Mission Analysis for the Optimization of the GPS Coverage for an Earth Observation Satellite

Roberta Falone[1](✉), Pietro Ivan Chichiarelli[2], Ennio Gambi[1], and Susanna Spinsante[1]

[1] Dipartimento di Ingegneria Dell'Informazione, Universitá Politecnica delle Marche, Ancona, Italy
r.falone@pm.univpm.it
[2] Satellite Operations, Telespazio S.p.A., Fucino Space Centre, Avezzano, Italy

Abstract. The goal of this work is to present an advanced study of the GPS coverage capability of a Low Earth Orbit (LEO) satellite. The motivation for this arises in the satellite control environment, during the operations preparation phase, by the need of predicting the time necessary to the on-board GPS receiver to fix the first orbital position, after the on-orbit injection at LEOP (Launch and Early Operational Phase). Once the first acquisition is performed, the satellite will be ready to enter the normal mode. The availability of a proper GPS coverage at LEO altitudes should be evaluated not only during the LEOP - clearly more critical - but also in the entire routine life of the satellite. Different approaches to optimize the GPS coverage, proposed by manufacturers and satellite operators, are considered, showing key strengths and weak points of the selected strategies. Operational and structural constraints must be taken into account when aiming at the proposal of different approaches to the GPS coverage issue, such as occultation of the on-board star trackers and the GPS antennas.

Keywords: LEO guidance · GPS · Coverage · Optimization · Satellite operations

1 Introduction: The Operational Context

Nowadays, GPS receivers are widely used for LEO spacecraft applications, in particular for precise orbit determination and geo-referencing the acquired images for Earth Observation purposes. Recent satellite LEO platforms rely so deeply on Global Navigation Satellite Systems (GNSS) that the on-board GPS receiver is switched on at launch phase and it is never switched off, apart from some contingency cases. GNSS integration has become such a well-established standard and a recognized support for LEO navigation that unavailability periods of the on-board receiver are always subject to an attempt of minimization, with any kind of proper strategy.

P. Pillai et al. (Eds.): WiSATS 2015, LNICST 154, pp. 199–211, 2015.
DOI: 10.1007/978-3-319-25479-1_15

Nevertheless, performances of spaceborn GPS receivers are deeply affected by the geometry of the subset of visible satellites in the GNSS constellations and by the variability of the ionospheric layer, in terms of residual altitude (above the LEO satellite) and electronic density. These factors influence the Time To the First Fix (TTFF) too, a critical parameter to be carefully considered after the first switch on of the on-board GPS receiver. TTFF includes a structural time needed to the receiver to perform a *cold start*, rather than a *warm start*. Furthermore, the switch-on operation can be performed only through a direct Telecommand (TC) sent by the Ground Control Centre (GCC) during a visibility opportunity between the satellite and the Main Control Station (MCS). In order to reduce the convergence time needed to the GPS receiver to supply a fixed position, we can operate on the deterministic constraint mentioned above, i.e. the available GPS constellation geometry. The first attempt is to provide the GPS receiver switch-on at the most favorable orbital sections, in terms of GPS coverage and geometric visibility from the MCS.

The proposed analysis and the relevant simulations have been performed by distinguishing between LEOP/contingency phase (two very different phases but with similar constraints from the point of view of the on-board GPS receiver), and the routine phase of the satellite mission life.

Simulations have been implemented and run by means of *FreeFlyer* (a.i. Solutions' software tool) dedicated to the space mission design, analysis and operations for the satellite environment.

The paper is organized as follows: Sect. 2 introduces basic knowledge about the satellite platform and the orbit features. Section 3 presents the simulations performed on GPS coverage, that are discussed, together with possible improvements, in Sect. 4. Finally, Sect. 5 draws the main conclusion of the work.

2 The Satellite Platform: Architecture and Orbit Features

2.1 The Spacecraft Architecture

In this section we will briefly show the general architecture of the considered platform. We will not refer to a particular spacecraft architecture; the proposed one can be considered as a features' "merge" of several platforms. The following features are quite general and common among Earth Observation satellites. This is the reason why we can consider the following platform model without loss of generality.

Let us clarify the reference frame used to set up the satellite axes and the location of the useful sensors, i.e. the GPS antennas and the Star Trackers.

As the Fig. 1 shows, the satellite body axes are arranged in the following manner:

- X axis: the satellite main body axis; the camera for images acquisition is arranged along this direction (shaded red cone);
- Y axis: solar array panels direction;
- Z axis: it completes the right-handed orthogonal reference frame.

Then the GPS antennas are arranged in the following disposition:

- GPS Antenna 1: along $-X$ direction, perpendicularly to solar array panels;
- GPS Antenna 2: along $-Z$ direction.

They feature a Field Of View (FOV) of 40 degrees half cone. See Fig. 1(a).

In the end, the Star Trackers are arranged with the following LOS (Line Of Sight) main directions:

- Optical Head 1: $-X/-Y/+Z$
- Optical Head 2: $-X/+Y/-Z$
- Optical Head 3: $-X/-Y/-Z$

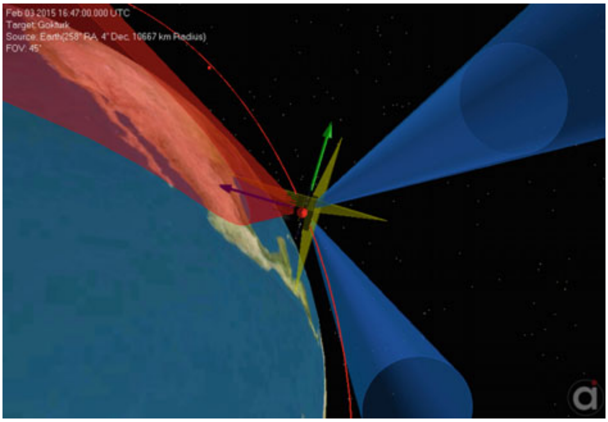
They feature a FOV of 12.5 degrees half cone. See Fig. 1(b).

2.2 The Navigation Guidance Description

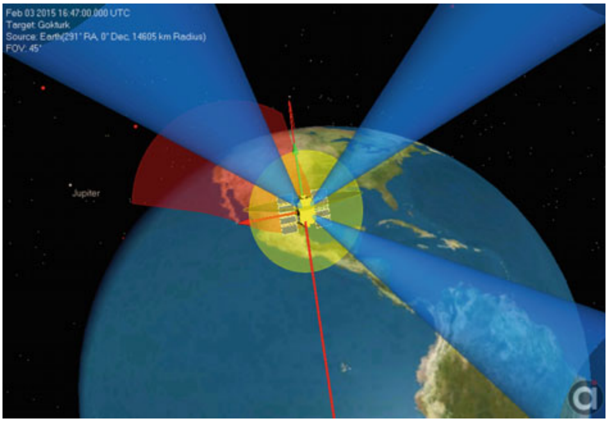
The navigation guidance is different for each phase of the satellite's mission life. For the purpose and the type of the satellite analyzed within this work, two main phases have been considered: LEOP and routine. They impose different control laws, attitude and management over the spacecraft. In the following subsections we will describe them in detail.

LEOP Guidance. Once the satellite has been released and injected into the orbit, a "stabilization" phase begins. For safety and charging batteries reasons, the satellite is oriented with its main body axis (X) aligned to the Sun vector, while it is spun around the same axis. Such a configuration is also known as *barbecue*, for clear analogies. In the Fig. 2, the spacecraft axes are shown, with the Sun Vector in yellow, and the useful sensors with their FOV. During the LEOP phase only the GPS Antenna 1 (yellow shaded cone) is active, while the telescope is not used, though displayed here (red shaded cone) for visualization scope of the attitude. Nominally, the satellite control remains in the barbecue phase until the stabilization of the spinning attitude, the first GPS fixing is reached and the star trackers are activated.

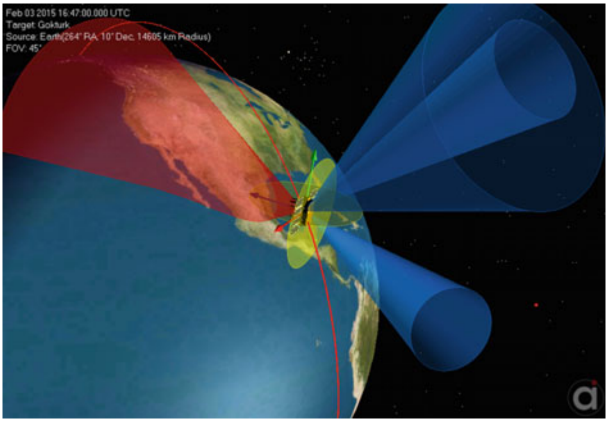
Routine Guidance. This phase is entered by the MCS with a proper TC, when the already mentioned conditions on attitude, GPS fixing, and star trackers have been gained. Once the normal-routine mode has been activated on-board, both GPS Antennas and Star Trackers are active and the guidance of the satellite changes from the barbecue to the Autonomous Navigation. This type of guidance is defined autonomous since it is self-managed by the satellite on-board software when some specific orbital events are triggered: the *eclipse entry*, the *eclipse exit*, and the *ascending node.* Clearly, the Autonomous Guidance is active only when no image acquisition activity is scheduled in the sun-lightened part of the orbit. The actual guidance of the spacecraft is featured by:



(a) GPS Antennas in shaded yellow



(b) Star Trackers in shaded blue



(c) Global view of the spacecraft

Fig. 1. Different perspective of the spacecraft's sensors (Color figure online)

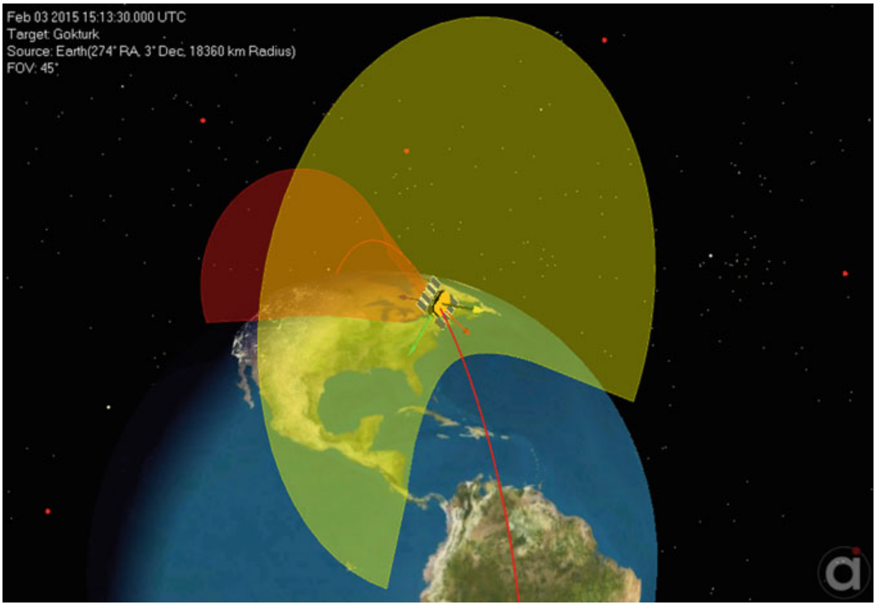
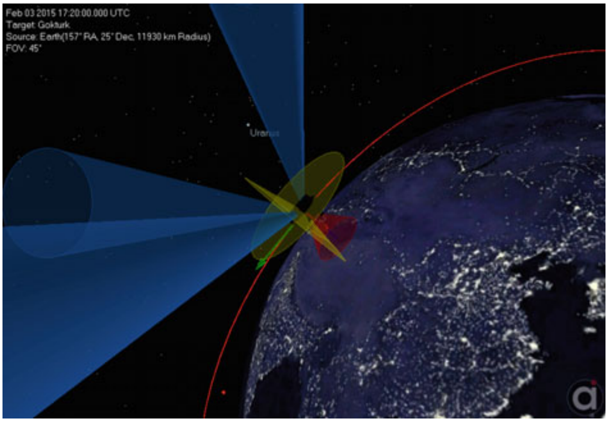
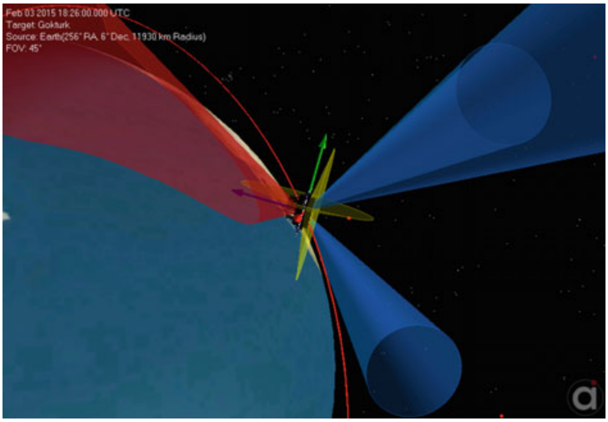


Fig. 2. Spacecraft attitude during the barbecue phase

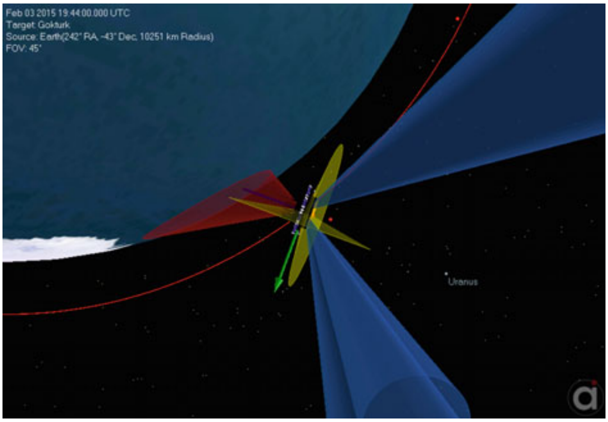
- **Earth Pointing:** In the Earth shadow orbit, the spacecraft has its main body axis (X) always oriented toward the center of the Earth, so the satellite constantly rotates along the orbital path. This guidance is triggered by the eclipse entry event (See Fig. 3(a)).
- **Sun Pointing**: In the sun-lightened part of the orbit, the spacecraft autonomously re-orient its main body axis toward the Sun, without spinning around the Sun Vector. Since the solar array panels of the modeled spacecraft are fixed (they are not able to rotate around their own axis - Y), the whole platform is forced to keep its panels perpendicular to the Sun Vector, in order to maximize the power generation by the panels. This guidance is triggered by the eclipse exit event (see Fig. 3(b)). Furthermore, the satellite exits the eclipse phase with the GPS Antenna 2 (on $-Z$) pointed toward the deep space. This orientation features the orbital path until the ascending node. Few minutes before reaching the ascending node, the satellite prepares for a yaw-flip maneuver: it is aimed to rotate the satellite around its Y axis (see Fig. 3(c)). In this new attitude, in fact, the GPS Antenna 2 is now pointed toward the North direction, allowing the platform to benefit from better GPS coverage, without the almost-total Earth occultation. This represents a first possible strategy to optimize the GPS coverage.



(a) Earth Pointing Attitude during eclipse phase



(b) Sun Pointing attitude after the Ascending Node



(c) Sun Pointing attitude before the Ascending Node

Fig. 3. Different attitudes during the normal autonomous guidance

3 GPS Coverage Simulations: Run and Results

In this section we will show the results of the orbit propagation for the LEO satellite and the GPS constellation. Synchronizing their epochs and running a propagation of one week, two different setups have been implemented relevant to the two mission scenarios, LEOP and Routine phase. The model used to propagate the orbit of the LEO satellite is quite standard for any mission at low altitudes: a fixed-step size (30 s) Runge-Kutta 8(9) integrator, adding a classical disturbing force model. We considered the effects of Earth, Moon and Sun, with Zonal and Tesseral Earth potential with solid tides, and the atmospheric drag, with the MSIS-2000 atmospheric density model. For the GPS constellation we used TLE files provided by NORAD.

3.1 LEOP Phase

We already mentioned the features of this mission phase: LEOP is characterized by a Sun Inertial Spinning attitude and the use of just one GPS Antenna to accomplish the first position fixing. A preliminary analysis has been performed on the coverage opportunity between the GPS Antenna 1 and the whole GPS constellation. In Fig. 4 some meaningful results can be gathered. Clearly, the polar diagram shows a statistical description of the number of the visible GPS satellites over 7 days of simulation.

The Fig. 4 is obtained by running the propagation in Sun Inertial Spinning attitude for 7 days and evaluating the number of visible GPS satellites at each propagation step (30 s). No data have been removed from the chart during the propagation, since the main scope of that was to evaluate which "orbital sections" benefit, on average, of the best GPS coverage. Clearly, the GPS geometry changes quite fast over the LEO satellite and it may be very different from one orbit to another.

Nevertheless, some peculiar orbital points feature quite a characteristic behavior of the middle-long term GPS coverage. With regard to this aspect, in order to aid in the readability of the results, in Fig. 4 two orbital sections are shown (eclipse and enlightened sections of the orbit) as function of the common reference theta angle (the argument of latitude, i.e. the angle between the position of the satellite on the orbit and the ascending node). Actually, for the aim of a better presentation of the chart, we have recorded the values of the argument of latitude plus 180 degrees. This was just to report the North Pole in the upper part of the chart. We can infer some important results from the polar diagram.

– The orbital points which statistically experience the best GPS coverage are reasonably comprised between intermediate latitudes over the ascending node, while gradually decreasing (the goodness of the coverage) when approaching to the poles: as is known, the GPS coverage at very high latitudes may experience a slight degradation. In general the entire section within this zone is a good candidate to schedule the switch-on of the on-board GPS receiver, considering that the Fucino Ground Station (involved in our simulation and

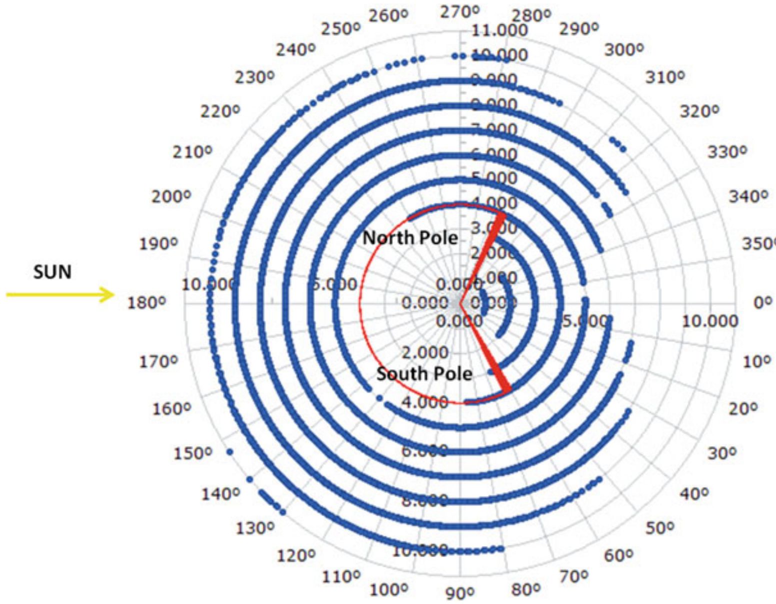


Fig. 4. Number of visible GPS satellites from Antenna 1. On theta angle the Argument of Latitude, on radial axis the number of visible GPS satellites. The solid line is added to show the relation between orbital section (high value in eclipse, zero value in the enlightened part of the orbit) and the statistical coverage.

deputy to the control operations) is also well located in terms of latitudes in order to command the satellite in direct visibility: this is necessary to achieve a real-time control and monitoring during the switching-on of the GPS receiver. Clearly, not every orbit may be as good as expected from this point of view, since the variability of the geometry of the constellation may cause a poor configuration in terms of number and quality of the geometry (DOP values). In Fig. 5 a demonstrative case is shown: this is an extract of the time diagram, where it has been possible to find out that only the shown opportunities give an unavailability to track in the enlightened arc. In this case, it may be necessary to wait for successive orbits in order to match the adequate conditions. Nevertheless, excluding the previous finite circumstance, in the enlightened orbital arc the coverage capability never decreases under the minimum required number of GPS satellites, i.e. four. This observation gives us good expectations about the possibility to even perform a cold start in this orbital arc.

– The polar diagram gives more information and confidence about the orbital arcs which must not be taken into account, regardless the presence of the Ground Station in visibility with the satellite. As expected, the sections to be avoided are those at high latitudes (in absolute value) and those in eclipse: within these sections, the variance of the number of available GPS satellites is significant in a limited timing window, which implies that the on-board GPS receiver may be unable to track the same 4 satellites for a sufficient time to achieve a FF.

– The central eclipse arc is another “hole” for GPS visibility. The diagram clearly shows that the maximum number of satellites in visibility may be 4 (or less): nevertheless, these satellites are visible with very low elevations with respect to the GPS Antenna 1 FOV, and the combination of them changes quite rapidly. This prevent the on-board receiver to have time enough to receive the navigation signal from the same 4 satellites, i.e. enough time to accomplish a trilateration.

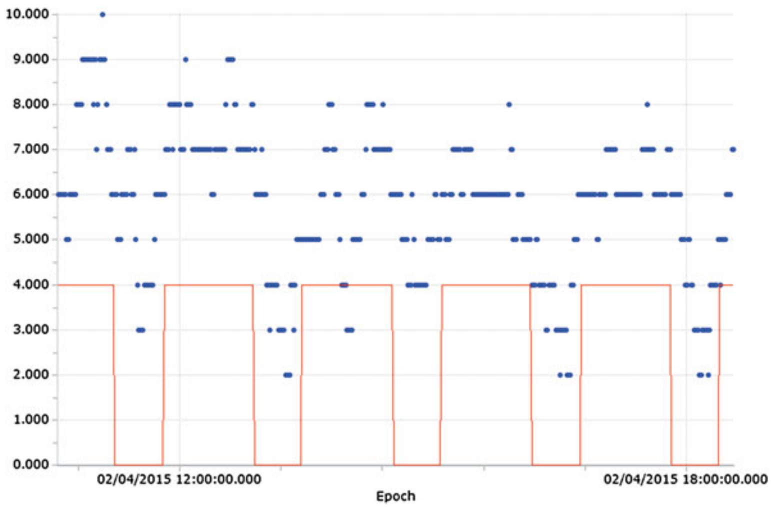


Fig. 5. Time Diagram. The number of visible GPS satellites is shown as a function of the time. This is the only opportunity of “unavailability” of the GPS system encountered during 7 days simulation, limited to the enlightened arc of the orbit.

There are other important observations which cannot be inferred by a diagram like the previous one. Nevertheless, they are equally important in the analysis we are proposing (statistical description parameters).

3.2 Routine Phase

We have already described the routine phase of the satellite, in terms of attitude and navigation. In the diagram of Fig. 6, the results are reported on the helpful polar plot.

Clearly, the switch-on and the actual utilization of the second GPS Antenna, introduces significant improvements. The minimum number of visible GPS satellites never decreases under the value of 8 satellites; the maximum reaches even

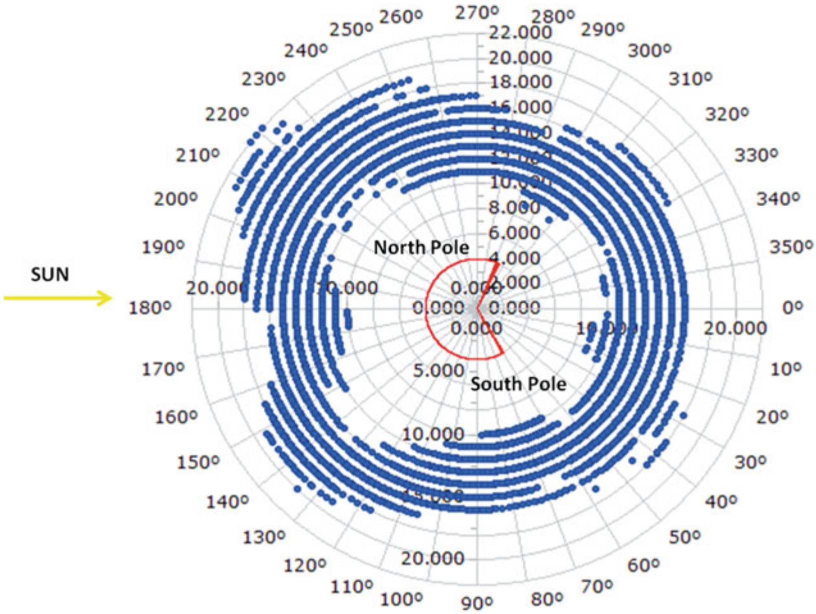


Fig. 6. Polar diagram. Cardinality of the visible GPS satellites observed during the routine phase.

22 satellites in particular favorable conditions of visibility and orbital phase of the LEO satellite. Once the satellite has entered the nominal navigation phase, only severe conditions affecting the on-board GPS receiver (internal failures, platform issues, channel propagation errors or interference) could compromise the tracking and consequently the fixing, since the opportunities to choose the better subset of incoming ranging signals become considerable.

Nevertheless, from the point of view of the Satellite Operations, a yaw-flip maneuver at the ascending node means an increasing complexity to the management of the satellite, especially when acquisition images' activities are scheduled in the arc close to the ascending node itself. In fact when an image is planned to be acquired at latitudes close to zero, the autonomous guidance has to be disabled at least some (about 5) minutes before the ascending node crossing, otherwise the satellite will autonomously start the preparation of the maneuver. Once the preparation has started, no image or other activity's request can be submitted on board. Operationally speaking, the yaw-flip maneuver is very useful to improve the GPS coverage (keeping at the same time at least two star tracker's optical heads not obscured), but it is tedious in some way for the satellite's activities planning.

4 Variations over the Nominal Attitude: Room for Improvement

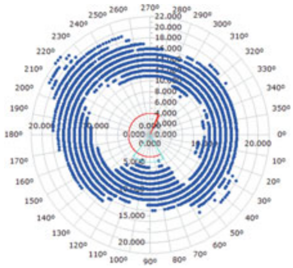
For the reasons mentioned above, the goal of this work is to justify (or refuse) the actual benefit coming from the yaw-flip maneuver. If another "stationary" attitude could replace the solution shown before, we might encounter a little underperformance of the GPS coverage, with the benefit of completely avoiding the maneuver at the ascending node. The simplification of the operational life of the satellite is the main purpose of the proposed solution.

Nevertheless, when introducing a fixed attitude which keeps the satellite pointed toward the Sun, the constraint requested for the Star Tracker (two optical heads out of three must be not occulted) fails, as the Fig. 7 shows. The solid line with radial value of 5 represents the orbital arcs during which two or even three optical heads are occulted. The only exploitable degree of freedom is the rotation around the X axis: in fact, a complete rotation has been simulated and tested in terms of GPS coverage. No significant coverage variation has been found, only the introduction of issues related to the occultation of the Star Tracker. The Fig. 7 clearly shows the trend of the occultation as a function of the rotation around the X axis: as the satellite attitude varies from the reference attitude, some orbital arcs are featured by the occultation of the Star Tracker. It is interesting to note that the trend is clearly linear as a function of the rotation: once the attitude is established, the orbital arcs featured by occultation remain constant in the total sum, but they change in the "distribution" along the enlightened orbital section. The geometrical arrangement of the optical heads plays a strategic role to these results.

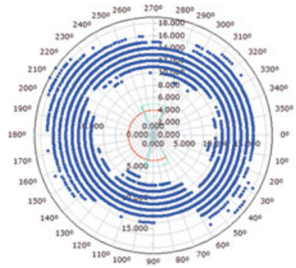
From the operational point of view, the possibility to forgo one occulted optical head's support, in favor of a good GPS coverage together with a simpler autonomous guidance management, seemed to be a good trade-off. This strategy is a potential solution considering that during the autonomous guidance the acquisition of the images is not allowed, hence a highly precise geo-referencing of the images (given by the attitude information in addition to the navigation information) is not strictly needed. Based on these considerations, other simulations have been proposed and performed assuming the new following conditions:

- Research of X axis rotated attitude which minimize the occurrences (duration) of one or two occulted optical heads. No instance of total occultation is allowed;
- Evaluation of GPS coverage is clearly taken into account.

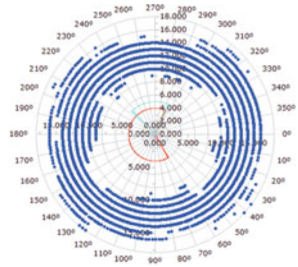
In the same Fig. 7 the results of the simulation are shown. The condition of three optical heads occulted is never verified, whatever the attitude is rotated. This means that at least one optical head is available to provide information about the spacecraft attitude. If we accept this type of availability of the attitude sensor, only the optimization of the GPS coverage remains to be considered in the selection of the best attitude for the autonomous guidance. It is easily remarkable that not every rotation is a good solution, for a simple reason: the



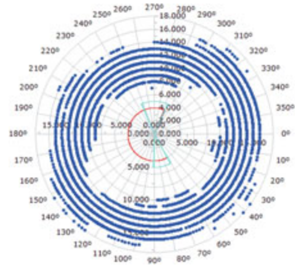
(a) Occultation and GPS coverage with a rotation of 0 deg



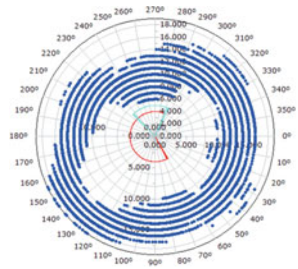
(b) Occultation and GPS coverage with a rotation of 45 deg



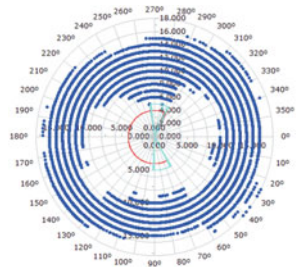
(c) Occultation and GPS coverage with a rotation of 90 deg



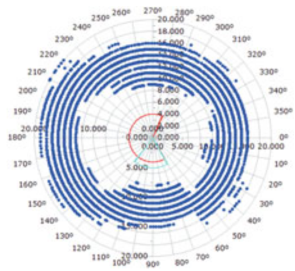
(d) Occultation and GPS coverage with a rotation of 135 deg



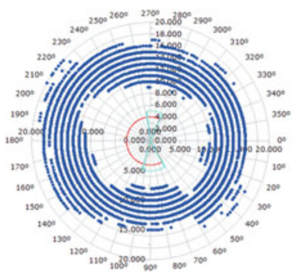
(e) Occultation and GPS coverage with a rotation of 180 deg



(f) Occultation and GPS coverage with a rotation of 225 deg



(g) Occultation and GPS coverage with a rotation of 270 deg



(h) Occultation and GPS coverage with a rotation of 315 deg

Fig. 7. Different attitudes tested for the autonomous guidance. The rotation is stated with respect to the reference attitude coincident with the Sun Pointing Reference Frame with the $-Z$ axis toward the North direction.

symmetry that features the arrangement of the optical heads does not affect the GPS antennas, too. We identified in the configuration shown in Fig. 7(c) and (g) or (h) the best trade-off taking into account all the considerations presented along the dissertation.

5 Conclusions and Future Works

This work presents a mission analysis oriented to the study of the GPS coverage by the on-board GPS Receiver on a LEO spacecraft. The main issues, specific for an Earth Observation mission, have been explained and a further approach to the yaw-flip maneuver has been proposed, supported by the simulation results. These ones allow us to accept the validity of an alternative solution to the problem of the GPS coverage, simplifying, at the same time, the operational management of the spacecraft.

The study will be successively deepened by simulating other features of the on-board GPS receiver and trying to build a cost-function shaped in order to optimize the DOP values along the time (rather than the mean value of the GPS visible satellites), considering a model of the upper atmosphere layer affecting the GPS signal, a statistical description of the phenomena and the possibility of a slight de-pointing of the spacecraft with respect to the Sun Vector during the enlightened orbital arc.

References

1. Hauschild, A., Markgraf, M., Montenbruck, O.: GPS receiver performance on board a LEO satellite. Inside GNSS
2. Liu, J., Gu, D., Ju, B., Yao, J., Duan, X., Yi, D.: Basic performance of BeiDou-2 navigation satellite system used in LEO satellites precise orbit determination. Chin. J. Aeronaut. **27**(5), 1251–1258 (2014). ISSN 1000–9361
3. Wermuth, M., Hauschild, A., Montenbruck, O., Kahle, R.: TerraSAR-X precise orbit determination with real-time GPS ephemerides. Adv. Space Res. **50**(5), 549–559 (2012). ISSN 0273–1177
4. Misra, P., Enge, P.: Global Positioning System: Signals, Measurements, and Performance