Expanding the Capability of Satellite Operations Using a Global Federated Ground Station Network

Matthew J. Szczerba, Justin H. Schachter, Kaylee E. Bell, Michael E. Wilson, James W. Cutler
University of Michigan – College of Engineering
1320 Beal Ave, Ann Arbor, MI 48109; 810-922-9593
maszczer@umich.edu

ABSTRACT

Small-scale spaceflight programs such as those found at universities and start-up companies may operate satellites from a single ground station. This station's location may not be optimal for radio communications, and a single station limits the contact time available to conduct operations. The idea of a global federated ground station network (FGN) has been theorized in the past, and with today's wide-spread internet connectivity it is now possible for such a network to exist. One example of an FGN that is functioning today is an open-source project called SatNOGS. The Michigan eXploration Laboratory (MXL) at the University of Michigan has applied the benefits of this network to enhance operations of their Tandem Beacon Experiment (TBEx) CubeSat mission by gathering 2.2x the beacons gathered by their home station alone. 93% of those additional beacons were collected by six SatNOGS stations. Augmenting MXL's home station with these six stations increases access time to the TBEx satellites by a factor of 5 to 15. This increased temporal coverage also enabled MXL operators to identify their spacecraft after deployment and correct an error causing the TBEx radios to function intermittently, saving the mission in its earliest days.

INTRODUCTION

In this paper, we address the challenges of small space programs conducting mission operations with limited ground station resources. Small space programs such as those found at universities and start-up companies are typically constrained by time, available resources, personnel skill-level/experience, and team size. These constraints make running successful missions a logistically complex challenge [1].

It is the job of the spacecraft mission operations teams to assess the condition of their spacecraft, determine what is happening with their asset(s) if there is a problem, and attempt to make a sequence of contacts in order to maintain or gain control of their asset. This can be a challenge for small space programs due to their limited resources. The success rate for CubeSat missions is about 45% in academia and about 75% in industry, which is low compared to large corporate missions that have near-perfect success rates [2,3]. That low success rate mainly pertains to the onboard vehicle hardware or software failing upon deployment, but it can be attributed to operational challenges as well. Of the CubeSat missions that made it to orbit, nearly 37.5% of the vehicles were dead on arrival or had an early loss, and 30.2% of them did not complete their full missions [4]. Teams can prove their systems work on the ground, hopefully demonstrating the end-to-end capabilities of the vehicle and ground operations systems, but if their systems experience anomalies or partial failures after deployment, reliable and frequent communications with the spacecraft is another tool for saving the mission.

The Michigan eXploration Laboratory (MXL) at the University of Michigan has faced the challenges of operating a small space program first-hand. As an example of an academic small space program, MXL has built and flown seven successful CubeSat missions over the past decade, operating primarily from a single ground station in Ann Arbor, Michigan, USA. This presents challenges including limited contact time with the spacecraft, and low data throughput capacity. These issues adversely impact mission operations performance for any team. In the worst of cases, these limitations could lead to the loss of a spacecraft, such as a time-sensitive anomaly that can only be corrected by a command from the ground.

One potential solution to the issue of limited resources for small space programs is the idea of federated ground station network (FGN). This idea proposes a loose collection of ground stations connected to a network and can be operated remotely and even autonomously by others to utilize the often-vast idle time of these resources [5]. This vision includes stations owned by various entities and individuals that can join or leave the network at any time as allowed or required by local constraints. This heterogeneous model encourages increased diversity of hardware, enabling a wider range of missions to be supported. Given a sufficiently large network with robust software, such a network could provide missions with 24/7 contact availability and provide rapid, autonomous detection of on-orbit failures [5]. Networks of ground stations connected via the internet and accessible to operators other than their owners have been studied and suggested by other groups as well [6, 7].

Data capacity models for an FGN have been developed to analyze contact time and data throughput [8]. The overall conclusion is that by leveraging an FGN, teams can increase data throughput by downlinking data over multiple, geo-spatially compact ground stations to increase link efficiency, or by downlinking data over multiple, geo-spatially sparse ground stations to increase link availability. The small space community has recently seen attempts at large-scale implementation of FGNs, such as Mercury [9] and GENSO [10]. One promising rendition of this idea is SatNOGS, an open-source FGN that has garnered worldwide use. Satellite operators at MXL have begun using this network for their regular CubeSat operations, providing two main benefits:

1) Increased amount of link availability for downlinks, which allows for increased:
    a. Number of beacons collected.
    b. Data throughput capacity.
    c. Visibility on satellite behavior.
2) Possibility of multiple ground stations observing a spacecraft at once, which can decrease overall packet loss.

The Satellite Networked Open Ground Station (SatNOGS) Project

SatNOGS is a fully open-source global ground station project created by the Libre Space Foundation in 2014 [11]. Today, the network is made up of more than 350 stations spanning six continents [12]. Each ground station is receive-only and consists of a Raspberry Pi (or similar internet-enabled board computer) with the SatNOGS software client, a software defined radio (SDR), an antenna, and an optional antenna rotator. The network supports listening on most major spacecraft amateur bands, with the ability to add custom bands that user hardware can support. The network also allows users to request for new satellites (specifically their transmitters) to be added to the database to support scheduling of their passes and logging data with the input of a few key pieces of information, including the spacecraft's transmitter modulation mode. Users can suggest the addition of satellites owned by any organization (i.e. NOAA satellites), or even their own satellites in the case of small space programs (i.e. CubeSat teams). A map of SatNOGS station locations is shown in Figure 1.

The SatNOGS site boasts a large web database of past historical data and a robust ground resource scheduling tool [12]. The database is an effort to create a holistic, unified, global, public transmitter database for all satellite transmitters as well as host tools to visualize the collected data—helping create diagnostic tools and giving teams an opportunity to streamline their telemetry acquisition and monitoring. The ground resource scheduling tool is a feature of the SatNOGS project which allows any user who has an account with at least one live ground station contributing to the network (in an active state) to schedule observations. Any available global station with band-appropriate hardware and predicted line-of-sight on a selected spacecraft not more than 48 hours in advance of the pass can be scheduled for observation.

It is quick and easy to establish a SatNOGS station and begin contributing to the network. This is important because a difficult or long setup procedure could deter potential members from joining the network, and setup also allows stations to be established in harder-to reach locations. Traditionally, radio frequency (RF) ground stations require extensive background knowledge in RF equipment (antennas, rotator equipment, etc.), SDRs, and space system hardware. As an example of the ease with which a new station can be established, the operations team at MXL was able to set up a station of their own in the span of an afternoon, once they had acquired the necessary hardware.

The SatNOGS wiki, available through its website [12], provides building guides for antenna and rotator hardware; suggested hardware to purchase (or build), such as an RTL-SDR (USB software defined radio dongle to be able to receive RF signals); as well as instructional guides for setting up a Raspberry Pi to be flashed with the SatNOGS client, which allows a station to operate without any user interfacing after the initial setup. Once the client has been configured with information such as sampling rate, gain value, and geographical coordinates, the ground station is ready to be an operational asset and can be scheduled by the user and other operators on the network. The cost of materials for a simple SatNOGS station design is less than $100 USD and less than $500 USD for a complex design (with high gain, directional antenna with a rotator).

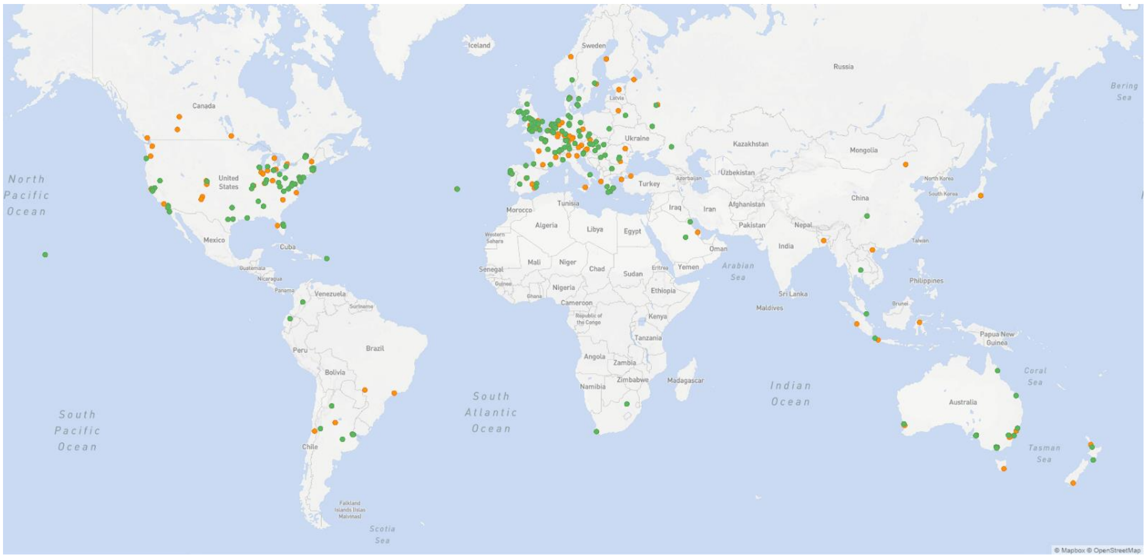


Figure 1: Locations of SatNOGS stations worldwide. Green dots indicate operational stations. Orange dots indicate connected stations in "test mode" and are not open to public operation [12]

MXL USE OF SATNOGS

MXL has made use of the SatNOGS network to improve its own satellite mission operations. It uses the network to collect large amounts of spacecraft telemetry from The GEO-CAPE ROIC In-Flight Performance Experiment (GRIFEX) and Michigan Multipurpose Minisat-2 (MCubed-2) CubeSats [13], which have been in orbit for over five years. MXL has also used SatNOGS as a science operations tool by conducting end-to-end tests of the payload on the Tandem Beacon Experiment (TBEx) CubeSats using a SatNOGS station for observation of the spacecraft payload radio signals. For all its purposes, MXL uses an in-house database architecture called MXL Integrated Data Analysis System (MIDAS) to collect information from SatNOGS and integrate it with data from other ground stations, whether that station is MXL's home ground station or stations at other institutions. This data is then made available for query by the operators via an API as well as being accessible through other platforms such as Grafana, an open-source dashboard for data analytics, and Jupyter, an open-source web-based integrated development environment [14]. For this paper, benefits provided by SatNOGS to the TBEx mission will be the main focus.

TBEx Case Study

The Tandem Beacon Experiment (TBEx) is a pair of NASA-funded 3U CubeSats that carry payloads from SRI International for the study of the structure and evolution of plasma bubbles in the ionosphere [15]. The two satellites, TBEx-A and TBEx-B, are shown in Figure 2. They were launched on a SpaceX Falcon Heavy rocket as part of the U.S. Air Force's Space Test Program 2 mission on June 25, 2019 and placed into low-Earth orbits (LEO) of 300-by-850 km altitude and 28.5 degrees inclination.

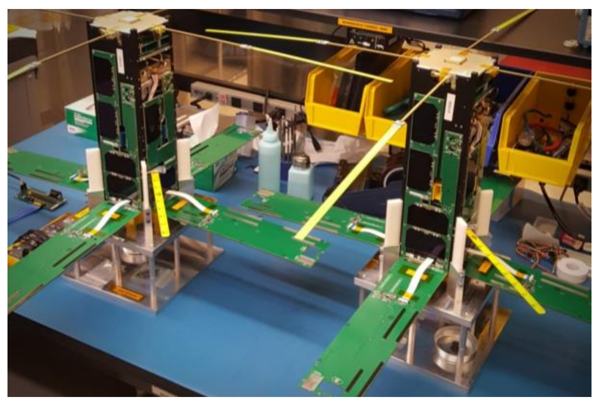


Figure 2: Both TBEx satellites at the University of Michigan prior to launch vehicle integration

For context, several orbital parameters of the TBEx satellites are plotted over time in Figure 3. This orbital configuration comes with the challenge of limited data throughput due to reduced contact time with MXL's home ground station in Ann Arbor, MI. As noted by measurements made in [8], the existence of an FGN could increase data transfer capacity by increasing both link availability and efficiency, and thus aid some of these challenges.

Operational Challenges

The home ground station for MXL is in Ann Arbor, MI atop the University of Michigan's François-Xavier Bagnoud building (FXB). Unfortunately, this station is located at 42.29 degrees North latitude, more than 13 degrees higher than the 28.5-degree inclination of TBEx's orbits. This difference between inclination and latitude limits contact times. This effect is amplified for satellites in orbits of lower altitudes since the size of the line-of-sight footprint on the Earth decreases with decreasing altitude. A ground station with a latitude too far above the inclination of its target satellite may not be able to ever attain line-of-sight.

Immediately following deployment, SatNOGS was used by the MXL team to identify and stabilize communications with both TBEx spacecraft, saving the mission. Like many CubeSat missions, TBEx experienced its share of troubles following deployment. Radio instabilities prevented the satellites from contacting MXL's FXB station, since the satellites were not transmitting over the FXB, though they were beaconing over other locations. The ability to observe the satellites using stations elsewhere on the planet directly enabled the recovery of the spacecraft by allowing the MXL team to confirm the spacecraft was alive, identify the anomaly causing the spacecraft radio software to crash, and finally to correct it. Additionally, the routine hassle of pairing spacecraft with their Joint Space Operations Center (JSpOC) identifiers with the correct two-line element (TLE) sets was accelerated by observations made using the SatNOGS network. Following stabilization of the spacecraft radios, greater spacecraft contact time provided by the SatNOGS network resulted in greater possible downlink capacity. This allowed the team to more frequently monitor the health of the spacecraft and payload, and to implement fixes to future engineering challenges as they arrive.

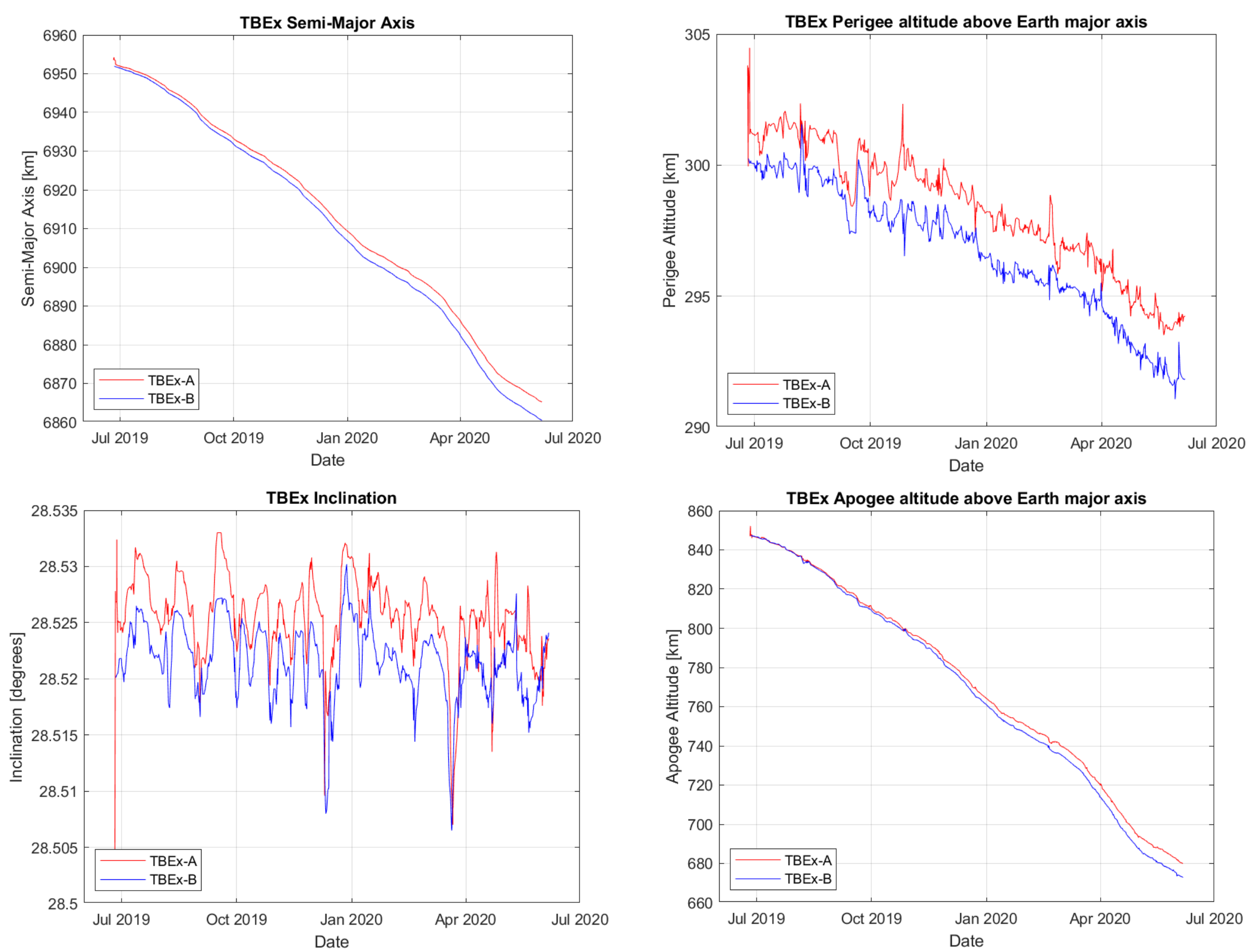


Figure 3: Several orbital parameters of the TBEx satellites over time. Note the similarity between the orbits of the two spacecraft

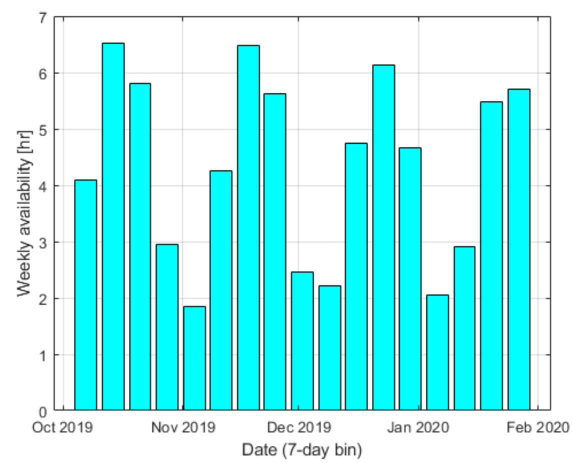
Expansion of Theoretical Contact Capacity

The theoretical data capacity between TBEx and the ground can be increased using SatNOGS. One way this can be measured by computing *availability*, one of the four factors of capacity as defined in [8] along with *efficiency*, *transfer rate*, and *ground station link*. Availability is the total duration of contact between the spacecraft and the ground station(s) over a period of time, and an increase in availability can be quantified by measuring how this quantity grows as ground stations are added to the network. Since the orbits of the two TBEx satellites are very similar, as seen in Figure 3, only TBEx-B contact times are used in this analysis.

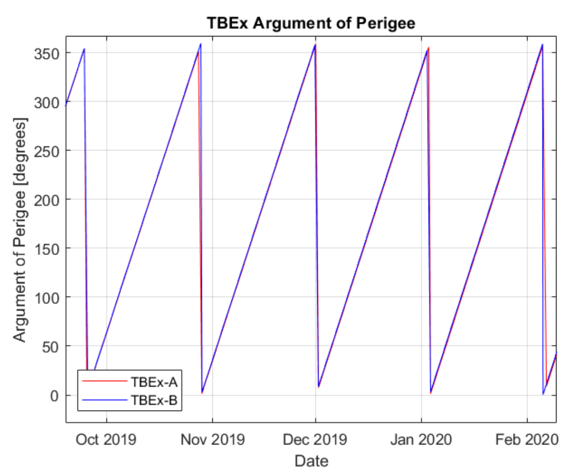
FXB's weekly availability with the TBEx satellites varies from two to more than six hours per week. This represents about 1% to 4% temporal coverage, respectively. This FXB-only analysis serves a baseline with which to compare when SatNOGS stations are added. The availability of TBEx-B from the FXB station in Ann Arbor was computed using the Systems Toolkit (STK) over a 17-week period from October 7, 2019 to February 3, 2020, and is shown in Figure 4. This period was selected for analysis because it contained a high density of beacons with few gaps, and because it is long enough to cover several precession periods of the argument of perigee, which affects contact window durations in this scenario. The precession of an elliptic orbit's perigee is new challenge for MXL, which has previously flown high-inclination, low-eccentricity orbits and this has not needed to deal with such large swings in contact time.

Next, the effect of augmenting the FXB station with stations from the SatNOGS network is analyzed. Of the twenty SatNOGS stations that received beacons from TBEx satellites, the six that collected the highest number of beacons were used for this analysis. These six stations account for 93.2% of all TBEx beacons collected by the SatNOGS network during the designated time period. It is important to note that these stations did not collect more beacons solely because they are better than other stations, but because they had systems operating on the same frequency bands as our spacecraft, performed well, and were scheduled more frequently by human operators at MXL. Most of these stations are in North America because the operators at MXL were particularly interested in offsetting data loss issues they were experiencing with the FXB station at the time (i.e., increasing link efficiency). These six SatNOGS stations, combined with MXL's FXB station, provide overlapping coverage over center-east North America and the Caribbean Sea and non-overlapping coverage over the Middle East and Australia.

With the addition of these six SatNOGS ground stations, the weekly availability with TBEx-B grew from two to 32 hours (16x, +1500%) during perigee passes and from six to 36 hours (6x, +500%) during apogee passes. This represents about 18% and 21% temporal coverage, respectively. To illustrate the effect of utilizing an FGN on availability for a spacecraft, the marginal availability of a link with TBEx-B due to the addition of each station from Table 1 was computed using STK. Figure 5 shows this data over the same 17-week window used in Figure 4.



(a)



(b)

Figure 4: (a) Simulated weekly availability between the FXB and TBEx-B. Note monthly periodicity. (b) Measured argument of perigee precession for TBEx. This is the main cause of periodicity in (a)

Table 1: Augmented ground station network used for MXL TBEx operations, in order of decreasing distance from the FXB home station

Name	Latitude [°N]	Longitude [°E]	Location	Horizon elevation [°]	Type
SN #692	-23.877	151.235	Queensland, Australia	0	Turnstile (UHF)
SN #146	24.771	46.708	Riyadh, Saudi Arabia	0	Vertical (UHF)
SN #623	18.479	-66.875	Puerto Rico, USA	1	Eggbeater (UHF)
SN #50	29.855	-96.535	Texas, USA	5	Eggbeater (UHF)
SN #853	29.855	-96.527	Texas, USA	3	Tracked cross-Yagi (UHF)
SN #2	39.236	-86.305	Indiana, USA	3	Tracked cross-Yagi (UHF, VHF)
FXB	42.294	-83.713	Michigan, USA	1	Tracked cross-Yagi (UHF, VHF)

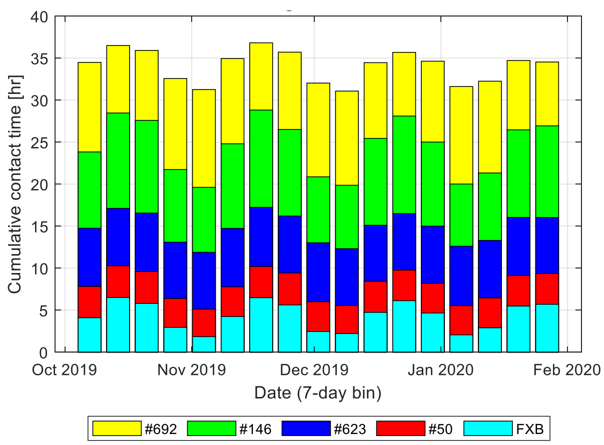


Figure 5: Weekly total contact time between TBEx-B and the augmented network. Colored bars indicate the amount of contact time gained per week by the addition of that station into the network. Stations #2 and #853 do not appear because they are temporally eclipsed by the others. Stations were added in order of increasing geographical distance from the FXB

As expected, and clearly seen, use of even four SatNOGS stations improves temporal coverage by several multiples. The addition of more ground stations would expand this coverage much further, especially if they are geospatially diverse. Further additions may enable contact between a satellite and the ground station network to be established whenever the operators choose, which was one of the key capabilities envisioned by [5] when such a network was a new idea.

Expansion of Real Data Downlink Capacity

In the period between October 7, 2019 and February 3, 2020, the MXL operations team was able to increase the number of beacons collected from both TBEx satellites by a factor of 2.20 (+120%) using the SatNOGS network. These beacons are important for monitoring spacecraft health over time. Increased temporal coverage increases the maximum theoretical number of beacons that could be collected in real time (as opposed to downlinked en-masse later).

Figure 6 shows how many beacons were received at the stations listed in Table 1 over the designated time interval. Here, beacons are regular radio signals which are transmitted by the spacecraft every ten seconds and contain 410 bytes of telemetry data spread across the payloads of two separate AX.25 packets. In Figure 6, reception of either of the two beacons is counted. To illustrate capacity expansion, beacons were attributed to SatNOGS stations only if they were not also received at the FXB. If more than one SatNOGS station received the same beacon but the FXB did not, the beacon was attributed via an even split across the stations where it was received.

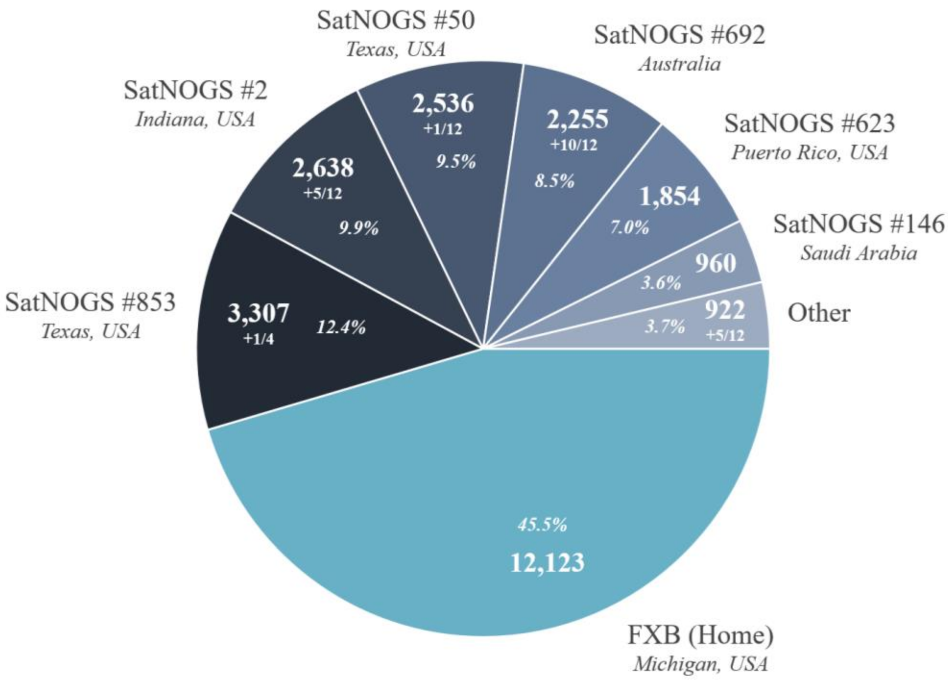


Figure 6: The total number of unique TBEx beacons collected from both satellites between Oct. 7, 2019 and Feb. 3, 2020 is 26,667. To illustrate ground station capacity expansion, beacons were only attributed to SatNOGS stations if they were not received at the FXB (MXL's home station). Duplicate receptions at SatNOGS stations were distributed in even fractions across the receiving stations.

Large Downlink Applications

MXL is working on using this increased capacity to downlink large files, such as historical beacon logs and high sample rate attitude determination sensor measurements [16]. Given the TBEx beacon size and rate, beacon logs grow by about 3.5 megabytes (uncompressed) per day per spacecraft while beaconing. In the case of TBEx's UHF radios, downlinking this data at 9600 baud and at 50% compression would theoretically take about three minutes, assuming no packet loss. This rate of half a megabyte per minute is faster than reality, however, since real downlink sessions suffer from commanding time and data loss. Currently, MXL can downlink about 600 kilobytes of compressed data per day at the from GRIFEX and MCubed-2 using only the FXB station.

It is desirable to use more than one ground station rather than one to reduce downlink latency. Even if the downlink rate was able to achieve the theoretical maximum of 9600 bits per second, downlinking over the home ground station eats into the amount of time available for commanding. Another reality is that this beacon log data has accumulated over the year of TBEx's orbital lifetime, meaning that now the beacon logs on each TBEx satellite contain hundreds of megabytes of data each (TBEx has had some periods without beaconing throughout its lifetime, which lowers this number from the 1.3 gigabytes of data that would have been theoretically generated per satellite).

The downlink of this data is aided by the existence of an FGN such as SatNOGS by increasing link availability (in the case of sparsely-distributed stations) and link efficiency (in the case of overlapping stations). MXL has recently developed the ability to schedule downlinks over other stations at future times. MXL is currently using this method in limited scope to retrieve beacon logs generated by GRIFEX to perform large-dataset fault analyses.

DISCUSSION OF THE SATNOGS FGN MODEL

SatNOGS is an modern example of a network demonstrating the potential of FGNs, and the advantages of it being open and easy to use are clear. However, the MXL team foresees additional challenges for the current SatNOGS model as more people join the network. Three such future challenges worth emphasizing want to emphasize are 1) how to fairly and efficiently allocate network resources when observation demand exceeds ground resource supply, 2) how to protect the priority of station owners over their own station's time, and 3) how to defend vulnerabilities due to the network's relatively ungoverned nature. The following paragraphs discuss these issues in more depth and hypothesize some solutions. MXL is not demanding a particular model to be used by the community, but rather suggesting possible solutions to investigate further. The model that this growing community decides to implement will set precedent for future networks and certainly influence the future of small space operations.

The first issue we see is one of network capacity supply and demand. Presently, it is clear from using SatNOGS over the past year that the capacity of the network far exceeds the demands of its users. However, this may not always be the case in the future, and it is worth thinking proactively about how to allocate station time when a scarcity arises. Resource allocation is currently first-come, first-served, but in the future, should users be required to apply for time on the network? Should they be allocated a budget based upon the resources they are contributing back to the network? How will one user's requests be prioritized over another? These model questions have been addressed in the fields of astronomy and computing, where solutions range from open peer-to-peer implementations to paid/application-based resource allocation. SatNOGS is most closely aligned with a peer-to-peer model where nodes (users with a station) have equal resource request power.

One possible way to solve the resource issue is by implementing a branched network system with the same foundational architecture as SatNOGS, but which divides the network capacity between amateur radio operators and users who own satellites, while keeping the collected data public. This would have the effect of shielding users who rely on the network from being crowded out at the cost of weakening the community aspect of the project, which has been a foundational aspect and focus of the network since its inception.

A second issue with the network is enforcing the priority of the station owner over other users on the network. If a station owner, who wants to use their station for research or hobby, is forced to compete with a worldwide community of users, they will be discouraged from continuing to share their resources or from joining the network in the first place. Currently, SatNOGS allows the station owners to set a "target utilization" rate to display on their station's information page, with no method of enforcement. There is little to stop the community of users – or even a single user – from temporarily crowding out the station owner. The strongest form of enforcement currently in place is an inability to schedule more than 48 hours in advance and a simple notice alerting a user that scheduling observations on too many stations at once is not proper etiquette. Scheduling too many stations at once consumes valuable network resources that might be needed by other users.

For guidance on how to address this issue, it may be worthwhile to take notes from the world of shared computational resources. Community-sourced cloud computing and serving frameworks have existed for some time, such as BitTorrent for file serving and communities of citizen scientists offering their personal computing power to large scientific simulations. In the case of the scientific project SETI@home, the user's computational resources are only consumed when the computer is not in use [17]. In the case of BitTorrent, the user can designate the amount of bandwidth they are willing to share, uniformly or depending on time of day and week. In the SatNOGS use case, the ability of a station owner to place simple time constraints on when users can schedule observations could be a good first step toward enforcing respectful use of resources.

The remaining issue we see with the network are its current vulnerabilities due to its relatively open nature. The SatNOGS project is open-source and welcoming of software plugins, and offers its own API. The paper has noted previously in the possibility of humans draining bandwidth by over-scheduling resources. However, there is also the possibility of software either mistakenly or maliciously draining network bandwidth in the same way human operators can mistakenly or maliciously over-schedule observations and create a DOS-style (denial of service) attack scenario. The developers and users of SatNOGS are continuously making the system better and adding features, but the community should keep in mind that abuse and misuse are a threat to consider. Possible ways to avert system vulnerabilities is to design in limitations for the users, which makes the network less capable and open; or to govern the systems and users in some fashion. It is possible that the network community decides that little network governance and limitations are desired and to keep an open and decentralized model moving forwards. In this scenario, the network community trusts in the global community to respect etiquette guidelines, safety protocols, and best practices.

Like many new technologies, the choices made in these early days will have a profound impact on the character of these networks in the future as they mature. These paragraphs have highlighted some possible models to investigate and a few of the apparent vulnerabilities that exist. Now that the infrastructure and community to support a large FGN is finally available, it may only be a matter of time before these hypothetical problems of resource scarcity, scheduling conflicts, and security breaches become reality. It will be important for users of these networks to work together to develop methods to solve these future issues proactively.

The use of SatNOGS has enabled the team at MXL to do some interesting things, from collecting extra data to saving an entire CubeSat mission on its first days. The hope of the MXL team is to see SatNOGS continue to grow in number of users and in maturity of technology. This section has stated the TBEx operations team's thoughts and concerns in hopes that the community can work together to support this project and the powerful advantages granted by its many stations and easy accessibility.

CONCLUSION

SatNOGS is a modern day realization of decades' worth of research and community efforts to establish an FGN for receiving spacecraft data. SatNOGS is a continually-growing tool that was originally intended for amateur radio operators, but is becoming increasingly relevant as a mainstream mission operations tool. MXL and other research programs have leveraged the network to improve spacecraft communications capabilities within their own programs and operational resources. The pairing of the powerful, global SatNOGS capabilities with the diversity of local, small space program ground stations have allowed for increased situational awareness during mission operations. As an example, MXL was able to save its TBEx mission after deployment issues and increase real-time beacon collection by a factor 2.20 using SatNOGS. With these groundbreaking advantages, SatNOGS will likely continue to grow. Since the network is currently very unrestricted in terms of how it is used, we caution the community to proactively consider issues related to resource shortages, protection of hardware owner priority, and security vulnerabilities.

REFERENCES

1. Berthoud, L., Swartwout, J., Cutler, J., Klumpar, D., Larsen, J., and Nielsen, J. D., "University CubeSat Project Management for Success," Proceedings of the 33rd Annual AIAA/USU Conference on Small Satellites, Logan, UT, August 2019.
2. Venturini, C.C., "Improving Mission Success of CubeSats," Proceedings of the Mission Assurance Improvement Workshop, El Segundo, CA, May 2017.
3. Jacklin, S.A., "Small-Satellite Mission Failure Rates," NASA STI Report, NASA Ames Research Center, March 2019.
4. Swartwout, M., "CubeSats and Mission Success: 2016 Update," 2016 Electronics Technology Workshop, NASA Goddard Space Flight Center, June 2016.
5. Cutler, J.W. and P. Linder, "A Federated Ground Station Network," Proceedings of the 2002 SpaceOps Conference, Houston, TX, October 2002.
6. Nakamura, Yuya and Nakasuka, Shinichi, "Ground Station Network to Improve Operation Efficiency of Small Satellites and Its Operation Scheduling Method," 57th International Astronautical Congress. October 2006. DOI: https://doi.org/10.2514/6.2008-3205
7. Schmidt, Marco and Schilling, Klaus, "Internet-Based Ground Stations Networks for Pico Satellites," SpaceOps 2008 Conference. May 2008. DOI: https://doi.org/10.2514/6.2008-3205
8. Spangelo, S.C. and D.R. Boone and J.W. Cutler, "Assessing the Capacity of a Federated Ground Station Network," Proceedings of the 2010 IEEE Aerospace Conference, Big Sky, MT, March 2010.
9. Cutler, J. W. and Kitts, C. A., "Mercury: a satellite ground station control system," 1999 IEEE Aerospace Conference Proceedings, Aspen, CO, March 7, 1999.
10. Leveque, K., Puig-Suari, J., Turner, C., "Global Educational Network for Satellite Operations (GENSO)," Proceedings of the 21st Annual AIAA/USU Conference on Small Satellites, Logan, UT, 2007.
11. White, D.J. and others, "SatNOGS: Satellite Networked Open Ground Station," Valparaiso Engineering Faculty Publications & Patents, vol. 40, 2015.
12. Libre Foundation, "SatNOGS Network," Web. Retrieved May 2020. URL: network.satnogs.com
13. Norton, C. D., Chien, S. A., Pingree, P. J., Rider, D. M., Bellardo, J., Cutler, J. W., and Pasciuto, M. P., "NASA's Earth Science Technology Office CubeSats for Technology Maturation," Proceedings of the 27th Annual AIAA/USU Conference on Small Satellites, Logan, UT, 2013.
14. Wilson, Michael, "Applying Modern Software System Design to Small Satellite Development and Operations," 34th Annual Small Satellite Conference, Logan UT, August 2020.

15. England, N., Cutler, J., and Sharma, S., "Tandem Beacon Experiment – TBEx: Design Overview and Lessons Learned," CubeSat Developers Workshop, San Luis Obispo, CA. Oral Presentation. April 2018.

16. Casting, Jeremy, "Scheduling Downloads for Multi-Satellite, Multi-Ground Station Missions," Proceedings of the 28th Annual AIAA/USU Conference on Small Satellites, Logan, UT, 2014.

17. Korpela E. and D. Werthimer, "SETI@Home - Massively Distributed Computing for SETI," Computing in Science & Engineering, vol. 3, no. 1, January 2001.