Design and mission planning of Bobcat-1, the Ohio University CubeSat

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BIOGRAPHIES

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ABSTRACT

Being a low-cost space technology, CubeSats enable the development of space missions for educational purposes as well as for technology demonstrations. Commercial-off-the-shelf (COTS) components are often an option to develop CubeSat missions meeting requirements in terms of performance, cost and development time. Bobcat-1 is the first CubeSat developed in the Avionics Engineering Center (AEC) at Ohio University, (School of Electrical Engineering and Computer Science), in Athens, Ohio. Bobcat-1 was selected for launch through the NASA CubeSat Launch Initiative (CSLI) and launched on October 2, 2020. In [1], which was produced by NASA to support CSLI, information and guidelines are provided, which have been followed to develop Bobcat-1. The project has two main objectives: one educational and one scientific. The educational mission of Bobcat-1 is to provide students (undergraduate and graduate) with hands-on experience with a spacecraft mission through all stages including design, development, control, operation, data management, data processing, and analysis. Furthermore, a larger number of undergraduate students and high-school students will be involved through the outreach program with the involvement of Ohio University's Amateur Radio Club. The scientific objective is related to Global Navigation Satellite System (GNSS) interoperability, which is crucial in challenging environments such as high altitude Space Service volume (SSV) [1 - 4]. Bobcat-1 will enable an in-space experiment to evaluate the performance of GNSS inter-constellation time offset estimation from Low Earth Orbit (LEO). Details of the mission motivations are given in [5]. In this paper, the high-level mission

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requirements, the design and development of the CubeSat, and the design and development of the ground station will be detailed.

INTRODUCTION

Bobcat-1 is a CubeSat developed at Ohio University's Avionics Engineering Center and was selected for launch through the NASA CubeSat Launch Initiative (CSLI). It was manifested for flight on Educational Launch of Nanosatellites (ElaNa) Mission 31, which launched on October 2, 2020. The CubeSat deployment into space from the International Space Station is expected by the end of 2020.

The project has two main objectives, educational and scientific, respectively. The educational mission of Bobcat-1 is to provide students, undergraduate and graduate, with hands-on experience with a spacecraft mission through all stages from the design to development, control, operation, data management, data processing, and data analysis. **Figure 1** shows Bobcat-1 under development, in the Avionics Engineering Center laboratory at the Stocker Center, Ohio University, in Athens, OH.

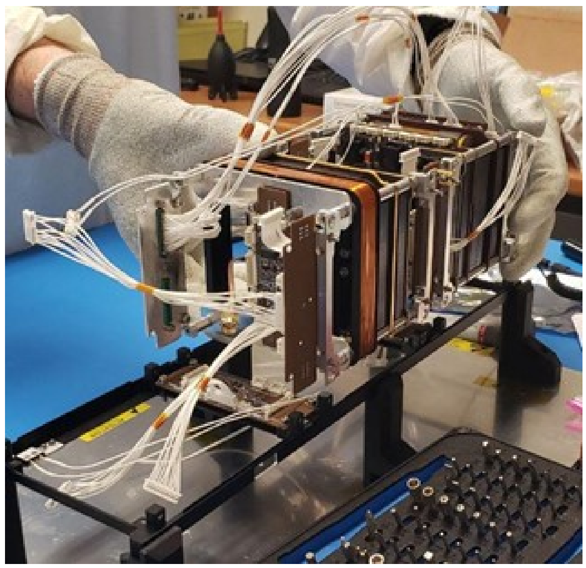


Figure 1: Bobcat-1 under development.

The outreach program, through the Ohio University's Amateur Radio Club, will involve a larger number of undergraduate and high-school students.

The scientific objective is related to Global Navigation Satellite System (GNSS) interoperability: the Bobcat-1 CubeSat mission will serve as an experimental approach to the in-space estimation of GNSS inter-constellation time offsets. Its Low Earth Orbit will allow it to take advantage of low multipath error, the absence of significant tropospheric error, and a relatively short orbit period (~90 minutes) which will allow for the visibility of a high number of GNSS satellites multiple times per day.

Inter-constellation time offsets exist since each GNSS system uses an independent time reference. As a consequence, the time offset between constellations represents an additional unknown to be solved for when a user calculates a multi-GNSS position, velocity, and time (PVT) solution. While for most users this is not an issue thanks to the visibility of multiple satellites per constellation, for users with limited visibility this offset can have a high impact: limiting the GNSS solution accuracy and availability. Therefore, users with limited GNSS visibility may improve their GNSS solution performance—in terms of both availability and accuracy—if they could use inter-constellation time offset estimates provided by an external source. The assumption is that, depending on the requirements, the user's receiver shall be opportunely calibrated [6]. Target users are then those users in harsh environments[6], particularly the users in the high altitude Space Service Volume (SSV), such as Geostationary Orbit (GEO) satellites. Possible benefits that GEO users could experience if provided with inter-constellation time offset estimates are discussed in [1 - 5]; in [5] simulation results are presented showing the possible improvement in terms of solution availability and geometric dilution of precision (GDOP).

The estimate of inter-constellation time offsets is a crucial topic, and different methods have been proposed and implemented. Large networks of receivers are utilized in order to cancel out the residual biases due to the estimating receiver, as well as the biases between satellites in the same constellation and within signals from each satellite [7, 8]. Bobcat-1 will collect GNSS data from Low Earth Orbit to enable a performance evaluation of an in-space inter-constellation time offsets estimate. A more detailed discussion of the Bobcat-1 mission is provided in [3], and additional discussion will be provided in a future paper when measurements are available after Bobcat-1 deployment. The algorithms and the calibration process are not discussed here. The focus of this paper is on Bobcat-1 design and mission planning.

The paper is organized into sections: mission planning, CubeSat design, data collection, and ground station design. Finally, conclusions and future work are outlined.

MISSION PLANNING

The CubeSat and the communication link design must satisfy the mission requirements. In order to keep the research opportunities open, and allow changes in the methodologies while observing the real GNSS data collected from LEO on the CubeSat, the decision was made to perform the data processing on the ground. The decision to post-process the data was done after an analysis of the amount of data needed and the downlink capability opportunities. The measurements can then be collected using a commercial GNSS antenna and a commercial GNSS receiver, stored on board the CubeSat until the ground station is in view, and then downloaded to the ground. **Table 1** shows a summary of the main mission requirements and consequent design decisions. Details about each requirement are provided in the following sections. In addition, the CubeSat had to satisfy all the requirements in [1], which include dimension and weight requirements, as well as safety requirements, involving a particular attention to the material used in order to be compliant to both the ISS safety requirements and the debris concerns.

Table 2 describes the data collection requirements. Different data collection modes have been implemented, allowing for the collection of either raw code and phase measurements or compressed measurements which will reduce the amount of data that will need to be downlinked. The sampling frequency can be adjusted as well. The maximum duration of a data collection primarily depends on the battery voltage: if the voltage drops too low, the data collection is safely interrupted to ensure the satellite has enough power to perform critical tasks. The desired minimum data collection duration is one orbit (about 90 minutes). Further details about the data collections are provided in the Section dedicated to the Data collection.

Table 1: Design requirements

Requirements	**Design Need**		**Design Decision**
Multi-GNSS, multi-frequency measurements	RF capability to collect all desired signals at the desired frequencies	multi-GNSS, multi-frequency antenna	Antcom G5ANT-1.9AS-1-3 antenna
	RF front-end with proper bandwidth; processing capability to measure all the desired signals	multi-GNSS, multi-frequency receiver	NovAtel OEM719
Data collection duration	Minimum: enough to allow visibility of at least 4 satellites per constellation Ideally: one full orbit.	**solar panels** number and efficiency	13 solar panels (3U CubeSat)
		power unit (in particular, **batteries**)	GomSpace P31U and BP4 batteries. Note: batteries are ISS launch compliant
		data-link: preferable to be able to download all the stored data during one pass.	GomSpace AX100 radio (100 kbaud capability)

Table 2: Data collection requirements

NovAtel Data	Data Types	Sampling Interval (min-max)	Duration	Comments
Estimated position	Best estimated position from NovAtel receiver	1 - 10 s	start-time and max duration depending on battery level; ideally: one orbit (90 min)	
Code measurements	GPS Galileo GLONASS Beidou QZSS	1 - 10 s	start-time and max duration depending on battery level; ideally: one orbit (90 min)	the option to compress these measurements is available
Phase measurements	GPS Galileo GLONASS Beidou QZSS	1 - 10 s	start-time and max duration depending on battery level; ideally: one orbit (90 min)	the option to compress these measurements is available
Temperature measurements	2 temperature sensors (integrated on NovAtel receiver)	5 - 60 s	start-time and max duration depending on battery level; ideally: one orbit (90 min)	
Other HW system parameters (NovAtel)		on demand	one measurement	to check for the proper functioning of the system

CUBESAT DESIGN

CubeSat Hardware Configuration

The Bobcat-1's hardware mostly consists of COTS components sold by GomSpace. In **Figure 2** a cutaway view shows the components, while **Figures 3 and 3a** show the completed CubeSat. In **Figure 3a** the communication antenna is undeployed, while in **Figure 3b** the communication antenna is deployed, after a successful test. In the following paragraphs each hardware subsystem is described.

Attitude Determination and Control Subsystem (ADCS)

All components of the ADCS subsystem are COTS products sold by GomSpace. The Bobcat-1 performs bdot detumbling and low-accuracy pointing using 10 magnetorquers: 9 integrated into the solar panels plus one internal z-axis magnetorquer [9]. The GomSpace NanoMind A3200 on-board computer (OBC) manages all ADCS functions and contains a Honeywell HMC5843 magnetometer and InvenSense MPU-3300 3-axis gyroscope [10]. In addition to the solar panels, accelerometer and magnetometer, knowledge of the antenna pattern of the GNSS patch antenna could be exploited to determine the attitude of Bobcat-1.

Command and Data Handling (CDH) Subsystem

The CDH subsystem consists of the GomSpace NanoMind A3200, which serves as the CubeSat's on-board computer (OBC), and the GomSpace DMC-3 motherboard. The A3200 contains an Atmel AVR32 microcontroller running FreeRTOS and allows for the execution of remotely issued commands. The OBC is connected to the other components of the CubeSat via I2C, SPI, and CAN bus and is responsible for coordinating all on-board operations.

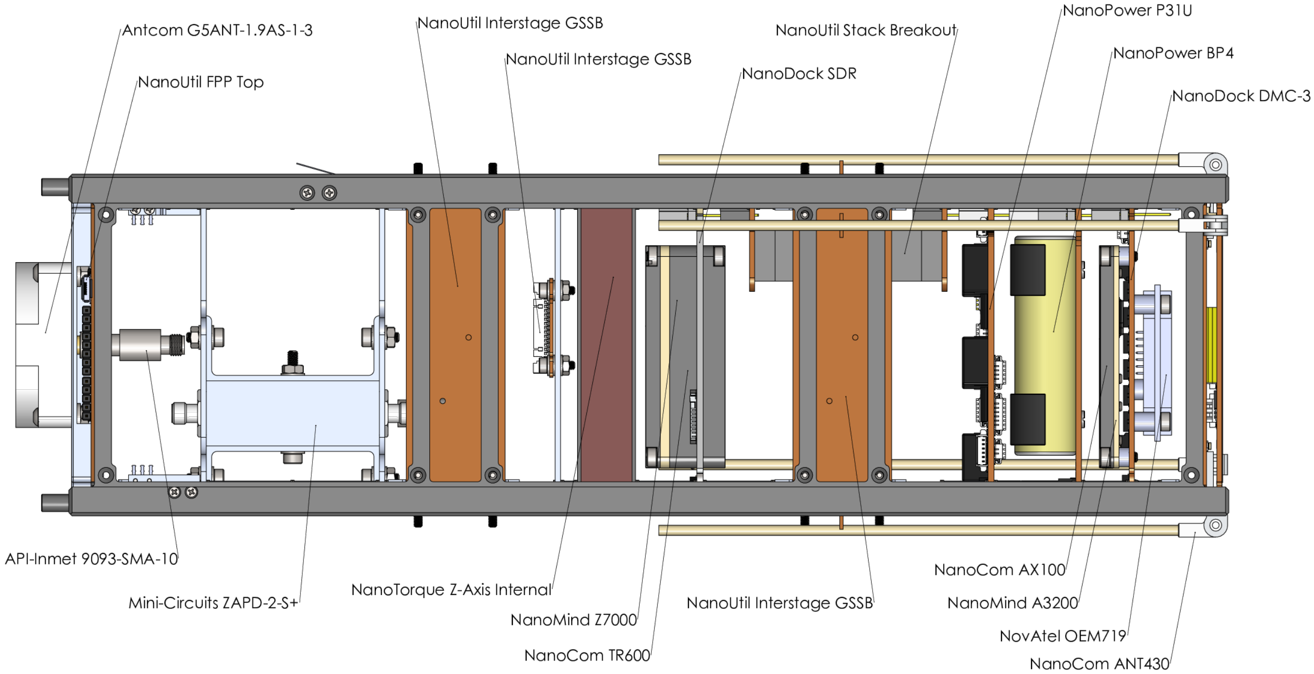
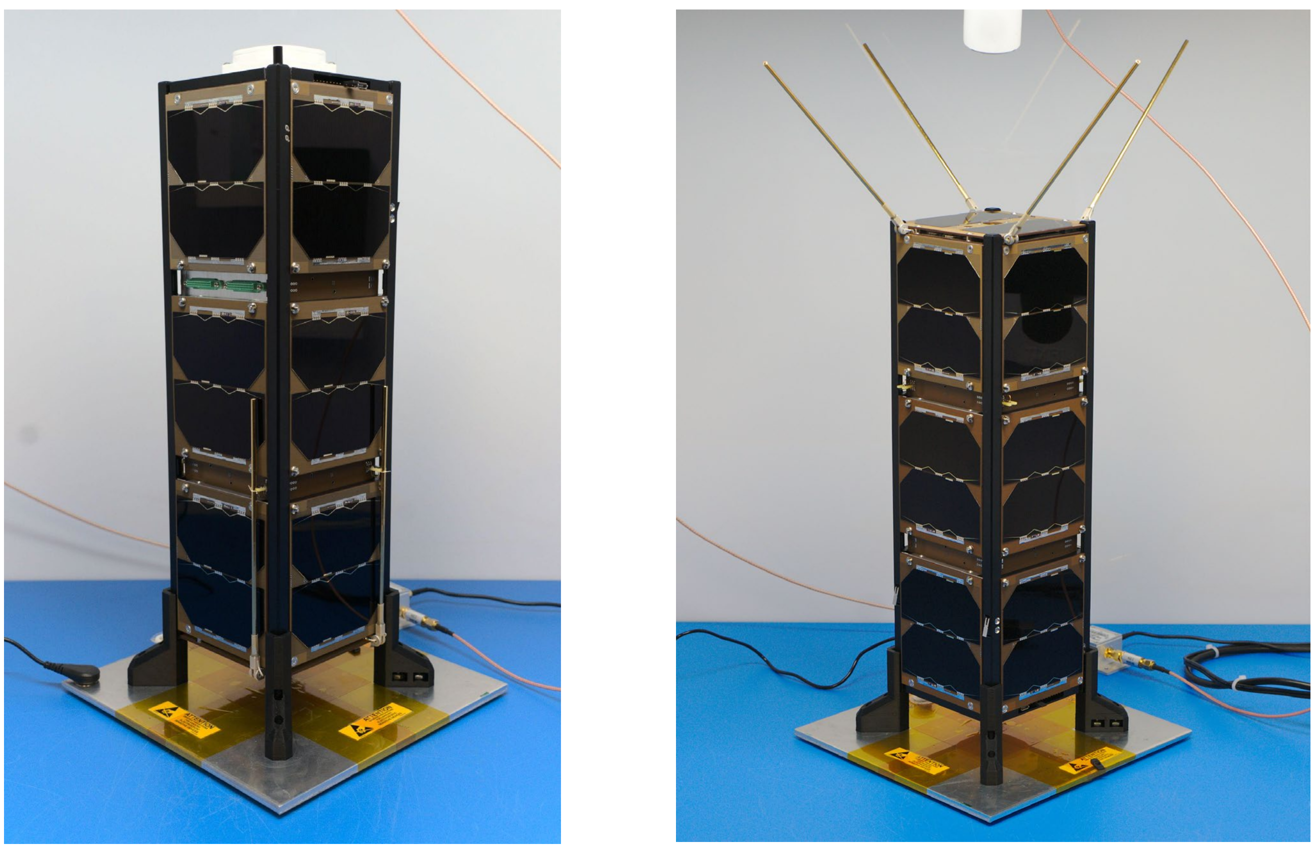


Figure 2: Bobcat-1 cutaway view (solar panels not pictured)



(a) (b)

Figure 3: Bobcat-1, with communication antenna undeployed (a) and with communication antenna deployed (b).

Electrical Power Subsystem (EPS)
The EPS is a direct energy transfer system using a solar array producing approximately 3.6W of orbit average power to charge the 38.5Wh battery. All EPS components are COTS products sold by GomSpace, including the system power supply (P31u), battery pack (BP4), and solar panels (13x P110's, each with 2 series connected AzurSpace 3G30A cells) [11 - 13]. The BP4 contains an internal heater and temperature sensor to manage battery temperatures in orbit. The orbit of Bobcat-1 was simulated using AGI's STK (System Tool Kit) software to conclude the number of solar panels needed to maintain battery power without entering into a low-power recovery mode, while also achieving the system requirements to run the desired experiments (**Table 1**).

Communication Subsystem
The communication subsystem consists of one GomSpace AX100 UHF (430-440MHz) transceiver connected to a GomSpace ANT430 deployable canted turnstile antenna. The AX100 is mounted directly to the DMC-3 motherboard [14 - 16].

Payload
Bobcat-1's primary payload is the NovAtel OEM719 GNSS receiver [17]. This receiver was selected for its ability to track a wide variety of GNSS signals, as well as its significant flight heritage and built-in hardware support in GomSpace's DMC-3 motherboard. The secondary payload is a GomSpace software-defined radio (SDR) (Z7000-FPGA module and TR-600-Receiver module), which embeds the QN400 GNSS receiver developed by Qascom and the University Of Padova as part of the Horizon 2020 ENSPACE project. Their objective is to develop a low cost GNSS receiver utilizing the Galileo constellation and targeting the smallsat community [18, 19]. Both the Novatel GNSS receiver and the SDR are connected to the top-mounted AntCom G5ANT-1.9AS-1-3 patch antenna, which connects through a 10dB API/Inmet RF attenuator to a Mini Circuits ZAPD-2-S+ RF splitter. The splitter routes one line directly to the NovAtel receiver, and the other through a Mini Circuits BLK-89+ DC block and on to the SDR. The AntCom patch antenna provides coverage of a wide array of GNSS frequencies while additionally satisfying size and outgassing requirements imposed by the CubeSat form factor and ISS safety considerations.

DATA COLLECTION

The Bobcat-1's flight software (FSW) is organized into data collection modes which can be configured from the ground station to sample experimental data at a desired sampling interval (typically 1-5 seconds). The collection mode, sampling rate, and all other parameters relevant to a particular experiment are provided to Bobcat-1 through a JSON configuration file uplinked from the ground station to the OBC's internal flash memory. This configuration file determines:

- The data that will be collected during the experiment (data collection mode)
- The sampling rate(s) of experiment data
- The minimum battery voltage required to start data collection
- The battery voltage at which a currently running data collection will be stopped to conserve power
- The minimum amount of flash memory that must remain free on the OBC (a collection will be stopped if too much of the flash memory is consumed)
- Whether or not a data collection is permitted to start and stop automatically, according to battery and flash memory parameters (otherwise a collection must be manually initiated via telecommand)
- The maximum size of an individual data file (to allow for easier organization of large data sets that are downlinked over multiple ground station passes)

Figure 4 shows the process for starting and stopping data collections, while **Figure 5** shows the operation of the data collection itself. Experiments are organized by the identification number of the configuration which generated a given data set, and the identification numbers for all data collections that ran from a particular configuration. For example, a configuration file can be loaded and a data collection task spawned if all start conditions are met. The data collection will continue to run until one or more stop conditions are met (e.g. the battery voltage drops below the defined minimum). Once the start conditions are met again, the collection will begin again automatically, and the collection ID will increment to distinguish the new collection from the previous one. This metadata allows for easier classification of what parameters were used to generate a given data set, and which portions of the data result from a particular continuous data collection.

Three primary collection modes are used for timing offset data collection. These collection modes are described in **Table 3**.

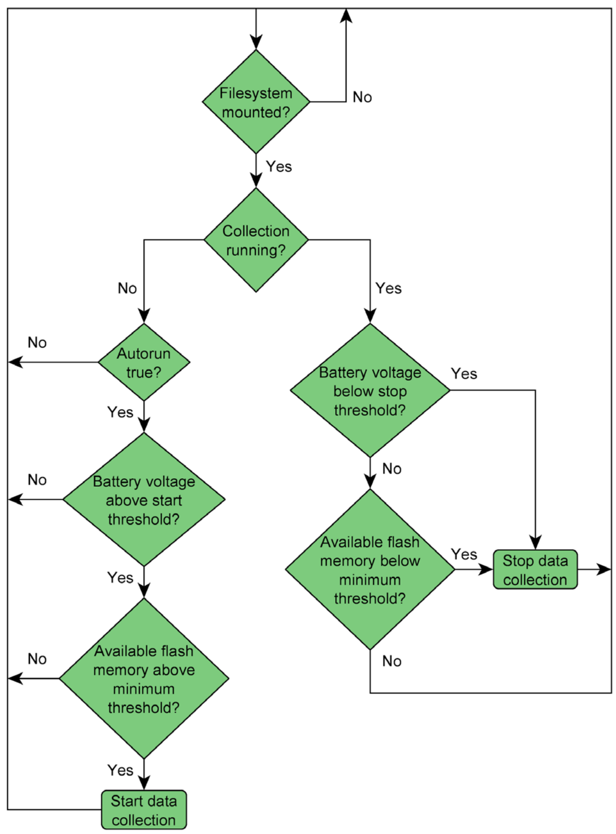


Figure 4: Data collection control flowchart

Table 3: Data collection modes

Collection Mode	Description
Mode 1 (Raw NovAtel messages)	Logs are recorded from the OEM719 GNSS receiver in the format the receiver provides: no extra formatting is performed. This mode is primarily used for debugging purposes: redundant data is stored and downlinked (NovAtel RANGEB, BESTPOSB, and HWMONB logs)
Mode 2 (Bobcat-1 Custom Messages)	The NovAtel logs are parsed by the CubeSat OBC. Unneeded data is disregarded, while desired data is used to create and record messages in a custom Bobcat-1 log format. The custom Bobcat-1 messages store the desired data using the same format and precision as the raw NovAtel messages.
Mode 3 (Bobcat-1 Custom Messages with Compression)	Similar to mode 2. The CubeSat OBC parses the NovAtel logs and disregards unneeded data while using the desired data to create and record messages in a custom Bobcat-1 log format. Unlike mode 2, several of the data fields are stored using a different format and precision than the raw NovAtel messages by "compressing" them in order to reduce the size of the data. Most notably, the pseudorange measurements are scaled and reduced modulo 20 km, allowing them to be stored as 21-bit unsigned integers while retaining adequate precision and range. Additionally, the carrier phase measurements are scaled and reduced modulo 3000 cycles allowing them to be stored as 22-bit signed integers while retaining adequate precision and range. These measurements can be "decompressed" to obtain the original values using knowledge of the CubeSat's estimated position at the time the measurements were recorded. Due to the large quantity of pseudorange and carrier phase measurements collected at each sampling interval, reducing their size from 64-bit double-precision floating point values to 21- and 22-bit integers results in large savings in data size while retaining necessary precision for the experiment.

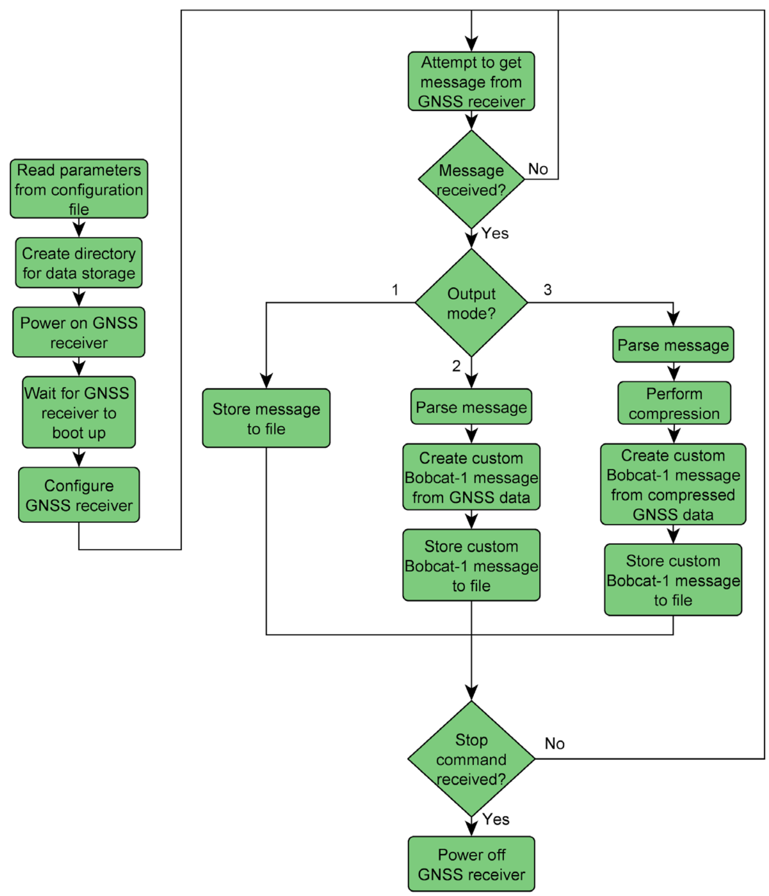


Figure 5: Data collection flowchart

GROUND STATION DESIGN AND LINK BUDGET

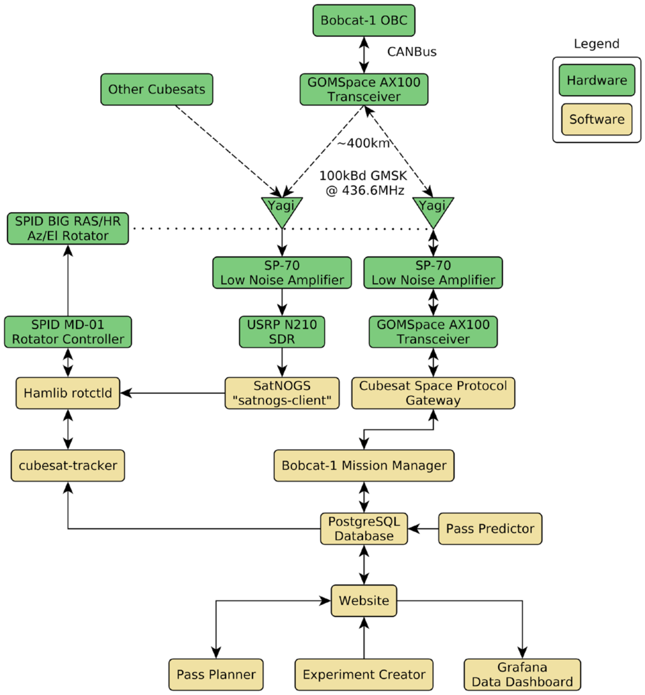
The Bobcat-1 ground station consists of several custom software systems developed around a PostgreSQL database. These components provide functionality including pass prediction, rotator control, semi-automated mission management with a pass planning utility, an experiment creation and data management system, and a web interface to allow operators to control the various systems. Additionally, it is integrated with the worldwide network of SatNOGS groundstations, allowing other users to access the Bobcat-1 groundstation hardware for tracking satellites. A block diagram, Figure 6 below, shows a high-level view of the groundstation's functional components.

Pass Predictor

The Pass Predictor uses a TLE for Bobcat-1 to precompute the next 48 hours of passes over the Ohio University ground station. TLE calculations are done using Python Skyfield. The decision to precompute passes rather than running in real time was made so that the groundstation could perform pre-pass tasks at the same time (generating plots to assist in decision making, preparing files for uplink, analyzing previous passes, etc) and minimize risk associated with operating the satellite with a Human-In-The-Loop doing real-time control of the satellite by an operator. Precomputing passes also reduces risk of a failed uplink or downlink due to resource exhaustion.

Pass Planner and Mission Manager

The Mission Manager interprets a Pass Plan in the database and executes commands on Bobcat-1. The Mission Manager has four main tasks: resilient file upload and data download, setting up experiments on the OBC, and changing baud rates for data transfer. File transfers can be interrupted and resumed within the same pass or in the next pass, allowing for more link capacity as even a short, low elevation pass can be utilized to retrieve a portion of data.



(a)

(b)

Figure 6: Ground Station block diagram (a) and Ground Station antenna(b).

Experiment Creator / Data Management and Export system

To start an experiment, a team member must fill out a form on the website with the required parameters. The Mission Manager uses this form data to generate a valid configuration file, uploads it to the OBC, and starts the data collection on the next pass.

When the data collection is complete, the groundstation Mission Manager is invoked again to download the collected data. Once all data has been downloaded, the data is ingested into the PostgreSQL database and stored as binary JSON ("JSONB"), as it has the best tradeoff between flexibility and efficiency for this use case. Once the data is in PostgreSQL, it can easily be imported into MATLAB using a simple REST API call, and is available in a backwards-compatible format for existing data processing scripts.

SatNOGS

SatNOGS, or the Satellite Network of Open Ground Stations, is an open-source project run by the Libre Space Foundation to connect ground stations around the world (as of writing, 234 active stations and 124 stations in testing). These groundstations may be run by universities, amateur radio operators, museums and libraries, or simply people interested in satellite communications. As the stations are all run by volunteers, there is a large variety in hardware and capabilities, however a typical station has a Raspberry Pi, a RTL-SDR (a basic Software Defined Radio based on a Digital TV receiver), and antennas ranging from an omnidirectional vertical antenna to Yagi antennas on an Azimuth-Elevation rotator.

Any user with an active groundstation on the network is allowed to schedule time on any other participating groundstation to observe a satellite and receive telemetry. Participating satellite operators who provide their telemetry format can have their telemetry automatically decoded and plotted in near real-time on the SatNOGS Dashboard website. SatNOGS has full support for Bobcat-1's health beacons, and the Bobcat-1 team uses SatNOGS extensively to aid in monitoring experiments as they run, monitoring satellite health, and informing operational decisions.

Rotator Control
The groundstation antenna rotator is shared between the Bobcat-1 tracking software as well as the SatNOGS Client software. The groundstation uses the Ham Radio Control Library ("hamlib") Rotator Control Daemon ("rotctld") to act as an interface between the controller firmware and pointing software. Rotctld supports most antenna rotator controllers through the use of standard interfaces, and is well tested by the amateur radio community. In order to share the rotator between the Bobcat-1 pointing software and SatNOGS-Client, a script automatically changes the rotctld listening port during a Bobcat-1 pass to ensure it cannot accidentally get pointed to the wrong coordinates.

Cubesat Space Protocol
All inter-component and satellite-groundstation communication is facilitated by the Cubesat Space Protocol (CSP). CSP is a very small network delivery protocol which is suitable for embedded devices and high-latency, unreliable links. It closely resembles TCP and UDP, but keeps features to a minimum to fit in very small microcontrollers. Bobcat-1 uses the CSP Reliable Datagram Protocol, which provides reliable, in-order delivery of packets, for file transfers such as uplinking configuration files and downlinking experiment data. Onboard the satellite, CSP is implemented in every component, including on the radios as a router. This allows direct communication between any two components using a simple programming interface.

Hardware
The Bobcat-1 groundstation has a redundant set of RF components (transceiver, LNA, antenna) set up in order to serve as a backup in case of an issue with the primary chain. The groundstation uses an identical transceiver as is on the cubesat, the GOMSpace AX100, to perform all communication with the cubesat. In addition to the AX100's 1 Watt output, the groundstation has an additional power amplifier which boosts the output power up to 25W, and a low-noise preamplifier which provides 22dB of gain. The transceiver is connected to the LNA via ⅞" Heliax coaxial cable, and from the LNA to the antenna, and ¾" flexible heliax from the LNA to the Yagi antenna. The use of these heliax cables minimizes cable loss such that over the 150ft from yagi to transceiver, there is less than 1dB of loss. The Yagi antennas feature 15.5dBic of gain with a 30 degree circular beam, and are pointed by a SPID BIG-RAS/HR rotator which can easily point both Yagi antennas with 0.1 degree resolution, very little backlash, and a full rotation in approximately 200 seconds.

CONCLUSIONS AND FUTURE WORK

The Bobcat-1 mission has provided an incredible learning opportunity for the students and staff involved. There is a large amount of educational potential in a CubeSat mission, from preliminary planning and requirement generation, to building, designing, and operating spacecraft and ground communication systems. Following Bobcat-1's deployment from the ISS the student team at Ohio University will work to establish contact and begin experimental data collection and processing. Bobcat-1 will serve additionally as a means for student outreach at Ohio University and in nearby High Schools in an effort to generate interest in space research and engineering.

ACKNOWLEDGMENTS

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