Mission analysis for a remote sensing CubeSat mission over the Amazon rainforest

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This paper describes a mission analysis process used to explore and assess mission feasibility of a CubeSat satellite class which main objective was to take images of the Amazon rainforest for later deforestation analysis. The presented process shows what could be expected, its limitations and how to improve its results. Some analyses were performed through simulations using Systems Tool Kit (STK) and General Mission Analysis Tool (GMAT) software. The process consists of lifetime, payload performance and CubeSat-ground station communication link analyses. The CubeSat parameters used for calculations and simulations came from specifications found on a commercial CubeSat website, while ground segment input parameters came from the Aeronautics Institute of Technology's (ITA) Ground Station specifications. It was assumed that orbit was not designable, thus orbital position parameters were derived from the International Space Station's (ISS) orbital elements, considering the in orbit injection will take place there. Then, January 1st, 2018, was aimlessly chosen to extract ISS's orbital parameters. Results show that the payload performance fulfills the mission objectives, however, limitations on the transmission data rate limit the number of pictures that can be sent from the CubeSat to the ground station making unfeasible to fulfill objectives. One solution for this limitation could be the use higher frequencies that allow transmit at higher data rate. However, this would require using the state-of-the-art transmission equipment and would increase the size of the CubeSat. Another solution could be to adjust mission objectives in order to reduce the area of interest. Results also showed that if the altitude of a CubeSat deployment from the ISS could be chosen, then, it is better to choose the highest altitude. This would increase the CubeSat lifetime (up to 2 months) and bring advantages for radio accesses affecting very little the payload performance.

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Introduction

The Systems Concurrent Engineering Laboratory (LSIS) of the Laboratory of Integration and Testing (LIT) of the Brazilian National Institute for Space Research (INPE) has functions such as explore concepts and propose viable solutions for complex systems as satellite systems. Due to one of its recent projects, the AESP14 CubeSat, the LSIS has begun to offer nanosatellite consultancy services. [1]

As an exercise to explore concepts, assess mission viability and develop a mission analysis process tailored for CubeSats for its use in the LSIS, it was proposed the study of a remote sensing CubeSat mission over the Amazon rainforest. In order to have all the inputs for mission analysis, some previous assumptions were taken following the Space Mission Analysis and Design (SMAD) process [2].

The Amazon rainforest was the subject chosen due to its world importance as “lungs of the world” and the concerns about global warming that have been growing in recent years. [3]

Objectives of this hypothetical mission were simplified to taking images in the visible spectral range for later deforestation analysis.

As mission concept, the CubeSat was thought to be launched from the International Space Station (ISS), orbiting around the Earth while taking images every time that subsatellite point is over the Amazon rainforest and the target region is illuminated by the Sun (since camera was assumed as optical). Simultaneously, every time that the CubeSat has radio visibility with the Aeronautics Institute of Technology’s (ITA) ground station, located in São José dos Campos, Brazil, the CubeSat is expected to send real-time transmission or on-board stored images. Subsequent mission operations with the received data by the ground station were considered outside of the scope of this paper. In addition, it was assumed that the CubeSat was launched using the Nanoracks, a small satellite deployment system from the ISS. This deployment system launches CubeSats at a separation velocity of 1.1 - 1.7 m/s with a deploy direction angle of 45 degrees from nadir to ISS aft axis [4]. Taking into account that the ISS is maneuvered periodically to keep an altitude between 385 and 425 km [5], there were considered two scenarios. The first scenario represented the case when deployment occurred at a 385 km altitude at perigee (the lowest altitude of ISS). The second scenario represented the case when deployment occurred at the highest altitude of the ISS (425 km at apogee). In both cases, separation velocity was assumed to be 1.7 m/s. These two cases would represent the worst and the best scenarios for the CubeSat mission in terms of lifetime, respectively. Other ISS’s orbital parameters as well as CubeSat and Earth’s ephemerides were obtained directly from simulators using aimlessly as date of deployment the January 1st, 2018.

In order to completely define the mission architecture to perform the mission analysis, the CubeSat platform and payload's parameters were taken from commercial CubeSats information available on the Internet, specifically from GomSpace's GOMX NanoEye CubeSat [6]. Additionally, it was considered outside the scope of this paper the communications architecture. The mission architecture is then summarized in Table 1.

	Mission architecture elements
Subject	Amazon rainforest
Payload	NanoCam C1U
Spacecraft bus	GOMX-Platform
Launch system	Nanoracks small satellite deployment system from ISS
Orbit	~ISS orbit (initially)
Ground system	ITA's ground station
Communications architecture	Outside of the scope
Mission operations	Outside of the scope

Table 1. Mission architecture elements.

With the proposed mission concept, main idea of this exercise was to perform mission analysis to assess the mission feasibility. Mission analysis refers to the process of quantifying the system parameters, the resulting performance, and how well the system meets its overall mission objectives [2]. Specifically, it was assessed the performance that a system composed by mission architecture elements of Table 1 would have performing the mission concept as described. Thereby, calculations aim to provide an order of magnitude of the required values and dimensioning. By doing this, it is known what should be expected by a real mission using this kind of technologies, concepts and architectures, so future missions with similar goals could use results found on this paper as a reference during mission design. In addition to results, the mission analysis process developed in this work could be used as reference for future works in the LSIS.

For developing the assessment, three aspects were analyzed for each scenario: the CubeSat lifetime, the payload performance and the CubeSat-ITA's ground station communication link. For lifetime analysis, it was studied how many days the CubeSat, in both scenarios, would last until decay. For the payload performance analysis, it was studied the number and duration of visibility accesses between the CubeSat camera and the Amazon rainforest, the number and duration of gaps between those accesses or passes, the number of images that should be taken during passes, the payload storage capacity and the camera ground sample distance (GSD) along its orbit. The ground sample distance (GSD) is the distance at which the sensor spatially samples the target

scene [5]. For the CubeSat-ITA's ground station communication analysis, it was studied the number and duration of radio accesses between the CubeSat and the ground station, the number and duration of gaps between accesses, the data rates that the CubeSat could deliver information at and then how many images could be sent during accesses.
All the information needed for those analyses was obtained by orbital simulations and optical mathematical calculations. For simulations, Systems Tool Kit (STK) [7] and General Mission Analysis Tool (GMAT) [8] software were used.
Next sections provide detailed information about the steps that were followed to perform the mission analysis, its results, a brief discussion of them, and finally some conclusions that were drawn.

Methodology

Methodology followed to develop this work is summarized in Figure 1. Starting from assumptions and conditions previously stated, the first task was to obtain the ISS's orbital parameters in January 1st, 2018. This was accomplished in STK by setting up a scenario starting at 00:00:00.000 (in the Gregorian Coordinated Universal Time, UTCG) on January 1st, 2018, and then importing the ISS from the satellites database. Orbital elements for the ISS according to STK by that date and time are shown in Table 2.

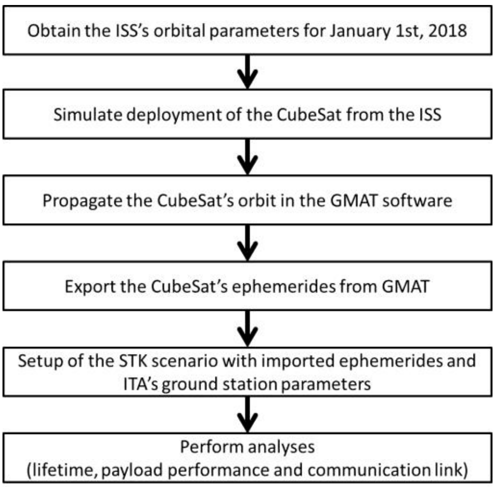

Figure 1. Methodology tasks summary.

Orbital element	Value
Semi-major axis (km)	6678.806
Eccentricity	0.001456
Inclination (°)	51.723
Right ascension of ascending node (°)	71.931
Argument of perigee (°)	123.166
True anomaly (°)	167.043

Table 2. ISS's classical elements on January 1st, 2018 (00:00:00.000 UTCG) accordingly to STK.

Considering that the equatorial radius of the Earth is 6378 km [2], the equivalent altitude of the ISS would be around 300 km (~291 km at perigee and ~310 km at apogee). Since the ISS has maneuver capacity and it is known that keeps an altitude between 385 and 425 km [5], the semi-major axis obtained by STK would not be completely accurate. This could be due to the fact that STK is possibly using input orbital parameters from satellites database and then propagating them to the date and time chosen without any considerations of maneuvers. To avoid that misleading result, an altitude of 385 km at perigee was selected for next calculations and simulations, which is equivalent to a semi-major axis of approximately 6772.861 km. This first scenario represented the lowest initial altitude for the CubeSat. Even when other classical elements could change with maneuvers from the values obtained by STK, they were kept as input. Change was made just to altitude since this classical element has a key effect on coverage, resolution and survivability [2], so it was considered as the most important for mission analysis. Second scenario was considered as the case where the CubeSat is deployed from the ISS at its highest altitude (425 km at apogee). For this second scenario, the only change in the orbital elements in comparison with the first was the semi-major axis. In this case, semi-major axis was calculated to be approximately of 6793.109 km.

Second task was to simulate the CubeSat deployment from the ISS. From ISS's initial classical elements, the deployment was simulated using GMAT software through a maneuver with a ΔV of 1.7 m/s in a direction angle of 45° from nadir to aft axis of the ISS [4], obtaining the injection orbital parameters. These parameters representing the CubeSat's initial classical elements after the deployment for both scenarios are showed in Table 3.

Orbital element	Scenario 1	Scenario 2
Semi-major axis (km)	6770.746	6790.984
Eccentricity	0.001740	0.001740
Inclination (°)	51.723	51.723
Right ascension of ascending node (°)	71.931	71.931
Argument of perigee (°)	115.815	115.806
True anomaly (°)	174.394	174.403

Table 3. The CubeSat's initial classical elements after deployment for both scenarios.

Third task consisted on the orbit propagation considering the atmospheric drag using GMAT. Atmospheric drag is the principal non-gravitational force acting on most satellites in low-Earth orbit. It slows the satellite and removes energy from its orbit. This reduction of energy causes the orbit to constantly get smaller until the satellite reenters the atmosphere. [9] Before the orbit propagation, the following parameters were chosen for the setup of GMAT software. Force model for gravitational field was set to Earth Gravitational Model 1996 (EGM96) rather than Joint Gravity Model 2 (JGM-2) since the first has replaced the last as a standard gravitational model [10]. Propagator was set to PrinceDorman78 since it is the best all purpose integrator in GMAT [11]. Drag coefficient of the satellite was set to its typical value of 2.2 [9] and finally the drag atmosphere model was set to Mass Spectrometry and Incoherent Scatter (MSISE90) since this is the one with the most complete information [12]. The result of this task was the obtainment of a file with the CubeSat's ephemerides.

Fourth task was to export the CubeSat's ephemerides from GMAT in order to be imported and used in STK in the next task.

Fifth task consisted on setting up the STK scenario by adding the CubeSat, importing the ephemerides that were created in GMAT, and adding the ITA's ground station. Parameters of ITA's ground station, such as latitude, longitude and altitude were obtained using Google Earth Pro, and a height above ground of 15 m was also assumed. Theoretically, the satellite can be observed from the horizon with respect to the ground station, however in practice an elevation angle of 15° is generally taken in order to take into account the effects of obstacles such as high buildings [13]. This value of elevation was considered for simulations.

Sixth task consisted on the execution of the lifetime, payload performance, and CubeSat-ground station communication link analyses. From results obtained by this task, a discussion was performed and then some conclusions were drawn.

Results and discussion

Lifetime analysis

When the CubeSat was assumed to be launched at the ISS's lowest altitude (385 km at perigee), simulations on GMAT showed that the CubeSat decayed approximately after 120 days (4 months) as can be seen in Figure 2.

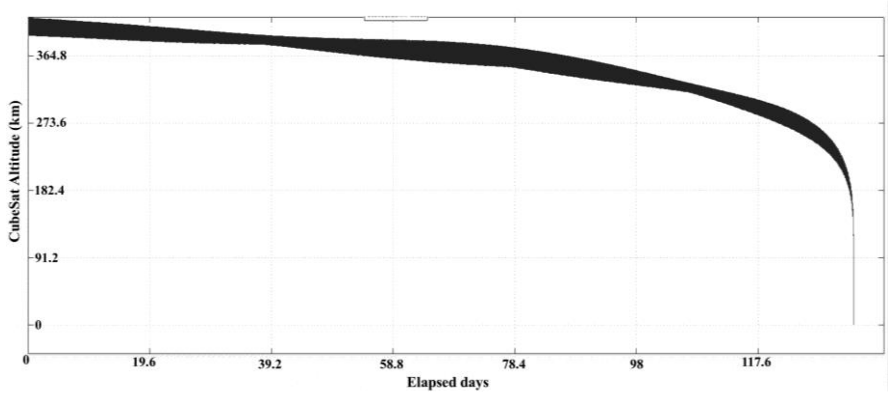

Figure 2. CubeSat altitude (*y* axis) against elapsed days (*x* axis) when initial altitude is 385 km at perigee.

On the other side, when CubeSat was assumed to be launched at the ISS's highest altitude (485 km at apogee), simulations on GMAT showed that the CubeSat decayed in more than 180 days (6 months) as seen in Figure 3.

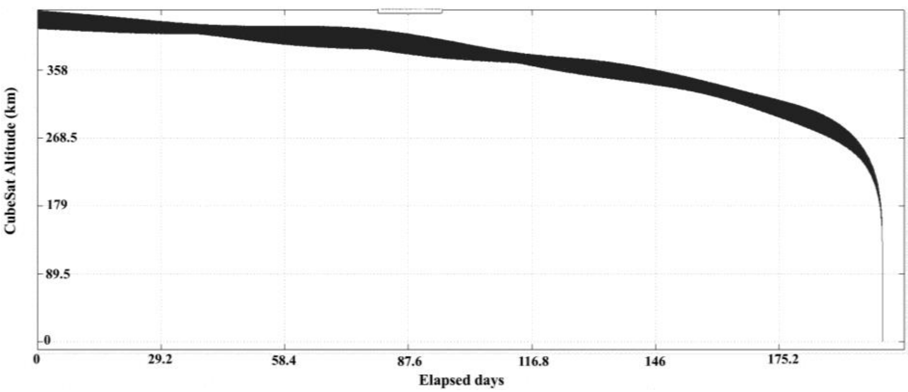

Figure 3. CubeSat altitude (*y* axis) against elapsed days (*x* axis) when initial altitude is 425 km at apogee.

From lifetime analysis results, it can be seen that launching the CubeSat when the ISS is on its highest altitude increases the mission lifetime in approximately two months.

Payload performance analysis

The NanoCam C1U payload is a Complementary Metal–Oxide–Semiconductor (CMOS) sensor. CMOS sensors have been the trend in CubeSats as they consume less power and can be used for longer time in space in comparison with CCD sensors [14]. NanoCam C1U payload has nadir pointing capacity, 5° attitude knowledge accuracy and 10° attitude control accuracy [6]. This control accuracy would mean that the CubeSat could point outside of the area of interest during its orbit. However, it is expected to obtain some images over the area of interest due to the several passes that the CubeSat would have until decay. Further attitude analysis in order to confirm this hypothesis and know the actual pointing limitations were kept outside of the scope of this work. NanoCam C1U also provides a 3 MP color picture with a resolution of approximately 80 m/pixel from a 650 km orbit [6]. The previous information together with the focal length of the sensor (35 mm), allowed the calculation of its pixel pitch using the Equation 1 [15].

$$\frac{focal\ length}{Altitude} = \frac{Pixel\ Pitch}{Ground\ Sample\ Distance} \qquad \text{[Equation 1]}$$

Payload specifications are summarized on Table 4.

Parameter	Value
Number of pixels	3 MP (2048 x 1536)
Spectral band	RGB 400-1000 nm
Radiometric resolution	10 bit
Field of View	9 °
Pixel pitch	4.308 µm
Focal Length	35 mm
Frame rate	3 fps
RAM memory	512 MB
Solid state storage	2 GB

Table 4. NanoCam C1U payload specifications [16]- [17].

Knowing the altitude of the CubeSat, the pixel pitch and the focal length of the camera, the ground sample distance (GSD) was obtained using Equation 1. Figure 4 and Figure 5 show the camera’s GSD through the mission lifetime for first and second scenario, respectively.

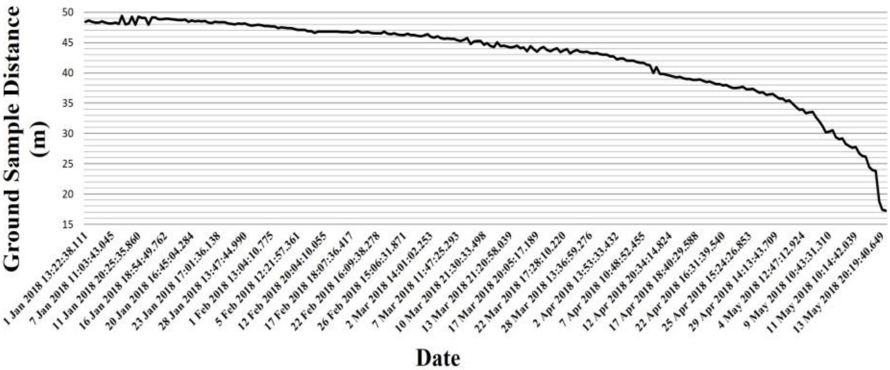

Figure 4. GSD against date when initial altitude is 385 km at perigee.

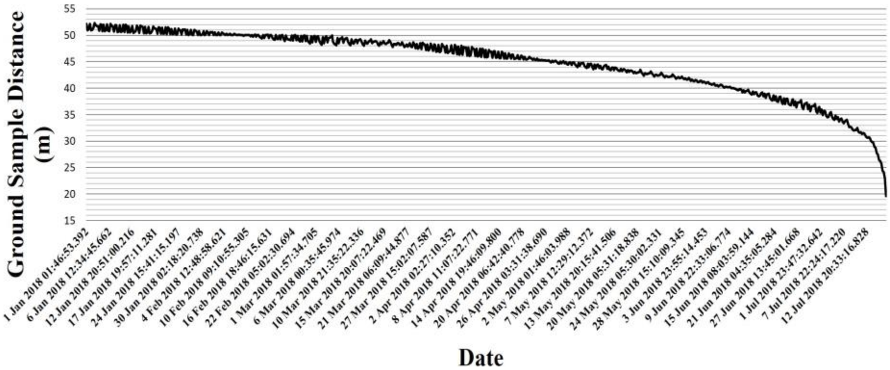

Figure 5. GSD against date when initial altitude is 425 km at apogee.

It can be seen that there was only a little difference among the values of GSD in both scenarios. GSD was approximately between 55 m and 30 m until the CubeSat decayed. This range of GSD would allow the discrimination between forest and non-forest areas, and also the identification of old and young woody secondary vegetation in the Amazon environment [18]. Then, preliminary results found up to this point showed that the mission objective, i.e. take images for later deforestation analysis, can be satisfied. However, they were not conclusive until the complete analyses were performed.

Other specifications listed in Table 4 were used as input for simulations in STK to obtain visibility access results. Accesses between the CubeSat payload and the Amazon rainforest in the lowest initial altitude scenario can be seen in Figure 6.

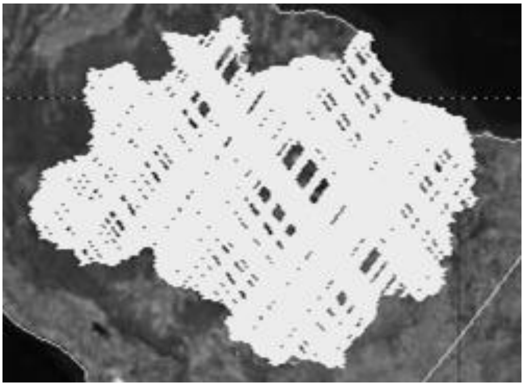

Figure 6. Accesses between the CubeSat's payload and the Amazon rainforest.

Figure 6 shows in white the areas that were scanned by the CubeSat and in black the areas that were not covered. Then, it can be seen that the Amazon rainforest was almost completely scanned using the CubeSat. The Amazon rainforest was covered mostly in the first two months, then, during the following months several of its passes were over some of the areas that were already covered.

In this first scenario, according to STK simulations, the NanoCam C1U payload had 244 accesses with the Amazon rainforest area. The longest access was of 6.74 minutes (approximately 400 seconds). In order to know how many images could be taken during these accesses, it was needed to calculate the frame rate of the camera. As Figure 2 and Figure 3 show for both scenarios, the CubeSat decayed constantly up to approximately 270 km, when it began to decay at quicker rates. Then, it was calculated the average altitude that the CubeSat had from its deployment up to 270 km. For the first scenario average altitude was 359.773 ± 36.619 km, while for the second it was 372.935 ± 41.915 km. These values allowed to obtain the average GSD for both scenarios (44.28 m and 45.10 m, respectively). Considering that the camera had 1536 pixel lines, the projection of the camera on the Earth's surface would be of approximately 68 km and 75 km. Next, it was calculated the speed that the projection of the camera would be moving at in order to know how many images should be taken by second. For this part it was assumed that consecutives images would not overlap and that the speed of the projection is much higher than the Earth's rotation speed, so the latter was neglected without affecting the order of magnitude of the results. This resulted on a frame rate of approximately 0.107 fps for the first scenario and 0.102 for the second.

Consequently, for the first scenario the CubeSat should take approximately 44 images to cover the Amazon rainforest during its largest pass. During the shortest pass that lasted 0.13 minutes (approximately 8 seconds) the CubeSat should take just one image. On average, the CubeSat lasted 3.43 minutes (205 seconds) over Amazon rainforest, equivalent to approximately 23 images per pass. On the other side, considering the number of pixels of each image and that the camera uses 10 bits for representing each pixel, then the size of each image was approximately of 3.9 MB (~31.4 Mb). The RAM memory of 512 MB was equivalent to 130 images, while the solid state storage of 2 GB was equivalent to 508 images. Consequently, using the RAM and the solid state storage, the total number of images that could be stored at the same time is 638. This would allow the CubeSat to store up to 20 consecutive passes's images. In addition to accesses, it was found that there were 244 gaps between accesses. The longest gap lasted 34.49 hours (almost 1.5 days) while shortest lasted only 7.2 seconds. On average, the CubeSat lasted almost 13 hours between passes over the Amazon rainforest.

In the second scenario, the NanoCam C1U camera had 700 accesses. The longest access was of 6.76 minutes (approximately 400 seconds), so 42 images should be taken during that pass over the Amazon rainforest. The shortest pass was of 0.06 minutes (almost 3.5 seconds) which would require the CubeSat to take just one image. On average, the CubeSat lasted 3.59 minutes (215 seconds) over the Amazon rainforest, equivalent to approximately 23 images per pass. In this scenario, using the RAM and the solid state storage would allow to store the images gathered from at least 23 consecutive passes. Simulations also showed 700 gaps between accesses. The longest gap lasted approximately 13.13 hours and the shortest 3.6 seconds. On average, the CubeSat lasted almost 6.78 hours (approximately 406 minutes) between passes over the Amazon rainforest.

Summarizing payload performance, it should be convenient to deploy the CubeSat when the ISS is at its highest altitude. Even when GSD and the average access time were very similar, deploying the CubeSat at the ISS's highest altitude would increase the number of access (directly related to the fact of increasing lifetime) and reduce the duration of gaps between accesses almost to the half. Major part of Amazon rainforest is covered in approximately two months, so up to this analysis, payload performance would satisfy mission objectives.

Ground station communication analysis

Data transceiver system of the CubeSat, according to its specifications [18], could downlink data to ground stations at data rates from 1200 bps to 9600 bps. In the scenario where CubeSat was deployed from the lowest initial altitude of the ISS, simulations indicated that there were 295 accesses from the CubeSat to ITA's ground station. The longest lasted about 5 minutes and the shortest lasted almost 30 seconds. On average, the duration of each access was 3.63 minutes. Considering the lowest data rate of the transceiver system (1200 bps) and that an image was represented by approximately 31.5 Mb (3.9 MB), then, less than one image could be sent over the longest access, specifically just a fraction of 0.012 of an image could be delivered. Consequently, for sending an image after taken, the CubeSat would require at least 112 consecutive passes to send one complete image. This number of passes represented approximately 45 days. With a data rate of 4800 bps, a fraction of 0.047 of an image could be sent during the longest access. Then, at least 27 consecutive passes would be required in order to deliver just one complete image. This is equivalent to 9 days that the CubeSat would require for sending one complete image. With a data rate of 9600 bps, a fraction of 0.094 of an image could be sent during the longest access. Then, 13 passes would be required at least to send one image. These 13 passes are approximately equivalent to 4 days.

It can be seen that limitations of fulfilling mission objectives appeared due to the transceiver limitations. While payload performance showed that the CubeSat is able to take several images during each pass, it would need several passes to download one image. Therefore, image coverage over Amazon rainforest would not be continuous during passes, so it would not look as shown in Figure 6. Then, there would be only images of some specific and small areas and consequently, mission objectives would not be accomplished. A solution to this problem would be to increase the data rates of the data transceiver system of the CubeSat. Another solution would be to change mission objectives in order to reduce the area of interest or to choose some specific and small areas of the Amazon rainforest as areas of interest.

In the other scenario where the CubeSat was deployed from the highest initial altitude of the ISS, there were 438 accesses from the CubeSat to ITA's ground station. The longest lasted around 5.4 minutes and the shortest lasted around 21 seconds. On average, the duration of each access was 3.9 minutes. Considering the lowest data rate of the transceiver system (1200 bps), a fraction of 0.012 of an image could be sent during the longest access. CubeSat would complete sending one complete image after at least 101 consecutive passes. This is equivalent to approximately 43 days. With a data rate of 4800 bps, a fraction of 0.050 of an image could be sent during the longest access. Then, the CubeSat would require at least 24 consecutive passes to completely deliver one image. This is equivalent to approximately 10 days. With a data rate of 9600 bps, a fraction of 0.099 of an image could be sent during the longest access. Then, it would be required at least 12 consecutive passes for sending one complete image. This is equivalent to approximately 4 days.

Similar than the other scenario, limitations of fulfilling mission objectives appeared due to the transceiver limitations. Again, the solution to this problem would be to increase the data rates of the data transceiver system of the CubeSat or to change the mission objectives to reduce the area of interest. The increase of data rates could be obtained using S-band transceivers. Common S-band transceivers increase the possible maximum data rate to 256 kbps [20]. This would allow the CubeSat to send 2.5 images and 2.6 images during the

longest accesses of first and second scenario, respectively. Even this number of images is not large enough compared to the number of images that could be taken during each pass over the Amazon rainforest. To provide higher transmission rates at S-band (up to 10 Mbps) or X-band (up to 500 Mbps), the satellite must be scaled up into a larger satellite [21].
Link budget analysis was also performed using the AMSAT-IARU link model [22]. For both scenarios, links closed with enough margin using specifications of CubeSat antenna [23] and transceiver [19] subsystems. Summary of these specifications can be seen in Table 5.

Parameter	Value
Modulation	Minimum-shift keying (MSK)
Transmitted Power	2 W (33 dBm)
Antenna Type	Canted Turnstyle
Antenna Gain	2.0 dBi
Data rate	9600 bps
Link Frequency	437.425 MHz

Table 5. CubeSat’s antenna and transceiver subsystem specifications.

Conclusions

Simulations performed showed that a CubeSat mission for remote sensing applications, such as deforestation analysis, has limitations on its data transmission rates for delivering a big number of images to a ground station. Even when optical performance of the payload could fulfill the mission objectives of taking several images over the Amazon rainforest, data transmission rates of common commercial CubeSats, such as the GomSpace’s GOMX NanoEye CubeSat, limit the number of images than can be transmitted to ground stations. Then, mission objectives requiring continuous coverage would not be fulfilled. This kind of CubeSats would only work in those cases which images over some specific points are required rather than over big areas. One solution to these limitations is to use transmission frequencies on the S-band or higher in order to use transmit at higher data rates. However, this would require using the state-of-the-art transmission equipments and would increase the size of the CubeSat. Another solution would be to adjust mission objectives in order to reduce the areas of interest or to choose some specific and small areas of the Amazon rainforest as areas of interest. For instance, an educational mission for obtaining images of the Amazon rainforest could not require a complete coverage so in this case, objectives could be satisfied. Furthermore, other solutions could be the use of a CubeSats constellation or the use of other satellites for the downlink of images.
Other results obtained by this work showed that if the altitude of deployment

of a CubeSat from the ISS could be chosen, then, it is better to choose the highest altitude. By doing this, lifetime could be increased up to 2 months and the number of accesses and average duration of each could be increased too affecting very less the payload performance.
Further studies should be performed regarding the pointing limitations since some of the areas that the CubeSat should cover according to simulations could not be covered in a real scenario due to its attitude control accuracy.

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