Extension of the GMAT analysis report to the formation with both CubeSats

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Abstract

This study is part of the National Science Foundation (NSF) sponsored VISORS (Virtual Super-resolution Optics with Reconfigurable Swarms) space physics mission project. The goal of the mission is to detect and study fundamental regions of energy release in the solar corona. The mission engages a formation of two flying 6U CubeSats. One of the spacecrafts will support the optical package for observation while the second will contain the detection instrument.

The simulation of the spacecrafts' trajectory is an essential step in the development of the mission. This study allows to verify the theoretical training trajectory and to ensure the reliability of the mission. More particularly, we verify the behavior of both CubeSats from one relative to the other and their trajectory in the different possible configurations. We will also analyze the power generation and the influence of the RAAN parameter. The last point consists in evaluating the duration of antennas contact between both spacecrafts. Both configurations considered correspond to the two possible orbits of the mission: a standby orbit and a science orbit for observation. Results will allow to obtain a precise analysis of the objectives of the mission in terms of feasibility and will allow some adjustments of the parameters studied to date.

This report is based on the work of the Georgia Tech team and the other participating universities. The work and the code used for this study is based on a development made by Antoine Paletta for a single CubeSat of the formation. The results obtained are in line with the continuity of the VISORS project whose work is becoming more precise for a launch of the mission planned in 2024.

I. Acronyms

DCM = Direction Cosine Matrix

EUV = Extreme Ultraviolet

LEO = Low Earth Orbit

LVLH = Local-vertical-local-horizontal

NSF = National Science Foundation

VISORS = Virtual Super-resolution Optics with Reconfigurable Swarms

II. Introduction

This report is part of the research work for the Virtual Super-resolution Optics with Reconfigurable Swarms (VISORS) mission for the National Science Foundation space physics. The objective of the mission is to detect and study fundamental energy-release regions in the solar corona. The VISORS mission will image EUV features on the Sun at a resolution of at least 0.2 arcseconds from LEO [1]. VISORS will use a pair of CubeSats, one called the chief carrying the observatory optics while the other, the depute, will contain the detection instrument. Both spacecrafts are interchangeable. The mission aims to obtain at least one 10-second exposure image of the solar corona over the planned six-month flight. Meeting the stringent relative orbit requirements during science observations will demonstrate several technologies critical to accurate formation flight, including inter-spacecraft linkage, relative navigation, and autonomous maneuver planning. Therefore, this report will focus specifically on the inter-spacecraft management part. To meet these stringent mission requirements, a concept of operations has been established that requires maneuvering between a standby orbit where housekeeping tasks are performed and an actively maintained science orbit where observations are conducted. Formation acquisition and re-acquisition, fault recovery, and escape operations are also included [2]. The following report provides simulation tests of the formation orbit that will validate the selected configuration. It focuses on the analysis of the trajectory, the power generation and the contact between both CubeSats.

This step is important for the project because it allows to simulate the behavior of the spacecrafts simultaneously. It is this training which will allow the obtaining of images of the solar corona. The work proposed in the report follows the work of Antoine Paletta. A first simulation of the standby and observation orbits had been made for one of the two spacecrafts and I oversaw the continuation of this study.

III. State of progress

For the present study, the MATLAB-GMAT interface is used. My work is the continuation of the first study done by Antoine Paletta and the Georgia Tech' team which was presented in a first report. The previous analysis tackled with the attitudes, power and ground station overflights. It was focused on one CubeSat, and it was a preliminary study of the mission general overview. Antoine Paletta has developed a code under GMAT using some MATLAB functions for the modeling of attitude profiles, power analysis and evaluate the contact points with ground stations.

He was able to conclude on the viability of generating enough energy for standby and science attitudes over one nominal orbit with the use of one solar panel of 72W. This study must be deepened regarding different possible values of orbital elements. Then, he concluded on the attitude profiles that are mainly driven by power generation. Finally, he was able to conclude that assuming the activation of all ground stations for all ground passes (including staffing ground passes that occur out of business hours) the total commissioning duration is assessed to transfer the images data to the ground. This part is finalized, and adding the second spacecraft, we will study the contact between both knowing the results of the communication with ground stations.

IV. Approach and methodology

To meet the objectives of the project, the first step was to take in hand the code already made by my classmate to understand what had already been done. I also read up on the GMAT software and its features with the software guide [3] as I have read the documents written by the different project teams in order to understand the stakes of the mission and the context of the study. Then, I proposed to add some modifications to complete the simulation done with GMAT.

The first thing to do was to add the second CubeSat of the formation which will be called the depute in regard to the chief. The orbital elements of both spacecrafts were defined by the Stanford team, and will be presented below. Then, each objective was linked to a code part, and I defined the tool to use to complete the simulation. These different steps will be developed in the following sections. Firstly, we will focus on the relative views between both spacecrafts. In comparison with previous views of the chief, we will see the behavior of the depute from the chief around the orbit. Then, we will study the trajectory of the CubeSats thanks to an analysis with a MATLAB function. We will also look at the influence of the force model on these trajectories in different configurations. Then, we will be able to analyze the power generation regarding changes in orbital elements. Finally, I will develop a part focusing on the contact between both spacecrafts. The objective is to know the different configurations of the formation which ensures optimal data transfer. For each position of the depute in relation to the chief we will study the number of visible antennas.

Finally, the general aim of the report is to be able to provide a complete simulation of the formation chosen for the VISORS mission in order to satisfy the objectives to capture the energy of the solar corona.

V. Extension of the GMAT simulation

A. Relative views

In this first part we will look at the relative view of the depute in regard to the chief. Indeed, it is relevant to understand the behavior of one spacecraft relative to the other. For that, we will study more particularly the trajectory of the depute.

To do this, I have based my study on the GMAT code developed by my classmate for the study of one spacecraft of the formation. I made some modifications in order to make the simulation evolve and to complete it closer to the real mission.

Firstly, I added the second spacecraft to the mission's simulation. The orbital elements of both spacecrafts are summarized in the table below:

Orbital elements	*Value for the chief*	*Value for the depute*
INC - inclination	**98 deg**	**98 deg**
RAAN - right ascension of the ascending node	**329.56 deg**	**329.57 deg**
AOP - argument of periapsis	**45 deg**	**46.1381 deg**
TA - true anomaly	**1 deg**	**359.86 deg**

Tab.1 Orbital elements for both CubeSats of the formation

These orbital elements are used to locate the two spacecrafts to create the desired formation for the mission. We recall that spacecrafts are considered identical in terms of size, so we will not make the difference in simulation views. The orbital elements that are given here are those that were defined for the first case study proposed by the project teams. This case corresponds to a configuration where both spacecrafts pass from the standby orbit to the observation orbit in 5 periods. A second case could be studied, if necessary, with the orbital elements defined for the case corresponding to a transfer in 10 orbital periods.

To visualize depute's trajectory, I have created a new orbit view of the spacecrafts. In GMAT, I have used the OpenFrameInterface tool with the creation of a new relative view:

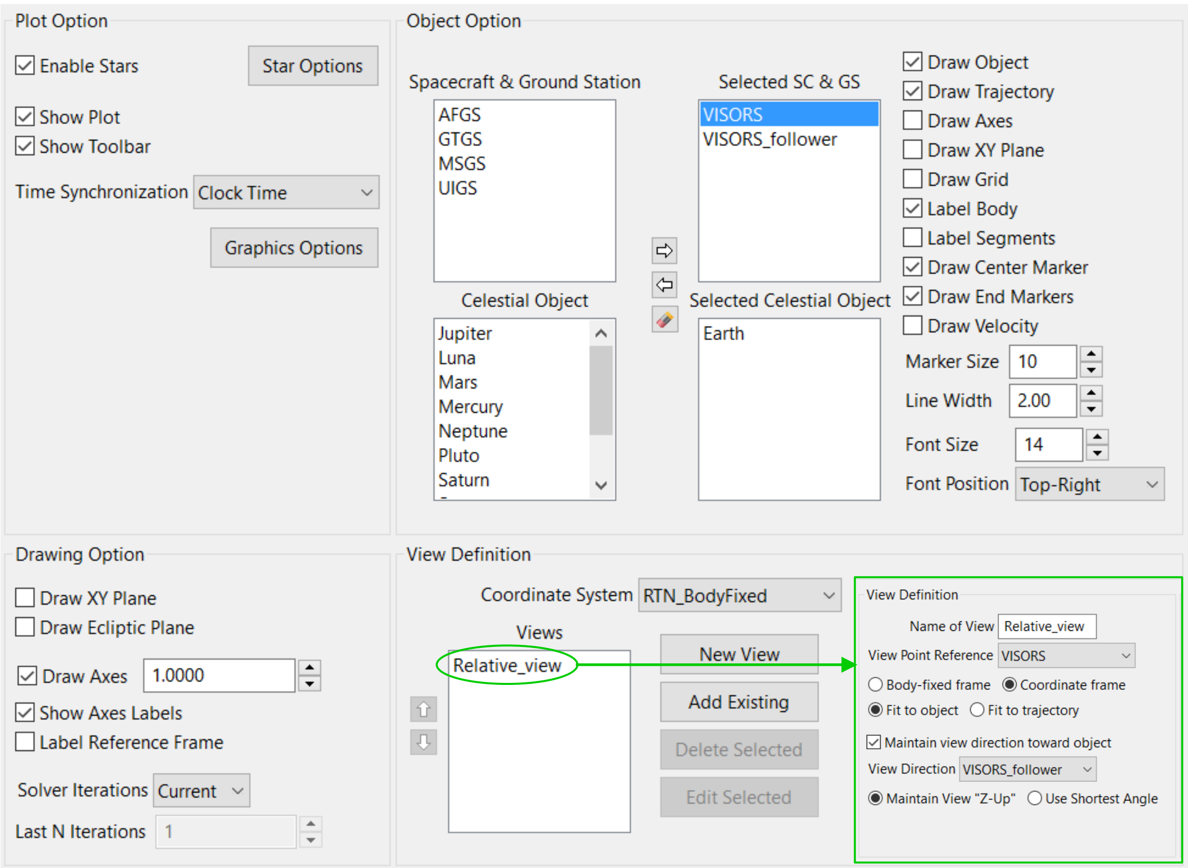


Fig.1 GMAT tool configuration for the Bodyfixed relative view

The relative view takes the VISORS spacecraft (which corresponds to the chief in the simulation) as a viewpoint reference. The view is always oriented to the VISORS_follower (which corresponds to the depute in the simulation) to have a representation of the depute view relative to the chief in the body fixed reference frame.

By also using the first view created during the development of the code, we can therefore have two relative views of the training. One in the RTN_LVLH reference frame and the other in the BodyFixed reference frame. In each of these coordinate systems, the trajectory of the deputy relative to the chief is different. We will study these trajectories more precisely in the next section.

1. *Science mode*

Firstly, we will study the science mode orbit. The following figures highlight the relative views of the spacecrafts in the two coordinate systems presented above. Precising the GMAT simulation code, we can note that both spacecrafts are propagating simultaneously at the same time step.

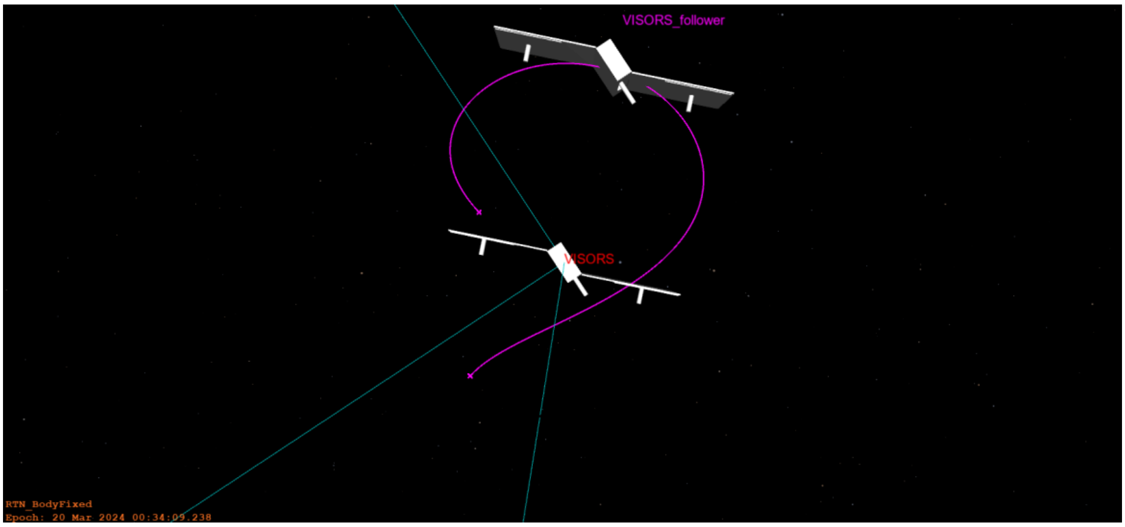


Fig.2 Relative view in the RTN_Bodyfixed reference frame – 20 Mar 2024 00:24:09.238

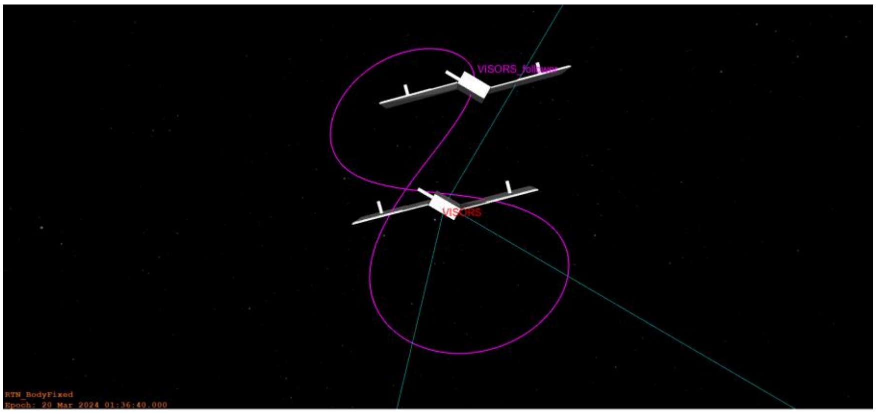


Fig.3 Relative view in the RTN_Bodyfixed reference frame – 20 Mar 2024 01:36:40.000

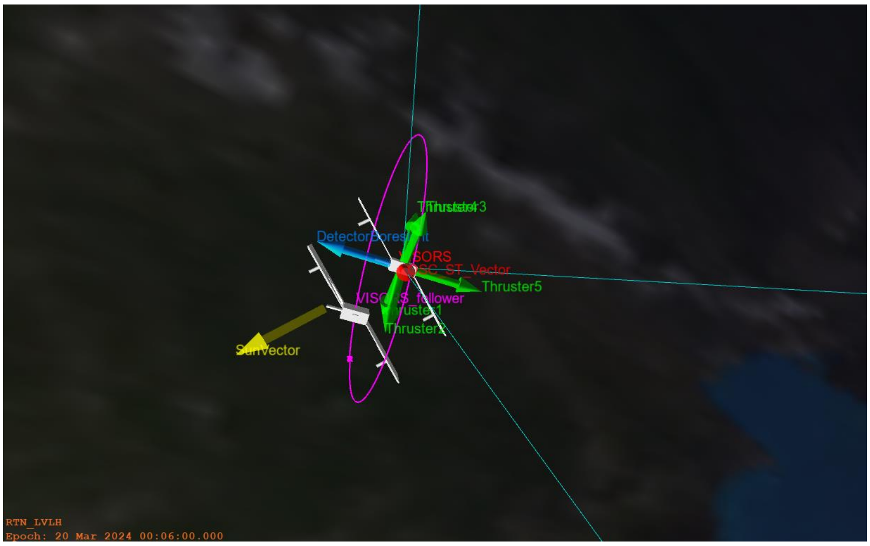


Fig.4 Relative view in the RTN_LVLH reference frame – 20 Mar 2024 00:06:00.000

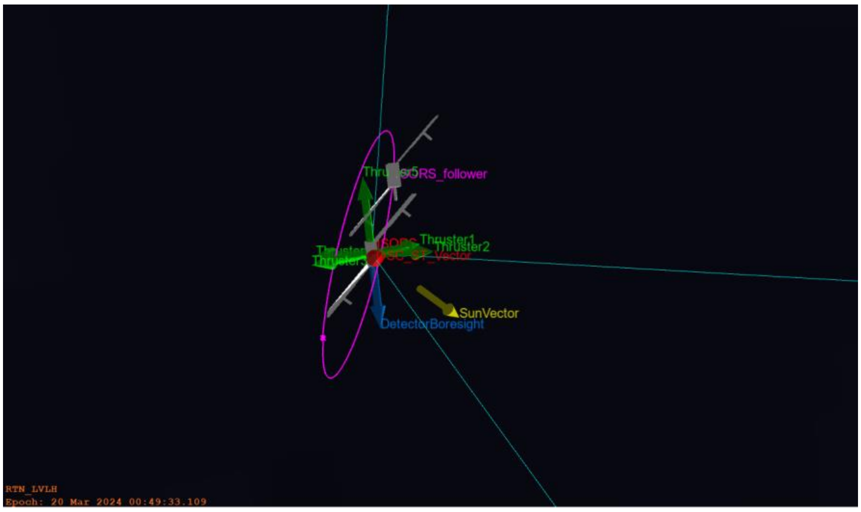


Fig.5 Relative view in the RTN_LVLH reference frame – 20 Mar 2024 00:49:33.209

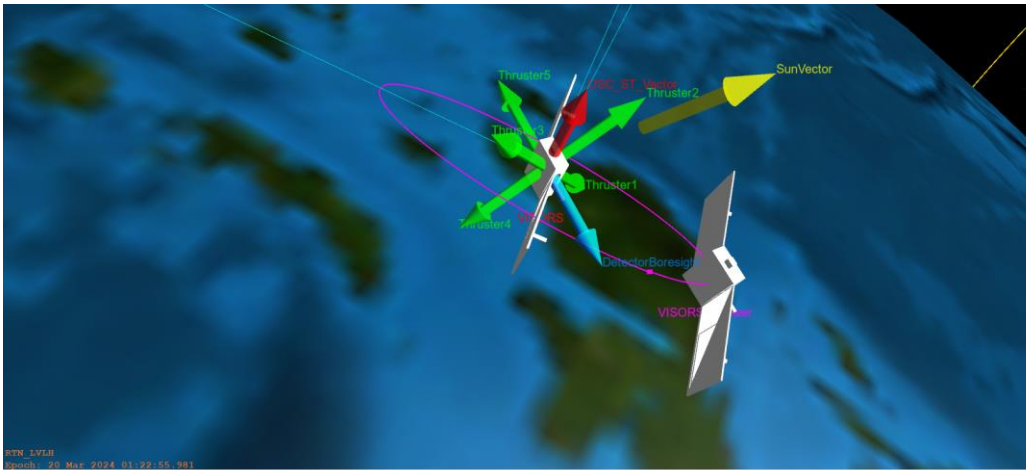


Fig.6 Relative view in the RTN_LVLH reference frame – 20 Mar 2024 01:22:55.981

This first simulation allows to visualize the trajectory and the behavior of the depute in relation to the chief. It can be noted that in the body fixed reference frame linked to the chief CubeSat, the depute presents an "eight" trajectory whereas in the LVLH reference frame the relative motion with respect to the reference CubeSat corresponds to an elliptical trajectory.

This simulation also highlights another problem of the mission. It allows to visualize the orientation of the depute in relation to the chief at each moment of the trajectory. Indeed, the position of one in relation to the other is important to ensure the communication between both spacecrafts. The chief presents 6 antennas, oriented along the positive and negative x, y and z axes. Depending on the relative position of the depute, the visible antennas will be different, and some positions will be more relevant than the others for the mission. We will study these profiles and the visibility of antennas in the following sections.

2. *Standby mode*

On the waiting orbit, the trajectory profile will be unchanged in the two studied coordinate systems. We will see in the following section that only the distance between both spacecrafts will change. This parameter will not be relevant for the studied features in this report.

B. Study of the trajectory

In this second part, we will look at the trajectory of the depute relative to the chief in terms of position and velocity. The objective is to verify the behavior of the formation regarding the state of each spacecraft. To do that, I needed to retrieve the state values of the CubeSat at each step of the simulation. The first step was to write data in a text report and then, I have processed data with a MATLAB code to obtain the following plot. The analyze is done for both configurations and both coordinate systems.

1. Science mode

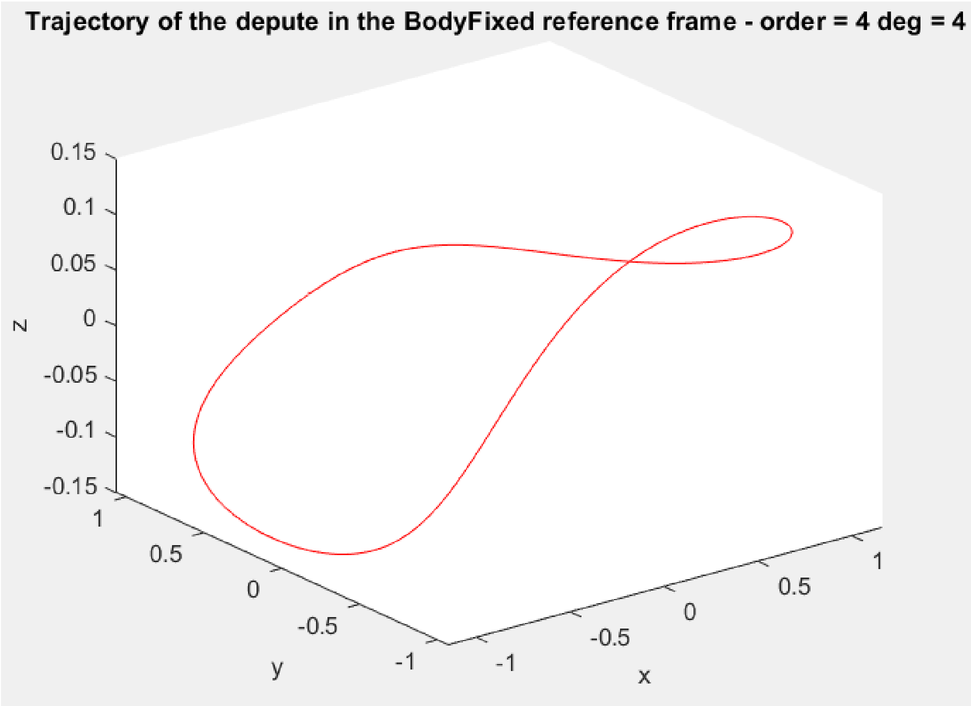


Fig.7 Plot of the trajectory in the BodyFixed reference frame in science mode

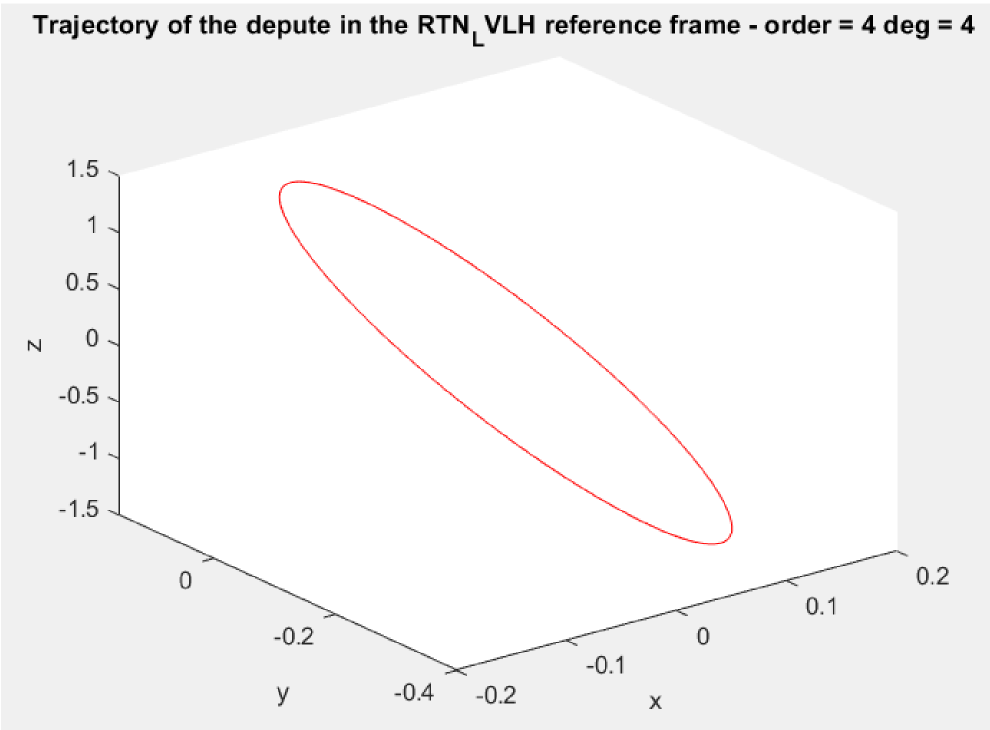


Fig.8 Plot of the trajectory in the LVLH reference frame in science mode

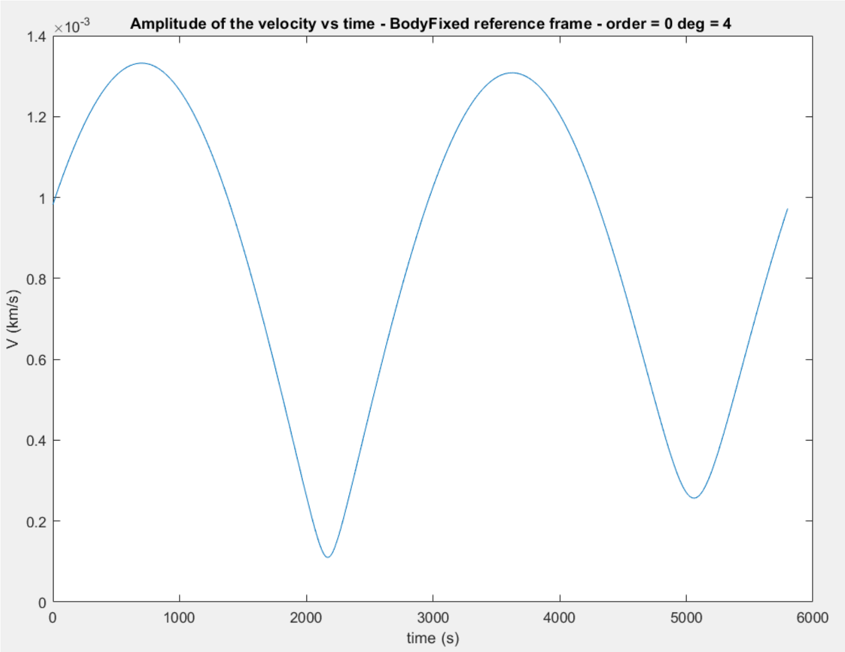


Fig.9 Velocity of the depute in regard to the chief in the BodyFixed frame in science mode

From the above plot, we can see a variation of the relative velocity of the second spacecraft with respect to the first one as a function of time and therefore as a function of the position of depute on its elliptical trajectory (Fig.8). This observation allows to highlight that the risk of collision between both spacecrafts can be evaluated in a more or less severe way according to the position on the different parts of the orbit. This severity study will not be conducted in this report but may be the subject of a future risk analysis.

2. Standby mode

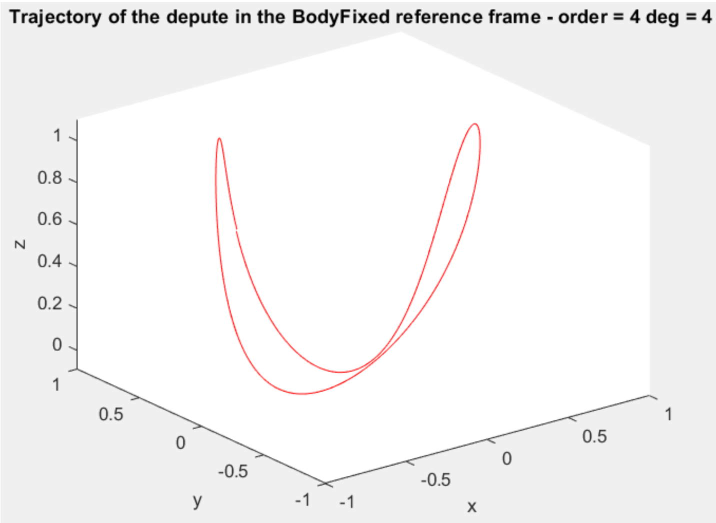


Fig.10 Plot of the trajectory in the BodyFixed reference frame in standby mode

The figures presented in this section will serve as a reference for the following section where we will evaluate the influence of two parameters of the force model on the trajectory. We note that the profile remains similar in science and standby mode as the “eight” profile in the body fixed reference frame. We can just note a variation in the position values.

C. Influence of the force model

In this part, we will study the influence of the force model on the trajectory of the formation. The objective is to begin a study to bring closer the simulation to the reality. Adding the second CubeSat to the simulation could slightly modify trajectories. In this way, it seems relevant to adjust the force model we use to bring precision to the simulated trajectories in GMAT. Firstly, we will only focus on the influence of the gravity model. In this report, we will only study differences bring by modifying the order and degree under gravity. This parameter allows to change “the representation of the Earth”. As an example, an order and degree forced to 0 will represent the Earth as a point mass. The parameters come from the definition of the spherical harmonics that are special functions defined on the surface of a sphere to describe this one.

These functions take their simplest form in Cartesian coordinates, where they can be defined as homogeneous polynomials of l in (x, y, z) that obey Laplace's equation. More precisely, we call the Laplace spherical harmonics Y_l^m, the function that can be visualized by considering the "nodal lines", that correspond respectively to the set of points on the sphere where $Re[Y_l^m] = 0$, and alternatively where $Im[Y_l^m] = 0$. Nodal lines of Y_l^m are composed of ℓ circles: there are |m| circles along longitudes and ℓ−|m| circles along latitudes. Then, considering Y_l^mas a function of θ, we can determine the ℓ−|m| nodal ‘lines of latitude’ and considering Y_l^mas a function of φ, we can determine the |m| nodal ‘lines of longitude’ [4].

When the spherical harmonic order m is zero, the spherical harmonic functions do not depend upon longitude and when ℓ = |m|, there are no zero crossings in latitude. In GMAT, we are currently using the *DefaultProp* model, which is initially configured to use Earth as the central body with a nonspherical gravity model of degree (m=0) and an order of 4. We will change these values and look at the trajectory of the formation. The different cases are:

Order	Degree
4	4
0	0
0	4

Tab.2 Force model parameters

The results with MATLAB did not reveal a significant influence of the variation of order and degree on the trajectory of the spacecrafts for a duration of one relative orbit. A future study could consist in adjusting the other parameters of the force model used in the simulation to evaluate a possible influence.

D. Power analysis

In the previous report, some results have been presented for the power generation in standby and science attitudes over one nominal orbit. Based on the following figures, we will complete this study of power generation with respect to the argument of latitude. Then, as supposed before, we will also consider a full orbit study starting from the orbit's node on the night side of Earth. We note a maximum panel generation capability of 72W, and the solar panels are directly normal to the Sun.

The following figures highlight the influence of one of the orbital elements on the energy generation profile of the solar panels in standby and science mode. The power generation is evaluated for the nominal case with a RAAN equals to 329.56 degrees for the chief, and two other cases at *RAAN = 290.5°* and *RAAN = 359.5°*. The code used for this study is based on the power generation code developed by my classmate. I have added the second CubeSat and complete the necessary features.

1. Science mode

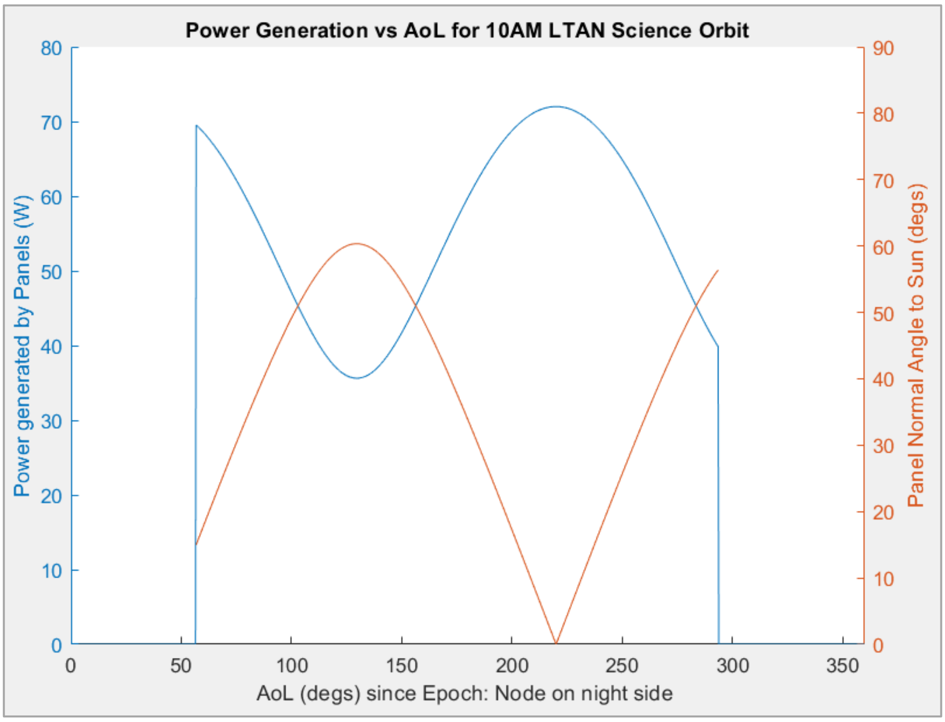


Fig.11 Science orbit power generation for a RAAN of 329.56° (nominal case)

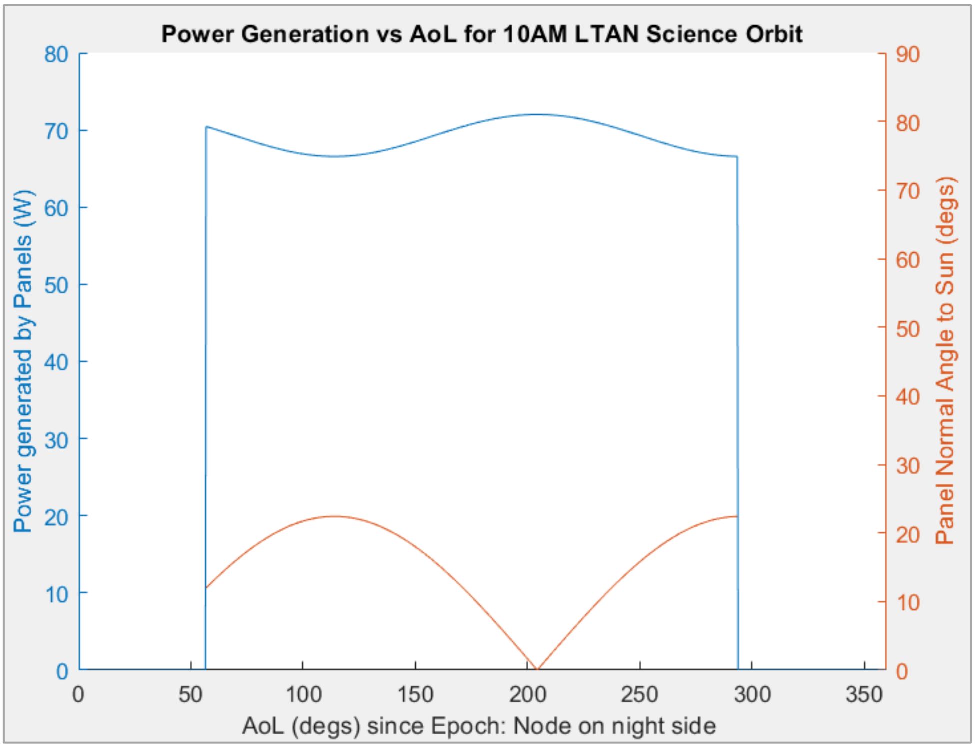


Fig.12 Science orbit power generation for a RAAN of 290.5°

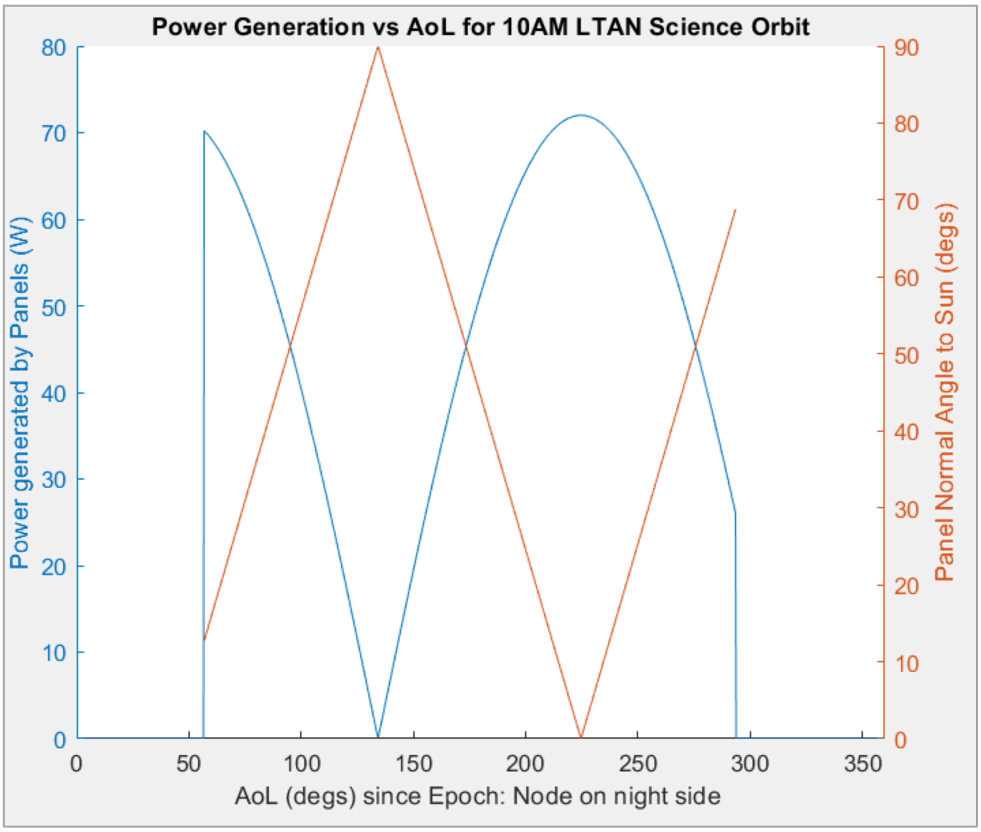


Fig.13 Science orbit power generation for a RAAN of 359.5°

2. *Standby mode*

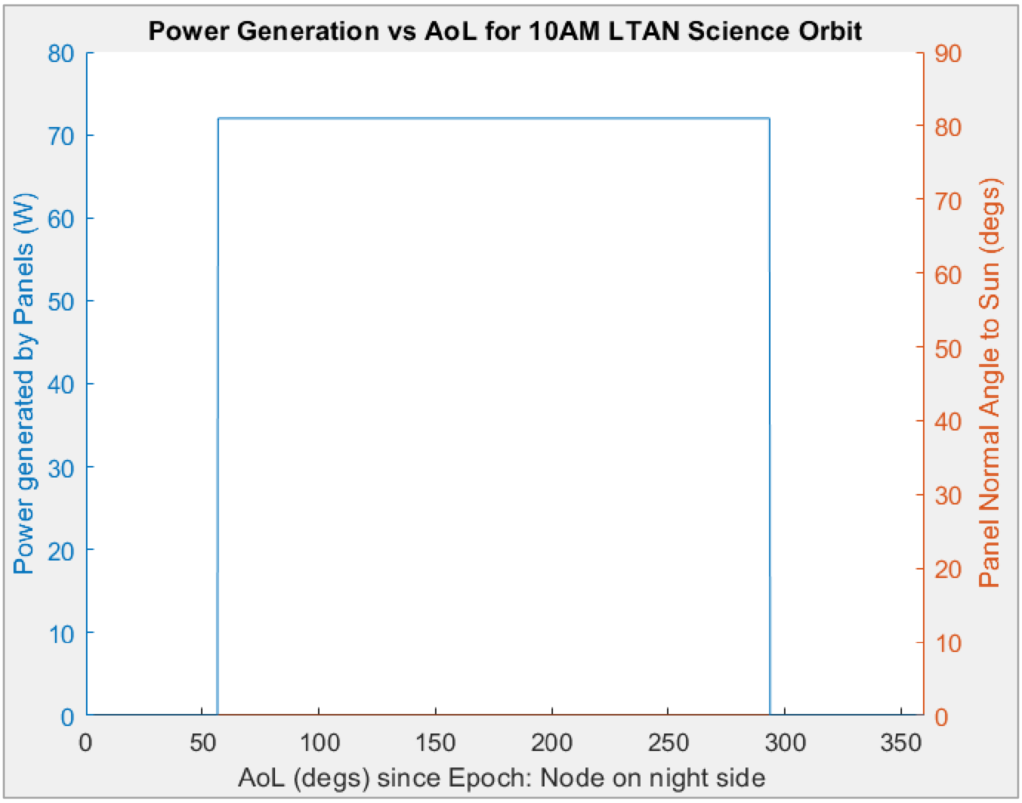


Fig.14 Standby orbit power generation for a RAAN of 329.56° (nominal case)

3. *Results*

The power energy generation results are shown in the table below for both attitude profiles:

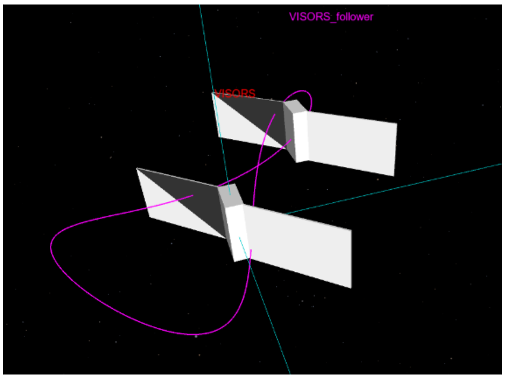
Attitude profile	RAAN (chief)	Max of power (W)	Min of power (W)	Average power (W)
Science mode	359.5	**72**	**0**	**47.4**
	329.56	**72**	**35.6**	**55.5**
	290.5	**72**	**66.5**	**69**
Standby mode	All cses	**72**	**72**	**72**

Tab.3 Power generation results for nominal orbit for both attitude profiles

The results presented in the table above, based on the study of the previous figures, allow to highlight the influence of the RAAN on the power generation profile of the solar panels. Indeed, this variation has an influence on the trajectory and thus on the position of the two spacecrafts with respect to the sun vector. However, we note that this difference is only valid in science mode. In standby mode, the chosen orbit allows a constant power generation as shown in Fig.15.

We can also note that the power generation profile is different from that presented in the previous report for one given RAAN. Indeed, the addition of the second CubeSat makes the sun vector exposure profiles evolve. We note here the importance of such a simulation to validate the features of the mission.

Finally, depending on the RAAN value chosen in science mode, we note that the min, max and average values of power generation vary. We can associate to each of these values, a trajectory profile given on the following figures:



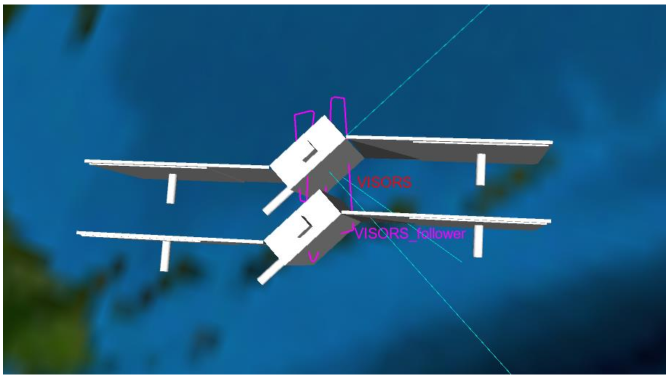


Fig.15 Attitude profiles for RAAN = 290.5° (right) and 359.5° (left) in science mode

One will notice that for a RAAN of 359.5°, the relative trajectory of the depute with respect to the chief seems chaotic and that this profile is not possible for the mission.

For the case where the RAAN is equal to 290.5°, we find a relevant and plausible profile. However, the trajectory is not "symmetrical" as in the nominal case (329.56°) and this difference could have an influence on other characteristics, notably studied in the following section which can make this value less relevant.

This study allows us to confirm the value chosen for this orbital element at this stage of the mission development.

E. Contact with antennas

This last part will focus on the problem highlighted in the first part. We will study the visibility of the leader's antennas by the deputy according to the position of the latter with respect to the former.

To do that, the reports used for the trajectory part will be reused here. For each position (x, y, z) of the depute, we evaluate the value of the cosine of the angle between the two vectors (position vector and the unit vector representing the orientation of the antenna) and its sign. Indeed, we consider that an antenna is visible from the depute when the angle between the two vectors is less than 80° and the sign of the cos is positive (to eliminate the cases where the angle is valid but the depute is "on the other side" of the studied antenna). The limit value of 80° for evaluating the visibility of the antenna may be varied in a future analysis to adjust the risk margins. Indeed, the communication between the CubeSats is possible with only one antenna seen from the depute, but we have one on each side of the chief (6 in total) to have a security margin in terms of communication. These antennas mainly allow to communicate GPS signals.

With a MATLAB function, I was able to recover the results presented in the table below. They show the percentage of visibility of each antenna for a relative orbit of the depute.

Antenna	Percentage of visibility
1	49.7847
2	50.2153
3	35.6589
4	64.3411
5	50.1292
6	49.8708

Tab.4 Visibility per antenna

It can be seen that not all antennas are equally visible during the orbit. The trajectory of the depute relative to the chief shows that some antennas are "more important" since they will be solicited more often for data transfer.

In the following figure we evaluate the inverse variable which corresponds to the number of visible antennas for each of the depute positions. We will observe that each position allows to visualize 3 antennas simultaneously. The relative positions of the satellites allow for redundancy of the systems and therefore for the safety margins taken for the communication between the CubeSats.

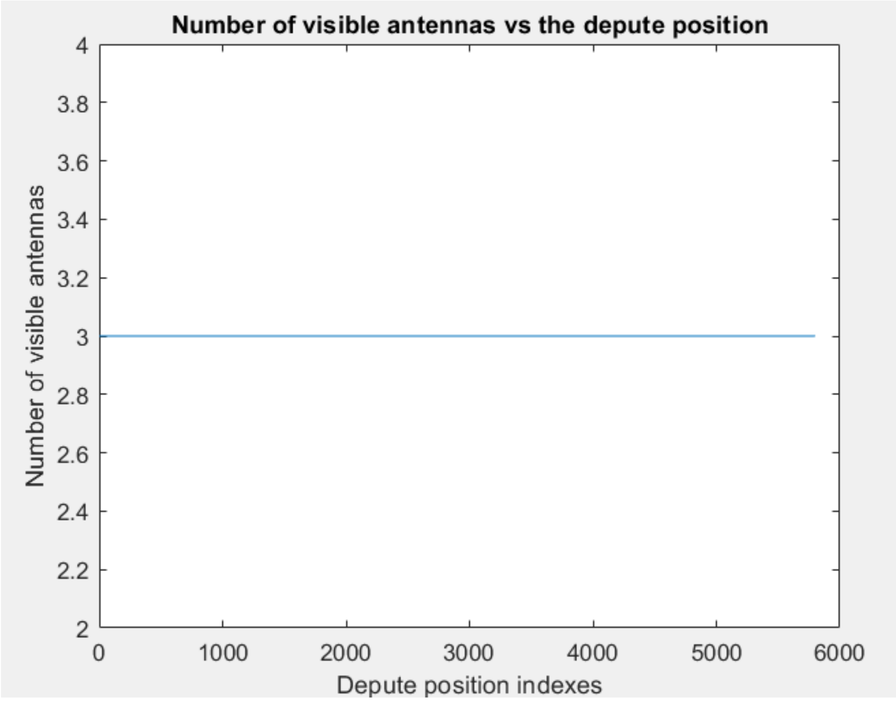


Fig.16 Number of visible antennas vs discrete positions

Finally, the last figure summarizes the last two results. Indeed, it can be shown that for each discrete position evaluated, we always have 3 antennas in view and that some antennas are more often visible than others.

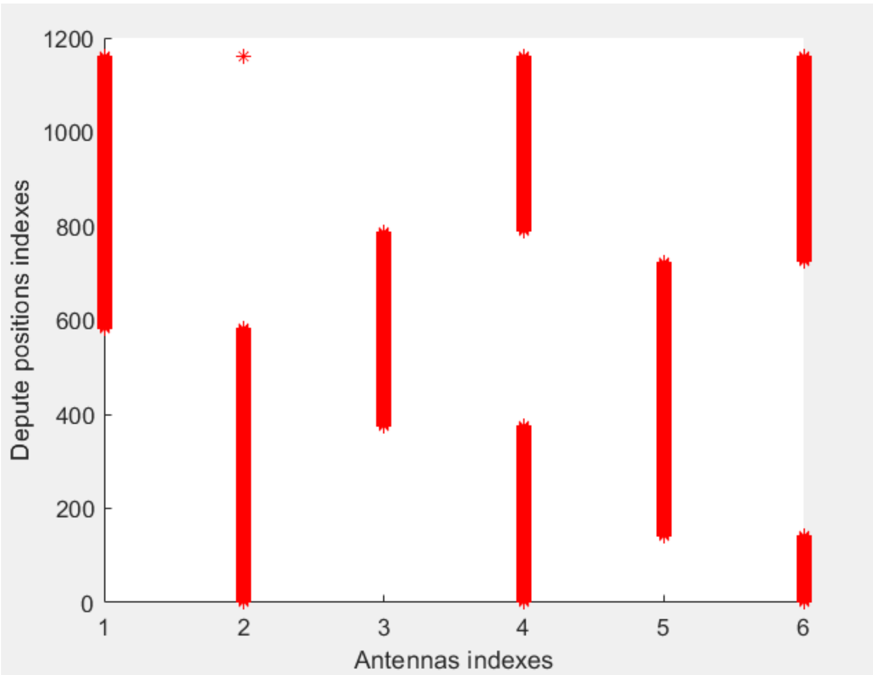


Fig.17 Distribution of the visible antennas on the relative orbit

VI. Results

This study provides an overview of the mission. The results allow to verify the global functioning of the system. More precisely, we were able to study the behavior of the two CubeSats of the formation in a simulation involving both of them simultaneously.

Firstly, we were able to visualize the relative trajectory performed by the depute with respect to the chief in two different coordinate systems. This allowed us to highlight some challenges such as the communication between both spacecrafts in flight or the possible collision issues depending on the relative velocity. We were also able to test the influence of the force model used so far in the study.

Then, the report focused on the study of power generation by solar panels. We have highlighted the differences brought by the addition of the second CubeSat to the simulation as well as the influence of the RAAN orbital element.

Finally, the last section allowed us to verify the hypotheses that had been made about the communication between the spacecrafts. We were able to show that all 6 antennas of the chief are sufficient to ensure the data transfers with a sufficient safety margin without affecting the service continuity.

More generally, this report was a verification of the whole system completing the GMAT simulation initiated by the project teams.

VII. Conclusion and future works

This study contributed to the VISORS project of the NSF, which includes a dozen American universities. The study of the simulation of the orbits of the two CubeSats in simultaneous makes it possible to check the viability and the reliability of the mission in progress. Even if the independent orbits of the two spacecrafts had already been used as a test for the study of the attitude of the formation, the analysis of the power and the contact with the ground stations; it was essential to add a complete simulation which gets a little closer to the real mission in order to validate the formation and the relative behavior of both spacecrafts.

The mission is scheduled for 2024. Until then, other simulation tests will be performed. Some parameters and models will be refined to be even more faithful to the real case.

VIII. Personal conclusion

This research project allowed me to realize the importance of each step of a space mission study. I had the chance to take part in the VISORS project, which brings together several important universities. I understood the importance of the communication between the different work teams. Each one brings its expertise and allows to realize a considerable work to propose a unique space mission. It was a real challenge to take part of a such program for three months regarding the duration of the project. Indeed, it was not easy to find a place in the project for such a short period of time, especially since I was mainly working alone or remotely with my main reference student, Antoine, who helped me a lot during these last months in order to complete the projects ‘objectives for the mission.

I had to take a moment to understand correctly the stakes of the mission, of the project itself as well as a moment to apprehend the work already done and the objectives to reach during these few months of work. This project also allowed me to deepen my technical knowledge. Indeed, I had the opportunity to learn and use the space mission simulation software GMAT, developed by NASA and to use MATLAB. The biggest difficulty encountered during the project was to learn the software and to appropriate the code developed by one of my classmates in order to continue his work.

I enjoyed finishing my master’s degree at Georgia Tech on a such project. The technical knowledge and skills required for this study were an extension of the education I received in my course.

IX. Acknowledgements

I would like to thank Dr. Lightsey, for being my advisor for my two semesters at Georgia Tech. Thank you for your teachings and willingness to pass on your knowledge with passion to your students.

Thanks to Antoine Paletta, for being an excellent mentor on this project. Thank you for your precious help, for all the theoretical and technical knowledge you brought me.

X. References

[1] CONCEPT OF OPERATIONS FOR THE VISORS MISSION: A TWO SPACECRAFT CUBESAT FORMATION FLYING TELESCOPE, E. Glenn Lightsey, Ebenezer Arunkumar, Elizabeth Kimmel, Maximilian Kolhof, Antoine Paletta, William Rawson, Shanmurugan Selvamurugan,a John Sample,b Tommaso Guffanti, Toby Bell, Adam Koenig, Simone D'Amico,c Hyeongjun Park,d Douglas Rabin, Adrian Daw,e Phil Chamberlin,f Farzad Kamalabadig.

[2] GMAT Attitude, Power, and Ground Pass Analysis Report, Antoine Paletta.

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[4] https://en.wikipedia.org/wiki/Orbital_node