L-Band Satellite Tracking and Characterization System

Final Project Binder

Authors:

* Charles Kente Van Horn Jr. (Team Leader) - RF and Microwave Engineering (EE)
* Samuel Walker Taliaferro VIII Velasquez - Machine Learning (CPE)
* Justin Ward Daigle - Communications (EE)
* Ethan Christopher Duval - Networking and Cyber Security (CPE)
* Jared Jamison - Controls Robotics and Autonomy

Date: Dec 01, 2023

Abstract

Satellite Tracking and Characterization System. The system aims to provide efficient and accurate tracking and data collection of L-Band satellites using a Raspberry Pi 4 as the main processing platform. The design consists of several interconnected subsystems, including the computer system, operations software, mount subsystem, enclosure, receiver, power system, and antenna. The document provides a comprehensive overview of each subsystem, its specifications, connections, and implementation. Additionally, the document includes an acceptance test plan to evaluate the system's performance and ensure it meets the design requirements.

Table of Contents:

[**Final Problem Analysis 2**](#_pnbzyjbglnr2)

[Objective 2](#_1l1prvb8nhv5)

[Requirements 2](#_8duswptwgruv)

[Preliminary and Critical Design Reviews 4](#_uhlhoabfmvvz)

[Constraints 4](#_vyqpv67h24cq)

[Engineering Standards 4](#_uszrgaappz93)

[**Updated Final Documents & Code 5**](#_katnsi7zaqrd)

[Detailed Design Documentation 5](#_l9ew4quxvsb3)

[Construction Manual 5](#_3882ckecqlmz)

[User Manual 5](#_ylsu80hgl01t)

[Software Code Repositories 5](#_6m7ztq6hpj3a)

[**Build & Test 5**](#_444vqqyu67cl)

[Project status/results 5](#_c7wnislw9n5x)

[Test Results and Analysis 6](#_eviorutc85ow)

[Key Accomplishments 6](#_71d6llb70gx)

[**Delivery 7**](#_pljducb41uey)

[Overall Project Performance 7](#_jd30nkutzf23)

[Customer Satisfaction 8](#_uldyfarx4c9f)

[Deliverables Status 8](#_8gozrsclr4gh)

[Challenges and Issues 8](#_m9nxo0wz1jos)

[Schedule and Costs Status 9](#_j0cn02yvsji4)

[Lessons Learned 9](#_5osssxjssm8a)

# Final Problem Analysis

## Objective

### Background

Radio signals transmitted by satellites create troublesome interference for radio telescopes (see e.g. [1] and references therein). Virginia Tech is sponsored by the National Science Foundation (NSF) to research methods for mitigating this interference [2]. To support this research, we would like to acquire and characterize examples of these signals as they are received. We would like to do this at the highest possible sensitivity so as to allow us to examine the spectral sidelobes of these signals. Our highest priority is the L-band downlink from the low-earth orbiting (LEO) satellite mobile communications system known as “Iridium”. However, we are also interested in the L-band downlink signals from other systems, including the various global navigation satellite services (GNSS), INMARSAT, and NOAA’s Geostationary Operational Environmental Satellites (GOES).

### Project Description

We seek a portable system consisting of a high-gain antenna on a portable mount with

motorized two-axis (i.e., “az-el” or equatorial) positioning to keep the antenna pointed at the

satellite for the duration of an observation. The system includes a sensitive receiver with a high

immunity to spectrally-disjoint signals not of interest, and continuous Nyquist-rate sampling and

streaming to local non-volatile storage.

## Requirements

For detailed information, refer to '[solutions\_requirements\_v5.0.xlsx](https://docs.google.com/spreadsheets/d/15DPWjj7SIo2j9cXfnoLrDDS24Eu9Rd5p/edit?usp=drive_link&ouid=116263820077964886954&rtpof=true&sd=true)'.

| **Category** | **REQ-#** | **Requirement** |
| --- | --- | --- |
| **Functional** | FUN-1 | The system shall physically rotate the antenna 0-360 degrees in azimuth, and 0-180 degrees in elevation. |
| FUN-2 | The system shall have a receiver noise temperature less than 200K |
| FUN-3 | The system shall have an antenna that is RHCP polarized. LHCP Polarization is desired but not required. |
| FUN-4 | The system shall have a receiver whose bandwidth is variable up to 2MHz minimum, with up to 10MHz desired |
| FUN-5 | The system shall have >40 dB rejection of 0.5-1350 MHz and 1800-2700 MHz signals |
| FUN-6 | The system shall track a satellite until the signal from it disappears. |
| **Performance** | PER-1 | The system shall have an antenna gain that is maximized subject to constraints imposed by other requirements. |
| PER-2 | The system's receiver shall have a tunable range between 1550-1700MHz. 1400-1700MHz desired. |
| PER-3 | The system shall record multiple preset satellite signals autonomously |
| PER-4 | The system shall be designed such that self-generated radio interference is minimized and undetectable by the system. |
| **Compliance** | COM-1 |  |
| COM-2 |  |
| **Environmental** | ENV-1 | The system shall operate within a ambient air temperature band of 14°F to 100°F (-10°C to 40°C). |
| **Environmental** | ENV-2 | The system shall operate within the regular weather climate of Blacksburg (ex: light rain, snow). |
| **Reliability** | REL-1 | The system shall withstand lightning level current. |
| REL-2 |  |
| **Power** | POW-2 | The system shall be battery powered |
| POW-2 | The system shall be able to record and wirelessly transmit satellite data over an 18 hour timespan. |
| POW-3 |  |
| **Mechanical** | ME-1 | The system shall be transportable a minimum of 100 yards by two average adults. |
| ME-2 | The system shall be shut down, disassembled, and packed up in less than ten minutes |
| ME-3 | The system shall be assemblable in less than five minutes |
| ME-4 | The system shall fit into two medium sized hard shelled containers |
| **Input/Output** | I/O-1 | The system shall communicate wirelessly to an external device, preferably either bluetooth or Wi-Fi |
| I/O-2 | The system shall utilize continuous nqyuist-rate sampling |
| I/O-3 | The system shall store its data in non-volatile storage |
| I/O-4 | The system shall observe a point of space given an azimuth and elevation measurement. |
| I/O-5 | The system's shall observe a satellite track given two line elements(TLE). |
| I/O-6 | The system's software shall be free and open-source |
| I/O-7 | The system shall be accessible by the wireless user at any time during operation |
| **Testing** | TEST-1 |  |
| **Configuration** | CON-1 |  |
| **Cost** | COST-1 | The system shall be replicable for < $2000 USD |
| **Schedule** | SCH-1 |  |

## Preliminary and Critical Design Reviews

Refer to ‘[Preliminary Design Review](https://docs.google.com/presentation/d/1lgGC2DvTayT1eNzwPuoIXg0kybszu15eXM3VI02RxwE/edit#slide=id.p)’ for the Preliminary Design Review presentation.

After this presentation, we were given a month to revise our design and make any changes deemed necessary by the customer. These can be seen in slides 49-51.

Refer to ‘[Critical Design Review](https://docs.google.com/presentation/u/0/d/15SeHId47s849kS8t54xM4YOoTSQarLB6Zu4SPrC-CTw/edit)‘ for the complete presentation.

This document was also updated after the actual review. The changes made can be viewed on slides 50-53 of this document.

## Constraints

The constraints for our system are based on the requirements document listed above. For further details, refer to '[solutions\_requirements\_v5.0.xlsx](https://docs.google.com/spreadsheets/d/15DPWjj7SIo2j9cXfnoLrDDS24Eu9Rd5p/edit?usp=drive_link&ouid=116263820077964886954&rtpof=true&sd=true)'.

## Engineering Standards

The engineering standards for this project were done separately, and the documents are listed below. Each team member did a separate analysis based on their own unique subsystem.

For power standards, refer to ‘[Jared\_J\_Engineering\_Standards.pdf](https://drive.google.com/file/d/1azrU5u0uHrVCbJCnCqobSohozH1MBKuf/view?usp=drive_link)’

For mounting standards, refer to '[Justin\_Daigle\_Engineering\_Standards.pdf](https://drive.google.com/file/d/12CfnstJXxffqkRJOlynH6jyVnhRlLayI/view?usp=drive_link)’

For antenna polarization standards, refer to ‘[Charles\_Van\_Horn\_Engineering\_Standards.pdf](https://drive.google.com/file/d/1ZPw0gxz8HQLNIyY56VrbTi7NBpmYdjuw/view?usp=drive_link)’

For antenna measurements standards, refer to ‘[Samuel\_Taliaferro\_Engineering\_Standards.pdf](https://drive.google.com/file/d/1SUktipoCFYAsWMB_chTYf3QQRoVDVK4m/view?usp=drive_link)’

For tuning range standards, refer to ‘[Ethan\_Duval\_Engineering\_Standards.pdf](https://drive.google.com/file/d/1LR0gvO2SWVqtaDj6JIWx7a5lsJg9paPa/view?usp=drive_link)’

# Updated Final Documents & Code

## Detailed Design Documentation

Refer to ‘[LBST\_detailed\_design\_V1.0.docx](https://docs.google.com/document/d/1uOGEV6zQou5qu9N2J8zJVtcnQKx2ouCr/edit?usp=drive_link)’ for the complete detailed design document.

## Construction Manual

Refer to ‘[LBST\_construction\_manual\_V1.1.docx](https://docs.google.com/document/u/4/d/1bek6y4nOyYfJDPBJqe-CSwfM2AnO1pV1uRzMdPPT_JI/edit)’ for the complete construction manual.

## User Manual

Refer to ‘[LBST\_user\_manual\_V1.1.docx](https://docs.google.com/document/d/1wkOwWlwhrdVZX_x9B1R4DTas78BJ8Exk/edit?usp=drive_link)’ for the complete construction manual.

## Software Code Repositories

Refer to ‘<https://github.com/Ethancd19/LBand-Satellite-Tracking-System>’ for access to the home base repository for our project, where we store all documentation, diagrams, and links to other repositories.

Refer to ‘<https://github.com/samueltv250/MDE>’ for access to the full backend code that goes into the client's computer, the Raspberry Pi, and the Arduino.

Refer to ‘<https://github.com/Ethancd19/L-Band-satellite-tracking>’ for access to the full frontend code that goes into the client's computer.

# Build & Test

## Project status/results

The project has successfully achieved completion and delivery to the client, featuring a fully functional autonomous backend for our satellite tracking system. Each subsystem has undergone rigorous testing, ensuring robust performance. The fully assembled system has been delivered to the client, marking a significant milestone in the project's lifecycle.

## Test Results and Analysis

* Rotor Movement: The backend's ability to control the rotor has been confirmed through precision movement tests, ensuring accurate alignment with satellite positions.
* Scheduling Validation: Utilizing publicly available data on satellite passes, the scheduling function has been cross-verified for accuracy in predicting satellite rise and set times.
* Satellite Positioning Program: The program's calculations of azimuth and elevation have been validated by comparison with established free rotor controller software, ensuring reliability in its positioning algorithms.
* Mounting Stabilization: The rotator and mount have been tested to ensure proper load-bearing capacity and slew rate requirements were met to allow for tracking of overhead iridium satellites.
* Wireless Communication: Extensive testing of WiFi connectivity has been conducted, with successful data transmission through various barriers and at different distances. The backend has demonstrated a stable connection with offloading speeds peaking at 6 Mbps. Moreover, data offloading via a removable drive has been implemented, requiring system shutdown for secure transfer.
* Enclosure Weatherproofing: The enclosure has been tested to ensure waterproofing and wind resistance for all hardware components stored within.
* Recording raw iq samples: Extensive tests of raw data acquisition at 10MHz sample rate, writing directly to the USB drive.
* Antenna tests: The antenna has been tested using a Keysight Programmable Network Analyzer. The antenna was tested for its S11 parameter to confirm that it is resonant at the correct center frequency of ~1.5GHz, has the expected bandwidth of ~55% of its center frequency, and its loss was estimated from the S11 plot.

*S11(dB) vs. Frequency (GHz):*

Refer to ‘[trackin\_and\_data\_acquisition\_demo.mp4](https://drive.google.com/file/d/1wEeU2ubVosRNcIHlF-XRqU6fzxXdMt1o/view?usp=drive_link)’ for a full demonstration of satellite tracking.

## Key Accomplishments

* System Architecture Development: Designed and implemented a custom autonomous backend system for satellite tracking—Samuel Taliaferro.
* Rotor software development: Engineered an interface using Arduino, enabling precise rotor control and positioning—Samuel Taliaferro.
* Software Development: Authored multifaceted software in Python and Bash, integrating various technologies and protocols for system autonomy—Samuel Taliaferro.
* Data Communication: Implemented a robust communication protocol to ensure reliable data transfer over WiFi and through optional physical USB drive offloads—Samuel Taliaferro.
* Testing and Validation: Conducted a series of rigorous tests on each subsystem software interface to validate functionality and performance metrics—Samuel Taliaferro.
* Scheduling Algorithm: Developed a complex scheduling algorithm to accurately predict satellite trajectories using public TLE data and sgp4 algorithm—Samuel Taliaferro.
* Backend Readiness: Achieved full backend readiness for integration, fully functional through terminal commands. setting a solid foundation for the final assembly of the satellite tracking system—Samuel Taliaferro.
* Innovative Calibration: Crafted an innovative calibration protocol within the Arduino environment to define the system’s operational parameters—Samuel Taliaferro.
* Signal Processing: Designed, implemented and tested a signal processing pipeline for satellite data recording and analysis, optimizing for both single and dual tuner configurations—Samuel Taliaferro.
* Rotator: Implemented and tested azimuth and elevation rotator mounted on radio tripod - Justin Daigle
* Rotator Mounting: Designed, implemented, and tested antenna mounting system on chosen rotator - Justin Daigle/Jared Jamison
* Rotator Interface: Designed, built and tested onboard computer to system rotator controller interface based on common emitter circuit - Justin Daigle/Jared Jamison
* Enclosure: Designed and built waterproof system enclosure for non-weatherproofed systems - Justin Daigle/Jared Jamison
* Antenna: Designed, built, and tested axial mode helical antenna. Successfully resonated at 1.5GHz, with a VSWR of <2 between 1.3GHz, and 1.7GHz. – Charles Van Horn
* Battery: Tested and implemented onboard battery system - Jared Jamison
* Receiver: Designed, simulated, and sent out interdigital microwave filter to be fabricated. – Charles Van Horn
* Front-End Software Development: Designed a custom front-end user interface using PyQT which had to be learned on the fly, allowing for the user to have an intuitive GUI to interact with the system. - Ethan Duval
* GPS positioning: Designed and tested (though was not implemented fully) GPS positioning of the system - Ethan Duval

# Delivery

## Overall Project Performance

The delivered system has successfully completed the functionality of satellite tracking, with a fully autonomous backend onboard computer in addition to a wirelessly controllable user interface GUI. The assembled system is able to use TLE data provided by the user to track chosen satellites based on their azimuth and elevation. Additionally, the system is capable of offloading spectrum data and other metadata from the chosen satellite to the user interface, and plotting this data for the user. The system is powered by an onboard battery system capable of powering operation for 18 hours, and has both wireless and emergency power off systems. The antenna used to track the system has been developed to have the required beamwidth and high gain to make tracking of LEO satellites feasible, and the receivers were designed with a noise temperature of less than 200K to minimize the effects of noise on the gathered signal.

## Customer Satisfaction

Refer to ‘[client\_demo.mp4](https://drive.google.com/file/d/1A01P8f59smwimXq1eXv_Jd7qIJ2T1jnm/view?usp=drive_link)’ for a video of our customer handoff and demo.

## Deliverables Status

The fully developed system, as well as all parts that have been purchased by Virginia Tech, have been successfully returned to the customer of this project, Dr. Ellingson, as of December 1st, 2023. The main satellite tracking system, as well as all developed software, was provided to Dr. Ellingson on the day of final testing of the project on Wednesday, November 29th, 2023. After final disposition, the Amp Lab storage location was sorted and emptied of all items purchased through Virginia Tech, which were provided to Dr. Ellingson on December 1st.

## Challenges and Issues

Unfortunately, the list of requirements agreed upon by the customer and team were not all able to be met, even with the aforementioned development and testing procedures. The first of these requirements that were unable to be met was FUN-5: The system shall have >40 dB rejection of 0.5-1350 MHz and 1800-2700 MHz signals. As the custom filters were measured to have a passband of 2400-2700MHz. The reasoning behind this is currently still being researched, as the receivers were advertised to have a tunable range that fit our specifications. The filters worked as designed when simulated in Ansys Electronics Desktop HFSS, but once the schematic was converted to layout in KiCad, then sent to be fabricated, the filters exhibited a passband response exactly 1GHz higher than intended. Outside of potential user errors, it is suspected that this may be due to varying dielectric constants in the FR4 used by JLCPCB. The enclosure system was unable to fulfill the requirements of the system due to ME-2: The system shall fit into two medium sized hard shelled containers. The tripod used for this system was unable to fit within the containers used for the enclosure, which was understood when purchasing the components of the system. This was due to the fact that the tripod needed to be weatherproofed, able to meet the load-bearing capacity requirements for our project, costing less than $80, as well as having a 2 inch to 2 ½ inch central pole to be compatible with the Yaesu rotator masting clamps. As such, the tripod used for this project was chosen to fulfill all of these requirements but was larger than the enclosures selected to transport the system. A carrying case for the tripod was ordered to remedy this issue.

The GPS and magnetometer systems were also not fully integrated at the time of final testing due to an unforeseen technical error, and as such, calibration of the system was done using a compass to point the rotator North as well as manual input of the GPS coordinates. The final main issue faced during this project's development was the integration of the different subsystems. At the time of testing, we as a team had not fully tested the ability to acquire and display an Iridium Satellite spectrum successfully. However, numerous and thorough tests had been performed, validating the system’s ability to generate schedules, track a satellite in real time, acquire data, and store directly to the drive. If integration had been performed earlier, most of this project's final issues could have been ironed out, but this also proved to be a valuable lesson for future projects.

## Schedule and Costs Status

Refer to ‘[Project\_timeline\_temp.mpp](https://drive.google.com/file/d/1rV6L7oE_b-NnMoYhs1XMts4ydlDzvft3/view?usp=drive_link)’ for the complete timeline template.

Refer to ‘[Costs](https://docs.google.com/spreadsheets/u/0/d/1W_5VEpFF0bwDrhikkDXLFyUf1Pf6hZ4DmRind0RK42M/edit)’ for the complete parts list and costs.

## Lessons Learned

The main lessons that were gathered from working on this project as a team were that the integration and testing stage of project development takes a significant amount of time during a project’s life cycle (always more than expected) and that proper organization and scheduling is vital for the success of a project. At the beginning of the project, our SME and customer, Dr. Ellingson, gave us the valuable advice to remember that “you are already behind”, meaning that when working on projects like this, you should always treat yourself as though you are behind, and strive to stay ahead of your deadlines as much as possible. We tried to adhere to this as much as we could, but despite that, the integration stage of this project was started significantly later than necessary for the project to be fully completed, and as such major complications and issues during development of this system were unable to be answered until late into the project life cycle. In contrast to this, the use of Jira taskboarding software as well as weekly update meetings to keep track of the progress of development were vital for this project to be completed, as these meetings allowed the team to come together to discuss potential issues and roadblocks being held in development, and to ask for advice on how to handle issues. Overall, while delays in integration between different subsystems led to less time devoted to debugging issues, our team’s organization and documentation allowed us to stay focused on the goal of a successful project throughout the whole year.