rely on dedicated scintillation receivers such as Septentrio PolaRxS™ and NovAtel FlexPak6™.

One service provided by the Australian Government Bureau of Meteorology is a GPS TEC derived scintillation map. This map is derived using data with a 1 Hz sampling rate from GPS receivers. The underlying quantity computed is the variance of the time derivative of the TEC over 1 minute intervals. This is commonly known as ROTI (Rate of TEC) and serves as a measure of present ionospheric scintillation since the disturbed ionospheric conditions that cause scintillation lead to short timescale variations in the TEC.

Another system is disclosed by US2009224969, which describes a method for determining the ionospheric error across a network of GNSS reference stations. The method relies on dual-frequency phase measurements in a geometry-free linear combination. The data is filtered for ambiguities and the characteristic parameters of the ionosphere. In combination with filter results from other combinations of phase measurements (ionosphere free combination), the physically-based model provides ambiguity resolution. The method uses limited prediction of scintillation in time and space by fitting of spherical harmonic functions.

Although measurement of the error due to ionospheric scintillation is presently possible, it would be desirable to provide alternative services allowing prediction of scintillation in time.

BRIEF SUMMARY OF THE INVENTION

According to a first aspect of the present invention, there is provided a method of generating scintillation prediction data comprising:

a) for a plurality of satellites, and reference stations, measuring phase scintillation data, satellite by satellite for each reference station during multiple epochs;

b) forecasting an expected phase scintillation value for each satellite and reference station for a period of at least 24 hours based on a cyclical prediction model;

c) for a given user location and a given satellite, spatially interpolating the expected phase scintillation values of the plurality of reference stations to determine a predicted phase scintillation index;

d) repeating step c) for further satellites visible from the user location.

By separating the spatial and temporal prediction, greater accuracy is achievable and a useful result can be obtained, allowing a prediction to be made of the expected phase scintillation at the user location. This may allow a user to determine in advance whether or not to commence a particular operation within a given window, based on the likelihood of ionospheric disturbances.

According to one preferred embodiment, the method may further comprise a step e) of computing a Scintillation Dilution Of Precision (SDOP) index by mapping the predicted phase scintillation indices of the satellites visible from the user location onto the position domain. Such an index further simplifies the process of determining the likelihood of positioning error for a given period, since it better allows a user to take into account not only the likely error for a given satellite but the dilution of precision for the combination of satellites available. Thus if a high degree of scintillation is predicted for a given satellite, this may not lead to a lack of precision if a number of other (undisturbed) satellites will be visible at that moment in time.

In a particular embodiment, the cyclical prediction model of step b) is an exponential smoothing model, in particular a triple exponential smoothing model that takes into account seasonal changes as well as trends. This may be a Holt-Winters prediction model as further described in detail below.

According to experimental observations, it is believed that using a multiplicative Holt-Winters prediction model may give good results. This is because the observed seasonal pattern in the course of a day is proportional to the level of data, whereby for an expected phase scintillation value k epochs ahead, the sum of the local mean level and the trend over k epochs is multiplied by a factor indicative of the variation over a whole season.

According to another embodiment of the invention, step c) may take place by determining ionosphere pierce points (IPPs) for signals received from the given satellite for each of the reference stations. As a result of using IPPs, the mapping of scintillation effects

a horizontal displacement of the IPP by around 145 km. This may be used to determine a slant or curve of the ionospheric thin layer within the patch.

In a still further embodiment, the scintillation prediction data as generated in step e) may comprise converting a phase scintillation index for each satellite into a range error with respect to the user location. In terms of useful information, this data represents an important measure of what influence the scintillation may have on the user and may be better applicable for further processing to provide e.g. the SDOP index.

In a particular embodiment according to an example of the invention, the scintillation prediction data may be provided to a user at the user location. This data may be provided in real time, or quasi-real time.

According to a further example of the invention, the scintillation prediction data may also comprise loss-of-lock indications. For a GNSS signal, rapid fluctuation of TEC leads to phase scintillation of the signal. In case of severe phase scintillation, the carrier tracking loop in the receiver may have difficulties to track the signal. For a receiver tracking an L-band signal, a rapid change of only 1 radian of phase in a time interval equal to the inverse of the receiver bandwidth can be enough to cause problems for the receiver's tracking loop. In this case, the signal amplitude also fades enough to result in Loss-Of-Lock and consequently a phase discontinuity or cycle slip. The fading of signal due to ionospheric disturbances is called amplitude scintillation. The loss-of-lock indications may be predicted loss-of-lock indications, providing for a given satellite at a given user location an indication of whether or not loss-of-lock may be expected. In general, these values may be binary or Boolean values and the method may further comprise:

f) for the plurality of satellites and reference stations, determining loss-of-lock occurrences for a carrier tracking loop of a GNSS receiver at the reference station;

g) forecasting expected loss-of-lock occurrences for each satellite and reference station for a period of at least 24 hours based on a cyclical prediction model;

h) for the user location and given satellite, spatially interpolating the expected loss-of-lock occurrences of the plurality of reference stations to determine a predicted loss-of-lock indicator for the given satellite at the user location.

In one embodiment, the cyclical prediction model may consider the seasonal (24 hour) variation to be unity. Furthermore, the predicted loss-of-lock value may include a prediction of the chance to have cycle slips . The predicted loss-of-lock values may also be provided to the user at the user location. Basing the prediction model for the seasonal variation on the value for the previous 24 hours is considered a best-fit model for this value. By providing data including the chance of cycle slips to the user, the user can also determine the accuracy of this prediction over previous seasons and determine, based on the essential nature of the operation, whether to proceed or not.

Various methods are available for measuring the phase scintillation data. In one preferred embodiment the reference stations comprise multi-frequency receivers and step a) takes place by linear combination of dual frequency phase observations. This allows existing networks of reference stations to be used to provide the data without requiring additional scintillation receivers to be provided.

According to another example of the proposed method, the plurality of satellites are earth-orbiting satellites (e.g. GNSS satellites) and the method further comprises estimating the scintillation information for IPPs between the user location and geostationary satellites visible from the user location and transmitting the scintillation information to a user at the user location. Although the geostationary satellites are not usually relied upon for global positioning, they are used to provide correction signals by which the accuracy of e.g. GNSS positioning is enhanced. Loss of these correction signals can therefore seriously affect the positioning accuracy even if the SDOP index at the user location is otherwise favorable.

In view of the above, according to a second aspect of the present invention, there is provided a system for generating ionospheric scintillation prediction data from GNSS satellite signals and for providing the ionospheric scintillation prediction data to a user at a user location, the system comprising a plurality of reference stations having

multi-frequency receivers adapted to receive the GNSS satellite signals and further comprising a processing unit adapted to perform the method as defined herein.

According to a third aspect of the present invention, there is provided a computer program product enabling a user at a user location to receive ionospheric scintillation prediction data produced by a method as described herein and map the ionospheric scintillation prediction data into the position domain on a user display.

According to a fourth aspect of the present invention, there is provided a web based application enabling a user at a user location to receive ionospheric scintillation prediction data produced by a method as described herein and view the ionospheric scintillation prediction data on a user display at the user location.

BRIEF DESCRIPTION OF THE DRAWINGS

The features and advantages of the invention will be appreciated upon reference to the following drawings of a number of exemplary embodiments, in which:

Figure 1 shows the geometry of the thin-layer ionosphere;