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

Embodiments of the present invention provide methods 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.

According to a first aspect of the present invention, there is provided a method for generating ionospheric scintillation prediction data comprising: measuring phase scintillation data for a plurality of satellites; and forecasting an expected phase scintillation value for each satellite based on a cyclical prediction model. The method is characterized by

a) for a plurality reference stations 10) and for the plurality of satellites, measuring the phase scintillation data, satellite by satellite for each reference station during multiple epochs;

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

c) for a given user location (20) and a given satellite, spatially interpolating the expected phase scintillation values of the plurality of reference stations to determine a predicted phase scintillation index; and

d) repeating step c) for 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

Claims

1. A method for generating ionospheric scintillation prediction data comprising:

- measuring phase scintillation data for a plurality of satellites (12);
- forecasting an expected phase scintillation value for each satellite based on a cyclical prediction model;

characterized by

a) for a plurality reference stations 10) and for the plurality of satellites, measuring the phase scintillation data, satellite by satellite for each reference station during multiple epochs;

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

c) for a given user location (20) and a given satellite, spatially interpolating the expected phase scintillation values of the plurality of reference stations to determine a predicted phase scintillation index; and

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

2. The method according to claim 1, wherein the method further comprises a step e) of converting the phase scintillation index for each satellite (12) into a range error ($d\rho$) with respect to the user location (20).

3. The method according to claim 2, wherein the ionospheric scintillation prediction data comprises a Scintillation Dilution Of Precision, SDOP, index and step e) comprises computing the SDOP index by mapping the predicted phase scintillation indices of the satellites (12) visible from the user location (20) onto the position domain.

4. The method according to any preceding claim, wherein step b) takes place using a Holt-Winters prediction model with a seasonal cycle of one day.

5. The method according to claim 4, wherein step b) takes place using a multiplicative Holt-Winters prediction model, 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 the period.

6. The method according to any preceding claim, wherein step c) takes place by determining ionosphere pierce points (IPPs) for signals received from the given satellite for each of the reference stations

7. The method according to claim 6, further comprising performing linear spatial interpolation between the IPPs (14).

8. The method according to claim 6 or claim 7, further comprising determining the height (H) of the IPPs (14) by determining the time difference between scintillation start-up and sunset at ground level.

9. The method according to any preceding claim, further comprising providing to a user an effect of the predicted phase scintillation indices on GNSS positioning at the user location (20).

10. The method according to any preceding claim wherein the ionospheric scintillation prediction data comprises loss-of-lock indicators and the method further comprises:

    e) for the plurality of satellites (12) and reference stations (10), determining loss-of-lock occurrences for a carrier tracking loop of a GNSS receiver at the reference station;
    f) 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;
    g) for the user location (20) and given satellite, spatially interpolating the expected loss-of-lock occurrences of the plurality of reference stations to determine a loss-of-lock indicator for the given satellite at the user location.

11. The method according to claim 10, further comprising displaying the predicted loss-of-lock indicator to a user at the user location (20).

12. The method according to any preceding claim further comprising determining a user location (20) for a given user and generating the ionospheric scintillation prediction data on the basis of the determination.

13. The method according to any preceding claim, wherein the reference stations (10) comprise multi-frequency receivers and step a) takes place by a linear combination of the dual frequency phase measurements .

14. The method according to any preceding claim, wherein the plurality of satellites (12) are earth-orbiting satellites and the method further comprises estimating the phase scintillation information for IPPs (14) between the user location (20) and geostationary satellites visible from the user location and transmitting the phase scintillation information to a user at the user location.

15. 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 (20), 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 in any of the preceding claims.

16. A computer program product enabling a user at a user location to receive ionospheric scintillation prediction data produced by a method according to any of claims 1 to 14 and map the ionospheric scintillation prediction data into the position domain on a user display.

17. A web based application enabling a user at a user location to receive ionospheric scintillation prediction data produced by a method according to any of claims 1 to 14 and view the ionospheric scintillation prediction data on a user display at the user location.