Application of GNSS CORS in Earth Observation Satellites Ground Station Selection and Control for Nigeria Space Programme

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Abstract

In order to maximize global scientific collaboration on the utilization of data products from NigeriaSat payloads, there may be need to have additional ground stations in Nigeria, across Africa, Asia and Europe, etc. Ground station network is the means by which satellites stay in contact with the Earth, through which data reception and satellite controls are realized. The Global Navigation Satellite System (GNSS) Continuously Operating Reference Station (CORS) Infrastructure in Nigeria and IGS around are relevant in the site selection, data facility evaluation and EOS tracking/control of the Nigeria satellites payloads. The study used the GNSS CORS data of February 2010 and the Two Line Element (TLE) set of NigeriaSat-1 (N-1) Orbit to make sky visibility analysis for EOS ground Station selection in Nigeria and the trend analysis of N-1 orbital behavior for a period of seven years (1st January 2004 – 1st January 2011). The optimized DOP values of majority of the eleven stations were consistently poor (well above 4) between the hours of 10:20-11:00GMT and 13:10-14:00GMT respectively, but with mean values ranging between 2.4 and 3.2 (i.e. $2.4 \leq DOP \leq 3.2$). This technique is only one of many supporting technical and logistic criteria for ground station selection using GNSS-based LEOS tracking and control. NigeriaSat-1 showed a total orbital angular drift of about 00° 19' 03" of arc (equivalent to about 34. 29km, about 4.3km/year), towards the earth pole between 27th September 2003 and 27th September 2010. The eccentricity of the Orbit ellipse of the NigeriaSat-1 was slightly unstable and irregular in September 2004, which might have resulted in in-ordinate imaging of same ground area or swath on the earth during the period. The TLE set analysis shows that the N-1 Coefficient of Drag was small; hence not subjected to extreme vertical and lateral drag in orbit, which may not be unconnected with its light weight/mass of 98kg (micro-satellite). For sustainability of the Nigeria Space programme, periodic monitoring of the NigeriaSat-2 and NigeriaSat-X orbital status with the TLE set from the on-set of launch and completion of in-orbit callibration is imperative. This is because their weights/masses are quite higher than than that of N-1; hence would be more susceptible to drag in orbit. Secondly, due to periodic and sudden changes in space weather that could cause some orbit and altitude pertubations on the spacecrafts.

Key Words: GNSS, EOS, GCS, NigeriaSat-1, Orbit Inclination, Eccentricity

1.0 INTRODUCTION

Ground Control Station Network is the means by which satellites in space stay in contact with the Earth. Operators at the ground stations send commands to correct the satellites' trajectories, maneuver them into different orbits, and operate their instruments. The satellite transmits back to Earth not only the scientific data that it is gathering, but also the 'housekeeping' information needed by the operators to check the satellite's performance (ESA, 2008). The types of control necessary for earth observation satellites include those of orbit, attitude, pointing for observation instrument, thermal, telemetry, communication, command, and electric power (ERSDAC, 2010). With the rapid advancement in the technologies of Earth

Observation Satellites in low Earth orbit, the ability to precisely predict the position and velocity of the satellite is extremely important.

The ground station of an Earth Observation Satellites (EOS) system consists of all of the communicating earth stations which access the operational satellite. The ground station's job is two-fold, transmitting and receiving. In the case of transmitting, the terrestrial data in the form of baseband signals is passed through a baseband processor, an up-converter, a high-powered amplifier, and through a parabolic dish antenna up to an orbiting satellite. In the case of a receiving station, it works in the reverse fashion as the transmitting, by converting signals received through the parabolic antenna to baseband signal. The mission data acquired by the ground station from a spacecraft are transferred to the data users along with any telemetry and tracking information the data users may need for general house or station keeping. The basic functions of GCS include among others; *telemetry tracking and control support, satellite orbit determination and monitoring, general station keeping, satellite payload management* and *in-orbit test (IOT).* One of the strategic ways of monitoring the Orbit of an EOS is the use of TLE for velocity, *orbit inclination, eccentricity and coefficient of drag variation analysis.*

The need to obtain a precise orbit with sparse tracking data and the need to be able to accurately propagate it so that it can be used for the scheduling of instruments and ground station operations were important for the selection of the estimation algorithm and force modeling. When GPS observables had to be incorporated in the software, those suited for batch estimators must be used. The option would be to obtain processed baseline and navigation results using double differences of ionospheric free carrier phase and double difference pseudoranges.

Dow et al (1994) suggested that measurements with GPS observables should be implemented for pairs of ground stations, in order to improve the GPS satellite orbits or for geodesy, and for orbiting receiver/ground station pairs, in order to obtain precise orbits of the satellite carrying the GPS receiver. Most modern satellites utilize space-borne GPS receivers as primary navigation sensors, which allow positioning accuracies to the decimeter level due to the high precision of GPS carrier-phase measurements (Hauschild, 2008; ND). The determination of TLE sets are enhanced by GPS observable and receivers on Earth Observation Satellites, whose orbit attitudes are subsequently tracked, monitored, propagated and modeled.

1.2 Developments in the TLE Propagation Models

The equations-of-motion of an Earth Observation satellite such as NigeriaSat-1 and NigeriaSat-2 are usually described in an inertial reference frame as being composed of a sum of gravitational, non-gravitational and empirical or un-modeled forces (Rim and Schutz, 2002). The five mathematical models for predicting the satellite position and velocity include SGP, SGP4, SDP, SGP8 and SDP8 (Hoots and Roehrich, 1980; Kelso, 1998). The SGP, being the first to be developed by Hilton & Kuhlman (1966) and is used for near-Earth satellites like NigeriaSat-1. This model uses a simplification of the work of Kozai (1959) for its gravitational model and it takes the drag effect on mean motion as linear in time; assuming a quadratic variation of mean anomaly with time. The drag effect on eccentricity is modeled in such a way that perigee height remains constant (Hoots and Roehrich, 1980). Subsequently, the SGP4 model was developed by Ken Cranford in 1970 (Lane and Hoots 1979) and is used for *near-Earth satellites*. This model was obtained by simplification of the more extensive analytical theory of Lane and Cranford (1969) which uses the solution of Brouwer (1959) for its gravitational model and a power density function for its atmospheric model (Lane, et al. 1962).

The SDP4 model was later developed as an extension of SGP4 to be used for deep-space satellites (Hujsak, 1979). The SGP8 model is used for near-Earth satellites and is obtained by simplification of an extensive analytical theory of Hoots which uses the same gravitational and atmospheric models as Lane and Cranford did but integrates the differential equations in a much different manner (Hoots, 1980). The fifth model, the SDP8 is an extension of SGP8 meant for deep-space satellites.

1.3 Statement of Problem

The ground control stations provides highly-accurate ephemerides *Earth-centered inertial (ECI) coordinates, satellite sub-point* (latitude, longitude, and altitude for non-spherical earth), *look angles* (azimuth, elevation, range, and range rate), and *right ascension and declination. The e*stablishment of ground receiving stations co-located in Nigeria, across Africa, Asia and Europe with that of NASRDA, Abuja for enhanced tele-commands and data transmission on the ground may be of priority in the near future. GNSS technology is one of the best tracking types for Precise Orbit Determination of Low Earth Orbit Satellites because it combines high accuracy with unsurpassed observability. The major application areas of GNSS in EOS Technology include:

i. Determination and Monitoring of Orbital Elements of EOS;
ii. Sometimes spacecraft fly in modes that are not so predictable, as when they are performing frequent maneuvers or when they are flying at very low altitudes. GNSSs are very well suited for the determination of these trajectories because of its continuous coverage and great accuracy;
iii. Another important application of GNSS is its use on relative or differential modes in order to compute the relative position of two spacecraft.

High accuracy in EOS telemetry tracking and control is guaranteed using the GPS carrier phase observable, free of ionospheric errors when dual frequency data is used. The unsurpassed observability is provided by the high number of GPS satellites than can be simultaneously tracked by an orbiting receiver (http://nng.esoc.esa.de/gps/onboard_gps.html; Cox et al, 2000).
Therefore, for ground station site selection analysis, telemetry tracking, orbit monitoring and control of the Nigeria Spacecrafts, GNSS CORS infrastructure in Nigeria, the *IGS* and GPS-based predicted TLE set are of great relevance.

1.4 Aim and Objectives of Study

The study aims at the application of GNSS CORS pseudo-ranges, baselines, navigation data, and software in ground station site optimization/selection and control of Nigeria's EOS system for present and future space programme. The objectives of the study include:

i. Using DOP Analysis of NigNet COR Stations to support location selection of Ground Receiving Antenna in Nigeria to be co-located with NASRDA's, in Abuja;
ii. Identification of favorable orbit ground track window for high telemetry and navigation signals for sitting Ground Receiving Stations between latitudes 15°S-48°N and longitudes 24°W-48°E;
iii. Use the TLE set of NigeriaSat-1 to evaluate and model its orbit inclination and eccentricity for 1st January 2004 – 1st January 2011;
iv. Identify other infrastructure requirements for sustainable EOS tracking, command and control in Nigeria

1.5 NASRDA's Ground Station Facility and Satellite in Orbit

The NigeriaSat-1 has two ground stations located in Surrey, UK and NASRDA, Abuja receptively. The satellite is routinely tracked by the two ground stations, with a satellite pass in about 4-5 satellites days interval. The integrated Ground Station Telemetry Tracking and Control (TTC) also consists of GPS Receivers (*onboard N-1, N-2 and N-X, and operated at the ground simultaneously*) to create reference frame of the satellite. Inertial Reference Unit (IRU) to record attitude variations (pitch, roll and yaw) of the platform for carrying out attitude corrections for the satellite orbit.

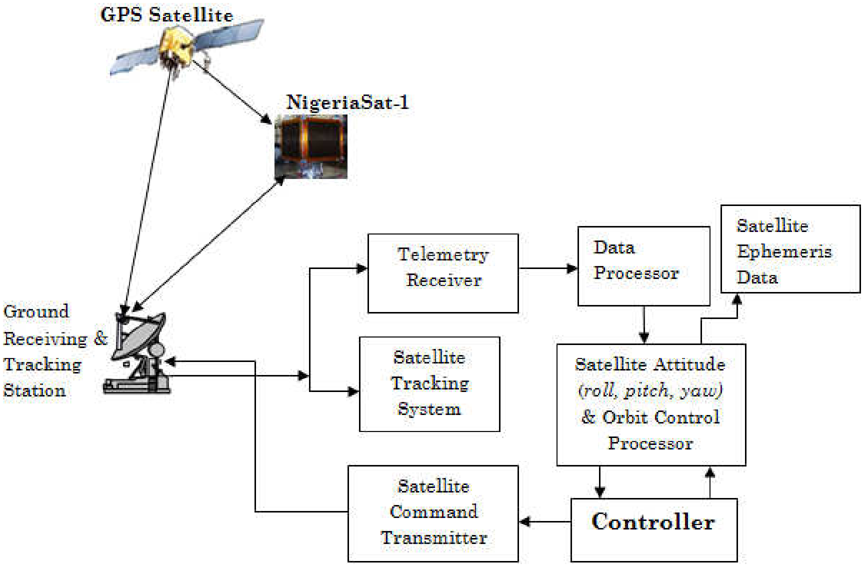


Figure 1.1: Model of Tracking and Control Functional Elements for the Nigeria Satellites and Ground Station Facility at NASRDA, Abuja, Nigeria.

The elements on the Mission Control Ground Station include the TTC antenna, telemetry receiver, command transmitter, tracking subsystem, and associated processing and analysis functions. Satellite control and monitoring is accomplished through monitors and keyboard interface. Major operations of TTC may be automated, with minimal human interface required. Parameters involved in typical command links include *changes and corrections in attitude control and orbital control, antenna pointing and control, transponder mode of operation and battery voltage control.*

1.5.1 Satellite Tracking Software

The Satellite Pass Update Program permits fully automatic processing of all of the TLE files without prompting, while the Pass Scheduler is a program which will allows for automatic generation of schedules of satellite passes from a set of pre-selected files of observation sites and NORAD two-line orbital element sets. *The schedule(s) generated is listed in order of increasing rise time and provides information such as satellite name, rise date, rise time, azimuth, elevation, time of culmination (maximum elevation), set time and visibility code*

1.5.2 NigeriaSat Hardware Infrastructure

The hardware infrastructure is comprised of the spacecraft (N-1,N-2 and N-X), the Ground Station Antennas (N1- & N-2), and Mission Control Ground Station *(Computers, Receivers, Transmitters, Thruster, Communication and Power control, etc).*

NigeriaSat-1, NigeriaSat-2/X are low earth orbit, sun synchronous satellites at orbit altitudes of 686km and 700km respectively. NigeriaSat-1 is a Camera-based multi-spectral system with sensors 3 spectral bands (RED, GREEN & BLUE) with images of 32 m GSD, while NigeriaSat-2 is also Camera-based; 2.5 m GSD panchromatic (very high resolution); 5.0m GSD (high resolution) in 4 spectral bands and 32 GSD also in 4 spectral bands (RED, GREEN, BLUE & NIR) (medium resolution).

Figure 1.2: (a) N1 GCS Antenna; (b); N2 GCS Antenna, (c) Mission Control Ground Station at NASRDA, Abuja, Nigeria

(i). NigeriaSat-1 *(ii) NigeriaSat-2* *(iii) NigeriaSat-X*

Figure 1.3: The NigeriaSat Engines (NigeriaSat-1, NigeriaSat-2 and NigeriaSat-X)

2.0 MATERIALS AND METHODS

2.1 Data Collection and Sources

The dataset collected include NigNet RINEX data for nine (9) COR Stations for February 2010 from the Office of the Surveyor General of the Federation (OSGoF), Nigeria, IGS Navigation Data and GPS-based predicted Two-Line Element (TLE) data generated for Disaster Monitoring Constellation Satellites by the North American Aerospace Defense Command (NORAD).

2.2 Description of NigNet CORS

The Nigeria Network (NigNet) of Continuously Operating Reference Stations (CORS) came into existence in 2008 and since then the number of stations have increased gradually to Eleven (11) as at April 2011. The CORS were established by the Office of the Surveyor General of the Federation (OSGoF). The eleven (11) NigNet COR Stations already installed and operational are located in: Abuja (OSGoF), Port Harcourt (RUST), Gembu (HATC), Lagos (UNILAG), Kebbi (WUFP), Zaria (ABU), Yola (FUTY), Enugu (UNEC), Calabar (UNICAL), Toro (CGG) and Maiduguri (RAMPOLY).

2.3 Description of NORAD Data Set

The North American Aerospace Defense Command (NORAD) is a United States and Canada bi-national organization charged with the missions of aerospace warning and aerospace control for North America. Aerospace warning includes the monitoring of man-made objects in space, and the detection, validation, and warning of attack against North America whether by aircraft, missiles, or space vehicles, through mutual support arrangements with other commands (http://celestrak.com/NORAD).

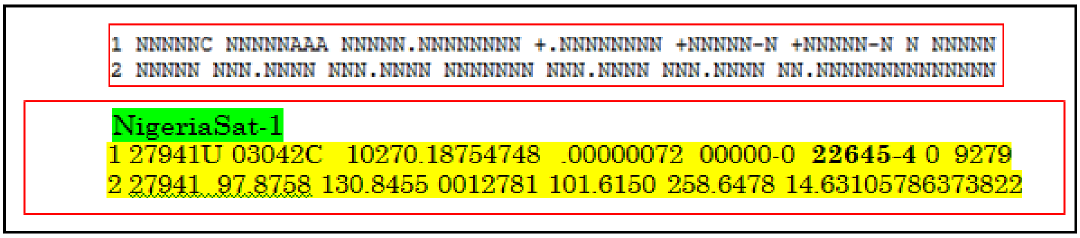
NORAD maintains general perturbation element sets on all resident space objects which are periodically refined so as to maintain a reasonable prediction capability on all space objects. In turn, these element sets are provided to users for propagating the element sets in time in order to obtain the position and velocity of the space objects. In order to obtain good predictions of the satellite positions and velocities, the periodic variations must be reconstructed in exactly the same way they were removed by

NORAD. The NORAD element sets must be used with one of the models used in its creation (*e.g. SPG4 and SDP4*), in order to retain maximum prediction accuracy (Hoots and Roehrich, 1980; Kelso, 1988, 1998, 2007)

2.3.1 NORAD Two-Line Element Set

A NORAD Two-Line Element (TLE) set consists of two 69-character lines of data which can be used together with NORAD's SGP4/SDP4 orbital model to determine the position and velocity of the associated satellite. Figure 2.1 shows the architecture of the TLE set and the valid number or sign characters for each column. Tables 2.1 and 2.2 define each of the individual fields for lines 1 and 2 of TLE set respectively.

The NORAD's Satellite Catalog (SATCAT) number is a unique identifier assigned to each earth-orbiting artificial satellite based upon when the object was first observed, whereas the International Designator is always tied to the original launch. For example, the Disaster Monitoring Constellation (DMC) launch of 2003 include **three (3) payloads** into orbit among others: NIGERIASAT-1 (Nigeria) UK-DMC (UK) and BILSAT-1 (Turkey), which were assigned International Designators 27941U, and 27942U and 27943U respectively, while their Satellite Catalog numbers were 27941, 27942, and 27943 respectively



```
1 NNNNNC NNNNNAAA NNNNN.NNNNNNNN +.NNNNNNNN +NNNNN-N +NNNNN-N N NNNNN
2 NNNNN NNN.NNNN NNN.NNNN NNNNNNN NNN.NNNN NNN.NNNN NN.NNNNNNNNNNNNNN
```

```
NigeriaSat-1
1 27941U 03042C   10270.18754748  .00000072  00000-0  22645-4 0  9279
2 27941  97.8758 130.8455 0012781 101.6150 258.6478 14.63105786373822
```

Figure 2.1: Two-Line Element Set Format

Table 2.1: Two-Line Element Set Format: Definition of Line 1

Field	Column	Description
1.1	01	Line Number of Element Data [**1**]
1.2	03-07	Satellite Number [**27941**]
1.3	08	Classification [**U**]
1.4	10-11	International Designator (Last two digits of launch year: [**2003**]
1.5	12-14	International Designator (Launch number of the year: [**042**]
1.6	15-17	International Designator (Piece of the launch: C)
1.7	19-20	Epoch Year (Last two digits of year: [**2010**]
1.8	21-32	Epoch (Day of the year and fractional portion of the day: [**270.18754748**]
1.9	34-43	First Time Derivative of the Mean Motion: [**0.00000072**]
1.10	45-52	Second Time Derivative of Mean Motion (decimal point assumed: [**0.0000-0**]
1.11	54-61	BSTAR drag term (decimal point assumed: [**$0.22645*10^{-4}$**]
1.12	63	Ephemeris type [**0**]
1.13	65-68	Element number [**9279**]
1.14	69	Checksum (Modulo 10) (Letters, blanks, periods, plus signs = 0; minus signs = 1)

Table 2.2: Two-Line Element Set Format: Definition of Line 2

Field	Column	Description
2.1	01	Line Number of Element Data [**2**]
2.2	03-07	Satellite Number [**27941**]
2.3	09-16	Inclination of the orbit (**i**): define the orbital plane in the equatorial system (measured in degrees to max. of 180°: [**97.8758**]
2.4	18-25	Right Ascension of the Ascending Node (Ω): *define the orbital plane in the equatorial system* (measured in degrees from 0° up to 360°: **[130.8455]**
2.5	27-33	Eccentricity (**e**): It is the deviation of the ellipse from circularity, define size and shape of the satellite orbit (decimal point assumed) [0<e<1]: **[0.0012781]**
2.6	35-42	Argument of Perigee (**ω**): *define the orientation of the satellite orbit* (measured in degrees from 0° up to 360°): **[101.6150]**
2.7	44-51	Mean Anomaly (**v**): *define satellite position in the satellite orbit* (measured in degrees from 0° up to 360°: **258.6478)**
2.8	53-63	Mean Motion (Revs per day: **[14.63105786]**
2.9	64-68	Revolution number at epoch (Revs): **[373822]**
2.10	69	Checksum (Modulo 10)

In aerodynamic theory, every object has a ballistic coefficient *(B)*, which is calculated as the product of its coefficient of drag (C_D) and its cross-sectional area *(A)*, divided by its mass *(m)* (*equation 1*).

$$B = \frac{C_D A}{m} \tag{1}$$

$$B^* = \frac{B\rho_o}{2} \tag{2}$$

B^* has units of (earth radii)$^{-1}$.

The ballistic coefficient represents how susceptible an object is to drag; the higher the number, the more susceptible. B^* (*equation 2*) is an adjusted value of *B* using the reference value of atmospheric density (ρ_o) (Kelso, 1998).

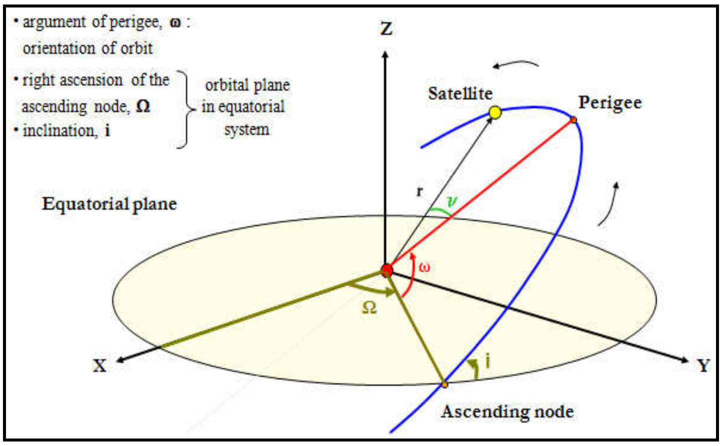


Figure2.2: Satellite Orbit Architecture and Keplerian Elements (Source: Ojigi et al, 2011)

In NORAD's convention, a revolution begins when the satellite is at the ascending node of its orbit and *a revolution is the period between successive ascending nodes*. The period from launch to the first ascending node is considered to be Rev 0 and Rev 1 begins when the first ascending node is reached.

2.4 GCS Site Selection Procedure with GNSS

The site slection was based on satellite sky visibility planning and dilution of precison. This is because signals from satellites behave in similar pattern in the atmosphere, so poor visibility in GNSS signal in a particular observation window translates relatively to poor orbit defintion signal for the EOS. The Ground elevation, geographical locations (coordinates) and time/season were used for the site slection procudure. Generally, the major factors for selecting ground receiving stations include geographic location, ground elevation, sky visibility, site stability, antenna diameter, power and communication facilities, security, Internet and data access, favorable climate, etc.

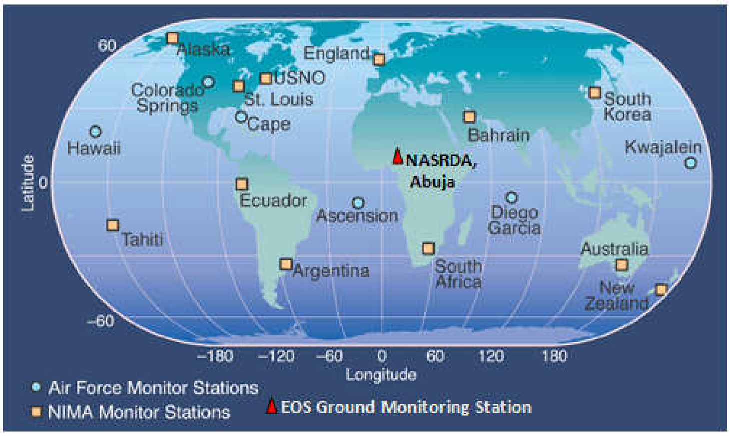


Figure 2.3: GPS Monitoring Stations, NIMA Tracking Stations across the globe and NigeriaSat Ground Monitoring Station ((Modified after Langer et al, 2002)

2.5 Orbit Evaluation and Modeling of NigeriaSat-1

The TLE sets generated by NORAD can be used to predict position and velocity of Earth-orbiting satellites such as NigeriaSat-1. Computation period for TLE-of NigeriaSat-1 spanned through 01-01-2004 to 01-01-2011. The Keplerian elements interpreted for analyses include orbit inclination angle (i), right ascension of the ascending node (Ω), eccentricity (e), argument of the perigee (w) and mean anomaly (v). The procedures used include data preparation, TLE propagation models, and analyses of the variation in *i* and *e* over the period of seven (7) years.

2.5.1 Data Preparation and Processing

The NigNet RINEX data for February 2010 were prepared and processed for interval of 10seconds. Fixed solution, ionospheric free computations and biased adjustment of the baselines and station coordinates were carried out using Trimble Total Control

Software. The TLE sets for seven years (2004-2011) were interpreted and prepared in a format that the Keplerian elements of the satellite orbit will be distinct. The satellite epoch (day of the year) which corresponds to the GPS Calendar day was used to filter and align the TLE set, 8-hourly data of September epoch for year 2004 to 2011. The month of September was chosen being the month of launch of NigeriaSat-1. An extension was made into 2011 with dataset for 4th May to 6th June in order to examine within month behavior model of the N-1 orbit. Line 2 of figure in this study consists primarily of mean elements calculated using the SGP4/SDP4 orbital model.

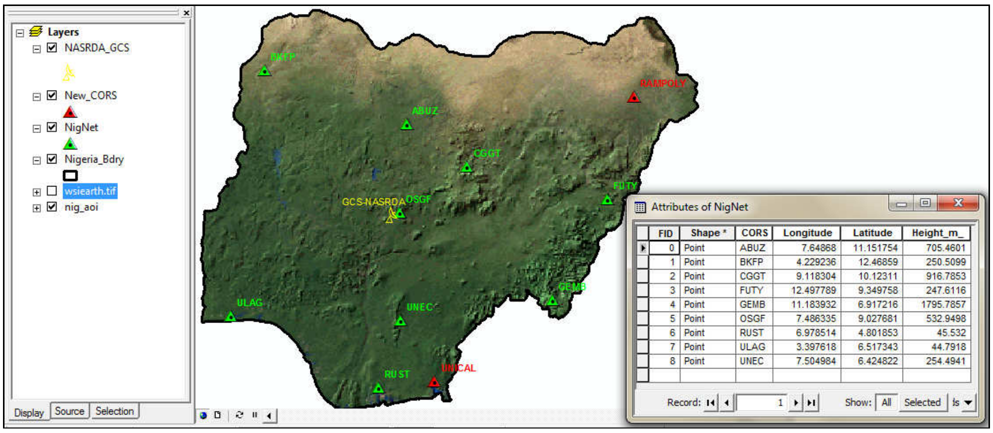
3.0 RESULTS AND ANALYSIS

3.1 Presentation of Results

Table 3.1 shows the post-processed curvilinear coordinates (ϕ, λ, h) of the nine of the eleven NigNet Controls in Nigeria. The relevance of these points to the selection of GCS is that it provides the frame work for baseline and spatial analysis in relation to the NASRDA Satellite Ground Stations in Abuja, Nigeria.

Table 3.1: The Adjusted Points in WGS84 (geographical coordinates and std. dev.)

Point	Latitude(ϕ)	σ(mm)	Longitude(λ)	σ(mm)	Height (m)	σ(mm)
ABUZ	N 11° 09' 06.26225"	0.0	E 7° 38' 55.22929"	0.0	705.4601	0.0
BKFP	N 12° 28' 06.87297"	2.7	E 4° 13' 45.22956"	6.8	250.5099	8.5
CGGT	N 10° 07' 23.14085"	1.2	E 9° 07' 05.87589"	1.6	916.7853	5.2
FUTY	N 9° 20' 59.07440"	3.2	E 12° 29' 52.02238"	9.0	247.6116	9.9
GEMB	N 6° 55' 01.92069"	3.5	E 11° 11' 02.13748"	7.7	1795.7857	10.5
OSGF	N 9° 01' 39.59767"	1.6	E 7° 29' 10.78586"	1.7	532.9498	6.1
RUST	N 4° 48' 06.61408"	5.4	E 6° 58' 42.63372"	12.3	45.5320	17.0
ULAG	N 6° 31' 02.37835"	3.1	E 3° 23' 51.40406"	8.0	44.7918	10.6
UNEC	N 6° 25' 29.30450"	3.1	E 7° 30' 17.92300"	5.9	254.4941	10.5



FID	Shape *	CORS	Longitude	Latitude	Height_m_
0	Point	ABUZ	7.64868	11.151754	705.4601
1	Point	BKFP	4.229236	12.46859	250.5099
2	Point	CGGT	9.118304	10.12311	916.7853
3	Point	FUTY	12.497789	9.349758	247.6116
4	Point	GEMB	11.183932	6.917216	1795.7857
5	Point	OSGF	7.486335	9.027681	532.9498
6	Point	RUST	6.978514	4.801853	45.532
7	Point	ULAG	3.397618	6.517343	44.7918
8	Point	UNEC	7.504984	6.424822	254.4941

Figure 3.1: NigNet Stations and NigeriaSat Ground Station at NASRDA, Abuja

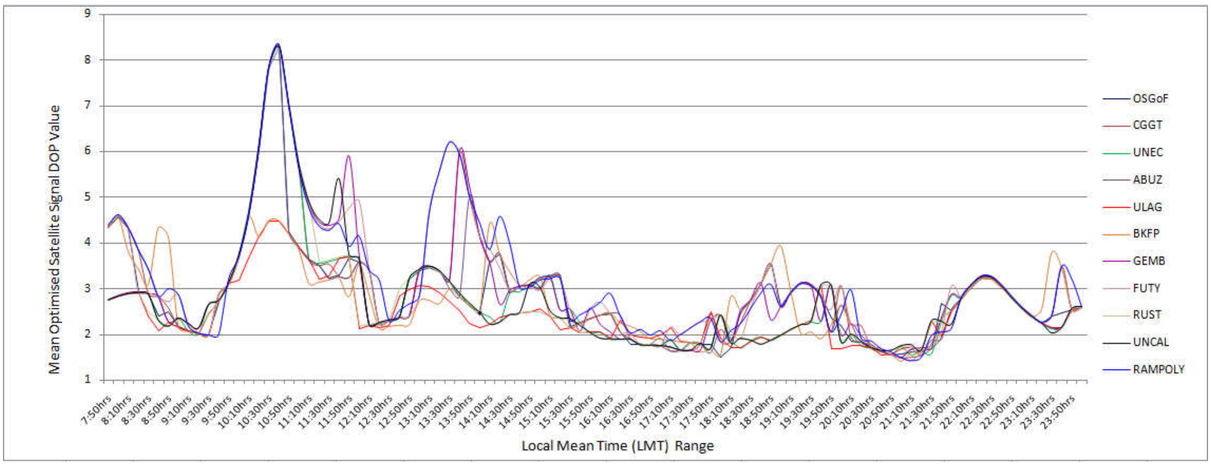


Figure 3.2 Mean Satellite Signal Dilution of Precision 11 selected Locations in Nigeria

DOP is a measure of satellite fix geometry quality, which is a product of signal travel time, overhead satellite geometry and the ranged positions (horizontal and vertical). This multi-station analysis as in figure 3.2 was simulated as a step to determine the availability of the Global Navigation Satellites during station and space craft tracking sessions. The more satellites that are being tracked and the more evenly they are distributed around the sky, the better the tracking accuracy of spacecrafts and ground stations. DOP values less than 4 are good, but between the hours of 10:20-11:00GMT and 13:10-14:00GMT respectively, the DOP values in most of the stations are poor (well above 4). However, the average DOP values for the eleven stations ranged between 2.4 and 3.2 (*i.e.* $2.4 \leq DOP \leq 3.2$), hence adjudged fair for any of the stations to selected as GCS. However, this technique is only one of many supporting technical and logistic criteria for ground station selection using GNSS-based LEOS Tracking and control.

Three optimal locations in figure 3.3 (Angola, Morocco and Bulgaria) were selected for future establishment of GCS outside Nigeria based on their location within the orbital ground track of a sunsynchronous or polar orbiting satellites, NigeriaSat-1 and NigeriaSat-2/X.

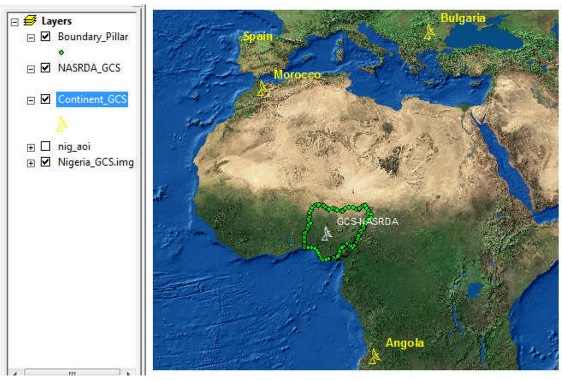


Figure 3.3: Selected NigeriaSat GCS Along the Sunsynchronous Orbital Highway

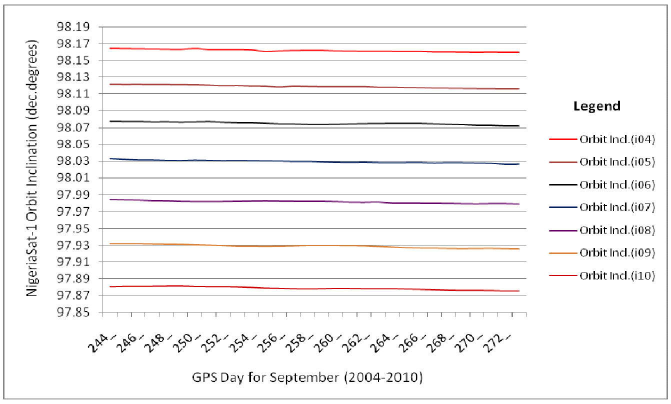


Figure 3.4: NigeriaSat-1 Orbital Inclination Variation Pattern for September Epoch [2004-2010]

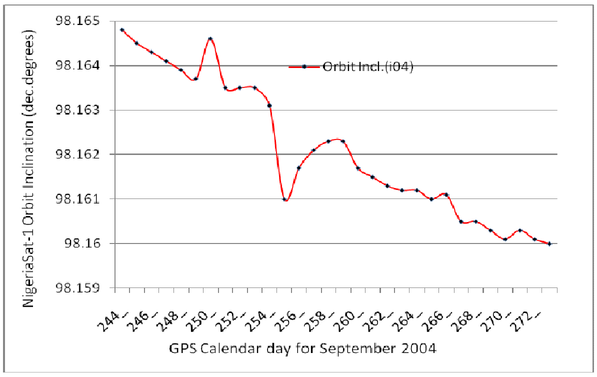


Fig.3.5a: Variation of Orbital Inclination of NigeriaSat-1 for September Epoch, 2004

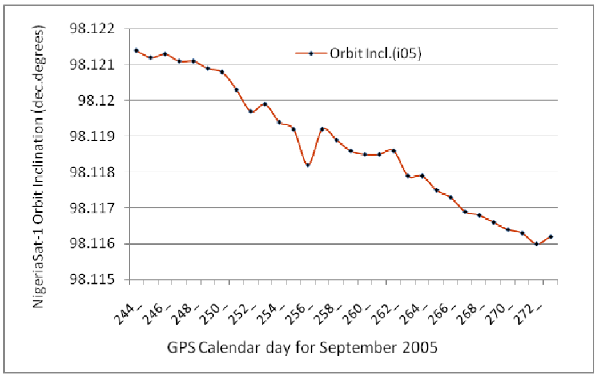
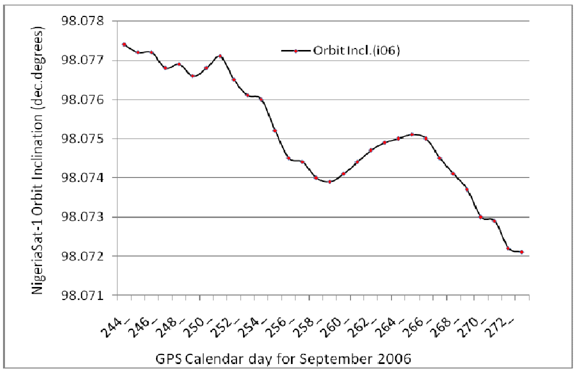


Fig.3.5b: Variation of Orbital Inclination of NigeriaSat-1 for September Epoch, 2005



3.5c: Variation of Orbital Inclination of NigeriaSat-1 for September Epoch, 2006

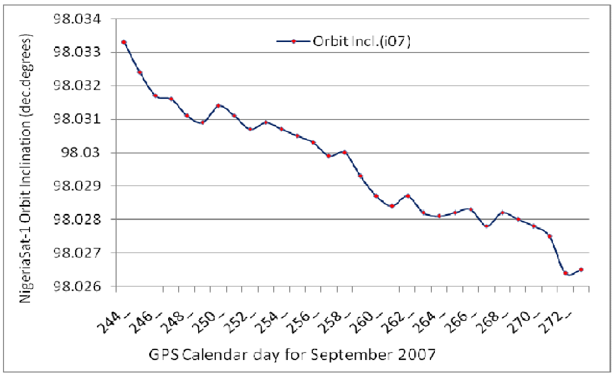


Fig.3.5d: Variation of Orbital Inclination of NigeriaSat-1 for September Epoch, 2007

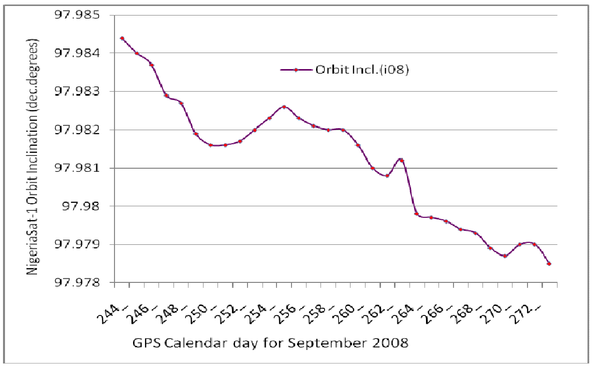


Fig. 3.5e: Variation of Orbital Inclination of NigeriaSat-1 for September Epoch, 2008

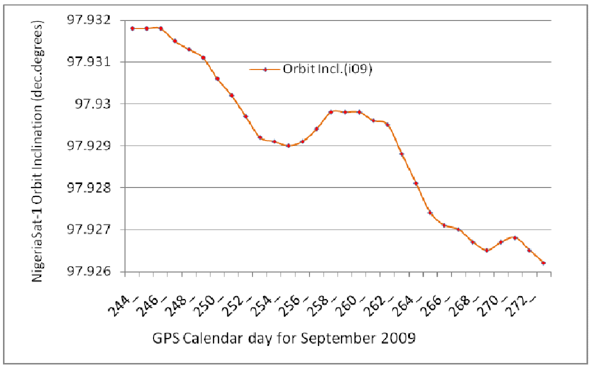


Fig.3.5f: Variation of Orbital Inclination of NigeriaSat-1 for September Epoch, 2009

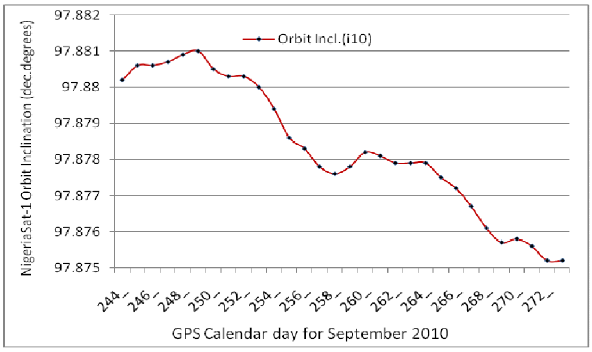


Fig.3.5g:Variation of Orbital Inclination of NigeriaSat-1 for September Epoch, 2010

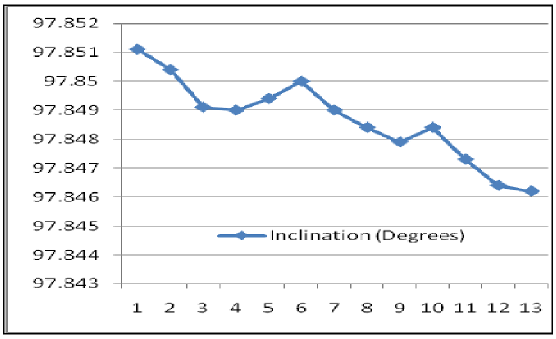


Fig.3.6a: Variation of Orbital Inclination of N-1 Orbit between May 4th –June 6th 2011

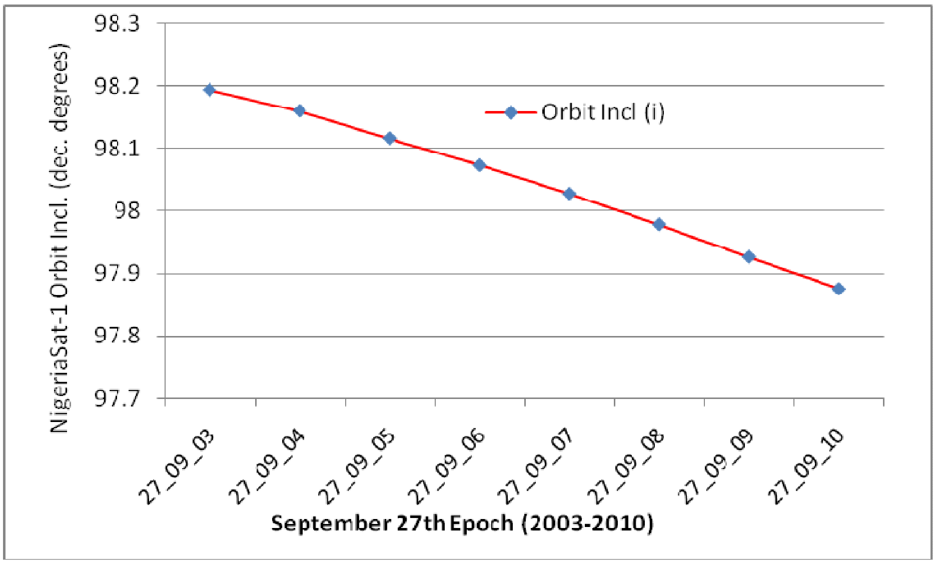


Fig.3.6b: The Angular Variation of N-1 Orbit inclination 27th Sept. Epoch (2003-2010)

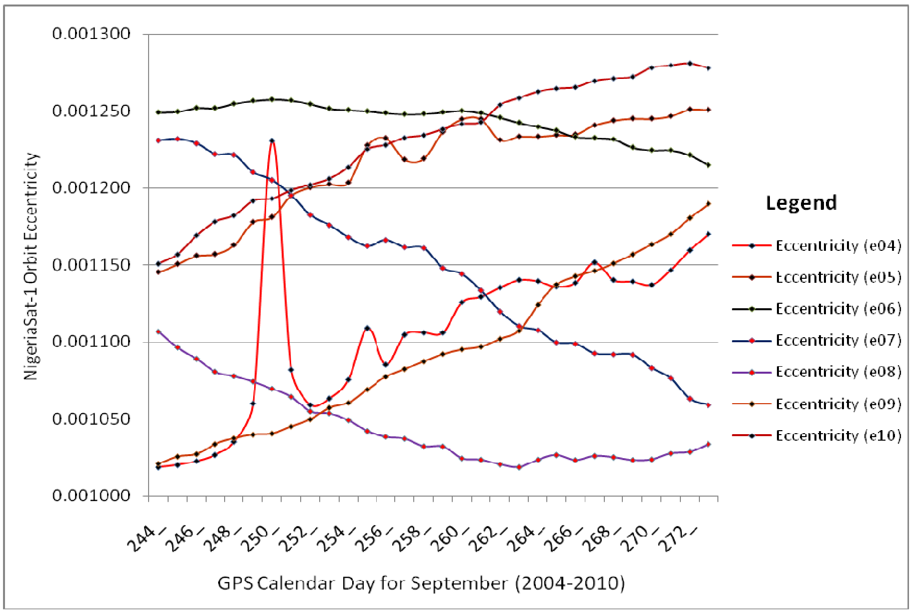


Fig.3.7: Orbit Eccentricity Variation Chart of the NigeriaSat-1 (2004-2010)

3.2 Analysis of Results

Table 3.1 shows the ionospheric-free, post-processed and adjusted WGS84 geographical coordinates with their corresponding standard deviations, while Figure 3.1 shows the geospatial locations of the 9 out of the 11 NigNet CORS on the ITRF-based global earth model (subset for Nigeria). These points provided the frame work for baseline and spatial analysis in relation to the NASRDA Satellite Ground Stations in Abuja, Nigeria in this study. Figure 3.2 shows the optimized DOP values in most of the NigNet stations are poor (well above 4) between the hours of 10:20-11:00GMT and

13:10-14:00GMT respectively, but fine in other times of the day. However, the average DOP values for the eleven stations ranged between 2.4 and 3.2 (i.e. $2.4 \leq DOP \leq 3.2$), which are fair for any of the stations to selected as GCS. However, this technique is only one of many supporting technical and logistic criteria for ground station selection using GNSS-based LEOS tracking and control

Figure 3.3 shows the three optimal locations selected for future GCS outside Nigeria based on their location within the orbital ground track or window of the sunsynchronous or polar orbiting NigeriaSat-1, NigeriaSat-2 and NigeriaSat-X respectively. The three locations selected within the 15°S-48°N and 24°W-48°E window for the ground window for continental GCS include Angola *[12°27'56".12S, 15°48'08".37E]* in Africa, Morocco *[34°31'28".20N, 4°10'22".26W]* in Africa and Bulgaria *[44°22'48.24N, 25°39'28.48E]* in Europe. However, the optimal points are not limited to the three above, because there are other countries that fall within the direct orbital foot print of the NigeriaSat.

This ground station geometry should favour high telemetry signal reception, easy data access in the host countries and optimum inter-operation with the main GCS at NASRDA, Abuja. This arrangemnt is however useful only when there is a bilteral agreement or scientific collaboration between the affected conuntries.

Figure 3.4 shows the combined pattern of NigeriaSat-1 orbit inclination for all September epoch between 2004 and 2010, while figures 3.5a-g show individual September epoch pattern of orbital inclination.

The analyses of these figures show that NigeriaSat-1 orbit inclinations for satellite epoch day 270 (corresponding to 27th September), between 2003 and 2010 recorded a total angular drift of about 00° 19' 03" arc (equivalent to about 34. 290km) towards the earth pole. This accounted for approximately *00° 2' 23.12"* of arc per year (equivalent to about 4.3km per year). Similarly, the periods of 1st to 30th September for year 2004 to 2010, showed a total change in orbit inclination angle of 00o 17' 22.56" of arc (equivalent to about 31.277km), which represents about *00° 2' 28.94* of arc per year (equivalent to about 4.47km per year). The significance of this is that it reveals the status of the satellite in orbit, which further informs decision for thrusting or firing of the spacecraft where necessary. Figure 3.8 is a model depicting the drift pattern of NigeriaSat-1 orbit inclination over the years (2003-2010). It is a graphic expression of the astrodynamic effect on the satellite since its arrival in orbit.

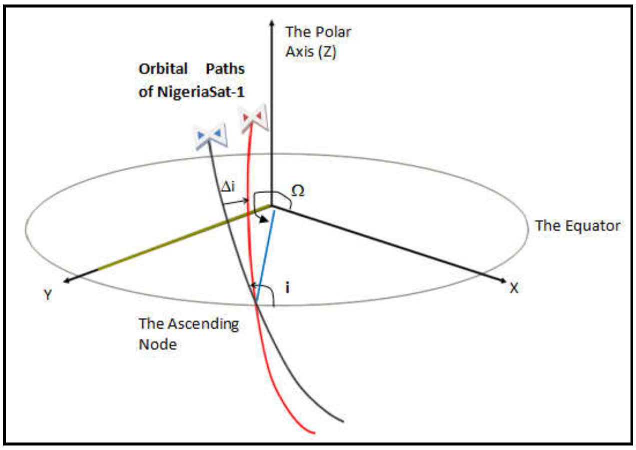


Fig. 3.8: The Drift Model of NigeriaSat-1 Orbit Inclination (2003-2010)

Figure 3.6a shows a 4-day interval trend in the variation of orbital inclination of N-1 orbit between May 4th and June 6th 2011, which still reflect the general oscillation towards the earth-pole. From figure 3.6b it is obvious that the drift of N-1 Orbit inclination (i) between 27th September 2003 and 27th September 2010 is linear drift towards the earth, resulting in reduction of the absolute angular value of *i*.

The eccentricity of the Orbit ellipse of the NigeriaSat-1 was slightly unstable and irregular in September, 2004, which might have resulted in in-ordinate imaging of same ground area or swath on the earth. The TLE Set analysis shows that the N-1 Ballistic Coefficient was small; hence not subjected to too much vertical and lateral drag. This was due to its light weight/mass of 98kg and the associated low coefficient of drag (C_D), which ranged between -

3.3 Summary of Findings

The following were the finding from the study:

1. The optimized DOP values in most of the NigNet stations are poor (well above 4) between the hours of 10:20-11:00GMT and 13:10-14:00GMT respectively, but fine in other times of the day. However, the average DOP values for the eleven stations ranged between 2.4 and 3.2 (i.e. $2.4 \leq DOP \leq 3.2$), which are fair for any of the stations to be selected as GCS. However, this technique is only one of many supporting technical and logistic criteria for ground station selection using GNSS-based LEOS tracking and control.

2. Three strategic locations in Africa and europe fall within the 15^{o}S-48^{o}N and 24^{o}W-48^{o}E window selected as the ground window for continental GCS. The countries include Angola (*12^{o}27'56".12S, 15^{o}48'08".37E*), Morocco (*34^{o}31'28".20N, 4o10'22".26*) and Bulgaria (*44^{o}22'48.24N, 25^{o}39'28.48E*). However, the optimal points are not limited to the three above, because there

are other countries that fall within the direct orbital foot print of the NigeriaSat.

3. NigeriaSat-1 whose design maximum and minimum orbital inclination were 98.4 and 97.8 decimal degrees respectively for the 5year lifespan has lived for over eight years and exhibited orbital inclination range of 98.1933 to 97.8752 decimal degrees, which has not exceeded the designed maximum and minimum range of orbital inclination.

4. NigeriaSat-1 showed a total orbital angular drift of about 00^{o} 19' 03" of arc (equivalent to about 34. 290km), towards the earth pole between 27th September 2003 and 27th September 2010, which accounted for approximately *00^{o} 2' 23.12"* of arc per year (equivalent to about 4.3km per year).

5. The eccentricity of the Orbit ellipse of the NigeriaSat-1 was slightly unstable and irregular in September 2004, which might have resulted in in-ordinate imaging of same ground area or swath on the earth within the period.

4.0 Conclusion

Ground stations acquire mission data from a spacecraft and transfers it to the data users and also supply any telemetry and tracking information the data users may need for general house or station keeping. The basic functions of GCS include among others; *telemetry tracking and control support, satellite orbit determination and monitoring, general station keeping, satellite payload management* and *in-orbit test (IOT);* which is done after the satellite arrive its mission orbit in order to determine that it is functioning properly and that it did not get damaged during the powered flight to space.
The study has demonstrated the relevance of GNSS observables in LEOS Ground station selection, and analysis of orbit dynamics of EOS such as NigeriaSat-1, NigeriaSat-2/X. The tracking and control of the spacecraft from the so selected GCS based on GNSS Signal dilution of precision of the Nigeria Space Programme is only sustainable when analysis of the TLE set are frequently and periodically carried out.

The NigeriaSat-1 which was designed for lifespan of 5years has lived for over eight years. It is significant to note that despite the longer live of the N-1 in orbit, its dance in the orbit highway never exceeded the design maximum and minimum orbit inclination angle of 98.4 and 97.8 decimal degrees respectively. The significance of the above information is that, it reveals the status of the satellite in orbit, which further informs decision for thrusting or firing of the spacecraft where necessary.

4.1 Recommendations

With the rapid advancement in space technologies of EOS and applications, the ability to predict the position and velocity of the EO satellite is extremely important. To sustainablly achieve this in NASRDA and Nigeria's space programme, the follwing are hereby recommended:

1. Periodic monitoring of the NigeriaSat-2 and NigeriaSat-X orbital status with the TLE set from the on-set of launch and completion of in-orbit callibration is imperative. This is because their weights/masses are quite higher than than that of N-1; hence would be susceptible to more drag in orbit. Secondly, there could be periodic and sudden solar and magnetic storms that could cause serious orbit and altitude pertubation on the spacecraft.
2. GNSS CORS co-located in NASRDA (top of Blue House) should be powered in order to enable linkage with the NigeriaSat Spacecraft and ground station's GPS receivers for baseline and navigation solutions using double differences of ionospheric free carrier phase and double difference pseudo-ranges for N-2 and N-X orbit probe.
3. Capacity building of scientists and engineers in the use of TLE set for Nigeria's EOS Orbit Monitoring and control is necessary.

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APPENDIX-1: Sample of the Final Interpreted/Processed TLE Set for N-1

EPOCH: SEPTEMBER 2010

Epoch Day	Orbit Incl.(i_{10}) (dec. degrees)	RA (dec. degrees)	Eccentricity (e_{10})	Argument of Perigee (w)	Mean Anomaly (v)	Mean Rev./day	Revolution number at epoch (Revs)	Coeff. of Drag
244	97.8802	106.0160	0.0011507	178.2226	181.9007	14.63100015	370024	0.85955E-05
245	97.8806	106.9312	0.0011569	175.2885	184.8421	14.63099898	370165	0.17593E-06
246	97.8806	107.8462	0.0011692	172.3705	187.7675	14.63100223	370301	0.95378E-05
247	97.8807	108.8265	0.0011781	169.2055	190.9410	14.63100918	370456	0.23369E-04
248	97.8809	109.7415	0.0011821	166.2783	193.8737	14.63100728	370593	0.13541E-04
249	97.8810	110.6567	0.0011915	163.3826	196.7777	14.63101227	370731	0.23979E-04
250	97.8805	111.7675	0.0011931	159.8706	200.2958	14.63100841	370904	0.39606E-05
251	97.8803	112.6170	0.0011984	157.3275	202.8459	14.63101078	371036	0.79067E-05
252	97.8803	113.5319	0.0012021	154.5373	205.6427	14.63102074	371170	0.32909E-04
253	97.8800	114.6425	0.0012060	151.0566	209.1291	14.63101804	371343	0.17305E-04
254	97.8794	115.4267	0.0012135	148.5729	211.6213	14.63102421	371464	0.28232E-04
255	97.8786	116.4717	0.0012252	145.3577	214.8426	14.63102490	371627	0.19464E-04
256	97.8783	117.3863	0.0012279	142.3190	217.8868	14.63102586	371767	0.18673E-04
257	97.8778	118.3011	0.0012326	139.3844	220.8290	14.63102834	371907	0.18615E-04
258	97.8776	119.2160	0.0012343	136.4132	223.8055	14.63102885	372041	0.15080E-04
259	97.8778	120.1961	0.0012381	133.3558	226.8689	14.63102921	372196	0.13417E-04
260	97.8782	121.3728	0.0012417	130.0675	230.1610	14.63103259	372376	0.19279E-04
261	97.8781	122.1569	0.0012429	127.7529	232.4797	14.63103440	372497	0.17174E-04
262	97.8779	123.4633	0.0012540	123.9093	236.3310	14.63103849	372697	0.27261E-04
263	97.8779	124.1166	0.0012585	122.0370	238.2053	14.63104031	372793	0.21034E-04
264	97.8779	125.0313	0.0012626	119.2878	240.9587	14.63104150	372934	0.18970E-04
265	97.8775	126.0763	0.0012646	115.8046	244.4449	14.63104523	373099	0.23855E-04
266	97.8772	126.9256	0.0012655	113.2607	246.9931	14.63104841	373228	0.22735E-04
267	97.8767	127.9710	0.0012695	110.2320	250.0236	14.63104841	373382	0.18920E-04
268	97.8761	128.8857	0.0012712	107.6230	252.6368	14.63105531	373525	0.28303E-04
269	97.8757	129.8000	0.0012723	104.6964	255.5651	14.63105718	373663	0.25713E-04
270	97.8758	130.8455	0.0012781	101.6150	258.6478	14.63105786	373822	0.22645E-04
271	97.8756	131.7597	0.0012797	98.8838	261.3818	14.63106331	373965	0.25829E-04
272	97.8752	133.0657	0.0012810	94.6540	265.6148	14.63106658	374161	0.34197E-04
273	97.8752	133.6538	0.0012778	92.8415	267.4245	14.63106761	374252	0.22027E-04

Appendix 2: The DMC TLE Structure (**20-05-2011**)

```
ALSAT 1
1 27559U 02054A   11140.19656675  .00000282  00000-0  55399-4 0  5691
2 27559  97.8413   1.4996 0022038 276.7821  83.0880 14.69537423452810
NIGERIASAT 1
1 27941U 03042C   11140.16590663  .00000112  00000-0  30362-4 0  6297
2 27941  97.8484 354.9026 0012850  81.2050 279.0592 14.63188816408187
UK-DMC
1 27942U 03042D   11140.06671734  .00000350  00000-0  56604-4 0  6512
2 27942  97.8592 359.3929 0067685  77.4614 283.4156 14.75759598408468
BILSAT 1
1 27943U 03042E   11140.17540309  .00000076  00000-0  23406-4 0  4841
2 27943  97.8445 354.0387 0012953  78.9470 281.3172 14.63023761408165
BEIJING 1
1 28890U 05043A   11140.16602431  .00000092  00000-0  28344-4 0  3663
2 28890  97.9592  16.9839 0014470 308.3703  51.6193 14.60163812296347
HJ-1A
1 33320U 08041A   11140.18172632  .00000545  00000-0  87238-4 0  9818
2 33320  97.9080 213.4111 0024299 346.7485  13.3110 14.75508838145392
HJ-1B
1 33321U 08041B   11140.21564873  .00000035  00000-0  12683-4 0   250
2 33321  97.9108 213.5849 0042939 357.6249   2.4789 14.75509957145386
YAOGAN 4
1 33446U 08061A   11140.18423320  .00000345  00000-0  59349-4 0  7360
2 33446  97.8355 212.3076 0016261 292.4213  67.5290 14.74369861132698
YAOGAN 5
1 33456U 08064A   11140.16138163  .00004430  00000-0  15885-3 0  7321
2 33456  97.2998 213.0172 0012949  70.4916  13.2376 15.29154573135132
DEIMOS-1
1 35681U 09041A   11140.14627790  .00000187  00000-0  39854-4 0    57
2 35681  98.0694  39.5732 0000901 105.5735 254.5575 14.69448637 96860
UK-DMC 2
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2 35683  98.0714  38.5998 0001356  68.6839 291.4500 14.69444228 96799
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