Location Based Payload Imaging

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***Abstract*—PISAT is a nano-satellite currently under development at PES University, Bangalore. It is an imaging satellite with the GOMSPACE Nanocam C1U as its main payload. It is three axis stabilized with active magnetic control system. Data reception and transmission is through S-band communication system. PES ground station has been commissioned exclusively for the purpose of communicating with PISAT. In the present configuration of PISAT, imaging can be carried out only during ground station visibility, which is for approximately 15 minutes. The dedicated ground station being located at Bangalore, the satellite can thus capture images only over Bangalore in this current mode. However, it is desirable that PISAT be able to carry out imaging at any commanded latitude and longitude. This paper presents a method to add this capability of imaging anywhere by including a provision to estimate the time required to reach the desired latitude and longitude using Location-Based Payload Imaging.**

***Index Terms*—Nano-Satellite, Location based Payload Imaging Software, Nanocam C1U, Orbit Propagation, Time-Tagged Telecommands.**

I. Introduction

The design and development of small satellites like Pico and Nano satellites (with wet mass of $0.1-1$ kg and $1-10$ kg respectively) has been an emerging trend in recent times, as they possess numerous advantages over their heavier counterparts. Heavier satellites require larger rockets with greater thrust, which increases their cost. In contrast, smaller and lighter satellites require smaller and cheaper launch vehicles and can sometimes be launched in multiples. University related experimental research can also be achieved using miniaturized satellites [1].

Satellites usually require actuation systems, power systems, on-board control units, attitude control and communication and navigation systems. For the purpose of locating the satellite in space, GPS modules are commonly used in larger satellites because of the relative ease with which positional information is obtained. For example, SNAP-1 [2] is a nano-satellite that uses the GEC Plessey "Orion" GPS Receiver module, which consumes 1.98W of power with an antenna. Introduction of such modules becomes expensive in terms of cost, power and weight for miniaturized satellites and hence the necessity for additional software to estimate satellite position arises. In this paper, the development of Location Based Payload Imaging software using analytic type of Orbit Propagation model has been proposed.

PISAT is a custom designed, low cost, three axis stabilized imaging satellite with a pointing accuracy of $\pm 5^o$ about yaw, roll and pitch axis. It uses a 32 bit AVR microcontroller (AT32UC3A0512) as its On Board Computer (OBC). The brief specifications of PISAT are summarised in Table I.

PISAT uses an on-board TTC RF Communication system,

TABLE I
PISAT Specifications

Subsystem	Features
Payload	Gomspace NANOCam C1U: 3MP 10 bit color CMOS sensor, 2048 x 1536 pixels, < 80m / pixel resolution from 650 Km, FOV − 9.22 deg, I^2C communication, onboard compression capability of 6MB to 200KB.
Structure	254 x 226 x 181 mm, Al 6061, Custom made Cuboidal structure, 5 Kg of overall mass.
RF Communication System	Uplink frequency 2030 MHz and Downlink frequency 2240 MHz, Uplink FSK/FM modulation- 100BPS Data Rate Downlink BPSK modulation 10kbps, RF Package tested at source.
OBC Hardware & Software	High Performance 32 bit AVR32 RISC μC, Clock speed 12MHz, 64 kB Static RAM, 512 kB Storage (Flash Memory), Serial interface : I^2C, Payload : 400kbps, SPI IMU 600kbps, External data bus and Address bus, Analog interface : Supports nine temperature sensors, Supports Four Pi Sun Sensor (FPSS), voltage and current monitoring. Software Modular approach, ADCS, all interfaces to OBC, TM and TC is programmed
Ground station (S-Band frequency)	3.7m paraboloid antenna with Prime focus and Program tracking, Uplink : 2015 to 2125MHz, Downlink : 2200 to 2300 MHz.

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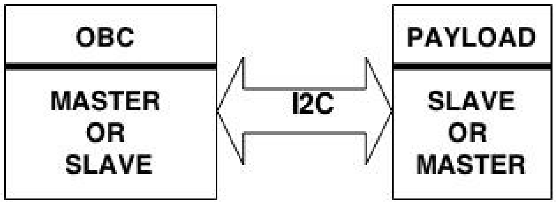

Fig. 1. Payload Interface

which is operated in the ITU specified S - band and facilitates command reception and telemetry data transmission. The payload is the GOMSPACE Nanocam C1U, which uses CSP (Cubesat Space Protocol) enabled I^2C Serial Communication Protocol to communicate with the OBC, as illustrated in Figure 1. [3]

The current configuration of PISAT allows it to image only during the visibility period. To explore the possibility of imaging at specified locations in the non-visible region, the technique of Location Based Payload Imaging has been developed. This process involves three major actions, which are detailed in this paper.

The first action is the on−ground estimation of the time at which the satellite traces a desired location, given its latitude and longitude as input. This is performed using Location Based Payload Imaging software which is detailed in Section II. Further, to perform the requisite payload operations at the desired time and location, the second action of utilizing time tagged telecommands is developed on-board. The design and execution of these commands is discussed in Section V. The final step involves the on−board storage of the captured image and its transmission to ground during the next visibility period.

II. Location Based Imaging Software Design and Development

If an image has to be taken over a location in California, for example, it is not possible to directly command the satellite to do so, as PISAT has no On-Ground command station in California. This software enables the capture of images at such locations, where it is not possible to command the payload directly from ground. This is achieved by predicting the time taken to reach the required location, and calculating the number of orbit counts after the current orbit taken by the satellite to reach it.

This section describes the need for non-visibility imaging of PISAT and the development of software to achieve the same. The design and implementation of this software are also discussed and its verification is illustrated at the end of this section.

A. Requirements

The software requirements are:

- Imaging should be possible during the non-visibility region.
- It should enable the satellite to capture images at any desired location.
- To predict time and orbit count of the desired location with the information of current time and orbit count of the satellite.

B. Design

The following section describes the selection of the modules that form a part of the Location-Based Payload Imaging software. This includes the choice of Two-Line Elements as the data format for passing positional information, and SGP4 as the orbit propagation model.

1) Two Line Elements: Positional information of the satellite is provided in the NORAD generated Two Line Element format. Each character or group of characters represents a different mean Keplerian orbital element of the satellite, as shown in Figure 2 [4]. This method of obtaining information about the satellite's position is advantageous as it is simple and free of cost. NORAD tracks all earth-orbiting bodies. As PISAT is yet to be launched, the following design and analysis sections are performed using the TLE files of satellites that are similar to PISAT in terms of orbital specifications. The two satellites used for the purpose of this paper are the Cartosat 2B (of the IRS) and HAMSAT.

2) SGP4 Model: Orbit propagation models use current positional information of the satellite and predict its motion over a period of time with a specified time step. They predict the path of a satellite, based on the forces affecting the motion of a satellite. The primary of these forces is gravitational attraction. However, to accurately predict the position of the satellite, additional perturbing forces or perturbations must be considered. For example, atmospheric drag contributes significantly to the motion of low-earth orbiting satellites.

The SGP4 model is one of the Simplified General Perturbations models, and the most commonly used. They apply for satellites having an orbital period of less than 225 minutes. [5] To reduce computations, certain simplifications are made in this model. In particular, the mass of the satellite relative to the mass of the earth is assumed to be negligible. In addition, the satellite is assumed to be in a low-eccentricity, near-earth orbit and not in a rapidly-decaying orbit.

The mean values for each element in a TLE file are generated using the SGP4 orbital model. The effects of the major perturbing forces are incorporated into these mean values

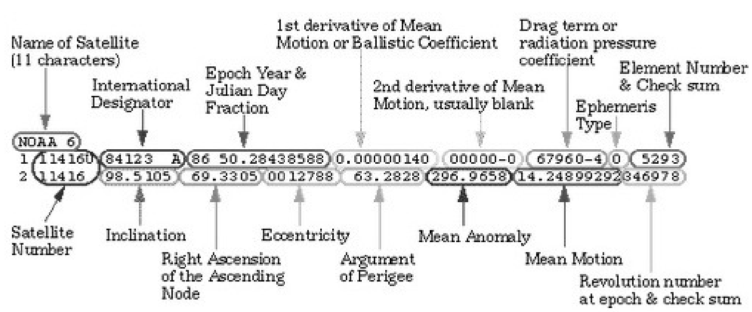

Fig. 2. TLE Format Example [4]

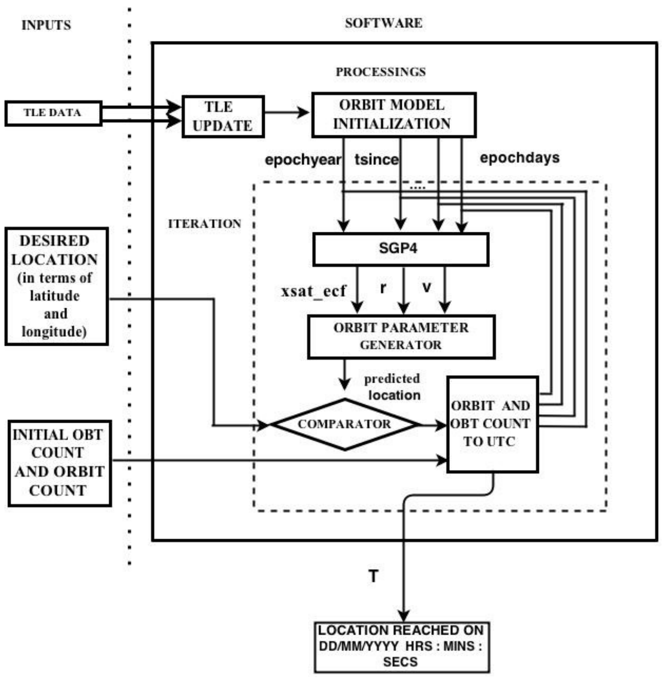

Fig. 3. Software Modules

in a very specific way using SGP4 and it must be used to generate accurate predictions. [6] In the case of SGP4, each element is perturbed, the newly perturbed TLE is initialized, propagated to the observation time, and any coordinate system conversions are performed. The difference between perturbed and nominal results is then taken. The SGP4 model has an error of approximately 1 km at epoch and grows at around 1 − 3 km per day.

C. Development

This section explains the modules used in the Location based Payload Imaging on-ground software. The module flow diagram of the software is shown in Figure 3.

TLE Update: This module considers the current TLE input file and decodes the required information as listed in Table II. **Orbit Model Initialization:** It considers the decoded TLE and initializes the other required variables during power-on initialization.

TABLE II
TLE PARAMETERS

Variable from TLE	Significance	Units
epochyear	Present Year	Years
epochdays	Day of the year and fractional portion of the day	Nil
bstartc	BStar Drag Term	Kgm2er
inclotc	Inclination	Degrees
nodeotc	Right ascension of node in deg	Degrees
eccotc	Eccentricity	Nil
argpotc	Argument of Perigee	Degrees
motc	Mean Anomaly	Degrees
notc	Mean Motion	Revs/day
ibexptc	Exponential Term of Bstar	Nil

SGP4 model: This is the orbit propagation function, which implements the SGP4 model. It takes data from the TLE as input, along with the time elapsed since the epoch. (tsince). It returns the position (r) and velocity (v) in km and km/sec respectively. The returned values are in terms of the three spatial coordinates x,y and z in the ECI (Earth centered Inertial) coordinate system. This system has its origin at the center of mass of the Earth. They can also be converted to ECEF (Earth Centered, Earth Fixed) frames, which remain fixed with respect to the surface of the Earth.

Orbit parameters generator: This function converts the positional data from Cartesian coordinates to declination and longitude format. As inputs, it takes the position and velocity in ECI system, and the position component of the ECEF system. As outputs, it gives declination, longitude, argument of perigee, inclination and true anomaly. Declination is comparable to geographic latitude, which, along with the longitude are used to compare the satellites location to the desired one.

Convert to UTC: This function converts the time from the count (in seconds or minutes, as specified) to UTC format.

Using these modules, the Imaging Time Prediction software takes the desired latitude and longitude as inputs, along with the current orbit count and On-Board Timer (OBT) count. It generates the time, in both UTC form as well as in terms of the number of OBT counts, taken to reach the desired location from the time of update of the TLE. It will also give the number of orbits from the current orbit taken to reach the location.

The main program calls the first two functions only once. Then, a loop is started, which continues till the desired location is reached. Within the loop, the SGP4 model function is called, incrementing the time step by 128 ms after each iteration. (128 ms is the duration of one major cycle on PISAT). The output of the SGP4 function is then converted to latitude and longitude. These values are then compared with those of the desired location. If found to be within the specified range of 0.25, then the propagation is halted and the time elapsed is converted to UTC format and displayed. Else, another step of propagation is carried out and the steps are repeated till a match is found.If the propagation time exceeds three days, it is stopped and the location is classified as 'not reached'.

D. Verification

Systems Tool Kit (STK) is the means used to verify the correctness of the time output of the software. It is a software package from Analytical Graphics Inc. that can be used to map the path of an Earth-orbiting satellite. The time and position information of the satellite can be obtained in the form of an excel sheet or text file containing time in UTC, Latitude and Longitude as shown in Figure 4. For verification purposes, the latitude and longitude at one instant are given as inputs to the main MATLAB program as in Figure 5. Figure 6 shows the time in UTC given by the main MATLAB program and is further used to compare with the output of the STK.

```
30 Sep 2014 23:09:52.000        -23.506      150.744
30 Sep 2014 23:10:52.000        -27.144      149.871
30 Sep 2014 23:11:52.000        -30.779      148.957
30 Sep 2014 23:12:52.000        -34.411      147.990
30 Sep 2014 23:13:52.000        -38.038      146.958
30 Sep 2014 23:14:52.000        -41.659      145.845
30 Sep 2014 23:15:52.000        -45.272      144.629
30 Sep 2014 23:16:52.000        -48.877      143.281
30 Sep 2014 23:17:52.000        -52.470      141.763
```

Fig. 4. STK Output Format

```
Enter the desired latitude
and longitude in degrees :
[-38.038 146.958]
Enter the orbit count0
Enter the OBT count0
USING 2-Line Elements:
1 36795U 10035A   14273.79158067
  .00000879  00000-0  12672-3 0  7239
2 36795 097.9316 331.1316 0015213
  359.7471 000.3733 14.78688200227824
```

Fig. 5. Input to MATLAB Program

```
Required location reached before Bangalore
30/9/2014 23:13:48.0259
Desired Location reached
Orbit count

obcount =

     3

OBT Count in seconds

obtcount =

      119027

Output OBT in form of UTC
30/9/2014 23:13:48.0259

TTcomm =

   1.5235e+04
```

Fig. 6. Output of MATLAB program

Using the TLE file of Cartosat 2B, the software was tested for various locations. It is observed that the results match with that of STK with an accuracy of ± 4 seconds, as summarised in Table III. In this way, the correctness of the software is verified.

III. PISAT Payload Details

PISAT OBC is designed to suit CubeSat specifications of GOMSPACE NanoCam C1U. It has a 3MP, 10 bit colour CMOS sensor with a frame rate of 12fps, giving a total capture time of 83.3 ms. The resolution is 2048 x 1536 pixels,

TABLE III
Results

STK Latitude and Longitude	MATLAB Latitude and Longitude	Time (STK)	Time (MATLAB)	Error in time (s)	Error in Position (km)
-50.748 1.294	-50.9965 1.3999	30 Sep 2014 22:00:52.000	30/9/2014 22:0:47.9939	4	28.623
62.413 29.446	62.6600 29.6313	1 Oct 2014 08:30:52.000	1/10/2014 8:30:47.9299	4	29.072
-49.093 165.730	-49.3414 165.8292	1 Oct 2014 11:00:52.000	1/10/2014 11:0:47.9939	4	28.554
-40.520 146.123	-40.2756 -146.0474	1 Oct 2014 18:43:52.000	1/10/2014 18:43:48.0899	4	27.929
-19.453 -110.707	-19.6980 -110.6522	2 Oct 2014 05:00:52.000	2/10/2014 5:0:48.1219	4	27.85
-75.894 -83.476	-75.8085 -83.2303	2 Oct 2014 12:45:52.000	2/10/2014 12:45:50.4579	2	11.622
37.656 -7.206	37.408 -7.1337	2 Oct 2014 21:30:52.000	2/10/2014 21:30:48.0579	4	28.313
48.348 132.988	48.5932 133.0836	3 Oct 2014 01:10:52.000	3/10/2014 1:10:48.0579	4	28.17
39.337 157.409	39.0891 157.4838	3 Oct 2014 10:30:52.000	3/10/2014 10:30:48.0579	4	28.317
-40.395 78.783	-40.6423 78.8602	3 Oct 2014 16:38:52.000	3/10/2014 16:38:48.0579	4	28.271

which gives an image coverage of 165 x 125 km, with a resolution of 80 meters per pixel. GOMSPACE camera is built around 210 MIPS processor with 32 MB on board RAM, 2GB solid storage and JPEG compression capability. The image can be stored in .jpg or .bin format, and is compressed to a size of 200kB from 6MB.For communication with the OBC, the Nanocam uses CSP enabled I^2C Serial Communication Protocol at 400kbps. GOMSPACE supports the commands as given in Table IV. Figure 7 depicts the various operating modes of the payload during the execution of the commands mentioned in Table IV.

TABLE IV
Payload Commands

Payload command	**Function**
Snap	To take a picture. A successful snap reply will output to the first 50 bytes of the received buffer. During this command OBC is in master mode.
Store	To store the just snapped picture to the internal memory the cam store <filename> command. During this command OBC is in master mode.
List	Returns data about the picture file requested for, which includes size of the file, format, base address (location on memory). OBC is the master and Camera is the slave during the write mode which later interchanges during the read mode.
Peek	Returns 119 bytes from the base address mentioned. OBC is the master and Camera is the slave during the write mode which later interchanges during the read mode.

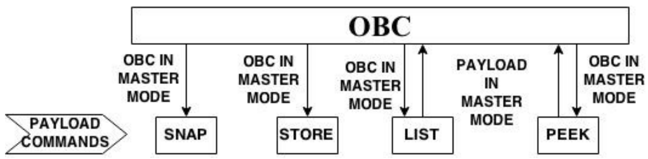

Fig. 7. Payload Operating Modes

A. *Payload Interface to OBC*

The payload - OBC interface is summarised in Figure 8. The present application of the software is performed using PISAT. This section provides the imaging details required to capture images during non visibility region.

1) Telecommand: Telecommand is the means by which the satellite is controlled from the ground station, and it facilitates the payload commands. Requisite information, be it an image captured by the payload, sensor information or housekeeping data, is stored in an external data card. This information in telemetered to the ground station accordingly.

Bit patterns of the telecommand are as shown in Figure 9. In the 100 bps FSK, the command length is 63 bits, and the frame duration is 630 ms. Once a command from the ground station reaches the OBC, it checks for the correctness of the command and raises the authentic pulse pin. Once this is raised, the microcontroller collects the 64 bits of command sent from the ground station, resets the authentic pulse pin, and starts processing the command.

2) Telemetry: Telemetry involves collecting housekeeping data about the space craft and transmitting it to the ground station. This includes health parameters such as the battery's current capacity, attitude information, temperature of subsystems, etc. A single frame of telemetry is 128 bytes long. The sampling rate is 0.1s when operated in real time telemetry and 1s when operated in either storage or payload telemetry. Frequency of transmission is 2240 MHz. Modulation scheme used is Binary Phase Shift Keying (BPSK) and the data transfer rate is 10kbps. A single frame, as shown in Figure 10. is formed every 128ms. Necessary data from data acquisition, attitude control system, Telecommand and payload are parts of real time telemetry. Of the 128 bytes in a frame, 9 bytes are used as 'FrameSync' bytes, thus giving an effective data length of 119 bytes.

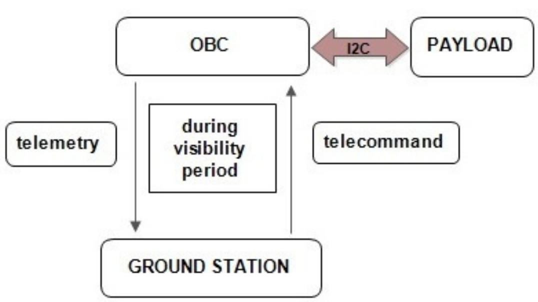

Fig. 8. Data Transmission and Reception

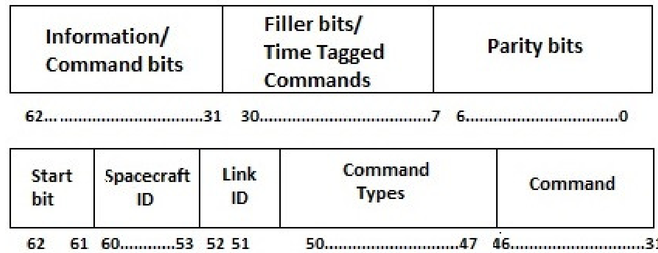

Fig. 9. Bit pattern of command

TABLE V
FUNCTIONS FOR PAYLOAD IMAGING

Command	Function
rTCCAMSnap()	Captures an image
rTCCAMStore()	Stores the image according to the specified name and compression technique (JPEG).
rTCCAMList()	Retrieves image size and base address which is used while executing the peek command.
rTCCAMPeekEnable()	Retrieves data from camera (depending upon the image size) starting from the extracted base address from list.
rTCCAMSnapToListEnable()	Executes snap, store and list command one after the other.
rTCCamDownloadCmdON()	Downloads an image from the camera.

IV. OBC DESIGN FOR IMAGING

The existing Telecommand and Telemetry interface is used to carry out imaging. Table V lists the commands supported by the payload.

These telecommands are provided to the OBC to perform basic imaging operations. An additional mode of telemetry provided is Payload Telemetry - it is the data coming from the payload. After every 9 frames of payload data, 1 frame of real time TM is transmitted, as shown in Figure 11.

V. TIME TAGGED COMMANDS FOR NON-VISIBLITY IMAGING

To increase the efficiency of imaging capability, PISAT is now provided with a provision to perform imaging at non-visibility period using the GOMSPACE NanoCam C1U Payload. This is achieved using time tagged telecommands. The

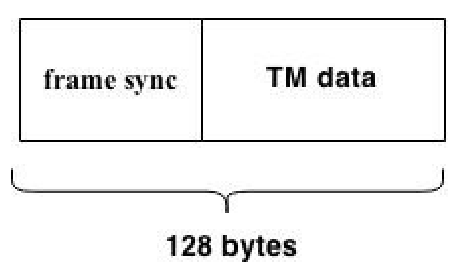

Fig. 10. Real Time Telemetry

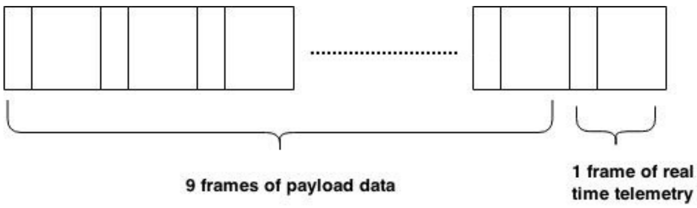

Fig. 11. Payload Telemetry

time taken to reach the desired location is now known from the software and can be utilized to make the satellite carry out imaging at exactly that location. Time tagged commands have an additional field indicating that the command must be executed with a certain delay.
A snap command is uploaded at the ground station, with a time tag equal to the length of time required to reach the desired location from the ground station. When this is done, the snap command is executed when the satellite reaches the required location, thus providing imaging even in the non-visibility region. Bits B7 to B30 of the Telecommand are used for time tagging. The OBC stores the Telecommand in a queue until the required time and then executes it. This can be utilised for imaging in the non-visible period by feeding in the time required for the satellite to reach the desired location in terms of OBT count. The format for the time-tagged commands is as given in Figure 12.

For a specific case of latitude and longitude -38.038 and 146.958 (near California) respectively, the OBC count obtained was 119027 as can be seen in Figure 6. in Section II D. Camera should be turned ON 10 seconds before the satellite reaches the location. 10 seconds is equivalent to 78 OBT counts. Camera should be turned OFF after 10 minutes to ensure the image is captured and stored. Equivalent OBT count for 10 minutes is 4688. This count should be uploaded in Hexadecimal format.
Camera ON: DBC455DC1D81C
Auto Payload: DBC455FC1D86A
Camera OFF: DBC455E01EABA

VI. Conclusion

This paper addresses the design, development and verification of the Location Based Imaging software. This software is implemented for non visibility imaging of PISAT. PISAT is designed as an imaging satellite for Remote Sensing applications of pico and nano satellites. Although these satellites have faster orbital decay, shorter working life and reduced hardware carrying capacity, they are still used when cost and weight become major constraints to design. The detailed requirement for On-board imaging is dealt with in this paper, which includes telemetry used for monitoring purposes. The On-board provision for Time-Tagged Telecommands in Non-visibility imaging is discussed in detail in this paper. This software can be used in other satellites that have size, power and cost constraints, thus GPS modules for tracking purposes. The major inputs to the software are the TLE data and latitude and longitude of the desired location. Additionally, the initial orbit count and OBT count can be mentioned to calculate the orbit number and OBT count at which the location is reached. The output of this software gives us the time the satellite takes to reach the desired location. It is seen from the verification that the software provides results with an accuracy of ± 4s. As PISAT is magnetically controlled and has a pointing accuracy of $\pm 5^o$, a drift of approximately 25km results. Given the constraints in the design and control of a low cost student satellite, this drift is considered acceptable.

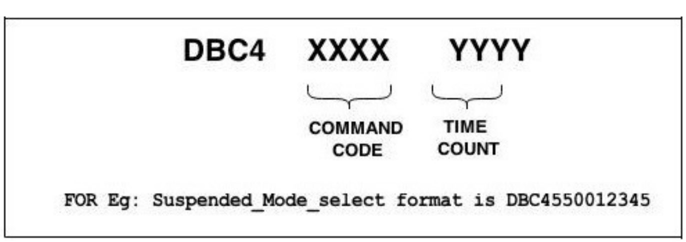

Fig. 12. Time Tagged Command Format

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