

DESIGN OF A LOW-COST AUGMENTATION NAVIGATION SYSTEM: THE UNITED KINGDOM'S IMMEDIATE ANSWER TO THE GALILEO BREXIT CONUNDRUM

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ABSTRACT

United Kingdom's Brexit from the European Union implies restricted access to the European Global Navigation Satellite System (GNSS) System - Galileo; with no access to the secured and encrypted signal used for defense and government purposes, which is restricted to European Union (EU) members. To mitigate this issue, the United Kingdom can, as a matter of urgency, launch a payload on a national military Communications Satellite to provide Navigation Overlay Services for the United Kingdom territory, surrounding waters and neighboring ally countries to meet the requirements of: Defense systems, Aviation, Maritime requirements and the effectiveness of Location-based Services for Emergencies and Crisis management etc. This paper describes the design of a navigation overlay service system as a hosted payload on a national satellite and the required supporting ground infrastructure, highlighting various applications, services and solutions.

Keywords: *Brexit, Communications Satellite, Defence, European Union (EU), Galileo, GNSS, Military, Precision Point Positioning, SBAS.*

INTRODUCTION TO GLOBAL NAVIGATION SATELLITE SYSTEM (GNSS)

The United States Global Positioning System (GPS) marked the beginning of Global Navigation Satellite Systems (GNSS). After the First World War, radio time signals offered alternative technology for determination of the Greenwich Time line and thus longitude at sea. The first manifestation of this new technology capable of usurping the super accurate mechanical chronometers occurred in 1904, when the United States Navy began to experiment with the transmission of radio-time signals as an aid to the determination of longitude (Davies, 1978; Lawal & Chatwin, 2011). The challenge in the precision of Navigation systems depends on measuring the transit times of electromagnetic waves travelling at 300,000,000 m/s, this means that one microsecond error in a vessel's clock will result in 300 metres of navigational error.

The Global Positioning System (GPS) originated from the Navigation System with Timing and Ranging known as NAVSTAR, which was initiated by the Joint Program Office (JPO) of the U.S. Department of Defence (DoD) in 1973. The first GPS satellite was sent into orbit in 1978. Initial Operational Capability (IOC) was reached in July 1993 with 24 satellites, while Full Operational Capability (FOC) was declared on July, 17th, 1995. The primary goals were military but the U.S Congress directed the Department of Defense (DOD) to promote civil use free of charge. As a result, the C/A signal on the L1 carrier was made public but intentionally degraded by Selective Availability (SA). Final deactivation of the selective availability was stopped on the 2nd May 2000 and improvement for civilian users went from 100m to about 20m accuracy (Parkinson & Spilker, 1996; Gregory, 1996; Kowoma, 2009; Dana, 1999).

The quest for performance focused on the ability to accurately transmit and keep timed signals stable up to the picosecond level and more in receivers and the clock reference accuracy of space systems especially in navigation satellites using high performance oscillators ranging from ultra-stable quartz crystals with ovenized control to high performance atomic circuits (Lawal & Chatwin, 2011).

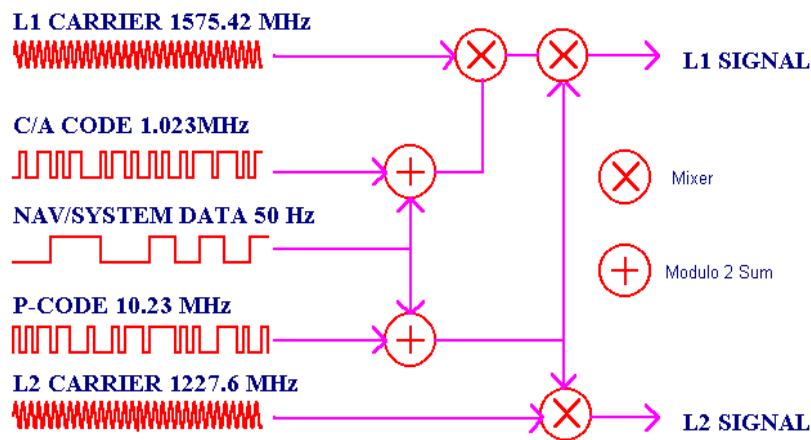
The Global Positioning System (GPS), one example of a Global Navigation Satellite System (GNSS), is primarily a ranging system as it tries to find how far an object is from itself (satellite). Thus, GPS operates on the principle of trilateration, which refers to determination of an unknown point by measuring the lengths of the sides of the triangle between the unknown points and two or more known points on the satellites in their orbits. Triangulation gives more meaning as it takes angular bearings from two or more known distances and computes the unknown points from the resultant triangle. The satellite carries out position determination by transmitting a radio signal code that is unique to each satellite. The GPS receivers receive these satellite signals and measure the time taken for the signal to be received. Thus, ranged distance is mathematically computed by multiplying the signal's speed (c) by the time it takes the signal to travel. However, the ranged distance is not enough to give the exact location of the object on the surface of the earth as it does not contain other vector information such as bearing and azimuth, thus there is a need for two more satellite signals to evaluate the precise location. Additional information from more satellites and other constellations increases the accuracy and integrity of the positioning or location-based services (LBS). Basically, at least four satellites are required for precise determination of position as the fourth satellite acts as a time reference for the receiver's accuracy. Usually each satellite carries four atomic clocks on board, which are precise to within billionths of a second per month. The correction for satellite clocks is important as runtime measurement of the signals through the process of cross-correlation and Doppler effect helps in determination of position and speed including the use of the precise point positioning

(PPP) model to improve the: precision, stability, accuracy, reliability and repeatability of results (Davies, 1978; Lawal & Chatwin, 2011; 2014;2015; Meng, Roberts, Dodson, Ince, & Waugh, 2006; Xu, Lui, Zhang, & Feng, 2012; Zhang, Liu, Shu, Qian & Zhang, 2015, Gregory, 1996; Kowoma, 2009).

Generally, for a GPS receiver to work properly, it is expected to carry out four tasks, namely:

- (i) Find the GPS signal frequency, code phase
- (ii) Track and demodulate the message from each GPS satellite at the same time.
- (iii) Calculate the position based on distances to the satellites
- (iv) Calculate the correction to your local clock.

The C/A code navigational information illustrated in figure 1, consists of a 50Hz signal and data such as satellite orbits, clock corrections and other system parameters of the satellite status. The correction for the satellite clocks is important as runtime measurement of the signals through the process of cross-correlation and Doppler effect helps in determination of position and speed. Each satellite continuously transmits this data.



GPS SATELLITE SIGNALS

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Figure 1: Composition of the signals from GPS satellites showing roles of Oscillators

(Sourced from: Dana, 1999 with permission).

GNSS refers to a constellation of satellites owned by a country or region providing signals from space that transmit positioning and timing data to GNSS receivers for determination of geographic location anywhere in the world. Table 1 below provides an overview of satellite systems with partial or global coverage.

Table 1: Overview of Global Navigation Satellite System (GNSS)

| System | No. of Satellites | Nominal Altitude (Km) | Orbit Inclination i (°) | Initiation and Current Operational Capability |
|------------------|--|---|---------------------------|--|
| GPS | 32 satellites (31 Operational, 1 in Maintenance) 12 th July, 2017) | 20,200 | 55 | Initiated 1973 by USA, 1995(FOC) |
| GLONASS | 27 Satellites (23 Operational, 2 under checks, 1 inflight tests phase and 1 spare) (12 th July, 2017) | 19,000 | 64.8 | Initiated by Russia in 1975, 1996(FOC) 2011 (Restarted Modernization) |
| GALILEO | 18 satellites (13 Usable, 1 Not Available, 2 Testing and 2 Under Commissioning) (As at 11 th July, 2017) (30) | 23,222 | 56 | Initiated by EU in 2000, 2014(IOC) 2016 (Galileo Initial Services) 2020(FOC) tentatively |
| BEIDOU (COMPASS) | Presently 23 Satellites (14 Operational, 9 not included in operational orbit constellation (12th July, 2017) (30) | 30 MEO Satellites (21,500) 5 IGSO Satellites inclined at 55 degrees | 55 | Initiated by China in 1990s. Regional System declared operational in 2011. 2020 (FOC) |

The performance of GNSS is assessed using four criteria namely:

- i. Accuracy: the difference between a receiver's measured and real position, speed or time;
- ii. Integrity: a system's capacity to provide a threshold of confidence and, in the event of an anomaly in the positioning data generate an alarm;
- iii. Continuity: a system's ability to function without interruption and
- iv. Availability: the percentage of time a signal fulfils the above accuracy, integrity and continuity criteria.

The performance of GNSS can be improved by satellite-based augmentation systems (SBAS) by improving the accuracy and reliability of GPS information through correction of signal measurement errors and by providing information about the integrity of the signals.

GALILEO; EUROPEAN GLOBAL SATELLITE-BASED NAVIGATION SYSTEM

Galileo is Europe's Global Navigation Satellite System (GNSS), providing improved positioning and timing information with significant positive implications for many European services and users. Unlike the American GPS or Russian GLONASS signals managed and operated by the military, the Galileo's system is under civilian control giving Europe a seat at the rapidly expanding GNSS global table. The programme is designed to be compatible with all existing and planned GNSS and interoperable with GPS and GLONASS. In this sense, Galileo is positioned to enhance existing GNSS coverage and thus provide a more seamless and accurate experience for multi-constellation users around the world.

Furthermore, Galileo provides Europe and European citizens with independence and sovereignty, an array of environmental benefits and several new services specific to the Galileo programme such as Open Service, Commercial Service, Search and Rescue as detailed on the European GNSS Agency (GSA) website; (Galileo, 2019).

The complete Galileo constellation will comprise satellites spread evenly around three orbital planes inclined at an angle of 56 degrees to the equator. Each satellite will take about 14 hours to orbit the Earth. One satellite in each plane will be a spare, on stand-by should any operational satellite fail.

From most locations, six to eight satellites will always be visible, allowing positions and timing to be determined very accurately to within a few centimetres. The interoperability of Galileo with *GPS* satellites will increase the reliability of Galileo services.

The performance of Galileo can be improved by the European Geostationary Navigation Overlay Service (EGNOS); a regional satellite-based augmentation systems (SBAS). EGNOS improves the accuracy and reliability of GPS information by correcting signal measurement errors and by providing information about the integrity of its signals.

The range of envisaged applications of Galileo is enormous, spanning both the public and private sectors across numerous market segments.

Galileo will play key roles in service delivery in many applications after full operational capability declaration tentatively by the year 2020. These applications are as detailed below:

The Internet of Things

The Internet of Things (IoT) is a key component of the fourth industrial revolution. In every sector of the economy, IoT is enabling objects to exchange data with manufacturers, operators and other devices – creating a vast integrated network of connected things and services that is expected to surpass 50 billion by 2020.

Galileo is poised to play a key role in the IoT, providing the positioning, velocity and timing information required by an increasing number of context-aware applications.

Location-based services (LBS)

LBS as the name suggests provides users with their locations as well as value-added services such as adverts about nearby businesses and services. Such LBS devices will be on high demand and increasingly represent a fundamental tool for tourists, hikers, amusement parks and museum visitors, and shoppers at large commercial centres.

Emergency, Security and Humanitarian Services

Natural disaster has become part of our existence; hence adequate preparation must be made for immediate recovery and future planning. Galileo signals will play a crucial role in civilian protection and humanitarian operations, such as in harsh environments including coastguards and border control authorities, ensuring faster rescue operations and the saving of more lives. Galileo's Search and Rescue (SAR) will help save lives by allowing quick and accurate emergency response

Science, Environment, Weather

Galileo will immensely support scientific research in such areas as meteorology, geology and geodesy, in tracking pollutants, dangerous goods and icebergs, and in the mapping and measuring of oceans, tides and sea levels. Precision mapping and land surveying today can better be done through a satellite positioning system to one millimeter (1mm) accuracy. Precision equipment like hand-held GNSS device and stations has replaced the old theodolite technology used for land survey and mapping

Galileo will improve scientific research such as atmospheric measurements, more accurate weather forecasting and climate change including study of the ionosphere and space weather, earthquakes' predictor events among others. Also of benefit to scientific community is Galileo's high-accuracy timing signals allowing for the precise adherence to international time standards and the calibration of atomic clocks – a key element to cutting-edge scientific research such as the Very Long Base Interferometry (VLBI).

Transport

From land to sea and air, safe navigation continues to generate concern and need for an appropriate solution. Road traffic technology would be enhanced with navigation systems integrated into the national road network with increased traffic safety and efficiency. Also the navigation electronic tolling system would help to monitor movement and ticketing. Increased traffic safety and efficiency also applies in maritime for Ocean, coastal, inland waterways, inland ports and port approaches under all weather conditions. Galileo signals deliver similar benefits in aviation, rail, and even pedestrian traffic.

Agriculture and Fisheries

By integrating Galileo signals with other technologies, the agricultural community benefits from an improved monitoring of the distribution and dilution of chemicals, improved farm yield per hectare, farm planning, field mapping, soil sampling, tractor guidance, crop scouting, and yield mapping. Precision agriculture is a highly effective farming strategy that allows farmers to better allocate inputs (e.g. seeds and fertilizers) and increase productivity,

while lowering costs and minimizing environmental impact. It also enhances fish farming with navigation and positioning support. Galileo provides the fishing industry with a more effective exchange of information between vessels and stations, and fishermen with improved navigational aids. Distressed Fishermen in the oceans will benefit from Galileo's Search and Rescue service (SAR).

Civil engineering

Accuracy, precision and reliability are absolutely vital in professional applications such as civil engineering Galileo System offers alternative to legacy system with increased productivity and allows construction companies to maintain high level of standards in civil engineering practice and across a project's entire lifespan. For Instance, sensors can be mounted on load bearing pillars of bridges, dams, high-rise buildings and critical national infrastructure to monitor deformation and the overall health of such structures.

A Crucial Time-Reference Function

Galileo satellites are synchronised to an extraordinary level of accuracy with the widely used Coordinated Universal Time (UTC) standard. This means Galileo is capable of delivering a timing signal demanded by such applications as terrestrial wireless telecommunication networks, space-based telecommunication networks, calibration of frequency references etc.

In Finance, banking and insurance, it offers data integrity, authenticity, certified time stamps necessary in electronic banking, e-commerce, stock transactions etc. Galileo's extremely accurate time reference makes it a formidable instrument for the time stamping of financial transactions and, in the future, for the authentication of the time stamp.

Similarly, accurate location systems are indispensable in the design, construction and operation of modern energy networks. Power grids must be continuously monitored, and when a power line breaks or a failure occurs, it is vital that monitoring instruments are synchronized with maximum accuracy. The high quality of time synchronization provided by Galileo means better services for the transportation and distribution of energy.

Furthermore, in the oil and gas sector, marine seismic exploration services are enhanced with Galileo's signals. With the high-resolution surveys of new sites and the identification of geomorphologic or geophysical risks that Galileo provides, drilling activities are becoming increasingly safer.

The above applications will be delivered through Galileo's services.

The Galileo system, once fully operational, will offer four high-performance services worldwide namely:

- I. **Open Service (OS):** Galileo open and free of charge service set up for positioning and timing services.
- II. **High Accuracy Service (HAS):** A service complementing the OS by providing an additional navigation signal and added-value services in a different frequency band.

The HAS signal can be encrypted in order to control the access to the Galileo HAS services.

- III. **Public Regulated Service (PRS):** Service restricted to government-authorized users, for sensitive applications that require a high level of service continuity. PRS is similar to Galileo's Open and Commercial *GNSS* services, but with some important differences:
- a. PRS will ensure better continuity of service to authorized users when access to other navigation services may be degraded (resilience).
 - b. In cases of malicious interference, PRS increases the likelihood of the continuous availability of the Signal-in-Space (robustness).

As a result of its signal and system design, PRS makes it more costly and difficult to attack its signals. Specifically, the service is more resistant to:

- a. **Spoofing**, i.e. the transmission of counterfeit *GNSS* signals that may force a receiver to compute an erroneous position and lead the user to believe they are in a different location from where they actually are. PRS also ensures that in such cases such authorized users as emergency forces, police and other relevant authorities retain the ability to serve the public using *GNSS* positioning information provided by PRS.
- b. **Jamming**, or the intentional transmission of radio frequency signals that can interfere with *GNSS* signals leading to a degradation or blocking of *GNSS* navigation and timing services. PRS reduces this risk and makes it easier to identify potential jammers.

The PRS service's end-to-end system design ensures the protection and availability of the signal and its associated data flows. Key elements for the services's end-to-end system design are comprised of:

- a. **Galileo Security Facility:** this includes the Galileo Security Monitoring Centre (GSMC);
 - b. **Ground Segment:** this includes the Galileo Control Centre, which consists of the Galileo Mission System (GMS), Galileo Control System (GCS), Galileo Sensor Stations (GSS) and the Uplink Station (ULS);
 - c. **Space Segment:** Galileo satellites broadcast the PRS signal in space
 - d. **User Segment:** this includes individual end-users with PRS receivers and a support and management framework within in each authorized PRS participant.
- IV. **Search and Rescue Service (SAR):** The Galileo SAR service is Europe's contribution to COSPAS-SARSAT, an international satellite-based search and rescue distress alert detection system. Galileo is the first *GNSS* constellation offering global SAR capability. The service will be available at sea, in the mountains, across the

desert and in the air inside the Galileo/SAR Service Coverage area, this essential Galileo service helps operators respond to a distress signal faster and more efficiently. Once fully integrated into the COSPAS-SARSAT system, the Search And Rescue Transponder on Galileo satellites will pick up signals emitted from distress beacons in the 406 – 406.1 MHz band and broadcast this information to dedicated ground stations (MEOLUTs) in the ‘L6’ band. Once these signals are detected and the beacons located by the MEOLUTs, COSPAS-SARSAT Mission Control Centres (MCC) will receive the beacon location information and distribute the data to the relevant rescue centres worldwide.

The Galileo SAR service is Europe’s contribution to the upgrade of COSPAS-SARSAT, an international satellite-based SAR distress alert detection and information distribution system. Figure 2 shows an overview of the COSPAS-SARSAT System. Established in 1979 by Canada, France, the USA and the former Soviet Union, it is used to detect and locate emergency beacons activated by aircraft, ships and individuals. It provides accurate, reliable and timely alert and location data to help SAR operators to find and help people in distress. COSPAS-SARSAT operates through a satellite system maintained and coordinated by its participants. This system detects distress alert transmissions from radio beacons that comply with COSPAS-SARSAT specifications and standards, determines their location, and provides the information to SAR teams.

Currently, 43 countries and organizations participate in the operation and management of the COSPAS-SARSAT system. COSPAS-SARSAT also cooperates with various international organizations including the International Civil Aviation Organization (ICAO), the International Maritime Organization (IMO) and the International Telecommunication Union (ITU).



Figure 2 shows an overview of COSPAS-SARSAT System (Source: “COSPAS-SARSAT”, 2019).

With Galileo's SAR integrated into COSPAS-SARSAT, users will benefit from:

- a. A reduction in the time it takes to detect a person at sea or in the mountains from one hour to just 10 minutes after the distress beacon is activated
- b. Improved localization of the distress beacon from 10 km to less than 5 km
- c. Increased availability.
- d. Better detection of signals in difficult terrain and weather conditions
- e. A return link that ensures users that their distress signal has been received and help is on the way.

Several research projects are creating end-to-end solutions based on the Galileo SAR service with leverage on its Return Link. These are:

- a. **SAT406M** is improving the mobility and safety of citizens through the design and development of a wrist-worn PLB beacon. The wearable device includes sensors to monitor the user's physiological characteristics, with this information being available to emergency responders via an innovative signal modulation technique.
- b. **HELIOS** is developing Emergency Locator Transmitters (ELT), Emergency Position Indicating Radio Beacons (EPIRB) and Personal Locator Beacons (PLB) beacons for end-to-end emergency readiness and response at sea and in the air. A range of products resulting from research and projects, are expected to be available mid-2019, to utilize the updated COSPAS-SARSAT satellite system.
- c. **GRICAS** is developing and demonstrating a whole set of innovative operational procedures for in-flight activation of SAR beacons onboard aircraft during abnormal situations, in order to improve safety and security of air navigation. It includes the development of an autonomous distress tracking (ADT) system for aircraft based on ELT-DT, using the unique Galileo SAR Return Link service and validation. ("SAR Success Stories", 2017)

PROPOSED LOW-COST AUGMENTATION NAVIGATION SYSTEM FOR THE UNITED KINGDOM AND ITS SURROUNDING ENVIRONMENT.

The Galileo system that will have 24 operating satellites with six orbiting spares it cost £9 Billion (\$11 Billion) with an original budget of €3 Billion. United Kingdom has invested approximately £1.2 billion in the Galileo program to date, with British industries providing key technologies including the encrypted Public Regulated Service System; providing encrypted data to military, security users for armed forces, defense purposes, government agencies and other security-related requirements.

As recently as August, 2018, the British Government set aside £92 (€104) Million to look at feasibility, options and the alternative of building a sovereign satellite-navigation system led

by the UK Space Agency (UKSA). Considering Britain's technical know-how it can certainly build a new satellite navigation network, crucially the UK is one of the foremost military powers in Europe and does require an accurate GNSS facility. The assessment report, which is expected in eighteen months-time, will outline: a potential design, its engineering requirements, schedule and likely cost of an independent alternative to Galileo (Jonathan, 2018).

Estimated cost of the UK building an alternative navigation system is between £3 to £5 Billion plus annual running costs running into millions of pounds with a long term commitment from successive governments. Equally, some of the components for the Galileo system have single suppliers in Europe. The estimated budget for an independent navigation system is expensive and a huge challenge for the UK as a nation considering that the annual UK space budget is just £370 Million.

United Kingdom's exit from European Union does not imply exit from European Space Agency (ESA); operators of Galileo and thus security agreements similar to USA's allies for access to the GPS military signal is technically feasible in the future. So, an amount equivalent to what has been earmarked for a feasibility study should be invested into design, assembly and integration of a low-cost Satellite-Based Augmentation System (SBAS) as a navigation overlay service (NOS) on a hosted national satellite utilizing GNSS especially GPS and Galileo as an alternative to the Galileo's PRS - with better performance in terms of Integrity, Reliability, Continuity and availability for UK's security-relevant operations.

The diagram below shows a system design of the low-cost navigation overlay system for the United Kingdom to be built on a Satellite Bus of Spacecraft manufacturers in any of the Five Eye Alliance Intelligence countries comprising of UK, USA, Canada, Australia and New Zealand. The notable satellite bus platforms for a navigation overlay system as a hosted payload are: Boeing 702 Satellite bus platform of USA with hosted Geo NOS payload by Raytheon Integrated Defense Systems, SSL 1300 of Space Systems Loral-Canada, A2100 of Lockheed Martin-USA, Spacebus 4000 of Thales Alenia Space, Eurostar E3000 of EADS Astrium - now Airbus Defense and Space; manufacturers of the Skynet satellite series for UK's military satellite communications, there are others.

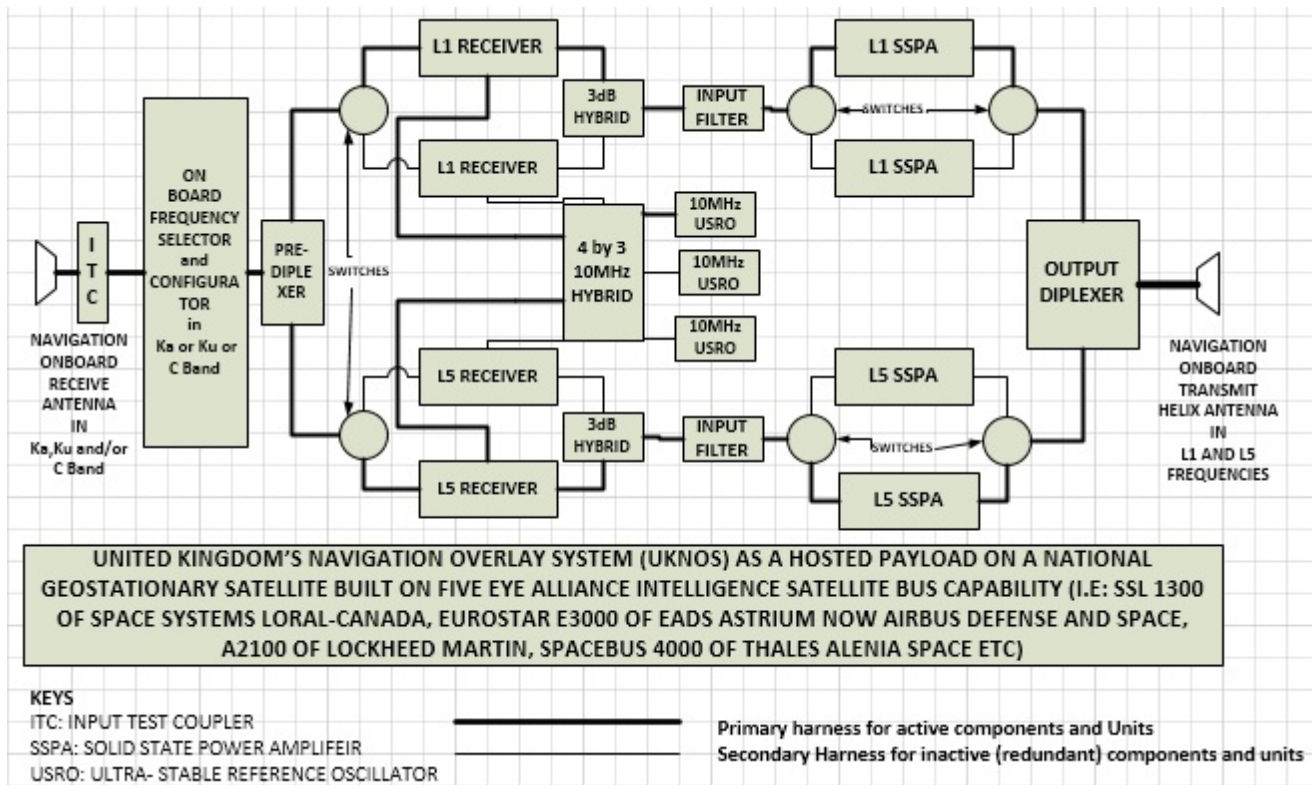


Figure 3: Schematic Design Overview of the Low-Cost Navigation System Hosted on a United Kingdom National and/or Military Geostationary Satellite.

The UKNOS Navigation (L-band) payload will provide a Navigation Overlay Service (NOS) similar to the European Geostationary Navigation Overlay Service (EGNOS) system. The system will augment the Global Navigation Satellite System (GNSS) over the world starting with United Kingdom, Europe, Africa and Surrounding Oceans. Recognizing the important advance of dual user frequencies over the single L1 frequency capabilities of previous GNSS, the UKNOS has additional signal on the L5 frequency band.

The receiver of the navigation transponders uses a 10MHz ultra stable crystal oscillator with two additional redundant spares via a 4 by 3 matrix hybrid as illustrated in figure 3 to meet the performance requirements of frequency conversion stability and accuracy. The system functions in a manner where a number of ground reference stations monitor the GNSS satellites signals and provide their observations to one or more Master Control stations (MCS). An augmentation message is then generated by the MCS and two (2) signals, C1 & C5 on C-Band or Ku1 & Ku5 on Ku-Band or Ka1 & Ka5 on Ka Band are transmitted via an uplink station within the uplink coverage areas on the C-band or Ku-Band or Ka-Band. The navigation payload down converts the signals to L-band, L1 and L5, and retransmits these signals globally to users within the coverage downlink areas.

The onboard navigation payload has various component redundancies as illustrated with secondary lines (thinner lines than the active components' connectivity; primary lines). It is a dual-channel bent-pipe transponder with reconfigurable frequency band on either C-Band or Ku-Band or Ka-Band as uplink signals from a ground earth station for down-conversion to

two downlink signals in the two separate bands, L1 and L5. A 4.0 MHz-wide C1 band or Ku1 band or Ka1 band uplink channel relays in the L1 downlink channel and allows the transmission of the L1 signal while a 20.0 MHz-wide C5, Ku5 or Ka5 band uplink channel relays in the L5 downlink channel and allows transmission of the L5 signal. The proposed center frequencies and polarization are as shown in Table 2.

Table 2: Downlink Frequency and Polarization of proposed UKNOS L-Band Payload.

| Channel | Frequency (MHz) | Polarization | Bandwidth (MHz) |
|-------------|-----------------|--------------|-----------------|
| L1-Downlink | 1575.42 | RHCP | 4 |
| L5-Downlink | 1176.45 | RHCP | 20 |

The beam from the downlink L-band navigation antenna is global, ensuring that UKNOS is capable of broadcasting to its coverage area, GEO ranging signals and Satellite Based Augmentation System (SBAS) signals through the L1 and L5 frequencies as depicted in Table 2. In-Orbit Test (IOT) after launch of the UKNOS payload on a hosted spacecraft shall be used to validate the functional capability of the navigation payload and its readiness for function and purpose.

The United Kingdom’s Navigation Overlay Service (UKNOS) shall be the UK's regional satellite-based augmentation system (SBAS) to improve the performance of global navigation satellite systems (GNSSs), such as GPS and Galileo with accuracy more than five times that of Galileo’s open service. It will be deployed not only to serve military purposes but also to provide safety of life navigation services to aviation and non-aviation sectors similar to European Geostationary Satellite System (EGNOS) and Nigerian Satellite Augmentation System.

The UKNOS shall use GNSS measurements taken by accurately located reference stations deployed across the United Kingdom. All measured GNSS errors are transferred to a central computing centre, where differential corrections and integrity messages are calculated. These calculations are then broadcast over the covered area using the national geostationary satellite serving as an augmentation and/or overlay, to the original GNSS message.

**SUMMARIZED ANTENNA AND PAYLOAD DESIGN OF UKNOS SHOWN IN
FIGURE 3**

Figure 3 gives an overview block diagram of the L band piggyback payload to meet the designed configuration of UKNOS. Preliminary design details of Antenna and Payload Design are further provided.

The C, Ku or Ka band Navigation antenna may be defined by boresight of ± 7.5 degrees for a minimum uplink service area coverage over the United Kingdom, Europe and Africa as presented in table 3. The antenna for the C, Ku or Ka-band will accommodate LHCP and is a dual-frequency conical horn antenna to be mounted on the earth deck of the hosted British/Military Geostationary spacecraft.

The antenna cut patterns will be analyzed using Ansoft HFSS while the contour patterns will be computed using TICRA GRASP 8 software.

The L Band Navigation Antenna defined by a boresight angle of ± 8.7 degrees will have a global coverage. The L Band navigation helical antenna will accommodate RHCP capable of dual-frequencies with a backfire cavity mounted on the earth deck of the UKNOS spacecraft. It shall be comprised of a helical unit, coaxial line, backfire cavity and antenna support structure (ASST) as shown in figure 4. The backfire cavity is used to reflect the EM waves and improve the gain of the center insert of the reflector. The antenna cut patterns shall be analyzed using Ansoft HFSS while the desired contour patterns shall be computed using TICRA GRASP 8 software.

Table 3: Analytical Parameters of C, Ku or Ka Band Uplink Navigation Antenna of UKNOS.

| Items | Navigation Antenna |
|--------------------------------|--|
| Coverage Zone | Coverage over United Kingdom, Europe and Africa defined by boresight angle of ± 7.5 degrees. |
| Frequency (MHz) Bandwidth | Receiving: Uplink To be determined (TBD) |
| Gain(dBi) | Uplink: (TBD) |
| Polarization | Uplink: LHCP |
| Mount Plane | Earth Deck of Spacecraft. |
| Antenna Type and Assembly | Conical Horn Antenna Horn, Square to Circular Transition, Polarizations, Waveguide Assembly, Support Structure. |

Table 4: Analytical Parameters of L-Band Downlink Navigation Antenna of UKNOS

| Items | L Band Navigation Antenna |
|---------------------------|--|
| Coverage Zone | Global coverage defined by boresight angle of ± 8.7 degrees. |
| Frequency bandwidth (MHz) | Transmitting: Down link 1166.45~1577.42MHz |
| Gain(dBi) | Downlink (To be determined based on SSPA Wattage, Coverage Area Design and Choice of Satellite Bus Platform for hosted payload) 13 Reference to Table D4.5 of Appendix D |
| Polarization | Downlink: RHCP |
| Mount Plane | Earth Deck of Spacecraft. |
| Antenna type and Assembly | Helical Antenna Reflector (Reflector Aperture Φ TBD) and Support Structure. |

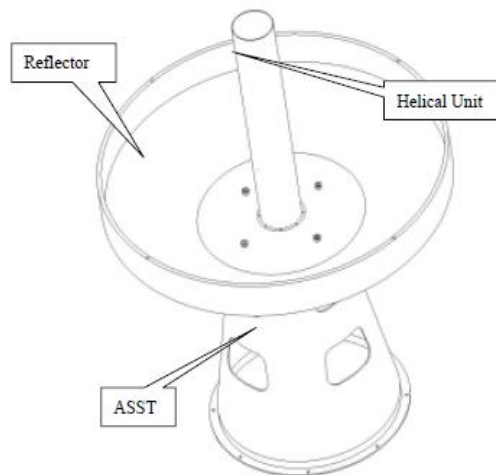


Figure 4: Helical L-Band Navigation Antenna Structure Configuration

The Antenna System Design Layout of UKNOS

In accordance with principles of Antenna layout design, the followings will be considered in the layout design of UKNOS as a hosted payload together with antennas meant for communications on a geostationary spacecraft (Lawal and Chatwin, 2012c):

- Antenna Size;
- Field of view of each antenna;
- Isolation between receiving and transmitting channels
- Connection with repeater;
- Mass of Antenna
- Desired coverage area.

Frequency Conversion Accuracy and Stability of Receivers

The frequency conversion and stability of all receiver units for the UKNOS must be tested and verified at mid-frequency, which shall be externalized outside the receiver and ovenized considering the criticality of frequency stability and conversion accuracy to time-based signals for precision and accuracy as it concerns location-based services and applications. Table 5 shows test item requirement to verify and validate frequency conversion accuracy and stability of 10MHz Ultra-Stable Crystal Oscillators to be used especially as one puts into consideration the minimum frequency conversion accuracy requirement of at least 2.0×10^{-7} over the service life time of the spacecraft (15 years) among others (Lawal and Chatwin, 2011).

Table 5: Typical test results requirements for 10MHz Reference Oscillators before acceptance for integration on the piggy back navigation payload.

| No | Test Item | Requirement | Initial Test | Final Test(Post Vibration Test) | Compliance | Power Voltage |
|----|----------------------------|---|--------------|---------------------------------|------------|---------------|
| 1. | Output Frequency (MHz) | 10 | | | | |
| | | | | | | |
| | | | | | | |
| | Initial Frequency Accuracy | $\leq 6 \times 10^{-8}$ | | | | |
| | | | | | | |
| | | | | | | |
| | Short-Term Stability | 10ms ; $\leq \pm 1 \times 10^{-11}$ | | | | |
| | | 100ms ; $\leq \pm 2 \times 10^{-12}$ | | | | |
| | | 1s ; $\leq \pm 2 \times 10^{-12}$ | | | | |
| | | 10ms ; $\leq \pm 1 \times 10^{-11}$ | | | | |

| No | Test Item | Requirement | Initial Test | Final Test(Post Vibration Test) | Compliance | Power Voltage |
|----|---------------------|--------------------------------------|--------------|---------------------------------|------------|---------------|
| | | 100ms : $\leq \pm 2 \times 10^{-12}$ | | | | |
| | | 1s : $\leq \pm 2 \times 10^{-12}$ | | | | |
| | | 10ms ; $\leq \pm 1 \times 10^{-11}$ | | | | |
| | | 100ms : $\leq \pm 2 \times 10^{-12}$ | | | | |
| | | 1s : $\leq \pm 2 \times 10^{-12}$ | | | | |
| | Output Power(dBm) | ≥ 10 | | | | |
| | | | | | | |
| | | | | | | |
| | Phase Noise(dBc/Hz) | @1Hz : ≤ -100 | | | | |
| | | @10Hz : ≤ -130 | | | | |
| | | @100Hz : ≤ -140 | | | | |
| | | @1kHz : ≤ -150 | | | | |
| | | @10kHz : ≤ -155 | | | | |
| | | @100kHz : ≤ -157 | | | | |
| | | @1MHz : ≤ -160 | | | | |
| | | @1Hz : ≤ -100 | | | | |
| | | @10Hz : ≤ -130 | | | | |
| | | @100Hz : ≤ -140 | | | | |
| | | @1kHz : ≤ -150 | | | | |
| | | @10kHz : ≤ -155 | | | | |
| | | @100kHz : ≤ -157 | | | | |
| | | @1MHz : ≤ -160 | | | | |
| | | @1Hz : ≤ -100 | | | | |

| No | Test Item | Requirement | Initial Test | Final Test(Post Vibration Test) | Compliance | Power Voltage |
|----|-----------------------------------|-----------------------|--------------|---------------------------------|------------|---------------|
| | | @10Hz : ≤ -130 | | | | |
| | | @100Hz : ≤ -140 | | | | |
| | | @1kHz : ≤ -150 | | | | |
| | | @10kHz : ≤ -155 | | | | |
| | | @100kHz : ≤ -157 | | | | |
| | | @1MHz : ≤ -160 | | | | |
| | Harmonics(dBc) | ≤ -30 dBc | | | | |
| | 500Hz-100kHz Spurious(dBc) | ≤ -120 dBc | | | | |
| | 100kHz-500kHz Spurious(dBc) | ≤ -100 dBc | | | | |
| | VSWR | ≤ 2.0 | | | | |
| | Power Consumption Warm-Up(W) | ≤ 10 | | | | |
| | Power Consumption Steady State(W) | ≤ 8 | | | | |
| | TM(V) | 0~5 | | | | |
| | Inrush Current(A) | ≤ 0.5 | | | | |

General guidelines for the selection of oscillators are as follows (Vig, 2007; John, 1992; TemexSpace, n.d.):

- (i) Choice of Nominal Frequency i.e variable: VCXO or Fixed: XO, TCXO or OCXO

- (ii) Choice of stability i.e low stability: XO, Medium stability: TCXO, High Stability: OCXO, USO etc.
- (iii) Frequency accuracy or reproducibility for the system to operate properly?
- (iv) Recalibration Interval requirement i.e. How long must this accuracy be maintained. Will the oscillator be calibrated or replaced periodically or should the oscillator maintain the required accuracy for the service life of the satellite?
- (v) Power availability and conditions
- (vi) Required or allowable warm-up time
- (vii) Operating environmental conditions of the oscillator.
- (viii) Short-term stability (phase-noise) requirement
- (ix) What is the size/mass constraint?

Generally and for the stringent requirements of stability, space-borne oscillators use customized ovenized controlled oscillators designed to suit the orbit and space environment in which they will be deployed; particularly in terms of radiation and temperature variations. Figure 5 shows a typical OCXO Block diagram while Figure 6 shows the 10MHz Master oscillator used in the navigation payload of Nigerian Communications Satellite (NIGCOMSAT-1R).

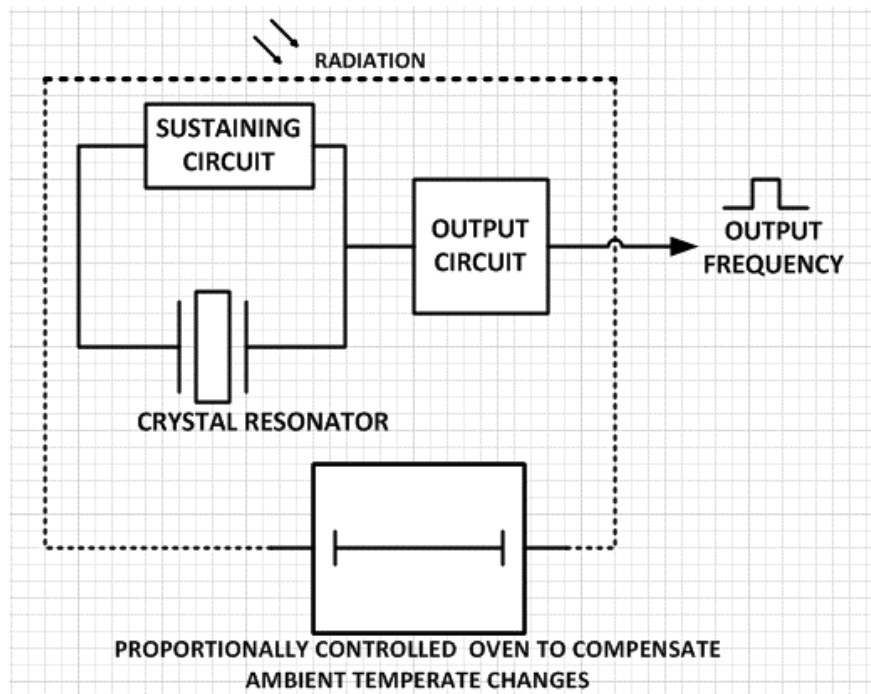
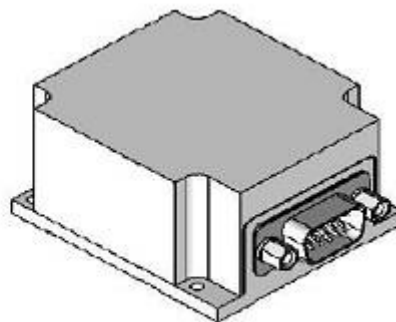


Figure 5: A Typical Ovenized Crystal Oscillator (OXCO) showing its Crystal Resonator and external circuits in a proportionally controlled oven to compensate ambient temperature changes.



10MHz Master Oscillator



10MHz ultra stable crystal oscillator

Figure 6: shows the 10MHz Master oscillator used in the navigation payload of Nigerian Communications Satellite (NIGCOMSAT-1R).

For the short and medium term objectives, rather than building and launching more than one satellite for redundancy, entire global coverage and reliability of services, a cooperative agreement can be reached with managers of the NIGCOMSAT-1R Navigation system; a geostationary satellite with a navigation overlay service broadcasting corrections and integrity information for GNSS satellites in the *L1* frequency band (1575.42 MHz) as well as *L5* in the frequency band (1176.45 MHz) with the service coverage area meeting the requirements of the United Kingdom ($EIRP \geq 30\text{dBW}$) in case of a geostationary satellite link failure.

The Navigation payload of NIGCOMSAT-1R has been designed to support and operate in both *L1* and *L5* frequency signals meant to augment the Global Navigation Satellite System (GNSS) over Africa starting with Nigeria by achieving its aim of improving accuracy, reliability, Integrity and Continuity of GNSS information through NOS on 2nd Generation Satellite-Based Augmentation System (SBAS) using Dual Frequency Multi-Constellation (DFMC) for the African continent and beyond. The Navigation Overlay Services is meant to serve maritime, defence utility, aviation, transport sector (roads & rail), public safety utility, and security of strategic national infrastructure, service and products in the African market and beyond. Figure 7 and 8 shows downlink coverage areas with overlaid Equivalent Isotropic Radiated Power of NIGCOMSAT-1R Geo-Navigation Satellite on both *L1* and *L5* frequencies. Figure 9 shows pictorial architecture of Nigerian Satellite Augmentation System (NSAS) (NigComSat-1R, 2009).

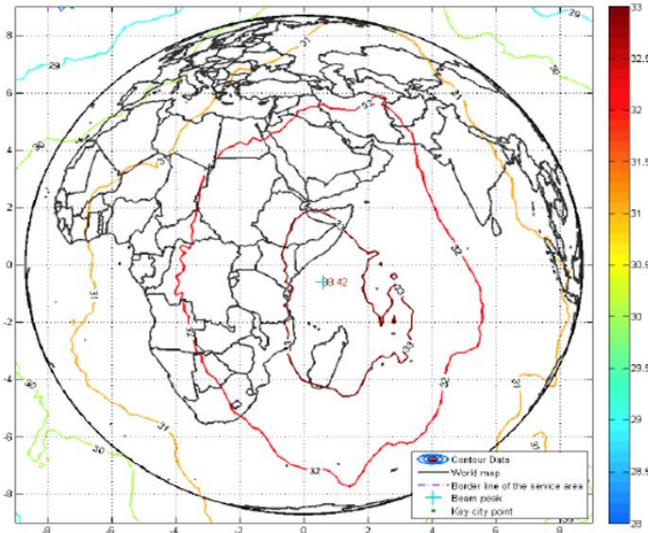


Figure 7: The downlink coverage beam of NIGCOMSAT-1R Geo-Navigation Satellite on L1 Frequency

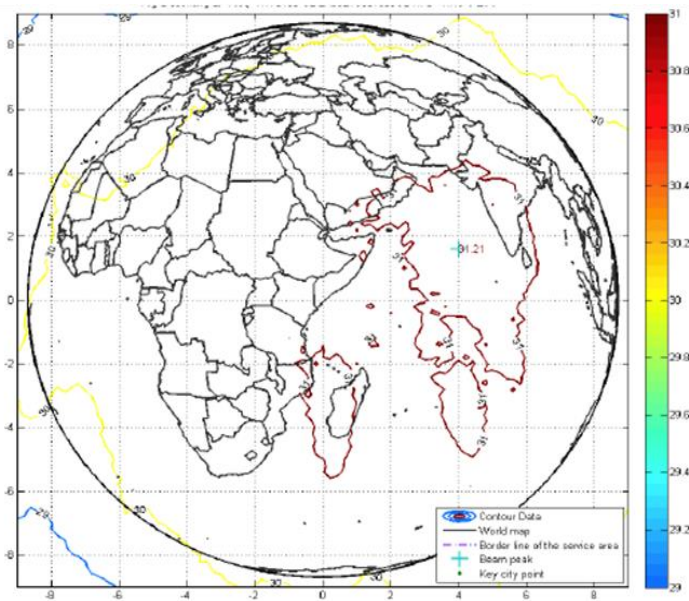


Figure 8: The downlink coverage beam of NIGCOMSAT-1R Geo-Navigation Satellite on L5 Frequency

Figure 9 shows pictorial overview of Nigerian Satellite Augmentation System (NSAS) Architecture.

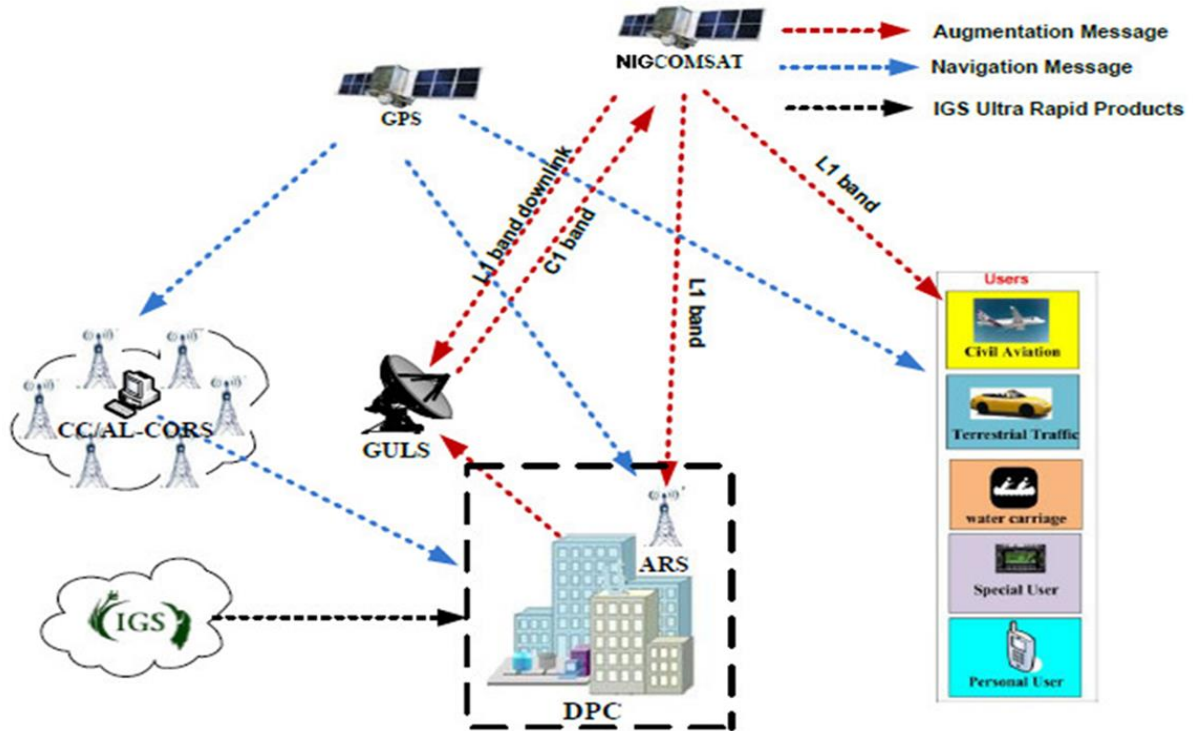


Figure 9: Nigerian Satellite Augmentation System Architecture.

UKNOS Ground Infrastructure

The UKNOS ground infrastructure shall be comprised of:

- A ground network of reference stations subject to land mass coverage of the United Kingdom and cooperating neighbours and countries.
- Two (2) mission control centres; one situated at the ground control station of the national geostationary satellite.
- UKNOS Wide Area Network, which integrates the reference stations across the UK and environs to the master ground station comprising of an uplink station and communication network for all the components of the ground segment. (The National Satellite Communication resources carrying UKNOS as a hosted payload can be used to integrate reference stations especially in areas lacking robust terrestrial communication infrastructure).

UKNOS Applications

The NOS Serving as an augmentation, or overlay, to a global navigation satellite system (GNSS) message will improve the accuracy and reliability of GNSS positioning information, and provides a crucial integrity message regarding the continuity and availability of the signal. Applications and service delivery aside military and defense related operations includes but is not limited to Aviation, Maritime, Precision agriculture, Location-based services (LBS), Mapping and Surveying, Rail and road transportation, timing & synchronization etc.

The UKNOS services can be designed with three core services:

1. **Military Grade Service (MGS):** For defense related operations including civil aviation with the required guaranteed performance and integrity warning system.
2. **Open Service:** free and open to the public for the public and cooperating nations and/or neighbours.
3. **Others may be UKNOS Data Access Service (UDAS):** offered on a controlled access basis via the Internet and mobile phones for customers requiring enhanced performance for professional use;

CONCLUSION

The United Kingdom can deploy a low-cost Satellite-Based Augmentation System (SBAS) as a navigation overlay service (NOS) on a hosted national geostationary satellite utilizing GNSS, especially GPS and Galileo as an alternative to the Galileo's PRS. The Open Service (OS) of Galileo can provide vertical and horizontal position measurement of within 1 meter precision while the High Accuracy Service (HAS) as the name depicts provides better accuracy for sensitive applications with higher degree of service continuity and encryption as may be applicable. The Public Regulated Services (PRS) of Galileo are restricted to government-authorized users for defense-related and sensitive applications requiring a high level of service continuity, integrity and are encrypted with anti-jamming mechanisms. The UKNOS system will deliver high performance in terms of Integrity, Reliability (availability), Service continuity and an accuracy of 5cm through precise point positioning (PPP) to meet UK's security-relevant operations. An African neighbour and former British colony; Nigeria is willing to enter into cooperative agreement with its existing Navigation Overlay system; Nigerian Satellite Augmentation System (NSAS), similar to EGNOS, with a service coverage area meeting the requirements of the United Kingdom ($EIRP \geq 30\text{dBW}$) as a short term measure and/or a redundant system after launch of a national satellite as a preemptive measure in case of a geostationary satellite link failure before consideration for full global navigation overlay service coverage in the long run. This has an additional benefit in that it would signal to the rest of the world that the UK has become a more outward looking economy.

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