TOLOSAT project: Gravimetry and Communication

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Abstract

The use of Constellations for weather science, security and disaster monitoring is a major challenge for space application services. Satellite to satellite communication using existing constellations has not been extensively explored yet. It can improve the communication times for small-satellite missions which have limited access to ground stations. Thus, a mission to demonstrate the feasibility of this link is required.

Another element of interest in space application is Earth Observation, especially in the context of Climate Change. Gravimetry allows an understanding of mass transport in the Earth System through the remote sensing of the time variation of the Earth gravity field. CubeSats are low-cost small-scale and hence lower risk solutions to Earth Observation missions. University CubeSats have shown their success in demonstration and scientific missions, and have a great potential in providing students with practice and application on real space systems.

In this context, the student associations ASTRE and SUPAERO CubeSat Club have joined in a CubeSat program called TOLOSAT, with the hope of demonstrating such technologies. Gathering 70 students from Toulouse, the team was split into subsystems in accordance with the concurrent engineering principles. The work performed followed recommendations from experts from the French National Centre for Space Studies (CNES) and the industry.

The TOLOSAT payloads have to test and demonstrate new means of measuring gravity and addressing communication issues. Firstly, for the gravimetry mission, our approach relies solely on GNSS to compute the gravity field, avoiding expensive gravimeters. For the communication mission: the Iridium constellation will be used as an intermediate between the CubeSat and the ground station. Off-the-shelf components such as patch antennas are planned to prove their efficiency in orbit. This would improve the coverage and the communication window.

The preliminary design was completed. TOLOSAT was designed as a 3-unit nanosatellite, on a 97.4° inclined, 500km high orbit. Margins were also ensured to allow a third payload to be defined in the future, that will be used for finance and partnerships.

Detailed designs are still required, but the educational purposes have been fulfilled, in terms of discovery of the development of space missions as well as in the teamwork culture. The team is now moving on to a new phase, dedicated to a more detailed conception with an on-going focus on the introduction to students to technical - but not only - fields of knowledge applied to space systems.

Keywords

Gravimetry, Iridium, Students

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1. Introduction

This paper goes in detail over the TOLOSAT student project and its current state as of March 2022.

Section *2* details all main aspects of the system ranging from technical to financial progress. It is important to note that the project is separated into subsystem teams which each focus on one aspect or system of the project. In subsection *2.1* the two payload teams for Gravimetry and Iridium explain their methodological approach and expected results. The systems and mission analysis team's role are covered in subsection *2.2*, and subsection *2.3* separates the space segment in the work carried out by each of the six technical teams. Finally, the finance and partnership aspect of the mission is addressed by subsection *2.4*.

2. Results, progress and discussion

TOLOSAT students achieved the preliminary design. Our satellite was designed as a 3 unit nanosatellite, on a 97.4° inclined, 500km high orbit. Margins were also ensured to allow a possible third payload to be defined in the future.

2.1. TOLOSAT payloads

The TOLOSAT payloads have to test and demonstrate new means of measuring gravity and addressing communication issues.

2.1.1. Gravimetry payload

Our gravimetry mission relies solely on GNSS to compute the gravity field and draw a geoid (Figure 1.) (while satellites typically deduce the gravity field from their orbit using complex and expensive on-board gravimeters coupled with GNSS data [3]).

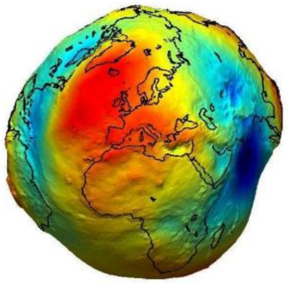

Figure 1. Earth's geoid as seen by European satellite GOCE (credit ESA) [1]

This does not require heavy equipment and was selected for the mission. This method was firstly described in detail by Ales Bezdek and al. [1]. Their work highlights that mapping the gravity field could be done without heavy and costly equipment, that is why we have based our studies on their research.

Here is a brief summary of the acceleration-based method:

The calculations are based on the fact that the geoïd is an equipotential. Thus, one has to solve a Laplace equation, Eq. 1:

$$\Delta V = \frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial z^2} \quad (1)$$

It could be demonstrated that the solution of this equation is of the following form, which introduce Legendre polynom and Stokes coefficients, in Eq. 2 :

$$V(\theta,\lambda,r) = \frac{GM}{r}\sum_{n=0}^{\infty}(\frac{R}{r})^n \sum_{m=0}^{n}[C_{nm}cos(m\lambda) + S_{nm}sin(m\lambda)].P_{nm}(cos\theta) \quad (2)$$

This equation can be simplify in Eq. 3:

$$V(\theta,\lambda,r) = \sum_{n,m}[C_{nm}V^{(c)}(\theta,\lambda,r) + S_{nm}V^{(s)}(\theta,\lambda,r)] \quad (3)$$

This solution is a development in spherical harmonics. Thanks to the four main GNSS constellations (GPS, GLONASS, GALILEO and BEIDOU) the latitude, longitude and altitude of the satellite in the *Earth Center Earth Fixe (ECEF)* frame are known. After converting the position in the *East North Up (ENU) frame*, the position became $\rho(r,\theta,\lambda)$, where the parameters are respectively the altitude, latitude and longitude of the satellite.

Then, its acceleration can be computed by a numerical derivation thanks to a Golay filter. The acceleration is decomposed in a sum of contributions, in Eq. 4:

$$\frac{d^2\rho}{dt^2} = a_{grav} + a_{LS} + a_{tide} + a_{NG} + a_{REL} = a_{grav} + a_{other} \quad (4)$$

With:

- a_{LS} and a_{tide} the acceleration due to lunisolar perturbations and tides
- a_{NG} and a_{REL} the acceleration due to relativity and non gravitational forces

By applying the third Newton's law, this acceleration can be linked to the gradient of the potential which is given by applying the nabla operator to Eq. 3. Eq. 5:

$$a_{grav}(\rho) = \nabla V(\rho) = \sum_{n,m}[C_{nm}\nabla V^{(c)}(\rho) + S_{nm}\nabla V^{(c)}(\rho)] \quad (5)$$

Then, the only things which remain unknown are the Stokes coefficients C_{nm} and S_{nm}. These coefficients can be determined by applying the least square methods to this last equation.

Then, all the terms of the spherical harmonic development in Eq. 2 are known and one has access to the local gravity potential.

2.1.2. *Iridium payload*

Nowadays communications with satellites are enabled by ground stations and limited by the rare passes of a satellite over an accessible ground station.

The TOLOSAT mission proposes a different type of protocol: exploit an existing telecommunication constellation (namely Iridium Next) in order to make a relay between the ground and the satellite. This additional passage may enable communication with the ground much more frequently: there are indeed up to 66 Iridium satellites and multiple Iridium ground stations.

Several aspects make the Iridium mission tricky.
First, the Iridium satellites' beams take the form of visibility cones that are designed so that the Earth's surface is entirely covered (Figure 2.)

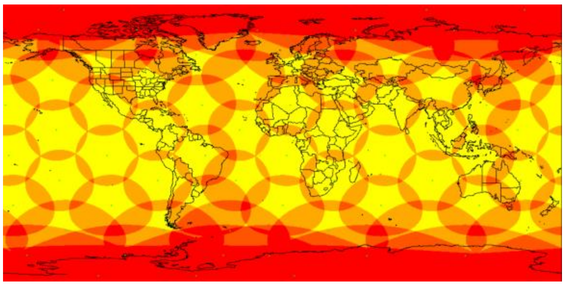

Figure 2. Coverage of Iridium Next Constellation on ground [2]

As the altitude rises, the coverage ensured by the cones decreases, which fixes an important constraint for our 500km high satellite:

- The satellite must be in the visibility cones.

Second, the existence of the Doppler effect further reduces the total time visibility of our nanosatellite. The Iridium antennas are indeed sensitive to the Doppler frequency shift. The modem algorithms hence imposed an additional requirement:

- The frequency shift caused by the Doppler effect should be limited to +/- 37.5 kHz.

According to certain sources (including specialists from aerospace industry), the time derivative of the Doppler effect (the Doppler rate) would also affect the communication. This has to be proven and backed by precise values.

These two constraints set a limit altitude of 650km and a minimum elevation angle of 24° for our satellite. For a 6 hours coverage simulation, we obtained the following estimations of Table 1:

Table 1. Table with visibility results for a 6 hours coverage simulation [1]

	Mean time session	Nb of sessions	Total time visibility
Only visibility	104s	31	214 min
With Doppler range	51,6s	39	134 min
With Doppler range and delta Doppler	63,5s	8	8 min

When it comes to hardware choices, the Iridium subsystem selected a L-band antenna (1621MHz) which has been subject to a link budget, and an Iridium modem which is in tested and operated thanks to a *PCB (Printer Circuit Board)* and driver software the subsystem developed.

2.2. *Systems & mission analysis*

The System engineering subsystem is in charge of creating and managing the complex architecture of the TOLOSAT project, seen as a whole system including the nanosatellite, the ground segment and the launcher.

This work requires the collection of data among all subsystems. The data is then formatted and well-structured through the *Valispace* browser, making sure there are no wrong assumptions between subsystems and the constraints defined in the System Technical Specification are respected. This is key when operating with large teams of students which are not always working on the same time slots. Furthermore work is under progress on validating the interfaces across the space segment.

The systems team's work also involves the monitoring of how the TOLOSAT project fulfills the on-going phase's objectives, by creating and updating the specific documentation required for each phase. Currently, the TOLOSAT project meets the methodological recommendations of the *Référentiel Normatif du CNES, RNC* to build a solid phase B documentation.

Mission analysis team on the other hand focuses on studying the implications of the orbit choice and its degradation on the mission.

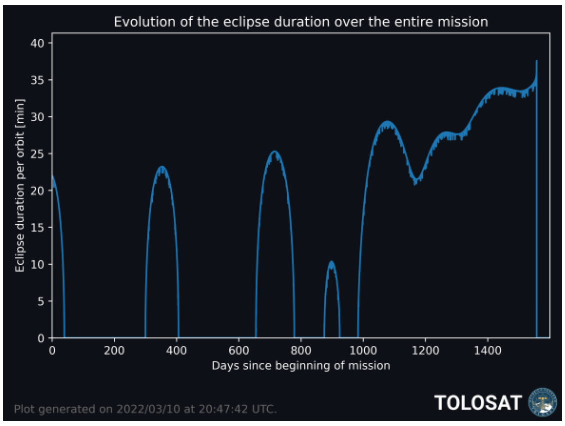

Figure 3. Evolution of eclipse duration over the entire mission [3]

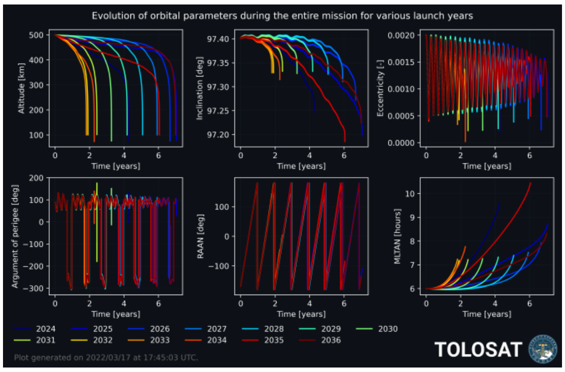

Figure 4. Evolution of orbital parameters during the entire mission for various launch years [4]

2.3. *Technical aspects of the space segment*

Currently, the TOLOSAT team focuses its efforts on the space segment, planning to elaborate its studies on the ground segment and the launch segment on further phases. Here are the main advances of the different subsystems.

2.3.1. *Structure and Thermal*

The Structure subsystem is in charge of designing a solid external structure and developing an internal structure that hosts the different components. Mass and volume budgets were done to make sure our satellite meets the requirements defined during our preliminary design. Our current budget shows that 1,5U is still available on-board, so that the implementation of a potential third payload would be possible. Currently, the Structure team is working on hosting and deploying our CubeSat's solar panels.

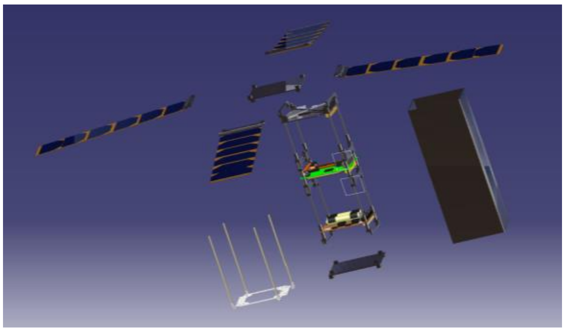

Figure 5. The phase A exploded view of the TOLOSAT nanosatellite [5]

Besides, the Thermal subsystem runs simulations to ensure our satellite handles the two extreme cases when the solar panels are oriented towards the sun: these two cases, the hot case and the cold case, are characterized by the thermal dissipation of components. We have observed that the temperatures of all the components stay within the limits.

2.3.2. *Power supply*

A budget is necessary to estimate the amount of electric power that each subsystem needs during the various operation modes of the CubeSat (safe, nominal, transmission, etc.). The eclipses are also to be considered because they deprive the solar panels of the sunlight for several minutes per orbit. Due to the orbit's features, the duration of such eclipses varies all over the mission duration.

Power subsystem is currently using a P31u card to ensure power supply and elaborate more and more accurate power budgets. The subsystem is also working on a *PCB (Printer Circuit Board)* to test the P31u.

2.3.3. Communications

Link budgets were established by the Communications subsystem, based on various parameters that have to be chosen eventually: the radio frequency, the ground and on-board antennas, the bitrate. Communications subsystem uses the same frequency for up-link and down-link, but is still working on its link budgets to choose between UHF frequency (30 MHz - 1000 MHz) and S-band frequency (2 GHz - 4 GHz). A choice is also to be made about bitrates, depending on whether the Gravimetry subsystem's data is treated on-board or at ground.

Our current link budgets demonstrate that the Communications subsystem gets enough electric power to compensate for the different physical sources of signal intensity losses.

2.3.4. On Board Computer

The On-Board Data Handling OBDH subsystem is in charge of storing the nanosatellite's data. This is currently done through the NINANO OBC card from Steel Electronics (a card that is required by the Nanolab Academy project of the CNES). The subsystem has also to choose a software architecture that manages memory, RAM, IO communication and software errors. Currently, the software *LVCUGEN* from CNES is used.

2.4. Finance and partnerships

Apart from the technical approach to conceiving a satellite, the last two subsystems created are dedicated to communication about the project, as well as finding partnerships and funding to support it. To do so, members of the 'Finance and partnerships' subsystem have been contacting several institutions (companies, schools, laboratories), resulting in the establishment of official partnerships. Indeed, TOLOSAT is now officially supported by five companies:

- Valispace offer us full access to their project management software;
- Syntony GNSS gift us a GNSS spatial receiver;
- Astreos Launch will provide us with some support regarding the budget, licensing and risk management of the project;
- Expleo and U-Space offer technical assistance to subsystems, on specific subjects.

Furthermore, our project having an educational purpose, it is important for us to establish sustainable relations with the universities our members belong to, and important institutions such as CNES and CSUT.

3. Conclusions

The TOLOSAT project has shown the feasibility of its mission through phase A. It has now to focus on detailed design and definition, but has already achieved its educational purposes in terms of discovery of the development of space missions as well as in the teamwork culture. The TOLOSAT team is starting a new phase, dedicated to a more detailed conception of the satellite. The project managers and the System engineering subsystem are currently working to provide clear and exhaustive phase B objectives to all the TOLOSAT subsystems.

During this phase, and as for all the project, TOLOSAT will remain true to its main objective by focusing on the introduction to students to technical - but not only - fields of knowledge applied to space systems.

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