

## An Updated Overview of the Satellite Networked Open Ground Stations (SatNOGS) Project

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### ABSTRACT

An overview of the SatNOGS project, a network of satellite ground stations around the world, optimized for modularity, built from readily available and affordable tools and resources. The rate of Low Earth Orbit (LEO) satellite launches increases with the participation of old and new entities. In this growing environment, SatNOGS provides a scalable and modular solution to track, identify, receive telemetry from, monitor, and assist operators in command/control of satellites. The SatNOGS global community, dedicated to its free and open-source values, develops hardware ground station designs (antennas, rotators, electronics), software for SDR-based communications, satellite scheduling and mission monitoring platforms. SatNOGS continuously develops and improves its infrastructure to allow observers to use this networked ground segment and remotely operate SatNOGS ground stations around the world. It also provides an easy way to store, access and view increasingly received satellites data, by supporting VHF, UHF, L and S bands.

### 1 INTRODUCTION

Once an individual or organization builds a ground station for small satellite downlinks, especially if not a commercial venture, the hardware ends up sitting idle for a great majority of the time. This capability, when not being actively used by the local owner, could be utilized for reception of other satellites. The SETI@home project is one of the earliest and well-known projects to make use of idle resources – compute cycles in that case.<sup>1</sup>

Recent advances in low-cost, software-defined radio (SDR) technology and 3D printing have put ground station ownership within the reach of individuals. Largely composed of Amateur Radio operators, these

people receive telemetry and data from many satellites and provide the information to the owners and the general public.

What is missing is a civilian infrastructure to connect these many owners and ground station operators in a way that is flexible and open. Services, such as RBC Signals,<sup>2</sup> KSAT,<sup>3</sup> and Leaf Space<sup>4</sup> are also addressing this issue from the commercial side. The FUNcube project is a prime example of a well-organized effort to receive and collect data from satellite for educational outreach.<sup>5</sup>

## 1 History

Members of *Hackerspace.gr*<sup>6</sup> in Athens Greece first proposed SatNOGS as a part of the 2014 International Space Apps Challenge's "Virtual Ground Station App – Global Crowdsourcing of CubeSats" Challenge.<sup>7</sup> It was later submitted as an entry to the 2014 Hackaday Prize, ultimately winning the grand prize of \$196,418.<sup>8</sup> The funds provided seed money to start the Libre Space Foundation,<sup>9</sup> a non-profit dedicated to supporting free and open source space and related projects. One of the first extension projects from this was a collaboration between the Libre Space Foundation and the University of Patras with the QB50 project on the 2U CubeSat UPSat.<sup>10</sup> The satellite, launched on April 18, 2017 and deployed from the ISS on May 18, 2017, was one of the first open source satellite designs.

A unique aspect of the project is its position bridging the Maker, Hacker, and Amateur Radio communities. The 2015 TAPR/AMSAT Banquet's speaker, Michael Ossmann ADØNR of Great Scott Gadgets and creator of the HackRF, at the 2015 TAPR/AMSAT Banquet, pointed out the many characteristics valued and shared by these two communities.<sup>11</sup> Ward Silver, NØAX's article for Makezine also draws these connections.<sup>12</sup>

## 1 Overview

This paper gives an overview of the SatNOGS<sup>13</sup> project's major components. Figure 1 gives a high-level overview of the relationship between users and ground stations. Figure 2 illustrates the relationship of the four major sub-projects: Network, DB, Client, and Ground Station, to the other components of a ground station. Each sub-component is described in the following sections. The modular approach promotes re-use of existing components at a ground station.

All code and hardware designs for the project are publicly available under Open Software (AGPLv3 and GPLv3) and Open Hardware (CERN OHLv1.2) licenses.<sup>14</sup> Software documentation may be found at.<sup>15</sup> Additional information and tutorials are at the community-supported Wiki.<sup>16</sup> Data collected and stored in the Network and DB components are freely available under the Creative Commons Attribution-Share Alike license.<sup>17</sup>

## 2 NETWORK

The SatNOGS Network is accessed by users via a web interface. The user provides details about observation that they would like to schedule (which

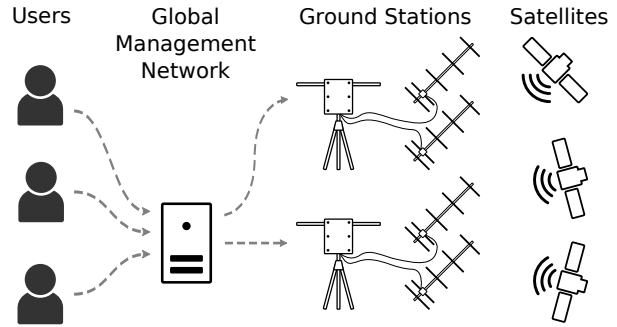


Figure 1: General architecture of SatNOGS interactions.



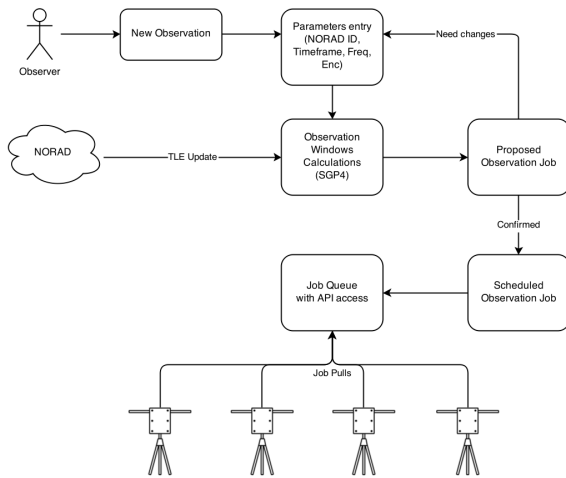
Figure 2: Four major software components of SatNOGS.

satellite, which band, time-frame, signal encoding, etc.). From this information, the system calculates the possible observation windows from the currently available Ground Stations connected to the Network having the necessary capabilities. Once the observer confirms the proposed "Observation Job" then it is sent as a job to each Ground Stations' job queue to be executed. Figure 3 diagrams this process.

The Network website provides a real-time count of the ground stations registered on the network. At the time of the writing, there are 261 online and 148 additional stations in testing mode (typically due to a new station being commissioned). This represents a 6x increase in online stations since our previous 2018 SmallSat publication.

An additional staging server is available to allow testing of ground station client software before being made available for scheduling on the production network.<sup>18</sup>

Account holders on the Network site (owners of connected ground stations), are able to schedule observation jobs on any of the ground stations for any configured satellite. Users search for either desired satellite or ground station and the server computes



**Figure 3: Network operations involved in scheduling an observation of a specific satellite by a certain ground station.**

pass information for matching observation windows. Then they select the desired passes and schedule the jobs.

Ground Stations query the Network server for its current list of scheduled jobs, execute those observations, collect observation data, then upload it back to the Network through a REST API. Uploaded data is then made available to the initiating user and any other third party via the observation's ID. Modern web technologies are used on the Network website to provide timeline and recording visualization and playback directly in the browser. Download links are also provided for further offline analysis. No special software or installation is necessary for users to interact with the Network. SatNOGS Network provides an API to allow other applications and services to query information and, in the future, automatically schedule observations.

Figure 6 shows the metadata and waterfall plot that is recorded for a successful job. In this case, it is for the VHF FM downlink portion of an ARISS<sup>19</sup> school contact with an ISS astronaut, recorded as observation #130609. Also, Figure 7 shows the web view of the embedded audio player widget which allows listening to the demodulated downlink audio.

The Client component uploads a waterfall plot of the received spectrum, demodulated audio recording, and decoded data frames found in the recording. The audio recordings are then archived at the Internet Archive in the SatNOGS collection.<sup>20</sup> Figure 8 shows an example of the Network website's display

for uploaded data-under-voice (DUV) frames from AMSAT-NA's AO-85 or FOX-1A CubeSat.<sup>21</sup>

### 3 DATABASE

The coordination and aggregation provided by the Network component requires a centralized source of satellite information such as frequencies and transmission modes. SatNOGS DB was created to address the fact that there was no known public source for this information in a machine-readable format. In the same spirit of the rest of the project, the database is open access and not specific only to the SatNOGS project. For example, the Android and iOS app ISS Detector uses SatNOGS DB for obtaining satellite information.<sup>22</sup>

Specifically, DB is a crowd-sourced suggestions app for transponder data. Satellites are identified by their NORAD space object catalog number, a UUID-based SatNOGS Satellite ID, and their common name. Each object has an associated set of transponder records which indicate frequencies and modulation formats. SatNOGS Network pulls this information when calculating possible observations. Orbital information (TLEs) is sourced from numerous sources including Celestrak<sup>23</sup> and stored in the DB along with each observation's metadata.

Updates to information in the database are encouraged and accepted from the public and also from other sources of satellite information with open APIs. As with the Network, user interaction is purely web-based and requires no additional software besides a modern web browser.

Besides satellite information, the DB component is a repository for collected telemetry data. The API works with third-party apps including the DK3WN TLM Forwarder<sup>24</sup> and gr-satellites.<sup>25</sup> The database currently stores information about 828 satellites with 1,479 transmitters and over 16 million telemetry frames.

If the binary format of the telemetry is known (for example, either through collaboration with the team or public documentation), a Kaitai Struct<sup>26</sup> can be created that allows for automatic parsing of the binary and creation of JSON. This JSON is then stored in the SatNOGS InfluxDB instance, which is made publicly accessible via a Grafana<sup>27</sup> dashboard at dashboard.satnogs.org.

### 4 CLIENT

SatNOGS Client consists of software running a computer which controls the ground station hardware. Figure 12 diagrams the internal, modular, components of the client's interaction with the Network.

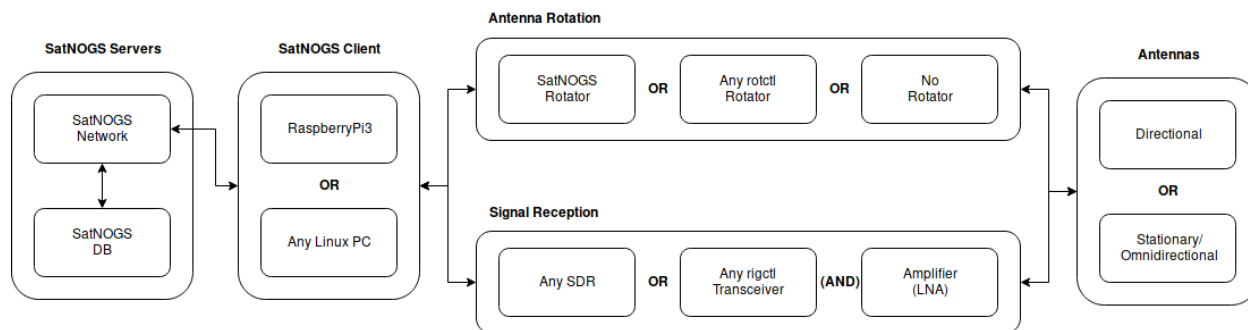


Figure 4: Interactions between the SatNOGS Network servers and a ground station.

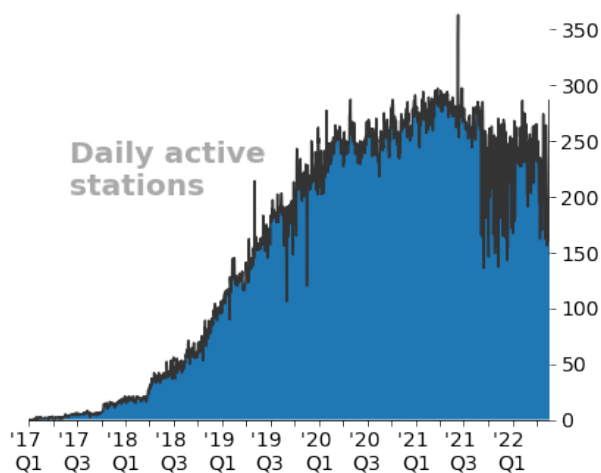


Figure 5: Daily Active Stations (at least one observation in 24hr interval)

The poller regularly checks the Network API for observation jobs scheduled for the local Ground Station. Information contained in each job includes satellite orbital elements, receiver tuning and demodulation parameters, and timing. The PyEphem<sup>28</sup> library is used to calculate the necessary antenna pointing and relative velocity for doppler shift calculation during the pass.

Where possible, existing standard interfaces are used within the Client. These include using the daemons `rotctl` for rotator control and `rigctl` for frequency control from HamLib.<sup>29</sup> Any rotator controller which works with `rotctl` automatically works with the SatNOGS Client by providing the appropriate serial port or IP address the rotator is listening on.

Control and operation of the receiver hardware and processing uses GNU Radio.<sup>30</sup> Flowgraphs from the out-of-tree module `gr-satnogs` contain the Doppler tuning, translation, demodulation, and decoding con-

figuration for each of the *transmitter modes* as defined in the DB. These are either generic modulation and baud rate tags such as `BPSK1k2` or `GMSK9k6`, or satellite specific settings such as the AMSAT FOX series data-under-voice, DUV.

At the end of a pass, an image is rendered from waterfall data, then it and other demodulated signal data is placed in a queue for later upload to the Network. Logs and other reports are also sent back to the Network by other API actions.

#### 4 Raspberry Pi 4, Raspbian image

The reference ground station is based on the Raspberry Pi 4 single-board computer.<sup>31</sup> A custom operating system image based on Raspbian is available that includes all necessary software for setting up a ground station client.

Figure 13 shows a screenshot of the `satnogs-config` terminal program for configuring client parameters such as API key and custom pre/post observation scripts. These scripts, if configured, are written by the end user to properly startup and shutdown any additional unique services or configuration, such as antenna switches.

### 5 GROUND STATION

The SatNOGS Ground Station sub-project encompasses the hardware at a specific receiving location including computer, rotator, antennas, and RF path. Figure 14 illustrates the modular nature of the system.

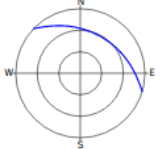
#### 5 Computer

Ground station owners execute the Client software on either an embedded single-board computer such as a Raspberry Pi 4 or on a PC. This computer also, via network TCP connections or a direct USB/RS232 connection, communicates with the rotator controller

# Observation #130609

Discuss

Timeframes are in UTC

**Satellite** 25544 - ISS  
**Station** 2 - KB9JHU  
**Observer** Dimitrios Papadeas  
**Status** Good  
**Transmitter** Mode U/V FM Voice  
**Frequency** 145.800 MHz  
**Encoding** FM  
**Timeframe** 2018-05-07 13:53:04  
 2018-05-07 14:03:45  
**Rise** 313.0°  
**Max** 31.0°  
**Set** 107.0°  
**Client Version** 0.6.1  
**Metadata** ▶ { 4 items }  
**Polar Plot**  
  
**Downloads**

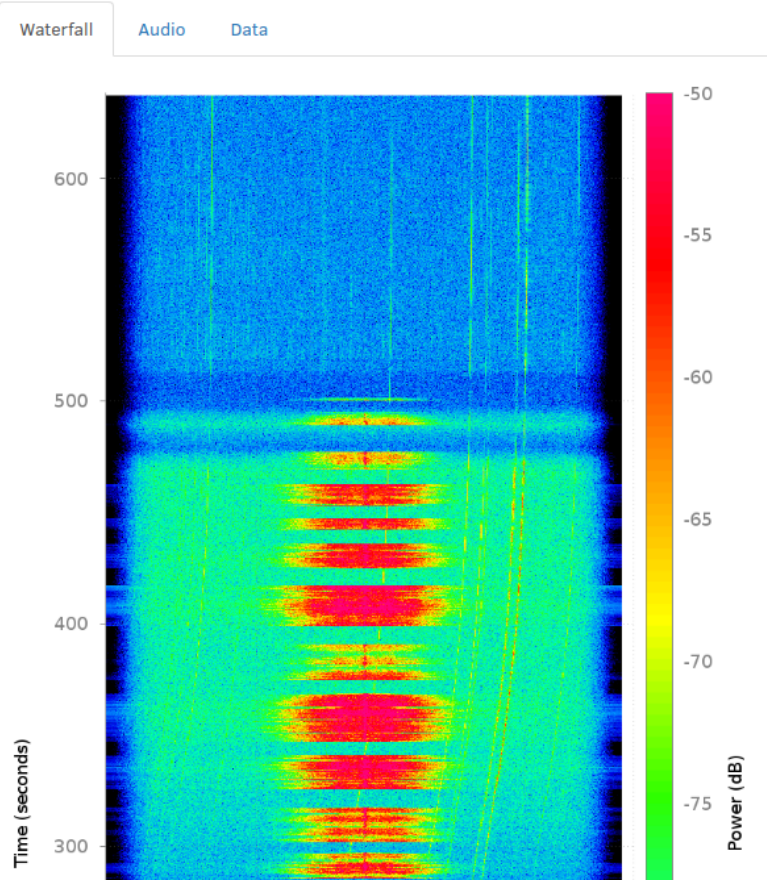


Figure 6: Observation information and waterfall plot of signal received from ARISS contact.

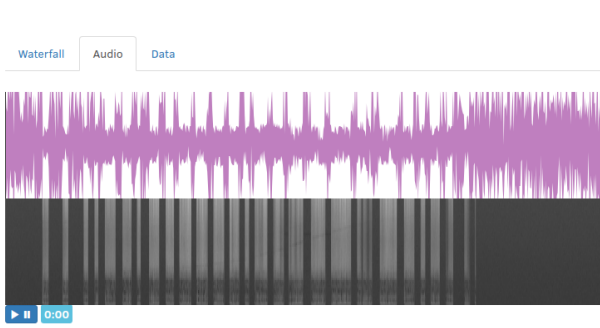


Figure 7: Demodulated audio player tab from observation #130609.

Waterfall Audio **Data** 2

```

data_obs/159177/data_159177_2018-06-12T14-46-36
F9 17 05 5B 6A 58 4D FB EE F4 3F 03 17 17 17 17 57
14 D5 06 08 18 3D 03 BB E3 36 9E 48 72 91 28 7B 78 D1 F1
14 D7 64 80 81 25 10 69 66 85 FB 60 FE 43 02 03 07 1B 22
22 A2 72 90 23 22 22

data_obs/159177/data_159177_2018-06-12T14-51-42
F9 17 8D 5F A4 9A 9B 9B 9B 4C 49 9B 9B 1B 88 E0 F0 F0 79
10 10 DD DD 1B 3B D9 75 64 80 61 A8 F8 58 48 48 20 7F 02
03 B7 15 64 46 24 C8 10 7F B9 57 67 07 10 43 02 CA 27 10
27 07 AE 16 38 AC 39
    
```

Figure 8: Decoded DUV telemetry data from FOX-1A.

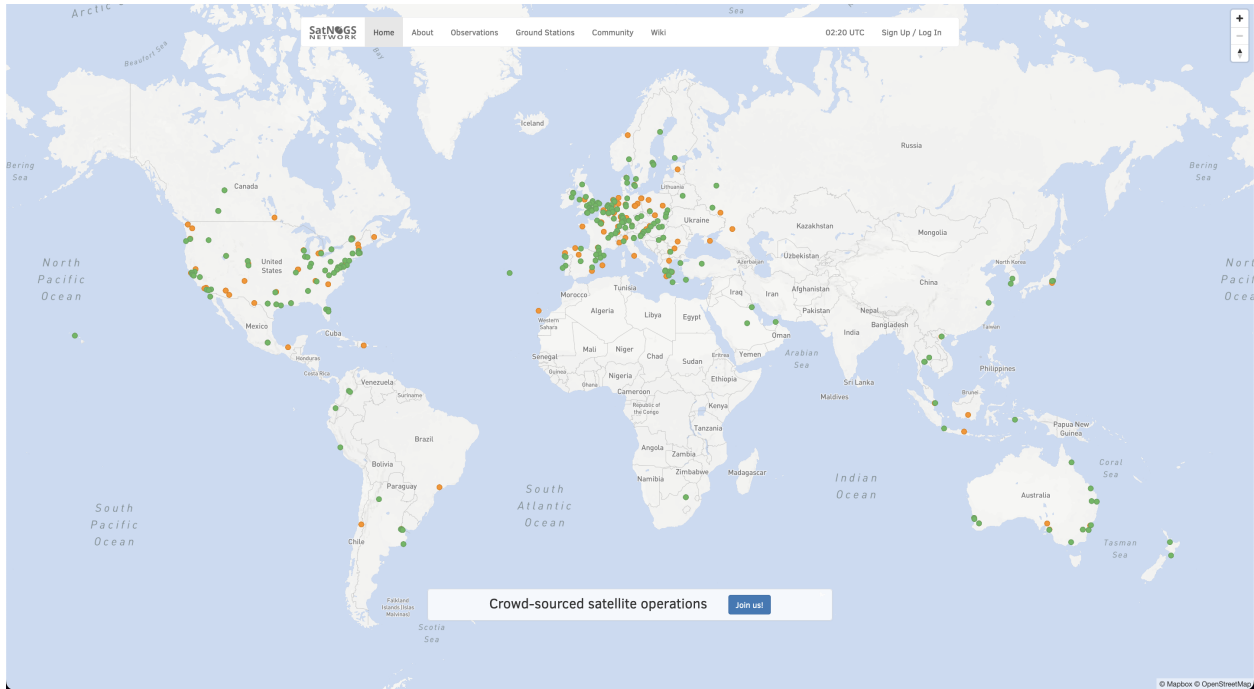


Figure 9: Active SatNOGS Ground Station locations.

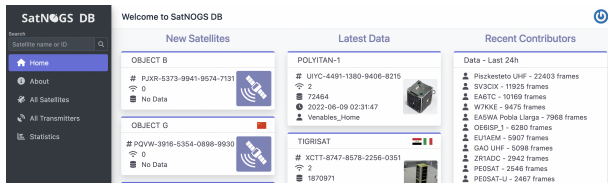


Figure 10: Screenshot of the SatNOGS DB front page.



Figure 11: Screenshot of an example SatNOGS Dashboard.

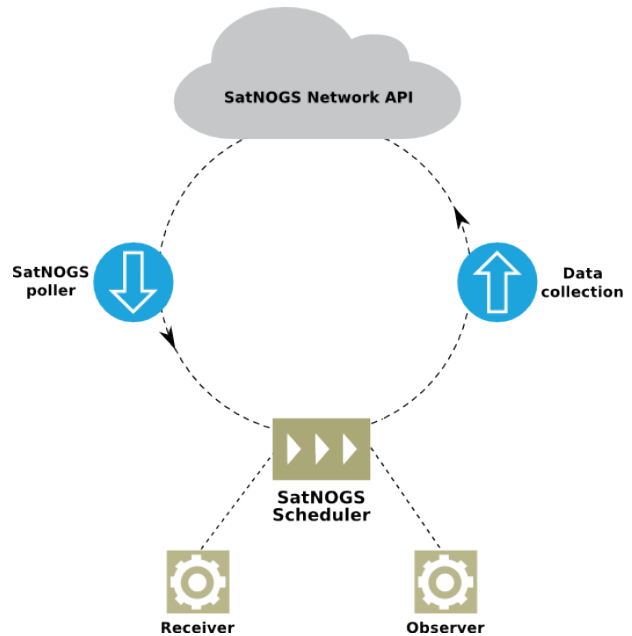


Figure 12: Client communication and operation modules.

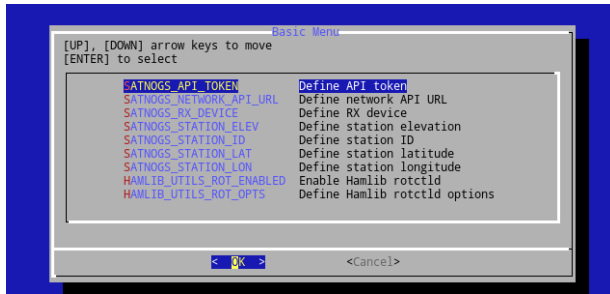


Figure 13: satnogs-config on Raspberry Pi 4

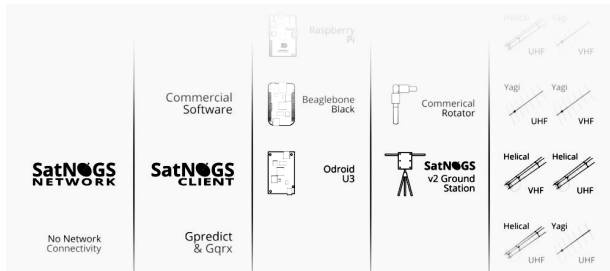


Figure 14: Ground Station modular options.

and receiver hardware. A software-defined radio receiver, such as the inexpensive RTL2832U-based USB device,<sup>32</sup> is attached to the computer and the connection configuration setup with the satnogs-config utility.

## 5 Antennas

The station antenna(s) may range from an omnidirectional antenna to a rotator with directional antennas (Yagi or parabolic). Typical omnidirectional antenna choices are turnstiles, quadrifilar helix (QFH), or vertical base station antennas. A COTS LNA is often paired with these omnidirectional antennas to increase sensitivity to weak signals. The hardware may be any combination of commercial or custom hardware. Figure 15 shows a commercial rotator with a pair of commercial antennas. Omnidirectional antennas, such as in Figure 16 require the minimum of hardware for a functional SatNOGS ground station.

There are designs for every component necessary for a SatNOGS-compatible ground station as part of the project. Antennas and RF path hardware may be use SatNOGS, homebrew, or commercial as the station owner deems appropriate. To help the goal of easily constructed ground stations, the project’s designs focus on common hardware, 3D-printed parts, and tools available in most experimenters’ shops of local “maker spaces.”



Figure 15: Corey Shields KB9JHU ground station #2 with commercial rotator with UHF and VHF antennas.



Figure 16: Omnidirectional antenna for Rick Zathras’ ground station #23 in Perth, Australia.

## 6 CONCLUSION

The SatNOGS project aims to provide and promote free and open source satellite ground stations. Modern open software and web technologies are used to coordinate these stations to more fully utilize the reception capabilities for low earth orbiting satellites. By using a modular approach to the ground station segment, the existing stations of radio amateurs and others may be used with the network. Avoiding custom, network-specific software and hardware and ensuring all design information, code, and received data is and remains freely available is a core tenet of the project. Individuals and organizations are encouraged to partner with the project to help realize these goals.

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