Navigation services from large constellations in low earth orbit

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Abstract. Very large satellite constellations in Low Earth Orbits (LEO) devoted to data broadcast could also help in providing navigation services. Lacking a specific payload onboard, the downlink can be exploited as a signal of opportunity, as an example looking at the carrier's Doppler shift. The number of sources and the short distance to users, enabling indoor positioning, are significant advantages of this option. However, recent studies confirmed that commercially-oriented designs partly miss the advantage on the number of sources by directing just one or two beams at a given time to any area on the Earth: it is enough for communication services, it is not for navigation when several signals need to be received by the user at the same time. Looking at a possible service combining downlinks from more than one system to achieve the requested minimum of four signals, this work focusses on the dilution of precision proper to the novel concept. Therefore, the paper updates previous studies - concerning the effects of the orbital configuration of a single LEO system - extending the results to the new scenario.

Introduction

Satellite-based navigation services are a technological asset everyday more present in our life. Starting from GPS, continuing with GLONASS, Galileo and Beidou, these systems, continuously updated and increasingly completed by regional additions (e.g. EGNOS, QZSS) are quickly becoming an essential infrastructure. All of these Global Navigation Satellite Systems (GNSS) work on the time-of-arrival (TOA) principle, measuring the distances from the observer to at least four signal sources. The TOA principle calls for a specialized nature of the payload, including atomic time sources of exceptional stability onboard. Furthermore, a rich control segment is requested to achieve great accuracy in position and timing [1]. GNSS constellations are mainly deployed in Medium Earth Orbits (MEO) to reduce the number of spacecraft and the effect of perturbations: their large orbital radius, between 25000 and 30000 km, makes signals reaching users quite low in power, limiting the capability to receive in certain environments.

The recent appearance of extremely large constellation, with hundreds or thousands of platforms in LEO devoted to data broadcasting, suggested alternatives to traditional systems. In fact, the widespread distribution of these satellites offers a huge number of signal sources at a far shorter distance, enabling indoor service (see [2] and references therein). The interest for LEO systems is proofed also by some emerging commercial venture explicitly devoted to navigation and timing [3]; however, the huge number of satellites requested to provide an effective service suggested the idea of using instead the rich set of sources already in orbit for successful and large data broadcast systems, so called big-LEOs. Work has been done on the way to exploit the relevant signals from big-LEOs [4] as well as on the quality of the service attainable as function of their orbital geometry [5], [6]. These studied considered that Big-LEOs, not devoted – until now – to navigation, should be better seen as sources of signals of opportunity and the service completed by tracking and timing functions adds-on. More recent studies [7] changed the scenario making it far more complex. In fact, it has been observed that the more developed big-LEO, i.e. Starlink, provides at most two beams for any location on the Earth, with a dynamic distribution of resources focusing on current clients' demand. Indeed, the expected rich coverage is definitely apparent, ending up to be similar or even worse with respect to first generation large telecommunication constellations as Iridium or Globalstar. Notwithstanding this strong limitation, the large number of satellites into orbit still calls for the analysis of services combining signals of opportunity from different systems. This paper aims indeed to update the results referred to orbital aspects of the navigations solution presented in [6] by considering the integrated contribution of the two nowadays larger systems, i.e. Starlink and OneWeb. As the same idea could be applied with proper caution to other systems too, it is expected that findings will be useful independently on the current, still limited, development status of data broadcasting constellations. Focusing on the orbital aspects only, this approach acknowledges that several other, more important technical issues ([6], [7]) should be also considered.

Doppler as observable

Basic goal while navigating a standard terrestrial user (i.e. where high performance should not be requested) is the definition of a 4x1 set of unknowns given by the coordinates and the time

$$X = [\, x_u \;\; y_u \;\; z_u \;\; t]^T \tag{1}$$

(notice that this reduced kinematic state, missing velocity variables, perfectly fits stationary or very low-dynamics users). As recalled, traditional TOA technique is not exploitable form current LEO platforms due to the need of a specialized payload. Instead, it would be possible to extract the carrier of the (complex) modulated data broadcast signal [4]. Neglecting errors and noise, the carrier from source *i* recovered from a user *u* will be Doppler-shifted in frequency:

$$\Delta f_i = \frac{f_i}{c}(\vec{v}_i - \vec{v}_u) \cdot \vec{e}_i \; = \dot{\rho}_i \tag{2}$$

leading to the following relation between the range rate (expressed in Hz) and the variables:

$$\dot{\rho}_i = \frac{f_i}{c\,d}[(\dot{x}_i - \dot{x}_u) \cdot (x_i - x_u) + (\dot{y}_i - \dot{y}_u) \cdot (y_i - y_u) + (\dot{z}_i - \dot{z}_u) \cdot (z_i - z_u)] + \Delta f_u + \varepsilon \tag{3}$$

where $d = \sqrt{(x_i - x_u)^2 + (y_i - y_u)^2 + (z_i - z_u)^2}$ is the distance between the source and the user, Δf_u the frequency error at the receiver and ε the other errors affecting the measurement. Considering a linearization, it is possible to focus on the corrections with respect to the reference condition, obtaining a relation as

$$\Delta\dot{\rho} = H\Delta X \;\; , \qquad \Delta\, X = [\, \Delta x_u \;\; \Delta y_u \;\; \Delta z_u \;\; \Delta f_u\,]^T \tag{5}$$

where the time variable has been substituted by the drift of the receiver's oscillator with respect to the nominal frequency, from which the time is computed. According to Eq.3, the terms in H will clearly differ from the ones proper of the TOA scheme (i.e., the direction cosines of the line of sight of the sources with respect to the receiver, with the last column given by unity terms). Specifically, also following [8], it is possible to write

$$H_{i1} = -\frac{f_i}{cd_i^3}(x_i - x_u)[(\dot{x}_i - \dot{x}_u)(x_i - x_u) + (\dot{y}_i - \dot{y}_u)(y_i - y_u) + (\dot{z}_i - \dot{z}_u)(z_i - z_u)] - \frac{f_i}{cd_i}(\dot{x}_i - \dot{x}_u)$$

$$H_{i2} = -\frac{f_i}{cd_i^3}(y_i - y_u)[(\dot{x}_i - \dot{x}_u)(x_i - x_u) + (\dot{y}_i - \dot{y}_u)(y_i - y_u) + (\dot{z}_i - \dot{z}_u)(z_i - z_u)] - \frac{f_i}{cd_i}(\dot{y}_i - \dot{y}_u)$$

$$H_{i3} = -\frac{f_i}{cd_i^3}(z_i - z_u)[(\dot{x}_i - \dot{x}_u)(x_i - x_u) + +(\dot{y}_i - \dot{y}_u)(y_i - y_u) + (\dot{z}_i - \dot{z}_u)(z_i - z_u)] - \frac{f_i}{cd_i}(\dot{z}_i - \dot{z}_u)$$

$$H_{i4} = 1 \tag{6}$$

The relation for Doppler observables (Eq. 5) can be processed as done for pseudorange observables in TOA systems [1], to obtain an approximated error evaluation as the product of the error in measurements (σ_{UERE}) and a geometric factor known as dilution of precision (GDOP):

$$\varepsilon_{GNSS} = GDOP\ \sigma_{UERE}\ . \tag{7}$$

GDOP includes the effects of the relative geometry between satellites and receiver, indeed collecting the properties of the orbital configuration of the sources. Assuming the hypotheses of a stationary geometry during the measurements, of an uncorrelated behaviour in terms of errors among satellites and of a common error statistics among them, it can be computed as:

$$GDOP = \sqrt{tr(H^T H)^{-1}} \tag{8}$$

The correctness of the hypotheses leading to GDOP definition should be re-evaluated in the case of the Big-LEO. Specifically, the first hypothesis is certainly more relevant due to the higher velocity of the lower-altitude platforms, while the second hypothesis is in some way relaxed as platforms belong to different systems. The third hypothesis should be fully re-considered as the sources could even have different possible causes of errors (as an example, they can adopt different frequencies and very different hardware), and the condition of an equal value of the overall standard deviation of the error is really difficult to judge. If, pending some specific analysis, the hypotheses can be preliminarily accepted, it is possible to numerically evaluate the GDOP in the frame of an orbital propagation for some selected BigLEOs. In such a way, GDOP can be evaluated in time for any site, defining indeed the amplification factor on the error due to the specific, considered orbital configurations.

Simulations and discussion

Figures 1-6 refer to the configurations of Starlink and OneWeb constellations, currently the two largest big-LEOs, as per Fall 2022, when Starlink included 3049 satellites in various inclinations and altitudes, and OneWeb featured 424 satellites mostly at 1200 km altitude and 87° inclination. More recent data (July 2023) provide 4347 Starlink's and 631 OneWeb's spacecraft, not really changing the rationale of the analysis. The ephemerides requested for the orbital propagation have been obtained from Two Lines Elements (TLE) sets available online [9]. It can be first confirmed that large LEO have the possibility to provide navigation services. Fig. 1 shows the coverage in Padua area (45.41N, 11.88E) limited to sources above 15° elevation. As expected, Starlink is offering most of the coverage, even if, due to the nature of the constellation, in a way which is definitely non uniform in time. Notice that the coverage from OneWeb has a significant periodic behavior, with repetitive gaps: it reflects the more ordered nature of the OneWeb architecture, with higher, less perturbed orbits and a more regular spacing of the orbital planes.

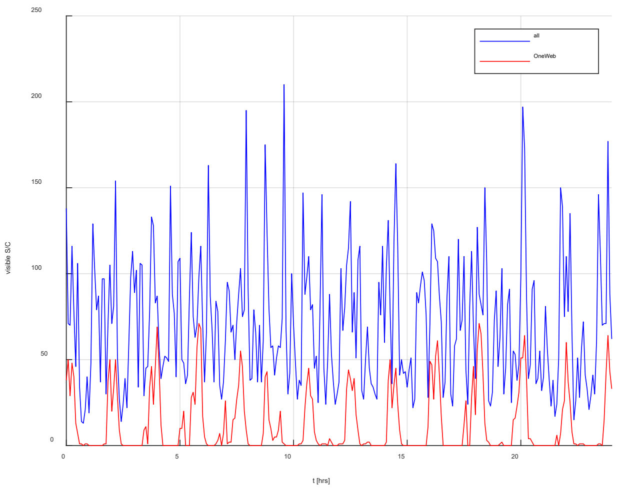

Fig. 1 – S/C above 15° from Padua (cumulative Starlink/OneWeb and OneWeb only)

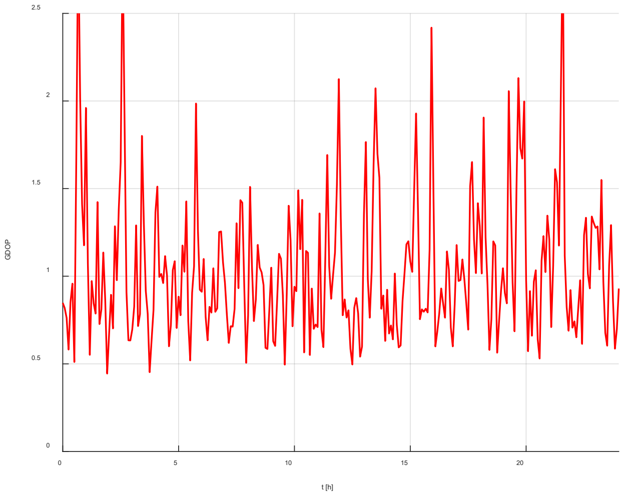

Fig. 2 – GDOP(Time of Arrival observables), full set of visible S/C

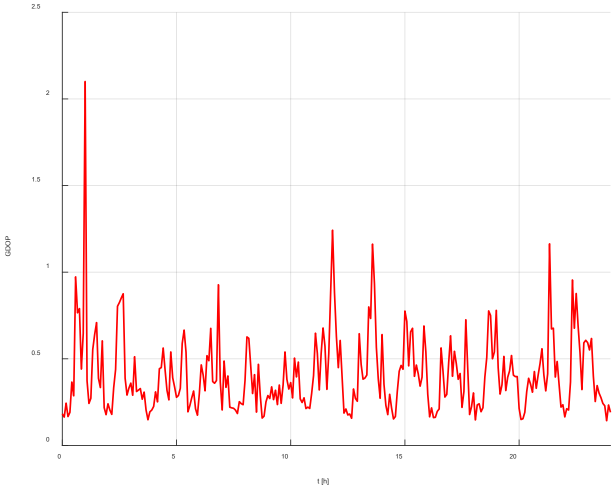

Fig. 3 – GDOP(Doppler), full set of visible S/C

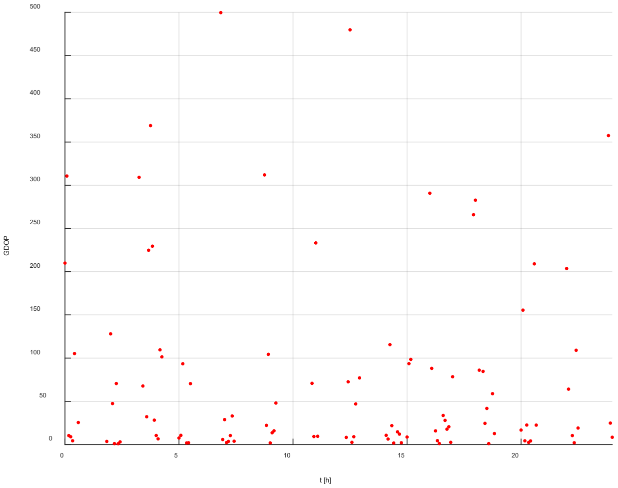

Fig. 4 – GDOP(Doppler), 4 satellites case

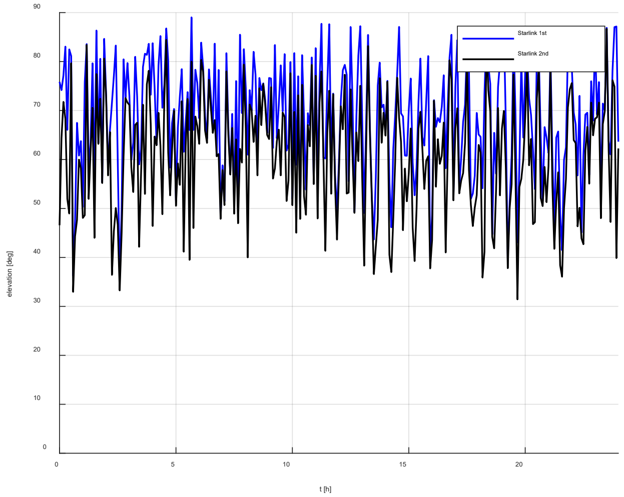

Fig. 5 – Elevation of the best and second best visible S/C of the Starlink constellation.

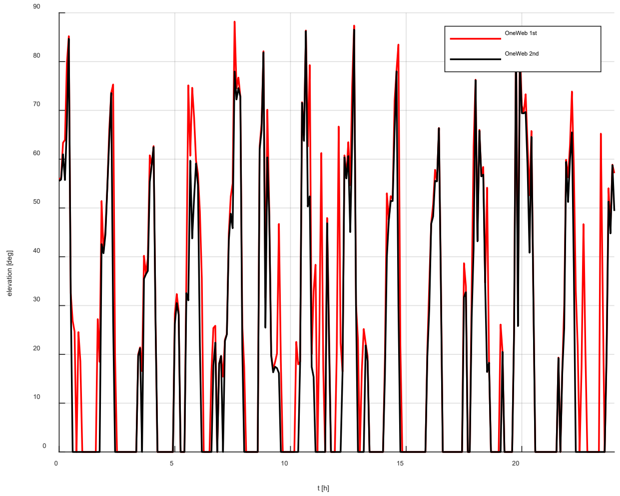

Fig. 6 – Elevation of the best and second best visible S/C of the OneWeb constellation.

Comparable plots referred to July 2023 constellation would show these gaps disappearing with at least one satellite visible above the horizon (elevation threshold equal to 0°). Fig. 2 and Fig. 3 show extremely low, and indeed good, values of GDOPs, for both time-of-arrival and Doppler observable cases, if all sources are considered: and obvious result of the rich coverage offered. If, looking at the new findings about signal distribution [7], the focus is instead on the case of 2-sources only from each constellation, Fig. 4 clarifies that spotted GDOP is higher and the coverage is non continuous. Only the Doppler observable case is here reported, but the behavior does not change for the traditional time-of-arrival case except for the magnitude of values, which is by the way not too significant as observable themselves do have a different magnitude. In fact, active satellites would be the same, i.e. the two from each constellation seen by the receiver with the higher elevation (indeed the closest one at the site). Fig. 5 clarifies that the rich, yet non regular, distribution of Starlink perfectly satisfy the coverage request, with even the second best always above 30°, and generally 40° elevation. Instead, Fig. 6 reports the spaced-out distribution of OneWeb, with the gaps where not even a satellite was available (as previously reported, OneWeb current configuration would offer a single coverage in these intervals, still not enough for a navigation service). Notice that, notwithstanding the (far from trivial) issues in capturing and elaborating different signals, the same approach could be extended to more than two constellations (as an example by adding Orbcomm or Iridium), achieving in such a way the requested coverage without gaps.

Conclusion

Big-LEOs systems can be helpful in providing navigation services in addition, or as a back-up, of existing GNSS, if considered as sources of signals of opportunity. The paper reports the evaluation of the geometry matrix for the Doppler shift observable and the simulations for the GDOP in case of two large (Starlink and OneWeb) systems, considering their current configuration and their specific limited irradiation characteristics.

References

[1] E.D. Kaplan, C.J. Hegarthy, Understanding GPS Principles and Applications, 2nd ed., Artech House, Norwood (MA, USA), 2006.

[2] T.G.R. Reid et al. (part 1), and Z.M. Kassas (part 2), Navigation from Low Earth Orbit, in: J. Morton, F. van Diggelen, J. Spilker, Jr., B. Parkinson (Eds.), Position, Navigation, and Timing Technologies in the 21st Century: Integrated Satellite Navigation, Sensor Systems, and Civil Applications, Volume 2, Wiley–IEEE, 2021, pp. 1359 ff.

[3] T. Reid, Commercial Satnav from LEO, Inside GNSS, May 2022.

[4] J.J. Khalife, Z.M. Kassas, Receiver Design for Doppler Positioning with Leo Satellites, IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), 2019. https://doi.org/10.1109/ICASSP.2019.8682554

[5] G.B. Palmerini, P. Kapilavai, Navigation Services from LEO Constellations, paper IAC-22-B2.7.8, 73rd International Astronautical Congress (IAC), Paris, France, 18-22 September 2022.

[6] G.B. Palmerini, P. Kapilavai, Orbital Configurations for Large LEO Constellations Providing Navigation Services, IEEE Aerospace Conference Proceedings, 2023. https://doi.org/10.1109/AERO55745.2023.10115563

[7] P.A. Iannucci, T.E. Humphreys, Fused Low-Earth-Orbit GNSS, IEEE Transactions on Aerospace and Electronic Systems (2020, *in press*). http://doi.org/10.1109/TAES.2022.3180000. https://doi.org/10.1109/TAES.2022.3180000

[8] M. Di Mauro, Doppler Positioning Satellite System, EWP1959, ESA ESTEC 1997.

[9] https://celestrak.org/NORAD/elements/