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been evaluated as well. Results confirm MPS-OS is a reliable approach to perform simulations including ionosphere, despite the trajectory of the LEO satellite.

The rest of this paper is organised as follows: Section II describes Multiple Phase Screen implementation, Section III describes MPS-OS and Section IV defines the set of scenarios used to validate MPS-OS. Finally, Sections V and VI present the results and final remarks.

II. MULTIPLE PHASE SCREEN

Wave optics propagators (WOP) have been used in radio occultation to reproduce the effects of Earth's atmosphere on radio signal in a GNSS-LEO scenario [15], [16]. MPS consists of a series of parallel screens oriented in y -axis and distributed along x -axis to model the refractivity throughout the atmosphere. The basic assumption of the WOP simulator is that polarization effects can be neglected, and that the atmospheric medium is linear, i.e. each frequency component of the GNSS signal can be simulated separately by considering the propagation of a scalar complex wave. Considering the GNSS satellite stationary during one occultation event, the 2-D wave propagation of the plane wave (u) at the leftmost screen can be achieved by the repetition of the following steps:

- Vacuum wave propagation between successive screens by incrementing the phase component as a function of the distance between screens (Δx),

$$\tilde{u}(x_{j+1}, q) = \exp \left(-ik \left(\sqrt{1 - \frac{q^2}{k^2}} \right) \Delta x \right) \mathcal{F}(u(x_j, y)); \quad (1)$$

- Incorporating the atmospheric effect on the wave corresponding to the next screen,

$$u(x_{j+1}, y) = \exp(ik(n-1)\Delta x) \mathcal{F}^{-1}(\tilde{u}(x_{j+1}, q)), \quad (2)$$

in which q stands for the angular spatial frequency, k is the wave number and n is the refractive index. A tapered cosine window (Tukey) is applied after the second step to avoid aliasing caused by the Fourier operator, with top and bottom 20 km-segment following a phase-shifted cosine function.

At the last screen, the scalar complex wave is propagated to the LEO orbit by solving

$$v(p_n) = \sqrt{\frac{k}{2\pi}} \int u(x, y) \frac{x_d}{\sqrt{x_d^2 + y_d^2}} \phi(x_d, y_d) dy, \quad (3)$$

in which v is the complex signal in the n -th point in orbit, d index refers to the horizontal and vertical distance between a point in screen and in orbit. The diffraction integral defined in (3) is based on Huygens-Fresnel diffraction and it is valid for propagation in vacuum [18]. A discrete version of the integral is implemented as

$$v(p_n) = \sqrt{\frac{k}{2\pi}} \sum_{m=1}^{M-1} u(x, y_m) \frac{x_d}{\sqrt{x_d^2 + y_d^2}} \phi(x_d, y_d) \Delta y, \quad (4)$$

in which M stands for the number of points in the last screen and $\phi(x_d, y_d)$ is given by

$$\phi(x_d, y_d) = \frac{\exp(ik\sqrt{x_d^2 + y_d^2} - i\pi/4)}{(x_d^2 + y_d^2)^{1/4}}. \quad (5)$$

Fig. 1. MPS geometry: Grey box represents the series of parallel screens modelling the atmosphere. (a) sketches an occultation event of a short segment of orbit with diffraction integral, (b) shows the same scenario with MPS-OS, including the LEO orbit inside the box (ΔL_x) and (c) compares the MPS set-up to MPS-OS in a long segment of orbit. Parameters given in kilometres.

A. MPS set-up

In order to establish the simulation environment of an occultation event, some MPS parameters must be defined. Considering the center of the Earth at the origin of the xy -coordinate system, the GNSS satellite placement is given by $x_t = \sqrt{R_t^2 - y_t^2}$, where $y_t = R_e$ is the Earth's radius.

The separation distance between screens (Δx) is bound up with the refractive index. The distance between successive phase screens should avoid adjacent grid points to differ more than π radians after one propagation step. Similarly, the vertical distance between points in a screen (Δy) should be less than half wavelength ($\lambda/2$) in order to solve regions with large refractive index gradient. A fine resolution of sampling points per phase screen, e.g. 2^{20} points, and $\Delta x = 3$ km should not be an issue for modern computers.

Regarding the calculation of the diffraction integral in (3), the distance D_x between the last phase screen and the closest point in LEO orbit is given by

$$(\Delta y/\lambda) f(u) < \pi, \quad (6)$$

where $f(u)$ is a dimensionless factor, given by $u = L_y/D_x$, and calculated as

$$f(u) = \frac{u}{\sqrt{u^2 + 1}}, \quad 0 \leq f(u) \leq 1, \quad (7)$$

which defines that the screen resolution must be comparable to the wavelength if the distance between LEO and the last screen becomes smaller than or close to the screen height. Thus, large screens require large number of screen points and, consequently, higher computational demands.

III. SAMPLING ORBIT USING MPS

The application of the diffraction integral to obtain the radio signal in orbit is suitable for scenarios under the assumption of propagation in vacuum. The position of the last phase screen must be such that the height range in the last screen has zero refractivity. However, the ionosphere yields a significant refractivity around 300 km, due to the peak of electron density in F-layer. Thus, the simulation box must be extended to a point where the height range at the last phase screen has negligible ionospheric refractivity. Unfortunately, this approach is not feasible in the simulation of every occultation event. For instance, an occultation event with long observation time requires a taller screen and consequently a farther distance between the last phase screen and the closest LEO orbit point (p_1), as indicated in (6) and (7). Such set-up does not fulfil the fundamental vacuum criterion necessary to apply the diffraction propagation.

This work proposes to use phase screens at each orbit point to sample the complex signal instead of using diffraction integral. As sketched in Fig. 1(b), the simulation box must be extended to fully include the LEO orbit. Phase screens covers the first part of the simulation with fixed inter-distance until the first LEO orbit point, p_1 . The remaining part of the propagation takes place from the first to the last point in orbit with inter-distance between screens defined by an consistent sampling rate. Interpolation of the complex signal is performed at $p(x_i, y_i)$ for every phase screen.

MPS-OS features suit the simulations of segments of orbits which limitations offered by (6) and (7) are an issue. Scenarios as sketched in Fig. 1(c) are the main focus and rationale of such proposal. The evaluation and validation of MPS-OS in this context is a novelty.

IV. METHODOLOGY

Some atmospheric scenarios have been simulated under the assumption of spherical symmetry in order to evaluate MPS-OS implementation. The validation set is composed of

- I. an exponential neutral atmosphere model neglecting ionosphere;
- II. a realistic neutral atmosphere profile neglecting ionosphere;
- III. an exponential neutral atmosphere with ionosphere (analytical model) and
- IV. a realistic neutral atmosphere and ionosphere.

Scenarios I and III have an exponential refractivity defined as

$$N = N_0 \exp(-(h - R_e)/H_s), \quad (8)$$

in which the refractivity at ground level is $N_0 = 350$, h stands for height and scale height is given by $H_s = 8$ km. Scenario II assumed refractivity profile 31 in [20]. The electron density in scenario III was modelled by α -Chapman function,

$$\rho = \rho_m \exp\left(\frac{1}{2}(1 - u - e^{-u})\right), \quad (9)$$

$$u = \frac{h - (h_m + R_e)}{H_F}, \quad (10)$$

given the electron density peak in F-layer $\rho_m = 12 \cdot 10^{11}$ el/m³, the electron density peak at $h_m = 288.5$ km and the F-layer scale height $H_F = 31$ km. The ionospheric contribution is combined to the neutral atmosphere refractive index, viz

$$n = 1 + N \cdot 10^{-6} - \frac{40.3 \rho}{f^2}. \quad (11)$$

Scenario IV is part of a dataset for processor and instrument testing of European Organization for Exploitation of Meteorological Satellites (EUMETSAT) Polar System Second Generation (EPS-SG). Profile 3 (summer, scenario 2) includes small-scale oscillations in the electron density profile [21].

A. Short segment of orbit

Every scenario has been simulated assuming an occultation event in which the receiver on board of the LEO satellite samples the GNSS signal within 100 and -100 km SLTA. Retrieved bending angles have been compared to forward Abel transform BA without ionosphere (reference). Standard ionospheric correction [4] has been applied to simulations including ionosphere in order to remove the first-order ionospheric contribution. The corrected bending angle,

$$\alpha_c(a) = \frac{\alpha_{L1}(a) f_{L1}^2 - \alpha_{L2}(a) f_{L2}^2}{f_{L1}^2 - f_{L2}^2} \quad [\text{rad}], \quad (12)$$

is a linear combination of the bending angles in L1 ($f_1 = 1575, 42$ MHz) and L2 band ($f_2 = 1227, 60$ MHz) as a function of a common impact height (a). The residual ionospheric error is the difference between the corrected bending angle and the BA reference (α_{ref}).

B. Long segment of orbit

A simulation with segment of orbit between 500 and -300 km SLTA has been performed assuming scenarios III and IV. This orbit spanning follows the specification of the second generation of MetOp satellites (MetOp-SG) [21] and requires a suitable set-up of the simulation box, i.e. tall phase screens. Given (6) and (7), larger screens (L_y) requires greater D_x to avoid aliasing in the diffraction integral solution. However, such set-up could result in a short span of phase screens so the placement of the last phase screen would not satisfy the vacuum requirement, as sketched in Fig. 1(c).

For long segment of orbit, the conventional MPS with diffraction integral can not be used for comparison in such a case. The residual ionospheric error given by MPS-OS is instead validated by comparison to the results obtained from (12) when L1 and L2 BAs are given by the forward Abel transform of the respective refractivity profiles.

V. RESULTS

A sampling rate of 50 Hz was considered to define the phase screen placement in the second stage of MPS-OS simulations, in agreement with the sampling rate in which the RO data product is available at COSMIC Data Analysis and Archive Center (CDAAC). Bending angles in simulations were inverted using the occultation geometry and Full Spectrum Inversion (FSI) method [1], [22].

Fig. 2. L1 bending angle difference to forward Abel transform for scenarios I (a), II (b) and the difference between MPS and MPS-OS (c), which is negligible. The noise in scenario II originates from interpolation effects in the realistic refractivity profile.

Fig. 3. Residual ionospheric error within stratosphere and mesosphere (a) and difference between approaches (b): scenario III. (a) RIE slightly increases with impact height as consequence of rays crossing longer sectors with ionosphere; (b) difference between approaches is not at a significant level.

A. Short segment of orbit

Comparisons between MPS and MPS-OS bending angles for scenarios without ionosphere have been performed up to 40 km (troposphere and stratosphere), since this is the standard altitude range for assimilation of radio occultation data in NWP algorithms.

Fig. 2 depicts the equivalence of both approaches regarding BA difference in L1 band for scenarios I and II, i.e. $\Delta\alpha = \alpha_{WOP} - \alpha_{ref}$. The equivalence of both approaches were expected since the simulation box is long enough to reach vacuum region in order to apply properly the diffraction integral. The deviation increasing monotonically below 15 km in Fig. 2(a) for single frequency measurements is a common feature in WOP implementations [16]. The difference is negligible compared to BA reference in the bottom of the atmosphere.

Fig. 4. Residual ionospheric error within stratosphere and mesosphere (a) and difference between approaches (b): scenario IV. Realistic electron density profile shows evidence of the error added by the ionosphere and accounted by MPS-OS.

Fig. 3 and 4 present results for scenario III and IV. MPS set-up has lowest height around 650 km on the last phase screen (see point B in Fig. 1). The ionospheric refractivity is practically irrelevant at such altitude for these scenarios, fact confirmed by the similarity between RIE observed in MPS and MPS-OS simulations. Regarding simulation time, scenarios including ionosphere and assuming diffraction propagation were performed in 9 minutes whereas orbit sampling took around 25 minutes. Simulations have been performed in Matlab with Intel Xeon Processor E5-1620 v4 and 16 GB of memory RAM.

B. Long segment of orbit

This occultation event has the highest SLTA point at $p(x_1, y_1) = (1985, 540)$ km. The screen at $p(x_1)$ has height extending from 877 km (see point C in Fig. 1) down to the Earth's surface and, consequently, violates the criterion to apply the diffraction integral. Fig. 5 shows the comparison between RIE given in MPS-OS simulation and RIE given by forward Abel transform for scenarios III and IV. The result of the proposed method shows good agreement with the reference. The maximum RIE level observed within 200 and 300 km is due to the electron density gradient around F-layer. Computational time increased drastically for the long orbit segment, around 190 minutes. Sampling from 500 to -300 km SLTA requires a larger number of phase screens and interpolation steps. Additionally, a larger number of points per screen (2^{21} compared to 2^{20} for short segment) also contributes for the longer processing time.

VI. CONCLUSION

MPS combined to the diffraction propagation has been used to model GNSS-RO events and to simulate the GNSS signal in an orbit either parallel to the last phase screen (straight line) or oblique (circular or non-circular) [14]–[16]. In this context,

Fig. 5. Residual ionospheric yielded by MPS-OS simulations of scenario III (a) and IV (b) compared to RIE reference, given by forward Abel transform. The higher noise in scenario IV is explained by small-scale undulations resulting from interpolation of the realistic refractivity profile.

implementation of a MPS in which the phase screens are used to sample the complex signal in a circular orbit is a novelty.

MPS-OS has been evaluated in short and long LEO orbit segments and under different atmospheric conditions. Among the short segment simulations, MPS and MPS-OS have shown to be equivalent. The screen height and the distance between the last phase screen and the closest point in orbit, assuming a setting occultation, are key aspects for MPS set-up. The major advantage of the MPS-OS is its capability to model occultation events including ionosphere during a long segment of orbit. Such scenarios are relevant for testing and validation of future RO missions. The approach was validated for long segments by comparison to the forward Abel transform of the refractivity profiles (including ionosphere) at individual frequencies. Additionally, the approach suits simulations with different LEO orbit height as long as the orbit segment is included in the simulation box.

The downside for MPS-OS is the requirement of using extra phase screens (and interpolations), increasing significantly the processing time. Further research should be conducted in order to improve this aspect.

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