Tethered Balloon-Based Experiment of Surface Water Height Using Satellite Signals of Opportunity

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Abstract—**Signals of Opportunity (SoOp) is an area of radio science that leverages existing ambient signals from spacecraft, aircraft, and ground-based radio systems to perform radio science without spending time or resources constructing new transmission infrastructure. It has been conceptualized that SmallSats or CubeSats can perform similar SoOp missions by augmenting pre-existing spacecraft missions — specifically radio/radar missions. During the summer of 2019, student-interns at the National Aeronautics and Space Administration's (NASA) Jet Propulsion Laboratory (JPL) under the Innovation to Flight (i2F) program tested the first airborne SoOp demo via a tethered aerostat — a valuable step towards getting a SoOp demo in orbit. The airborne SoOp demo received direct and bounced signals from multiple geosynchronous equatorial orbit (GEO) satellites by using two on-board wide-band grid antennas. One antenna was pointed at the sky at appropriate azimuth and elevation angles to receive a direct GEO signal. The other antenna was pointed at an identical azimuth angle with a mirrored elevation angle so as to receive the same GEO signal reflected from a body of water below. Both antennas were secured on adjustable mounts to allow for pointing changes and permit data collection from multiple satellites. This initial test proves the scientific and technological feasibility of doing further airborne SoOp tests, potentially on aircraft, unmanned aerial vehicles (UAV), high altitude balloons (HAB), and SmallSats or CubeSats.**

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1. INTRODUCTION

Building on a background of successful HAB launches during 2017 [1] and 2018 [2], the i2F team leveraged its HAB experience to facilitate a SoOp experiment. i2F is pursuing a collaborative relationship with several different interests across the JPL campus and this mission built on both i2F's experience with balloon launches and on SoOp's previous science validations. In this way, SoOp's technology was further validated in preparation for a full fledged CubeSat mission and i2F demonstrated the value of its HAB launch capability in facilitating scientific advancement.

SoOp [3] has been successfully used aboard offshore platforms to extract oceanography data; by receiving both direct and bounced signals from commercial satellites in geosynchronous equatorial orbit (GEO) and performing path length difference (PLD) calculations, sea surface height (SSH) was accurately measured. Previous experiments have validated SoOp as a tool for collecting oceanography data, specifically SSH. This was shown via an experiment on the oil rig Platform Harvest near Santa Monica, CA where researchers assembled a dual-band signal collection system and mounted it on the southern edge of Platform Harvest [4] [5]. From there, the system had an unobstructed view of both the sky and seawater some 52 m (170 ft) below the platform. The system aimed two directional antennas south; one antenna was angled upwards and received a direct signal from a satellite stationed in GEO while the other antenna was angled downwards and received the same satellite's signal after it had been reflected off of the surface of the Pacific Ocean. Using the known position of the receiver system, the position of the GEO satellite, and the slight difference in arrival times between the direct and bounced signals, researchers used PLD calculations to estimate the SSH at the point of signal reflection. The estimations closely matched ground truth data (collected from tide gauges), and as the tide gradually changed, so too did the path time difference in the signal. Other experiments have shown that SoOp can be used to measure snow-pack surface levels as well [6]. These experiments proved SoOp's usefulness in accurately measuring SSH in a real-world environment and opened the door for future uses.

The future utility of SoOp for NASA climate-data missions cannot be overstated. Its potential is enormous as a low-cost, overhead-free science payload on SmallSats and CubeSats capable of collecting SSH data while drawing purely from external and preexisting signals. A SoOp payload could potentially fly as it own dedicated mission on a single CubeSat [7] or as part of a constellation. It could also augment preexisting NASA missions. As an example, the Surface Water and Ocean Topography (SWOT) [8] satellite is an upcoming mission that will transmit signals and receive their reflections to collect marine and glacial climate data; SoOp-enabled CubeSats flying in formation beside SWOT could widen the mission's observable surface area by also receiving SWOT's reflected signals.

2. BALLOON-BASED PAYLOAD

Science Objective

i2F's science objectives were to miniaturize the technology used in the Platform Harvest SoOp test into a CubeSat form factor and to carry out a field test that measured SSH from an airborne platform. The purposes of these objectives are:

1. **Mobile Measurements:** Previous SoOp tests measured SSH with static, mounted rigs that received signals from a single predetermined GEO satellite. Validating SoOp's utility on a mobile platform that can move to new locations and take measurements from multiple GEO satellites is a key step towards the implementation of a SoOp CubeSat, as SoOp CubeSats would opportunistically use ambient signals from a large number of satellites as they orbit the Earth.

2. **Lightweight Platform:** Previous SoOp experiments were not affected by mass as they were statically mounted, which allowed for the use of large receiving antennas. Validating the miniaturization of SoOp technology into a lightweight platform will demonstrate its viability as a payload for future CubeSat or SmallSat missions.

Ideation

A tethered aerostat balloon would provide the lift necessary to elevate a SoOp test payload to an appropriate height above a body of water for signals to be received. The aerostat would lift a payload bay containing dual receivers to collect both the direct and reflected signals. Its design accomplished i2F's science objectives in the following ways:

1. **Mobile Measurements:** The test platform was elevated by a SkyDoc Model 18 Aerostat and was held in place by six tethers. Three tethers connected directly from the aerostat to the ground, and the remaining tethers connected the payload to both the aerostat and the ground. In addition to providing stability, the tethers allowed for the payload to be manually re-positioned. A diagram of the test setup can be seen in Figure 1. The following procedure was proposed for switching between target GEO satellites:

- Lower the platform
- Adjust antenna angles for new target satellite
- Elevate the platform
- Position the platform by adjusting the grounded tethers

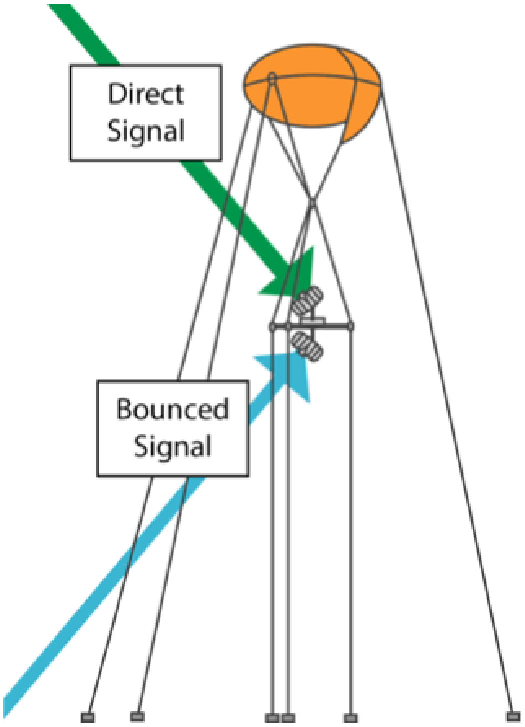

Figure 1. Diagram of payload receiving direct and bounced signals. Improved techniques to stabilize balloon/payload systems with multiple taut ground tethers is discussed in [9].

2. **Lightweight Platform:** Dual Bolton Technical UltraGain 26 Directional Antennas made up the receivers for this test. The antennas were attached to angled mounts at either end of a through-rod that extended past the top and bottom of the test platform. One antenna was mounted to the top of the platform and oriented to receive direct signals, and the other was mounted to the bottom and oriented to receive reflected signals. Signal processing, data storage, telemetry electronics, and batteries were all incorporated into the payload structure, which had a total mass of 9 kg (20 lbs). Additionally, it is important to note that 4.8 kg (10.6 lbs) of the mass was contributed by the antennas, which could be replaced with lightweight alternatives for a SoOp CubeSat mission, similar to RainCube [10]. The entire setup can be seen in Figure 2. In summary, the overall mass of 9 kg is on the same order of mass of a typical CubeSat and demonstrates the feasibility of miniaturization.

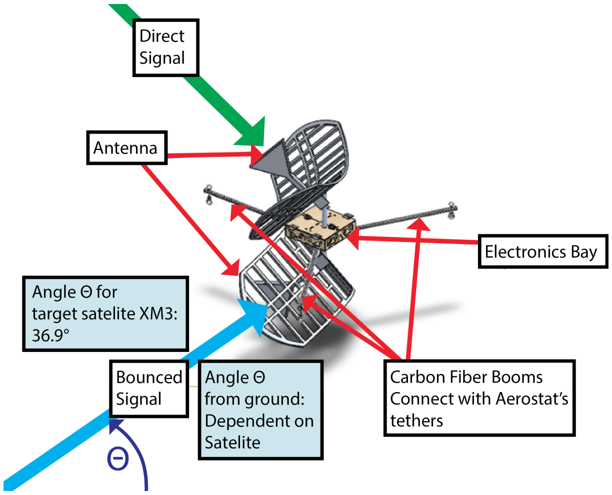

Figure 2. CAD rendering of the overall structure.

Payload

Structure—The payload structure primarily consisted of an electronics bay, a tethering system, and a pair of wide band grid antennas. Due to the 18 kg (40 lb) lifting capacity of the SkyDoc Model 18, the structural design was centered around minimizing mass. A rendering of the overall payload structure can be seen in Figures 2 and 3.

Electronics Bay—Due to the strict mass limit and fast-paced nature of the project, the electronics bay was designed to be lightweight, robust, and able to accommodate rapid design changes. As such, the electronics bay (shown in Figure 3) was constructed using laser cut birch plywood panels that incorporated weight relief cuts. Birch was selected over Delrin and acrylic as it is readily available (if rapid design changes occurred and pieces needed to be re-laser cut) and offers a comparable strength to weight ratio at a lower cost. The panels were joined using a combination of wood glue and interlocking cutouts. To allow for easy access to internal components, a hinged lid was fitted to the top of the electronics bay. The bay was then mounted onto three carbon fiber booms which provided clearance between the payload and tethering system. Finally, the structure was insulated using a mylar foil wrapping to prevent sunlight from heating the internal components.

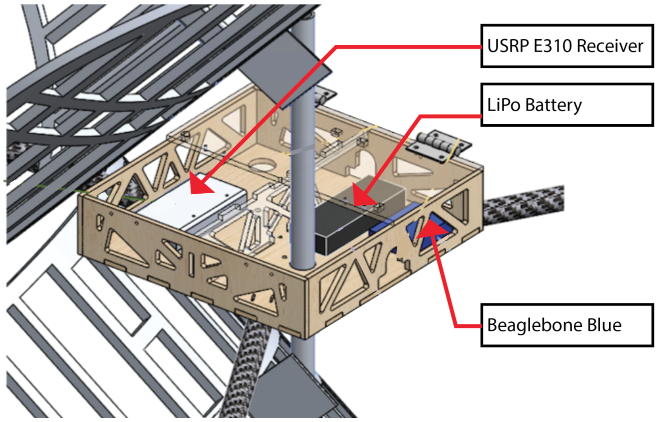

Figure 3. CAD rendering the internal payload configuration.

Tethering System—The overall payload system was tethered to the ground in six locations, three of which directly secured the aerostat to the ground. The remaining three tethers joined the payload to the aerostat with additional segments joining the payload to the ground. Between the payload and the aerostat, the tethers utilized a converging pulley system to improve stabilization. The pulleys were configured so that changes to the aerostat's pitch and roll were decoupled from the payload. An overview of the tethering system can be seen below in Figure 4.

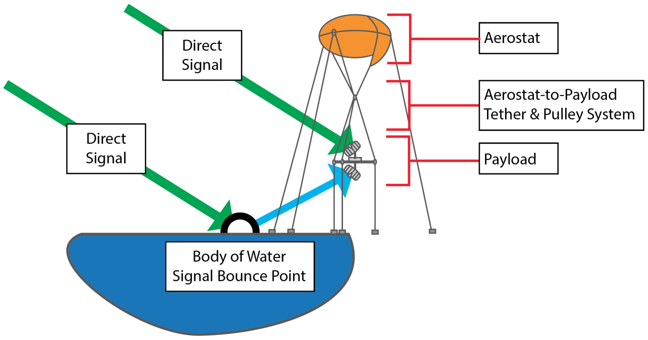

Figure 4. Tethering configuration overview.

Payload Stabilization—One of the primary concerns for the payload was ensuring that it remained stable during flight, as previous experiments had revealed that even moderate wind could cause a payload to shake violently. As the antennas required accurate pointing, it was determined that a stabilization method would be necessary. Three methods were considered in order to maintain proper pointing: gimbaling the antennas, stabilizing the payload with reaction wheels, and using a self-stabilizing tethering system.

To analyze the effectiveness of a gimbal system, the team purchased two off-the shelf camera gimbals: the MOZA Air 2 and the EVO Rage 2. Testing revealed that both devices were effective at controlling antenna yaw, but failed to maintain pointing in the pitch axis due to the large moment produced by the antennas. A counterweight system was designed to remedy this issue but it was also deemed ineffective as it required nearly 10 kg (22 lbs) of added mass.

Simultaneously, the team developed a reaction wheel system using a BeagleBone controller and 3D printed flywheels. This system proved to be effective in providing 3-axis stabilization for an unweighted payload. However, the design was not fully scaled and ready for integration by the August 15th launch date. As such, the final payload design utilized a self-stabilizing tethering system composed of pulleys, with the antennas statically secured to adjustable-angle mounts. In this configuration, the elevation angle of the antennas could be adjusted manually and the the azimuth could be adjusted by altering the tethering system's grounding points.

Power

The power system primarily utilized built-in battery solutions. The USRP E312 device contained an external battery that could provide power to the unit. A three-cell lithium polymer (LiPo) battery was used to power the BeagleBone Blue, which had drivers available for LiPo batteries. There was no need for a power distribution board (PDB) or specialized/custom power solutions, as the electronics were all commercial off-the-shelf (COTS) parts that used simple and low-mass commercially available power solutions.

Communications—The experiment employed two wide-band directional antennas, one mounted on top and one mounted on bottom. Both antennas were connected to the USRP E312 receiver. The USRP E312 was selected as it was available for use at JPL and included two channels, one for each antenna. The receiver was then serially connected to the BeagleBone Blue (different than the controller used for the reaction wheels) which sent and received data from the ground station via a WiFi connection. The command and data handling system is shown in Figure 5. This serial connection allowed full access to the receiver and enabled a live Fast Fourier Transform (FFT) diagram to be viewed from the ground, as seen in Figure 6. Also connected to the receiver was a GPS antenna which was used to time-stamp and synchronize the signals from both channels. This data was then stored onboard using an SD card.

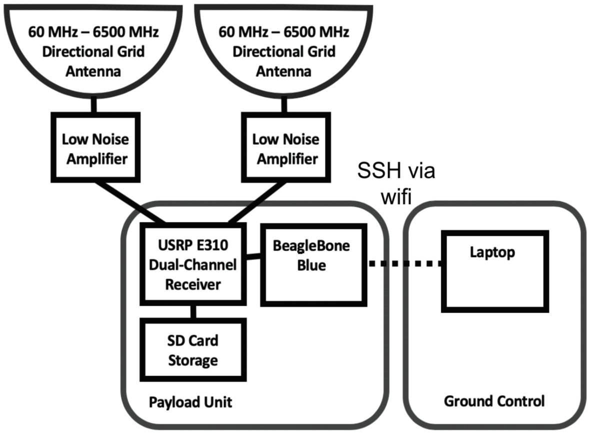

Figure 5. Command and data handling system diagram.

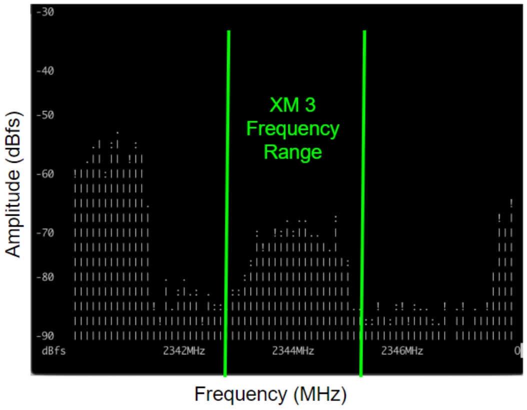

Figure 6. FFT of signal from XM-3.

To determine if the direct and bounced signals from the XM-3 target satellite [11] were being received, an FFT was performed on each antenna separately. XM-3 emits a signal with a frequency of 2344 MHz and, when pointing in the direction of XM-3, the FFT displayed an amplitude spike at 2344 MHz. This amplitude would remain unchanged as long as antenna pointing was maintained. As the data was recorded in binary, it was important to perform this function prior to recording to ensure the correct signals were being received. With both signals confirmed, a command could then be sent to execute the data record function. Figure 6 shows the amplitude spike at 2344 MHz resulting from the direct XM-3 signal. Over the course of the experiment two minutes of data was collected and stored.

Results

The flight test was conducted at the Caltech athletics field on August 15, 2019. The helium-filled aerostat was tethered in close proximity to the Caltech swimming pools, which were used as the body of water for the bounced signals. In order to receive these bounced signals from the XM-3 target satellite, the desired altitude for the payload was 15 m (50 ft). An image of inflation can be seen in Figure 7. However, due to high winds and a confined test area the test was aborted prematurely and the payload was only able to achieve an altitude of 10 m (33 ft), as seen in Figure 8.

Figure 7. Skydoc 18 aerostat during inflation.

Figure 8. Payload and aerostat during flight test.

Despite unfavorable flight conditions, the payload remained relatively stable in pitch and roll, and the overhead antenna was able to receive direct signals from the XM-3 satellite. Unfortunately, the insufficient altitude prevented the bottom antenna from receiving bounced signals. The WiFi connection between the payload and the ground station (via the BeagleBone Blue) was maintained throughout the flight and all other subsystems performed as expected.

3. FUTURE WORK

Due to time constraints, as this work was done over a single 10 week internship period and was just one of multiple flight experiments i2F conducted in 2019, the initial airborne SoOp test was inconclusive, but not failed since GEO signals were obtained from the top antenna. The equipment and setup for this test went through many iterations before the flight test was conducted, and it is safe to say that a similar setup should be employed for the next airborne SoOp test on a tethered balloon. Only when winds picked up to 20+ mph gusts did the balloon have to come down (for safety reasons). The team is interested in re-running this test in the future with more favorable weather conditions and after that, attempt to miniaturaze the components further to save mass and put the setup on other airborne platforms like high altitude balloons and UAVs. With the latter two examples, the team will continue the initial investigations into attitude control of the system, which will be needed in both airborne and spaceflight SoOp missions. In addition to the supporting work for the first balloon-based signals of opportunity test, the team was involved in additional technology development for future implementation.

4. CONCLUSIONS

The demonstration reported was successful in receiving the direct signal form the XM-3 target satellite. However, due to adverse testing conditions the experiment was aborted prematurely and a bounced signal was not received. Despite this, all other subsystems performed as expected and the test was successful in demonstrating the miniaturization of a SoOp payload (overall mass of 9 kg), thereby providing the scientific and technological feasibility necessary for conducting further airborne SoOp tests, potentially on aircraft, UAVs, HABs, and CubeSats or SmallSats.

ACKNOWLEDGMENTS

The authors would like to thank Dr. Leon Alkalai, Manager of the JPL Office of Strategic Planning, who initiated and funded the Innovation to Flight Program. The authors would also like to thank the various mentors and advisors who provided guidance and support, including Adrian Stoica, Oscar Avalos, Miles Pellazar, Kirk Barrow, Pasha Beglar, James Black, Eric Contreras, Benjamin Donitz, Jeffrey Hall, Corey Mack, Anne Marinan, Charles Norton, Leonard Ortiz, Michael Pauken, Doug Sheldon, Armen Toorian, Michele Verdugo, Antoni Viros, and Adriana Wall. Bewley gratefully acknowledges funding of a JPL Faculty Research Fellowship during summer 2019, part of which supported this effort.

The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (80NM0018D004). Copyright 2020 California Institute of Technology. Government sponsorship acknowledged.

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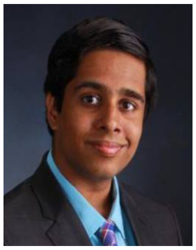

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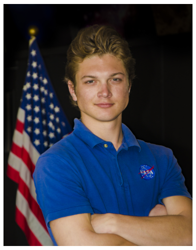

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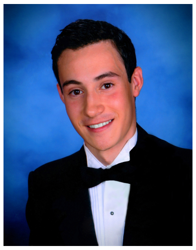

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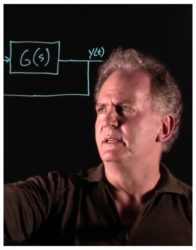

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