with a height dependent thickness parameter. The NeQuick2 v.P531-12 model gives the electron density and TEC along arbitrary ground-to-satellite or satellite-to-satellite paths.

The computer program and associated data files are integral digital products to this Recommendation and are available in the file [R-REC-P.531-12-201309-I!!ZIP-E](#).

3.2 Faraday rotation

When propagating through the ionosphere, a linearly polarized wave will suffer a gradual rotation of its plane of polarization due to the presence of the geomagnetic field and the anisotropy of the plasma medium. The magnitude of Faraday rotation, θ , will depend on the frequency of the radiowave, the magnetic field strength, and the electron density of the plasma as:

$$\theta = 2.36 \times 10^{-14} \frac{B_{av} N_T}{f^2} \quad (2)$$

where:

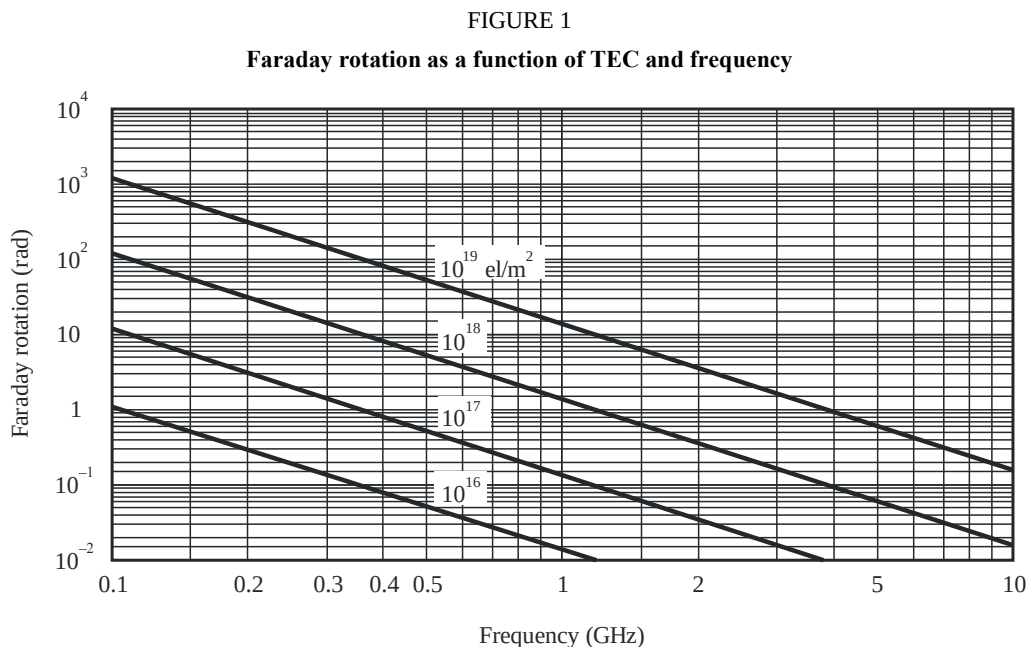
θ : angle of rotation (rad)

B_{av} : average Earth magnetic field ($\text{Wb} \cdot \text{m}^{-2}$ or Teslas)

f : frequency (GHz)

N_T : TEC (electrons $\cdot \text{m}^{-2}$).

Typical values of θ are shown in Fig. 1.



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The Faraday rotation is thus inversely proportional to the square of frequency and directly proportional to the integrated product of the electron density and the component of the Earth's magnetic field along the propagation path. Its median value at a given frequency exhibits a very regular diurnal, seasonal, and solar cyclical behaviour that can be predicted. This regular component of the Faraday rotation can therefore be compensated for by a manual adjustment of the polarization tilt angle at the earth-station antennas. However, large deviations from this regular behaviour can occur for small percentages of the time as a result of geomagnetic storms and, to a lesser extent, large-scale travelling ionospheric disturbances. These deviations cannot be predicted in advance. Intense and fast fluctuations of the Faraday rotation angles of VHF signals have been associated with strong and fast amplitude scintillations respectively, at locations situated near the crests of the equatorial anomaly.

The cross-polarization discrimination for aligned antennas, XPD (dB), is related to the Faraday rotation angle, θ , by:

$$XPD = -20 \log (\tan \theta) \quad (3)$$

3.3 Group delay

The presence of charged particles in the ionosphere slows down the propagation of radio signals along the path. The time delay in excess of the propagation time in free space, commonly denoted as t , is called the group delay. It is an important factor to be considered for MSS systems. Likewise, the phase is advanced by the same amount. This quantity can be computed as follows:

$$t = 1.345 N_T / f^2 \times 10^{-7} \quad (4)$$

where:

t : delay time (s) with reference to propagation in a vacuum

f : frequency of propagation (Hz)

N_T : determined along the slant propagation path.

Figure 2 is a plot of time delay, t , versus frequency, f , for several values of electron content along the ray path.

For a band of frequencies around 1 600 MHz the signal group delay varies from approximately 0.5 to 500 ns, for TEC from 10^{16} to 10^{19} el/m². Figure 3 shows the yearly percentage of daytime hours that the time delay will exceed 20 ns at a period of relatively high solar activity.

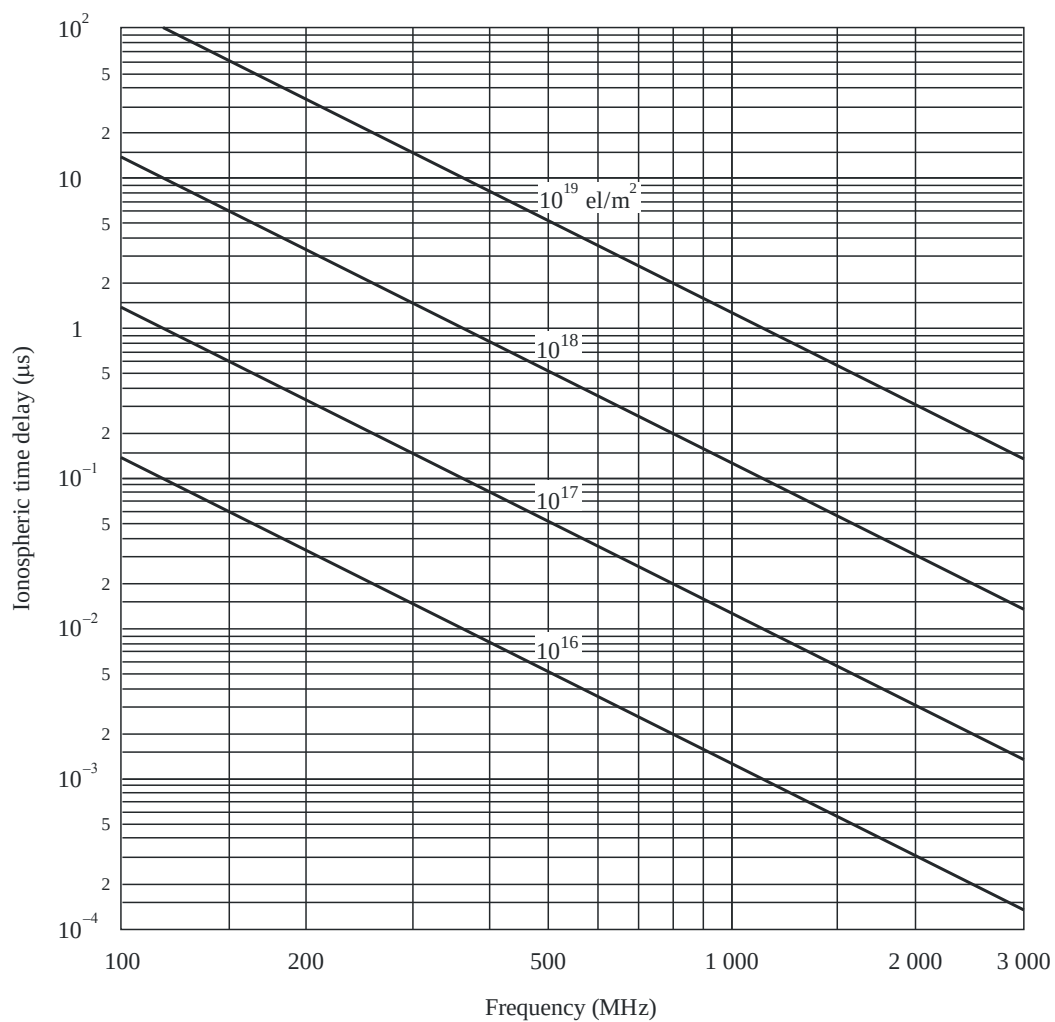
3.4 Dispersion

When trans-ionospheric signals occupy a significant bandwidth the propagation delay (being a function of frequency) introduces dispersion. The differential delay across the bandwidth is proportional to the integrated electron density along the ray path. For a fixed bandwidth the relative dispersion is inversely proportional to frequency cubed. Thus, systems involving wideband transmissions must take this effect into account at VHF and possibly UHF. For example, as shown in Fig. 4 for an integrated electron content of 5×10^{17} el/m², a signal with a pulse length of 1 μ s will sustain a differential delay of 0.02 μ s at 200 MHz while at 600 MHz the delay would be only 0.00074 μ s (see Fig. 4).

3.5 TEC rate of change

With an orbiting satellite the observed rate of change of TEC is due in part to the change of direction of the ray path and in part to a change in the ionosphere itself. For a satellite at a height of 22 000 km traversing the auroral zone, a maximum rate of change of 0.7×10^{16} el/m²/s has been observed. For navigation purposes, such a rate of change corresponds to an apparent velocity of 0.11 m/s.

FIGURE 2

Ionospheric time delay versus frequency for various values of electron content

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