LoRaWAN in Satellite Communications: Communication with the United States Naval Academy CubeSat

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***Abstract*—Internet of Things (IoT) devices are becoming ubiquitous within modern sensors to transmit information and interact with numerous networks. Long Range Wide Area Network (LoRaWAN) devices are low-power, efficient, long-range solutions for RF modulation solutions. LoRaWAN is an IoT system alternative to traditional cellular networks, Bluetooth, Narrow-Band IoT, and local area networks such as WiFi.**

An array of sensors and devices are used to expand the LoRa network. Historically, gateways can support over 10,000 devices. In the event extra sensors are required, additional gateways are all that are needed to grow the network. This is essential for satellite communications as signal coverage can span the globe.

This paper will discuss using LoRaWAN devices as a conceptual design plan for using the United States Naval Academy CubeSat with pre-flight readiness techniques.

Keywords: LoRaWAN, CubeSat, IoT, Satellite Communications

I. INTRODUCTION

The U.S Naval Academy's (USNA) Small Satellite Program (NASSP) has focused on CubeSat satellites since 2012, with a total of seven CubeSats developed and launched as of 2019 [1]. The University of New Mexico COSMIAC research center plans to integrate a LoRa sensor into a CubeSat with the Naval Academy Standard Bus (NASB) interface. The USNA CubeSat will orbit the Earth at a 400km altitude with a 45° inclination angle. The distance and minimal speed of 7.5km/s (17,000 mph) to maintain LEO orbit presents new challenges to robust LoRa technology. To collect data broadcast from a LoRa device installed on the CubeSat, an uplink to a LoRaWAN gateway will be established at ground level in Albuquerque, New Mexico. This paper defines the project as graduate-level student support for the sensor integration endeavor, with the satellite's anticipated launch date of late 2024 to early 2025.

A. LoRa and LoRaWAN

LoRa began in France circa 2009 by Nicolas Sornin and Olivier Seller. The technology initially targeted wireless communications with gas, water, and electric meters using Chirp Spread Spectrum (CSS) modulation technology [2]. As of 2023, LoRa connections are expected to reach 730 million devices in the IoT industry [3]. As part of the low-power wide area (LPWA) IoT category, LoRa has a CAGR of 38% in 2021-2022 and an estimated CAGR of 27% of the IoT market in 2022-2027 [4]. Integration into small satellites opens possibilities to the industry for another facet of IoT connectivity. Fig. 1 notes how the Physical Layer (PHYS) of LoRa devices interacts with the Media Access Control (MAC) layer of custom-driven APIs and applications.

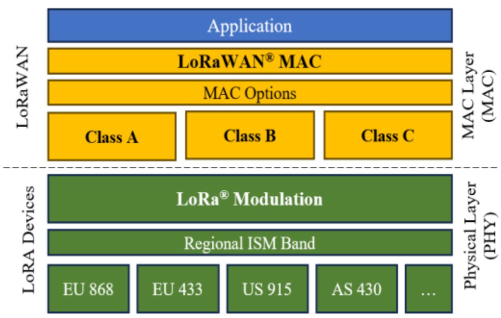


Fig. 1 LoRa Application Layer

LoRa devices encompass hardware within the LoRa frequency bands: 430MHz (Asia), 433-868MHz (Europe), and 915MHz (North America). LoRa Wide Area Network (LoRaWAN) adds HTTP connectivity through gateway devices, typically to a cloud service provider. As of 2023, the world record for LoRa transmission is 1336km (830 miles), set by LoRaWAN trackers on a fishing boat off the Sesimbra coast of Portugal [5]. While the record distance is encouraging, the speed and orientation of the CubeSat will need evaluation for theoretical maximum bit rates and achievable downlink reception. Furthermore, the record had been set by a LoRa STMicroelectronics STEVAL-STRKT01 [6] device with 860-930MHz channel operations achieved at mean sea level. The CubeSat will be subjected to vibration and possible single-event effects while orbiting above the Earth and beyond the ionosphere. The resiliency of the broadcast UHF signal depends on several factors, including its chirp Spreading Factor (SF), code rate (CR), and standard 125kHz bandwidth for LoRa modulation.

Constraints exist at the ground station as well. LoRa devices directly connected to a network, such as LoRa gateways, are described as LoRaWAN systems. A LoRaWAN gateway must be installed at a location with a non-tracking-enabled antenna. The location of the receiving gateway should be placed outdoors to limit building RF attenuation. Sites considered are on the rooftop of COSMIAC's research launch pad laboratory (35.05394N, 106.6205W) or in an isolated spot atop the Sandia Mountain crest in Albuquerque, New Mexico (35.2068N, 106.4131W). Minimal surrounding thermal noise from a rural area is ideal and assumed at 290K for this experiment. A gateway with a standard monopole antenna tracking antenna will be placed, unobstructed, to receive simple messages from the LEO CubeSat. However, this paper discusses the possible use of RHCP antennas to anticipate an active solar maximum during the launch of the CubeSat.

This paper will review the readiness of the LoRa integration, including an analysis of orbit parameters, link budget, and achievable satellite communication metrics. Adding the LoRa system into a CubeSat will use standard architecture functionality and may open possible research issues. Parameters analyzed in this paper will include:

- Hardware and Software
- Antenna Considerations
- Link Budget
- Orbital Parameters

Each category will weigh the effectiveness of sensor integration. The research will review the functionality of LoRa devices and the link margin constraints in a low-power LEO environment. Fig. 2 denotes the CAD rendering of the satellite. The LoRa module(s) will be placed within a 2U slot in the CubeSat Payload Module (PM).

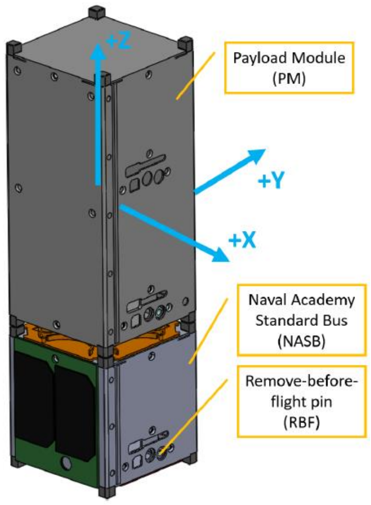


Fig. 2 USNA CubeSat

II. Hardware And Software

LoRa sensors and the connected gateway typically work with a cloud vendor service for node management. LoRa cloud services include "The Things Network," Amazon IoT Core for LoRaWAN, Arduino Cloud, and services from individual device manufacturers. The Things Network is used for the projects due to its ease of setup and device tracking. As a service used with IoT devices, the interface for the data can be accessed and controlled with HTTP-enabled devices, such as PCs or mobile phones. Fig. 3 addresses the high-level system configuration for accessing information transferred from the LoRa sensor to the ground station gateway. Table I contains the LoRa hardware used in the setup.

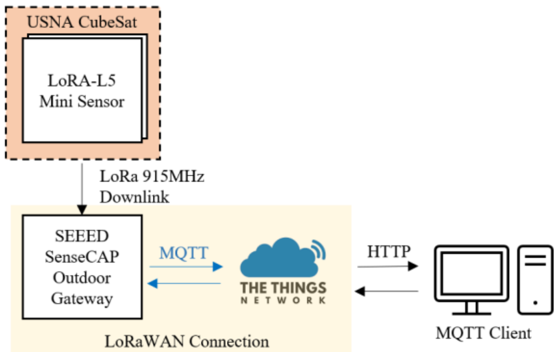


Fig. 3 High-Level Network Setup

TABLE I
HARDWARE USED IN SYSTEM

Device	Part No	Function
LoRa E5 Mini	STM32WLE5JC	CubeSat LoRa Radio
SEEED Gateway	LoRa-G-915-E/4G	SenseCAP LoRaWAN Gateway
Custom Deployable RHCP Antenna	N/A	LoRa Radio Antenna, 50Ω

A. LoRa Radio

Seeed Studio manufactures the LoRa radio chosen and is available in various form factors using the STM32WLE5JC, ARM Cortex-M4 microcontroller, and embedded SX126x radio. The radio is capable of the US915 channels.

Choosing an appropriate spreading factor for the LoRA signal and data is critical for an extended-range test. Increasing the spreading factor impacts the communication performance with large SFs, increasing time over the air, increasing energy consumption, and reducing the data rate, but improving the communication range. The gateway will have a more considerable reception sensitivity to the maximum SF12, but the airtime limits the amount of data packets sent in 24 hours per device. Varying the spreading factor on demand is an option for testing, as the gateway can send an updated command with a downlink message to the LoRa transmitter. The 2019 LoRa transmission record experienced excessive vibration within a high-altitude balloon [7], and faster SFs for airtime may be required regardless of the receiver sensitivity. Code rate will also be analyzed, as the portion of the transmitted bits that carry information can provide a gain via the information processing of the data packet with added data correction. The code rate is configurable and can be set to 4/5, 4/6, 4/7, or 4/8, having 1, 2, 3, or 4 bytes of redundancy, respectively.

The time for one bit, defined in (1), is determined by the bandwidth and spreading factor chosen.

$$R_b = SF \cdot \frac{BW}{2^{SF}} \tag{1}$$

SF is the spreading factor, and B is the 125kHz bandwidth configured for this test. FCC regulations limit the dwell time of messages to 400ms on uplinks and ten downlinks [8]. Uplink messages are defined as messages sent by end devices to Network Servers, while downlink messages are Network Server messages to end devices [9]. The overhead on the uplink/downlink messages contains a header with the MHDR, DevAddr, FCtrl, FCnt, and MIC, which includes 13 bytes of information. Furthermore, airtime will be limited to 30 seconds of uplink per device in a 24-hour window. At a spreading factor of SF10, the airtime would be over the 400ms limit unless the payload is 11 bytes or less. Fig. 4 describes the code factor rates under each spreading factor analyzed for this test with the airtime considered. Higher spreading factors will be attempted if packet loss or poor reception is too high.

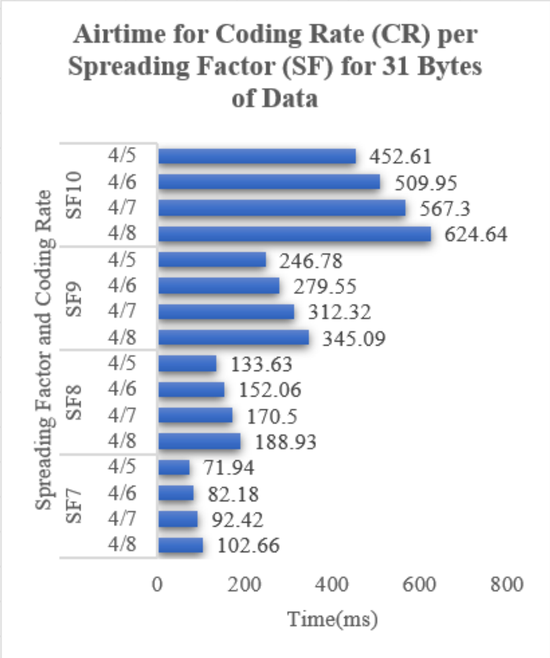


Fig. 4 Airtime for Various SFs and CRs

To stay within the fair use policy of the Things Network, multiple LoRa end devices could be employed on a separate channel or within time with time division multiplexing (TDM). Using the highest data rate, SF7, as a "wake-up" for the system while the satellite is in the receivable transmission range of the gateway can streamline the execution strategy.

B. Arduino Controller

Although subject to change before the flight test, an Arduino Nano 33 IoT device is planned to send messages via UART to the TX/RX pins of the Wio-5 mini. The Nano 33 IoT controller has an embedded Ublox NINA-W102, which will be used as an additional low-power IoT device. The unit has an intern inertial measurement unit and a real-time clock (RTC) that can be updated with its WiFi connection while on the CubeSat. This will be a crucial aspect to configure for the system as the radio will stop transmitting while not in view of the gateway. Fig. 5 is the LoRa-E5 mini radio board used in the CubeSat test. Fig. 6 is the Arduino Nano 33 IoT board, which will transmit message commands to the LoRa-E5 with the TX/RX UART pins and has a real-time clock chip for accurate timekeeping. Additional real estate in the 2U configuration of the payload will be used for batteries needed during events when the CubeSat's power bus is unavailable. The maximum amount of power for the 2U bus is 3 watts. The RF output power of the LoRa-E5 mini is -8dBW (158mW) at 915MHz [10].

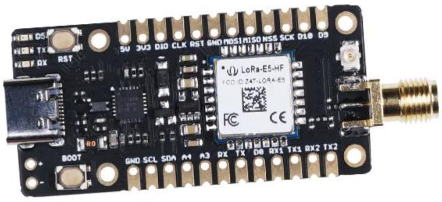


Fig. 5 LoRa-E5 Mini Radio

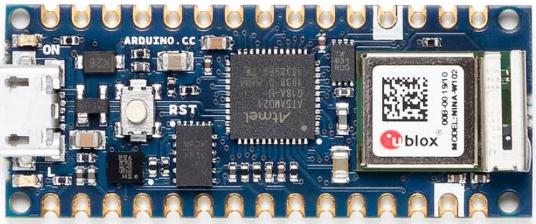


Fig. 6 Arduino Nano 33 IoT Board

Using commercial-of-the-shelf (COTS) parts is ideal with the low-cost, low-profile, and low-power requirements for CubeSat with a calculated sacrifice performance. IoT devices are meant for small-scale, ad-hoc systems tasked with redundant operations. The Arduino hardware was chosen for this CubeSat test based on its past performance with LEO CubeSat integration. Previous CubeSat missions with Arduino include weather forecasting, attitude determination, and preliminary thermal testing at different levels of fidelity [11]. These past tests also describe the Arduino boards surviving the vibration and radiation levels in a LEO environment. Ongoing research, including Linux headless operating system on Raspberry Pi devices, will open Broadcom system on a chip (SoC), integrated ARM-compatible CPUs, and on-chip graphics processing units (GPUs) for future IoT CubeSat systems.

C. Ublox ZED-F9R GNSS Receiver

In addition to the Arduino and LoRa system components, a Global Navigation Satellite System (GNSS) receiver will be utilized. The ZED-F9R receiver, noted in Fig. 7, can operate both upper and lower L-band GNSS (1164-1350MHz, 1551.9-1610MHz, respectively) through a single RF, multi-band antenna SMA connection. Information collected from the Ublox receiver is parsed from the Ublox \$PUBX00 ASCII message to include GPS Time, Latitude, Longitude, and altitude from mean sea level (MSL).

Fig. 7 Ublox ZED-F9R

Though a ruggedization process is needed, the simple configuration in Fig. 8 will suffice for the hardware setup. The setup's low real estate and power consumption will allow additional batteries and equipment within the 2U payload designation.

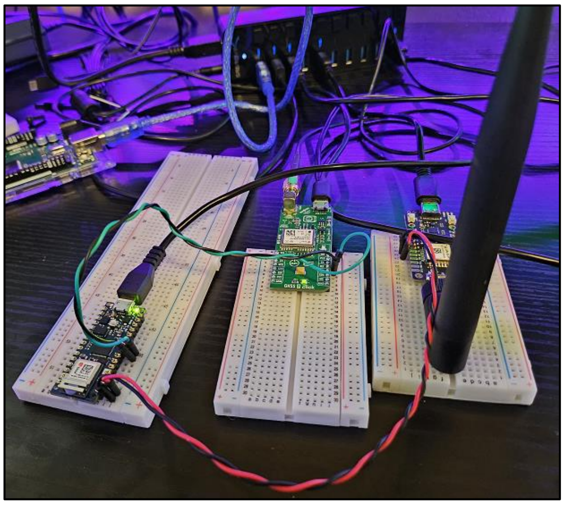


Fig. 8 Test Bench Setup of Arduino Nano 33 IoT, Ublox ZED-F9R, and LoRa E5 mini

B. Software

The software utilized for this project will encompass the Arduino IDE in C++ code. The Arduino Nano 33 IoT will read data from the ZED F9R Ublox, parse the GPS information, and send the message to the LoRa-E5 via UART. A total of 31 bytes will be used for the payload, including the header and CRC. With the worst-case scenario code rate of 4/5 and a spreading factor of 7, the signal will have a minimal 71.94ms airtime and will grant more messages per day. Adhering to "The Things

Network" fair use policy of 30 seconds of uplink time per device per day, a message could be sent 417 times in 24 hours.

D. LoRaWAN SenseCAP Gateway

Data packets received at the gateway will be sent via the MQTT server in hexadecimal format. The hexadecimal format is converted to a human-readable format using a converter java script on the Things Network website. After initial testing with code rate and spreading factor, a JSON string can be incorporated for the MongoDB database located within a cloud provider's data center. NodeJS is a popular API for receiving data packets for object storage and may be employed later.

The "Things Network" cloud will log the device operations for now. The LoRaWAN Network Server is a popular solution for managing applications, end devices, and gateways. Additionally, large cloud providers such as AWS, Microsoft Azure, and Google Cloud have integration tools established for Things Network applications.

III. Antenna Considerations

Selecting an antenna for the satellite requires understanding how CubeSats can deploy their hardware post-launch. An antenna that can deploy to maximize bandwidth and gain is ideal. Additionally, a solar maximum is expected to occur from 2024-2025 [12] and increase the ionosphere's total electron count (TEC). The solar maximum in 2017 caused a -10dB SNR reduction to right-hand circular polarized (RHCP) GNSS signals [13] and will undoubtedly affect a signal at half the frequency. LoRa hardware typically employs a vertical monopole whip antenna. The charged ionosphere could heavily influence the antenna. A RHCP Helix deployable antenna could be used to compensate for destructive interference. As illustrated in Fig. 9, this RHCP antenna can deliver near 10.7dBi gain compared to its linear counterpart with 5dBi. LoRa RHCP receive antennas are commercially available to eliminate the polarity mismatch. ISIS antennas are another popular option for CubeSat antenna deployment and will match the polarity of the gateway antenna. However, although ISIS antennas can cover a large azimuth and elevation during transmission, the antennas typically have 0dBi gain.

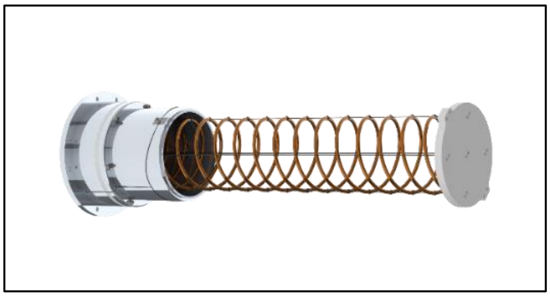


Fig. 9 University of Colorado Example Deployable Helix Antenna

IV. Link Budget

Various factors in the satellite link budget will be considered for the pre-CubeSat launch. The isotropic radiation of the antenna should be analyzed to understand a pragmatic link budget along with expected system losses in the system and free space attenuation. Ionospheric and tropospheric effects can attenuate a signal through destructive interference. Generally, this link budget is defined by (2):

$$\frac{E_b}{N_0} = \frac{P_t G_t G_r L_a L_l \lambda^2}{(4\pi R)^2 k T R_b} \quad (2)$$

A. Propagation Loss

To predict nominal RF propagation loss, free space path loss denotes the RF attenuation over a distance with (3):

$$FSL = 20log(d) + 20log(f) - 147.55 \quad (3)$$

Free space path loss is expected to be 143.7 dB. Atmospheric effects will change the losses while the satellite is overhead during daytime hours and are expected to be minimal at night. Peak total electron count (TEC) during daytime may obfuscate the signal beyond reception as up to -10dB of ionospheric loss is expected. Misalignment with the RF propagation [AML] adds to the loss of received power. SeeedStudio's LoRa-E5 mini radio output power is -8dBW. Adding the transmit antenna gain, the EIRP is -5.14dBW and the received power will be close to -148.84dBW after FSL, cable, and insertion losses. The SenseCap LoRaWAN gateway has a -169dBW reception sensitivity [14], which will be tested against the 400km distance and satellite velocity.

B. Spreading Factor and Coding Rate

Several other factors are evaluated with possible transmission loss over a significant distance. A bandwidth of 125kHz is ideal as the smallest LoRa bandwidth to reduce noise power and transmission time. The bandwidth of 125kHz can also compensate for a ±31kHz Doppler frequency shift.

As discussed earlier, the spreading factor SF and its coding rate (CR) are considered. The CR is the number of information bits divided by the total number of bits sent, as shown in (4).

$$C = SF \frac{CR}{\left[\frac{2^{SF}}{BW}\right]} \tag{4}$$

The coding rate provides a code gain considering the spreading factor and the channel capacity. A test conducted in September 2020 concluded that, with a LEO satellite at 550km and a worst-case CR of 4/5, a packet delivery ratio (PDR) is achievable [15] with SF7 to SF12. Theoretical results from the tests were calculated for the elevation angle of the satellite in Fig. 10. Between the two tests in the experiment, 68 packets were collected with a CR of 4/5, and 55 packets were collected with a CR of 4/6. Empirical results for the test for the PDR are noted in Fig. 11.

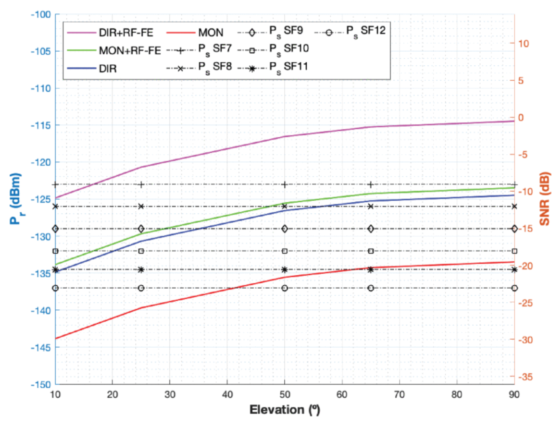
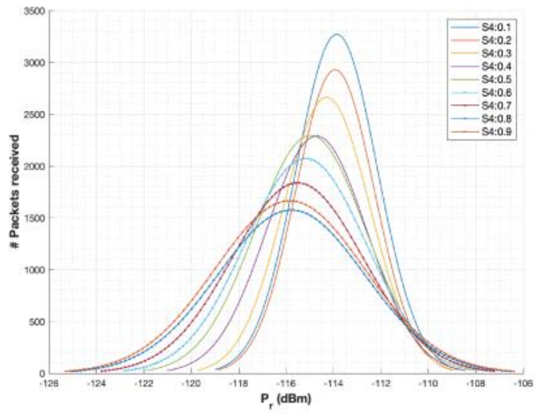


Fig. 10 Estimated Power Received at Satellite Elevation



(b) Number of received packets for the best case with a $CR = \frac{4}{6}$

Fig. 11 Recorded 97% PDR with Worst-case Scintillation at 87% PDR.

With link budget parameters calculated, carrier-to-noise ratio can be estimated. Table II denotes the calculated Carrier to Noise (C/N) expected at the receive antenna using the standard monopole whip antenna for both the LoRa-E5 and gateway.

TABLE II
SYSTEM LINK BUDGET

Quantity	Decilogs
[EIRP]	-5.15dBW
[FSL]	-143.67dB
[G/T]	2.85dB
[k]	228.6dBK
[Other]	-1.5dB
[BO]	-6dB
[AML]	-3dB
[BW_{TR}]	-51dB
C/N	21.13dBHz

V. ORBIT PARAMETERS AND TIMING

Understanding satellite orbit parameters is essential in calculating Doppler frequency offset and time because of the gateway's latitude. Calculating the mean motion, argument of perigee, right ascension of the ascending node, and the true anomaly are a paradigm of the test setup, as noted in Fig. 12.

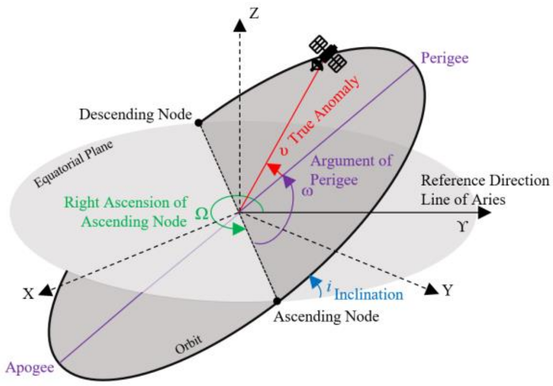


Fig. 12 Orbit Variables for UNSA CubeSat

LoRa communications are in North America's 900-928MHz frequency band per the FCC Certification Guide and 47 CFR § 15.247 [16]. The USNA CubeSat will be orbiting other countries with restricted 900-928MHz communication bands multiple times in 24 hours. Transmission will need to be shut off when not in range of the gateway. The period in which the satellite will be in view will also determine how many messages in the various spreading factors can be sent in the 30 seconds per day per device fair use restriction.

A. Mean Motion

Mean motion (n) is defined as the number of orbits the satellite completes about the Earth in 24 hours. Understanding the number of rotations is essential for knowing the number of potential data captures the gateway can expect from the LoRa transmission. Kepler's third law utilizes the nominal mean motion (n0) to find the mean motion of $1.13\text{x}10^{-3}$ radians/second ($6.47\text{x}10^{-3}$ degrees/second) described in (5). The axis (a) for a circular orbit is estimated at 6,771km with a mean earth oblateness of 6,371km. The inclination for the satellite is 45° as defined by USNA, and the eccentricity for a circular orbit will be 0.001 for a near 0 estimation.

$$n = n_0\left[1 + \frac{K_1 1 - 1.5 sin^2 i}{a^2(1 - e^2)^{1.5}}\right] \quad (5)$$

B. Orbit Revolutions/Day and Anomalistic Period

Considering the mean motion (n), the USNA satellite will have 15.6 revolutions per day while using (6) to understand an 86400-second period. The anomalistic period (7) equals <u>92 minutes and 22.8 seconds</u> to make one revolution from a zenith perigee above the gateway.

$$T = \frac{n}{2\pi}\Delta t_{sec} \quad (6)$$

$$P_A = \frac{2\pi}{n} / 60 sec \quad (7)$$

Along with the mean motion (n), we can find the rate of regression in (8) that equates to $1.63\text{x}10^{-6}$ radians/second.

$$K = \frac{nK_1}{a^2(1 - e^2)^2} \quad (8)$$

With both the mean motion and the rate of regression, we use this information to find the rate of regression at the nodes (9) and the rate of rotation at the apsides (10) at $1.16\text{x}10^{-6}$ radians/second. This is arguably 0 for a circular LEO orbit.

$$\frac{d\Omega}{dt} = -Kcos(i) \quad (9)$$

$$\frac{d\omega}{dt} = K(2 - 2.5 sin^2 i) \quad (10)$$

Although the nodes' regression and the apsides' rotation are effectively 0, the regression rate for the USNA LEO satellite is considerably large and will change the longitude daily. With (11), we see the right ascension of the ascending node or the point where the CubeSat will cross the equatorial plane moving south to north, changes by 5.72 degrees westward per day!

$$\Omega = \Omega_0 + \frac{d\Omega}{dt}(t - t_0) \quad (11)$$

I will need to consider not only the latitude in which the satellite will be visible by the gateway but also the difference in longitude. The satellite drifts out of range for a more extended period of close to 22 days for the satellite to be at the gateway zenith again and carefully consider a wide field of view antenna for the gateway ground station or cyclical adjustments to the ground antenna angle.

C. Mean Anomaly and True Anomaly

While we know the time and revolutions per day the satellite will be in view, and I also need to find the true anomaly (v). The mean anomaly is the angle between the periapsis and the satellite's current position measured from the center of the central body concerning time. True anomaly is the actual measured angle in the orbital plane between the vector extending from the focus to the point of periapsis and the vector extending from the direction to the object's actual position. For the circular LEO orbit, the identities are close to the same. Due to the oblateness of the Earth, both values should be measured with the short time in view over the gateway Earth station. The mean anomaly in (12) will change by 19.48° every 5 minutes.

$$M = M_0 + n(\Delta t) \quad (12)$$

Due to the circular orbit, the mean motion can equal the eccentric anomaly (E) for a minor eccentricity. After calculating the mean motion, we can understand the true anomaly by (13) is 19.50° after 5 minutes. This equates to 2,292 km of latitude change over 5 minutes, with 1° of latitude equating to 111km.

$$tan\frac{v}{2} = \sqrt{\frac{1+e}{1-e}tan\frac{E}{2}} \qquad (13)$$

D. Time in View

Understanding the time in view lets us know the satellite's time above the gateway during orbit. I can use Fig. 13 to understand the satellite's orbit and distance to the horizon.

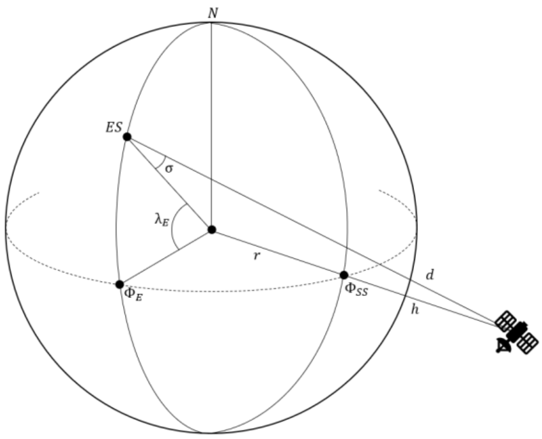


Fig. 13 Satellite Relative to Earth Station Horizon

Fig. 14 is the geometry of the satellite extract from Fig. 13 to illustrate the mathematics used to solve the distance from the horizon in (14).

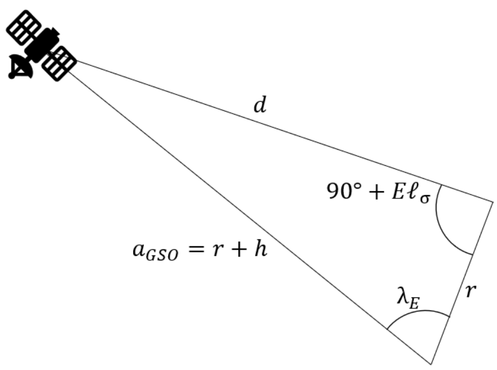


Fig. 14 Extrapolated Figure for Distance and Angle of Satellite to Earth Station

$$d = \sqrt{a_{GSO}^2 - r} \qquad (14)$$

Then, while the distance is known, we can calculate the angle λ_E with (15) to understand that the latitude changes by about 19.50° over 5 minutes. This matches the true anomaly calculated earlier due to the circular orbit.

$$\frac{d\lambda_E}{dt} = \left[\sin^{-1}\left(\frac{d}{a_{GSO}}\right)\right]\Delta t \qquad (15)$$

The change in the latitude degrees equates to a satellite position change of 2,292.8km. Considering the satellite speed of 7.668km/second, as calculated with (16), I can expect the CubeSat, when the satellite's longitude is the same as the earth station gateway's, to be over the horizon for about 300.23 seconds (5 minutes and 13.8 seconds) when using the calculated velocity for (17). Changes in satellite longitude over time and the elevation angle that is received by the gateway's antenna will affect the number of missed packets of information and the C/N of the signal. G is the gravitational constant in $m^3/kg^{-1}s^{-2}$, M is the mass of the Earth, and R is the 400km distance to the satellite.

$$v = \sqrt{\frac{G \times M}{R}} \qquad (16)$$

$$t_{visible} = \frac{\lambda\ E_{visible}}{360 / T_{Orbit(sec)}} \qquad (17)$$

Knowing the satellite's velocity, we can also calculate that the satellite will orbit the Earth 14.33 per day when using (18). Understanding both the time in view and orbits per day, the amount of LoRa broadcast on a selected SF can be calculated with the time on air. We will use these vectors to comply with the Things Network fair use policy over North America.

$$n_{orbit/day} = \frac{v_s}{M}s^{-1} \times \frac{\Delta t}{2\pi} \qquad (18)$$

E. Broadcast Timing Consideration and Summary

Due to the nature of the satellite's orbit and considering the Things Network fair use policy, we can conclude when the satellite should be broadcasting. Spreading factors of SF7, SF8, and SF9 were chosen for the test flight experiment. Table III summarizes the orbit parameters expected for the CubeSat flight experiment and the number of broadcasts made within the 5-minute in-view period.

TABLE III

ORBIT VECTORS AND LORA CONSTRAINTS

Orbit Vectors	
SV Time in View	300.23 seconds
Orbits Per Day	14.33 rev/day
Longitude Drift	5.72 deg/day
Mean Motion	$6.47\text{x}10^{-2}$ deg/sec
Velocity	7.668 km/sec
LoRa Constraints	
SF7 Max Messages	2922/day
SF8 Max Messages	1595/day
SF9 Max Messages	869/day
SF10 Max Messages	480/day

VI. CONCLUSION

In this paper, I discussed the integration of a LoRa transmitter into the U.S. Naval Academy UNSA CubeSat. Various factors, including RF propagation, code rate, spreading factor, Things Network restrictions, and orbital mechanics, must be understood before using a transmitting device from a CubeSat. Country restrictions prohibit certain bands regardless of U.S. FCC assignments, and the consideration for Things Network's fair use policy must be followed. A new era of IoT devices may be employed for CubeSat use over the next decade. LoRa is no exception as one fundamental building block for the next generation of IoT technology.

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