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HIGH ALTITUDE BALLOONS FOR SPECIAL OPERATIONS FORCES: SUPPLEMENTING SPACE WITH STRATOSPHERIC SOLUTIONS

by

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The U.S. military depends on space-based technology for communication, remote sensing, and position, navigation, and timing (PNT). Changing international dynamics in Great Power Competition, specifically the increase in antisatellite testing and development, threaten the space-based capabilities military forces utilize, including Special Operations Forces. In 2006, the Department of Defense developed the Operationally Responsive Space initiative which focused on decreasing the requisite time to place military satellites in orbit following asset loss; however, there is still no way to rapidly reconstitute space-based capabilities that have been compromised. As the space domain becomes increasingly contested, high altitude balloons (HABs) can offer a quick and efficient method to bridge the time gap between the loss of a space asset and its replacement. However, HABs require modularity to improve the time efficiency of payload integration. The purpose of this study is to develop a modular HAB bus, termed the Bento Box, designed to operate independently or integrated in a fixed-wing marsupial vehicle for precision recovery. The integration of three payloads into the Bento Box demonstrates the modularity of the structure, one of which is a software defined radio reconfigured as a bent-pipe communications payload to relay video transmission signals. The study concludes with a field test of the HAB-suspended Bento Box for beyond line-of-sight video relay between maneuver elements.

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HIGH ALTITUDE BALLOONS FOR SPECIAL OPERATIONS FORCES: SUPPLEMENTING SPACE WITH STRATOSPHERIC SOLUTIONS

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ABSTRACT

The U.S. military depends on space-based technology for communication, remote sensing, and position, navigation, and timing (PNT). Changing international dynamics in Great Power Competition, specifically the increase in antisatellite testing and development, threaten the space-based capabilities military forces utilize, including Special Operations Forces. In 2006, the Department of Defense developed the Operationally Responsive Space initiative which focused on decreasing the requisite time to place military satellites in orbit following asset loss; however, there is still no way to rapidly reconstitute space-based capabilities that have been compromised. As the space domain becomes increasingly contested, high altitude balloons (HABs) can offer a quick and efficient method to bridge the time gap between the loss of a space asset and its replacement. However, HABs require modularity to improve the time efficiency of payload integration. The purpose of this study is to develop a modular HAB bus, termed the Bento Box, designed to operate independently or integrated in a fixed-wing marsupial vehicle for precision recovery. The integration of three payloads into the Bento Box demonstrates the modularity of the structure, one of which is a software defined radio reconfigured as a bent-pipe communications payload to relay video transmission signals. The study concludes with a field test of the HAB-suspended Bento Box for beyond line-of-sight video relay between maneuver elements.

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LIST OF ACRONYMS AND ABBREVIATIONS

AI	artificial intelligence
ASAT	antisatellite
BLOS	beyond line-of-sight
C&DH	command and data handling
CAD	computer aided design
CONOP	concept of operation
COTS	commercial off-the-shelf
CSAC	chip-scale atomic clock
DA-ASAT	direct-ascent antisatellite
DC	direct current
DOD	Department of Defense
DSWA	Defense Special Weapons Agency
EO	electro-optical
EPS	electrical power system
FAA	Federal Aviation Administration
FEA	finite element analysis
FOBS	fractional orbit bombardment system
FOR	field of regard
GEO	geosynchronous
GPC	Great Power Competition
GSD	ground sampling distance
GSEAS	Graduate School of Engineering and Applied Sciences
GTO	geosynchronous transfer orbit
GUI	graphical user interface
HAB	high altitude balloon
JOC	joint operations center
LED	light emitting diode
LEO	low-earth orbit
LPD	low probability of detection
LPI	low probability of intercept

MHV	miniature home vehicle
MIRACL	Mid-Infrared Advanced Chemical Laser
MOBS	multiple orbit bombardment system
NPS	Naval Postgraduate School
NRO	National Reconnaissance Office
OPIR	overhead persistent infrared
ORS	operationally responsive space
PAROS	Prevention of an Arms Race in Outer Space Treaty
PCB	printed circuit board
PF	partner force
PNT	position, navigation, and timing
PPWT	Prevention of the Placement of Weapons in Outer Space Treaty
RAA	remote advise/assist
RDS	Russian Doll Satellite
RPO	rendezvous and proximity operations
SAM	surface-to-air missile
SATCOM	satellite communications
SDR	software-defined radio
SNC	Sierra Nevada Corporation
SNR	signal-to-noise ratio
SOF	special operations forces
SSAG	Space Systems Academic Group
STP	standard temperature and pressure
TT&C	tracking, telemetry, and command
TTP	tactics, techniques, and procedures
USAFA	United States Air Force Academy
USSOF	United States Special Operations Forces
VAFB	Vandenberg Air Force Base

EXECUTIVE SUMMARY

The U.S. military is heavily reliant on space system technologies for warfighting functions. Shifts in international normative behavior regarding the development and use of antisatellite (ASAT) weapons and the increase in orbital debris threatens the use of space assets in future conflicts. In addition to securing space assets, the U.S. military and special operations forces need to develop alternative systems that provide space-based capabilities in a satellite denied environment. High-altitude balloons (HABs) offer an advantage in dominating the high ground of the electromagnetic spectrum by operationalizing the stratosphere. This study examines the benefits of HABs, analyzes the threat posed by international ASAT development, and conducts a proof-of-concept on utilizing HABs in support of special operations via the Bento Box (see Figure ES-1), a modular structure designed for quick integration of mission specific payloads.

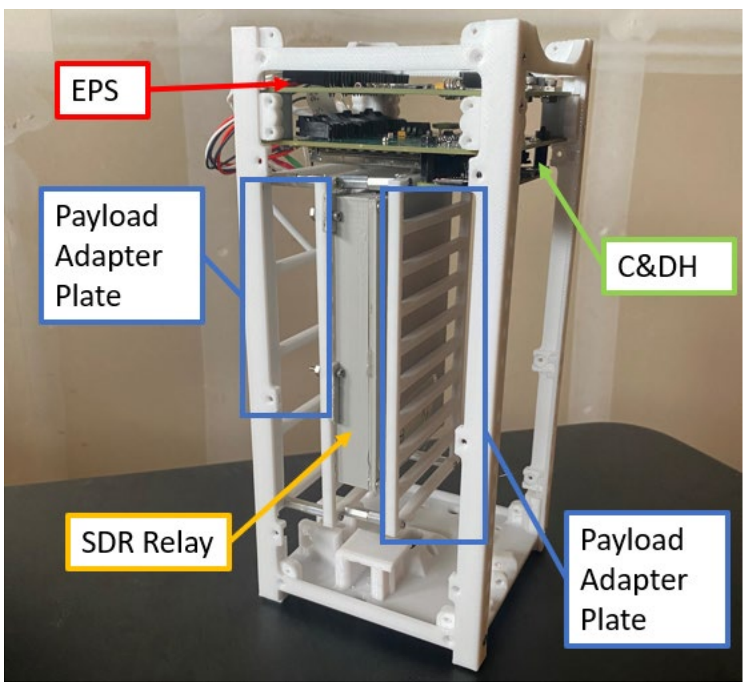

Figure ES-1. The Bento Box—a modular HAB bus for SOF

A. FLIGHT DEMONSTRATION

Three payloads with operational relevance were integrated into the Bento Box: an SDR analog video relay, an electro-optical (EO) sensor, and a light-emitting diode (LED) communications payload. The Bento Box supported a scenario involving a patrolling partner force of a U.S. special operations forces (USSOF) element (see Figure ES-2).

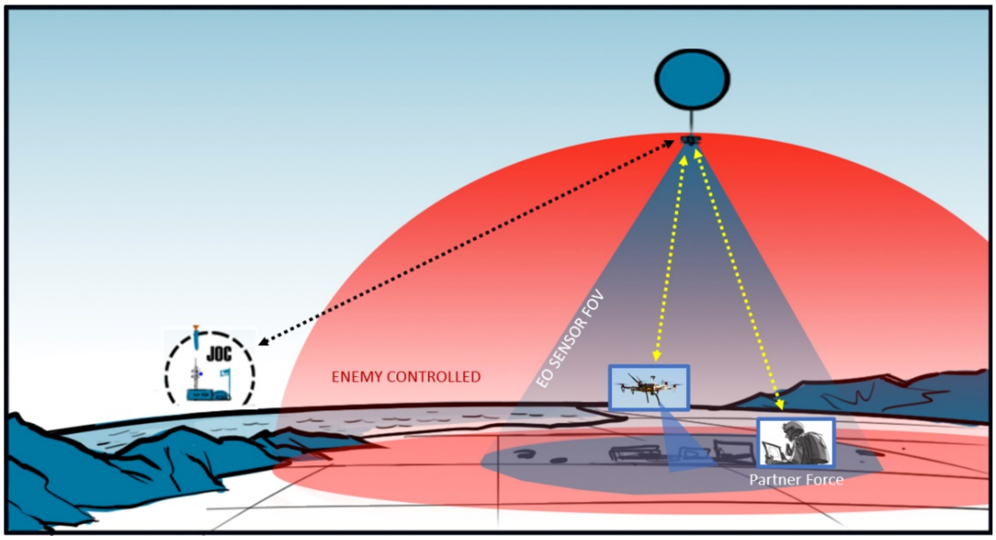

Figure ES-2. Concept of operations—the Bento Box flight demonstration

The SDR relayed video feeds from a drone and plate carrier-mounted camera (see Figure ES-3), the EO sensor provided overhead real-time video coverage of the target area, and the LED payload sent a simple message in morse code. The LED payload demonstrated the Bento Box's capability of integrating multiple payloads and is a preliminary design of an alternate optical tracking capability during loss of traditional means of communications with on-orbit assets.

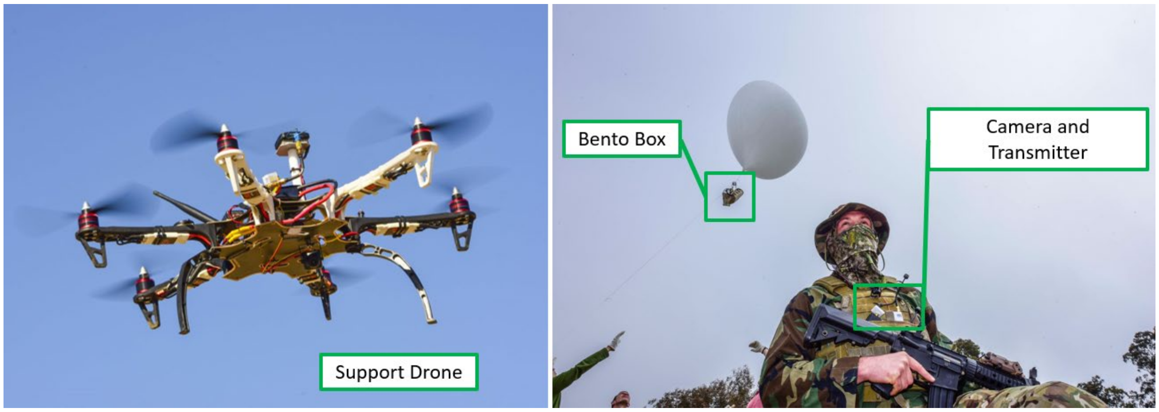

Figure ES-3. Support drone and plate carrier-mounted camera on partner force during HAB launch

B. RESULTS

The Bento Box performed as designed and successfully demonstrated the applicability of HABs in special operations. The SDR payload relayed the drone and plate carrier camera video feeds beyond line of sight to the joint operations center (JOC), and the EO sensor provided target area coverage to the partner force and the JOC. Figure ES-4 shows captures of the EO sensor and relayed drone video feeds received at the JOC.

Figure ES-4. Results of Bento Box payloads

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I would also like to thank Professor Terry Smith for his assistance in analyzing the spectral data of the payloads and pointing me in the right direction for the link budgets. David Rigmaiden deserves appreciation for his assistance in collecting the spectral data for the payloads.

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I. INTRODUCTION

International space norms are changing rapidly as great power competitors challenge the normative behavior established during the early years of space flight. The 1967 Outer Space Treaty and a series of U.S.-Soviet Union negotiations starting in 1977 established the international norm of preserving space for peaceful ventures and preventing antisatellite (ASAT) technology.[1] Pursuant to a voluntary moratorium in 1986, the United States and the Soviet Union observed "contingent restraint"[2] not to engage each other's satellites with destructive means; other nations followed suit. However, emerging technologies threaten the stability of our satellite constellations as great power competitors have conducted questionable demonstrations of potential ASAT weapons. In 2007, China indirectly challenged international norms by launching a missile at one of its own satellites, the Fengyun-1C weather satellite, to demonstrate its ASAT capabilities.[3] Likewise, in 2018, Russia launched a "Russian Doll Satellite" with potential ASAT capabilities that pose a potential risk to U.S. assets.[4] India followed with a successful ASAT test in 2019, indicating a shift in international norms regarding ASAT technology. The threat posed by the changing ASAT norms combined with the congestion of space and the increase in orbital debris caused by ASAT testing has increased the need for redundancy in the U.S. network of satellite capabilities as a warfighting function.

To build redundancy, the U.S. military needs to develop alternative methods of providing over-the-horizon communications systems to remote users; early warning

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[1] Samantha Potter, "Death from Below: Anti-Satellite Weapons and the Current Outer Space Security Crisis," *Oxford Political Review*, no. 1 (November 17, 2020), http://oxfordpoliticalreview.com/2020/11/17/death-from-below-anti-satellite-weapons-and-the-current-outer-space-security-crisis/.

[2] Joan Johnson-Freese, *Heavenly Ambitions: America's Quest to Dominate Space* (Philadelphia, PA: University of Pennsylvania Press, 2009), 47, https://www.jstor.org/stable/j.ctt3fhwsv.

[3] Leonard David, "China's Anti-Satellite Test: Worrisome Debris Cloud Circles Earth," Space, 2007, https://www.space.com/3415-china-anti-satellite-test-worrisome-debris-cloud-circles-earth.html.

[4] Paul McLeary, "Space Mystery: Are Russian Doll SATS a Threat?," Breaking Defense, August 16, 2018, https://breakingdefense.com/2018/08/details-lacking-over-u-s-concern-about-new-russian-space-objects/.

systems for ballistic missile defense; imaging systems for reconnaissance; and position, navigation, and timing (PNT) for ground forces and precision guided missiles. Recent advances in high-altitude balloon (HAB) technology make it a viable method for providing traditionally space-based capabilities; commercial entities have demonstrated the ability to keep 200-pound assets aloft in the stratosphere for over 300 days while maintaining position or traveling a designated route.[5]

A. PURPOSE

As international norms regarding ASAT development continue to trend toward a weapons race, Great Power Competition (GPC) further threatens the dependability of U.S. space-based systems in future conflict. The U.S. military utilizes orbital assets for communications, overhead persistent infra-red (OPIR) monitoring, reconnaissance, and PNT. Special operations forces (SOF) operate in small units that require support from conventional forces in the form of logistics, medical evacuation, and communications. Space-based assets provide the medium for a large portion of support coordination. Additionally, SOF relies on space-based assets for mission planning, situational awareness, and contingencies. Pawlikowski et al. note:

> Without exaggeration, the combat effects we have come to expect from our smaller, more mobile force structure would not be possible without space capabilities. The impact of GPS alone has fundamentally shifted the way U.S. forces locate and destroy targets, plan operations, control both material and war-fighting assets, synchronize effects, and guide both troops and remotely piloted aircraft (RPA) home.[6]

Great Power competitors have demonstrated the ability to target systems in orbit, and the international system currently lacks specific laws against the development and testing of ASAT weapons. As GPC increasingly threatens the readiness and availability of space-based systems, voice- and data-relay capabilities between remote SOF units and support

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[5] Karina Shah, "Google's AI Can Keep Loon Balloons Flying for over 300 Days in a Row," New Scientist, December 2, 2020, https://www.newscientist.com/article/2261369-googles-ai-can-keep-loon-balloons-flying-for-over-300-days-in-a-row/.

[6] Ellen Pawlikowski, Doug Loverro, and Tom Cristler, "Space: Disruptive Challenges, New Opportunities, and New Strategies," *Strategic Studies Quarterly* 6, no. 1 (2012): 33.

elements require redundancy and expedient capability-gap solutions. Loss or degradation of a SATCOM asset would prevent coordination between elements and would effectively isolate the SOF unit, leaving it vulnerable to attack without reinforcements, close-air-support, or resupply of ammunition during combat operations. The purpose of this study is to assess the feasibility of utilizing HABs to enable special operations forces conducting operations in a SATCOM-denied environment. The author of this paper and the Naval Postgraduate School (NPS) Space Systems Academic Group (SSAG) developed a modular HAB bus, termed the "Bento Box," specifically for this experiment.

This study and the concept of the Bento Box were conducted in coordination with Major Chris Gallegos; his research focuses on the history of stratospheric assets, current military programs seeking to implement HABs for military use, and the adoption barriers currently preventing the use of stratospheric assets in the U.S. military. Further information regarding current military programs can be found in his thesis, *Operationalizing the Stratosphere: A Warfare Design for High-Altitude Balloons.*

B. RESEARCH QUESTIONS

How can HABs strengthen network infrastructure to maintain communications links and how can the Bento Box tailor functionality of HABs to enable SOF operations?

C. THE ARGUMENT FOR HIGH ALTITUDE BALLOONS

The stratosphere, a layer of Earth's atmosphere between 15 and 50 kilometers, remains an unutilized domain in military operations; SOF and the U.S. military, in general, should invest in operationalizing it to contribute to dominance of the "high ground" of the electromagnetic spectrum. HABs offer a stratospheric platform to host payload systems currently in use on fixed-wing, rotary-wing, and space-based assets. An experiment by Swintek at NPS demonstrated that a HAB system carrying a software-defined radio operating at around nine kilometers can successfully provide a bent-pipe communications relay between elements beyond the horizon.[7] Operating in the stratosphere at ~30 kilometers, the degree of allowable separation between elements extends even further. HABs can provide capabilities similar to orbital assets with advantages in cost, overhead persistence at any latitude, ownership at the field-unit level, and improved performance of communications systems. However, the advantages of HABs come at the cost of smaller fields of regard, weight restrictions, and pointing accuracy. This study does not claim that HABs can replace orbital assets, rather that they can contribute to building redundancy in capabilities that utilize the electromagnetic spectrum to reduce the effects of adversary attacks on U.S. space assets or even prevent them through deterrence by denial—an adversary is less likely to utilize costly ASATs against orbital assets if it will not succeed in degrading the capability.

1. Advantages

The cost to place a HAB in the stratosphere is much cheaper than placing an asset into orbit. The following comparison excludes integration and asset monitoring since both methods require them and will be roughly equivalent. The advanced HABs capable of navigation, station keeping, and carrying up to 200 pounds cost in the range of $150k to $200k. The non-payload weight of the HAB (navigation, balloon, gondola) is roughly 50 pounds, leaving 150 pounds for the payload. To calculate the cost of helium required to suspend 200 pounds, consider the difference in density between helium and air at standard temperature and pressure (STP):

$$density(air) - density(He) = 1.225\frac{kg}{m^3} - 0.178\frac{kg}{m^3} = 1.047\frac{kg}{m^3}, \qquad 1.1$$

which means that 1 cubic meter of helium can suspend 1.047 kg. Next, calculate the required amount of helium required to suspend 200 pounds by first converting pounds to kilograms:

$$\frac{200lb \times 0.4536\frac{kg}{lb}}{1.047\frac{kg}{m^3}} = 86.65\ m^3. \qquad 1.2$$

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[7] Philip C. Swintek, "Critical Vulnerabilities in the Space Domain: Using Nanosatellites as an Alternative to Traditional Satellite Architecture" (master's thesis, Monterey, CA, Naval Postgraduate School, 2018), 76.

At most, the current price of helium is $14.50 per cubic meter, which means the total cost for the required helium is insignificant at ~$1,300. Finally, the HAB launch only requires ~48 man-hours ($2,400 at $50 per hour) for a total cost of less than **$210k** to place a 150-pound payload in the stratosphere.

Conversely, the cost to place a 150-pound payload into orbit is much higher. The average payload weight of a satellite is only 33–50% of the total spacecraft mass[8]—the total weight of a satellite with a 150-pound payload would be ~300-450 pounds. Calculating the cost to place the satellite in orbit is much more complicated than the HAB and changes based on the number of rocket stages, fuel-type, and total payload size—SpaceX is also reducing costs with reusable boosters. Fuel calculations alone are not sufficient because fuel is only a small fraction of the total cost. For example, the SpaceX Falcon 9 rocket costs $60M to produce but only utilizes $200k in fuel.[9] However, SpaceX provides price estimates of placing assets into a desired orbit altitude, based on weight, utilizing its rideshare program.[10] At the time of this writing, placing a 300-lb satellite into low-earth orbit (LEO) would cost ~**$1M** when utilizing the rideshare option. Placement of the HAB is roughly one-fifth the price with the added benefit that it can be recovered and modified as technology progresses. Persistence requirements further increase satellite expenses because the asset needs to be placed in geosynchronous orbit (GEO), requiring additional propellant for the geosynchronous transfer orbit (GTO), and increased size, weight, and power (SWaP) requirements due to longer transmission distances. Alternatively, a satellite constellation at LEO can meet the requirement, as demonstrated by Swintek, but it requires 24 satellites in 6 planes to provide 4 minutes of coverage every

[8] Committee on Earth Studies et al., *The Role of Small Satellites in NASA and NOAA Earth Observation Programs* (National Academic Press, 2000), 32, https://doi.org/10.17226/9819.

[9] Loren Grush, "SpaceX Successfully Landed Its Falcon 9 Rocket after Launching It to Space," The Verge, December 21, 2015, https://www.theverge.com/2015/12/21/10640306/spacex-elon-musk-rocket-landing-success.

[10] "SpaceX Satellite Rideshare," SpaceX, accessed May 8, 2021, rideshare.spacex.com/.

21 minutes.[11] The advanced HABs provide persistence at no extra cost. The relative low cost and launch simplicity make HABs viable at the team or battalion level, which would provide ground forces exclusive assets for communications, remote sensing, and PNT.

Another benefit of HABs is that they provide overhead persistence at high latitudes, making them good candidates for polar applications. Satellites providing communications and remote sensing coverage of the northern polar region utilize highly elliptical Molniya orbits at an inclination of 63.4° to increase dwell time over the area of interest; placement is more costly than LEO orbits because of the change in velocity (ΔV) required to increase the orbit apogee over the northern hemisphere. HABs are an economical option to supplement assets in Molniya orbits or to perform expedient mission-specific objectives at any location on the globe.

The lower altitudes utilized by HABs and advances in station keeping make them applicable for operations requiring low probability of intercept (LPI) and low probability of detection (LPD) communications. First, the lower altitude reduces the transmit power requirements for the link budget. Based on the free-space loss equation:[12]

$$L_{FS} = \left(\frac{4\pi d}{\lambda}\right)^2 \qquad 1.3$$

where *d* is the distance the electromagnetic wave travels and λ is the frequency of the wave, the transmit power requirements increase by the square of the distance between the user and the asset. Therefore, to maintain the same link budget margin, the transmit power requirements when utilizing a HAB at 30 kilometers (Tx_h) versus that of a geosynchronous satellite at 35,800 kilometers (Tx_g) can be calculated as follows:

$$\left(\frac{1}{30^2}\right) Tx_h = \left(\frac{1}{35800^2}\right) Tx_g \qquad 1.4$$

$$Tx_h = \left(\frac{30^2}{35800^2}\right) Tx_g = 7.02x10^{-7} Tx_g \qquad 1.5$$

[11] Swintek, "Critical Vulnerabilities in the Space Domain," 24.

[12] Derived from: Leon Couch, *Digital & Analog Communication Systems*, 8th edition (Upper Saddle River, N.J: Pearson, 2012), 599.

The transmit power required to relay through a HAB is seven orders of magnitude lower than the requirement for a satellite at geosynchronous orbit. Even at LEO, the transmit power is ~70 times the requirement for HAB altitudes. The reduction in transmit power reduces the probability of an adversary detecting the operators transmitting the signal from the earth's surface. Second, the lower altitude and steady state of the HAB—as opposed to a satellite traveling 7.8 km/s in LEO—means that the expeditionary element can use antennas with a smaller half-power beam width pointed towards a designated azimuth and elevation angle, thereby reducing detectability while still ensuring communications link closure.

The lower altitude of HABs also results in better ground sampling distance (GSD) for EO sensors. Considering that the equation for calculating *GSD* is:[13]

$$GSD = 1.22\left(\frac{\lambda}{a}\right)R \qquad 1.6$$

where λ is the wavelength of the electromagnetic wave, *a* is aperture diameter, and *R* is the range to the target, *GSD* increases proportionally with the distance between the sensor and the target. At 30km, a HAB-suspended camera will produce images with 0.12 times the *GSD* of a camera at 250km with the same aperture.

Finally, HABs offer advantages in competitive strategies in terms of adversarial targeting costs. HABs are observable to the naked eye and countries like Russia, China, Iran, and North Korea have the capability to target them; however, the missiles required to target stratospheric objects are extremely cost prohibitive. For example, the Russian S-300 surface-to-air missile (SAM) has a maximum altitude of 35 kilometers[14] and costs $120M per system, which includes 48 missiles,[15] equating to $2.5M per missile to target a HAB costing ~$200k plus payload. It follows that using a multi-balloon strategy would cause an

[13] R. C. Olsen, *Remote Sensing from Air and Space*, 2nd ed. (Bellingham, WA: SPIE Press, 2016), 69.

[14] Ehsan Ostadrahimi, "S-300PMU-2 Favorit: Long-Range Air Defense Missile System," Military Today, accessed April 15, 2021, http://www.military-today.com/missiles/s300_pmu2.htm.

[15] "S-300," Deagal, accessed April 15, 2021, https://www.deagel.com/Artillery%20Systems/S-300/a000372.

asymmetrical financial burden on an adversary trying to disrupt a HAB network with a mix of real and dummy payloads.

2. Trade-offs

It is important to understand the trade-offs in utilizing HABs to supplement space-based systems. While several disadvantages exist in comparison to orbital assets, they do not outweigh the advantages but require due consideration for concept of operation (CONOP) development.

First, due to the lower operational altitude of HABs, they cannot achieve the same field of regard (*FOR*) as satellites in LEO; the access area is smaller. The *FOR* is calculated using the maximum earth-central angle (λ_0 – see Figure 1).

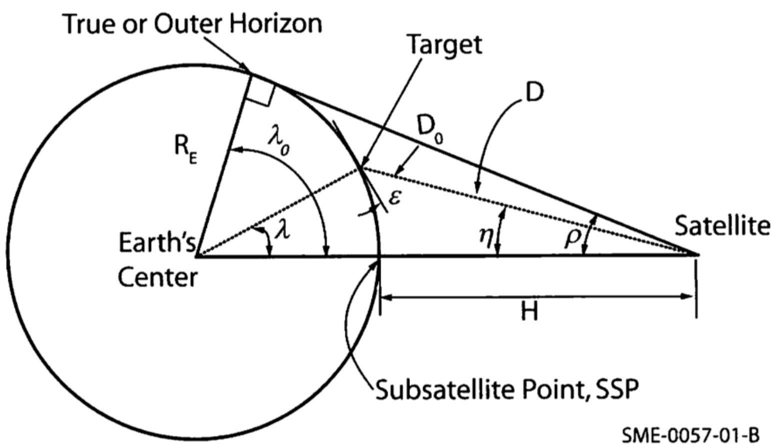

Figure 1. Angular relationships between asset, target, and Earth's center.[16]

To calculate and compare the difference in *FOR* of a HAB at 30km and a satellite in LEO at 250km, first calculate λ_0 utilizing equations from the New SMAD:[17]

$$cos\lambda_0 = \frac{R_E}{R_E + H} \Rightarrow \lambda_0 = cos^{-1}\left(\frac{R_E}{R_E + H}\right) \qquad 1.7$$

$$\lambda_0(HAB) = cos^{-1}\left(\frac{6378}{6378 + 30}\right) = 5.5°$$

[16] Source: James R. Wertz, David F. Everett, and Jeffery J. Puschell, eds., *Space Mission Engineering: The New SMAD*, First edition (Hawthorne, CA: Microcosm Press, 2011), 173.

[17] Wertz, Everett, and Puschell, 173.

1.8

$$\lambda_0(LEO) = cos^{-1}\left(\frac{6378}{6378 + 250}\right) = 15.8° \quad 1.9$$

Next, use the maximum Earth Central Angle to calculate the entire access area (*FOR)*:[18]

$$FOR(HAB) = 2\pi\big(1 - cos\lambda_0(HAB)\big)R_E^2 = \ 1.2e6\ km^2 \quad 1.10$$

$$FOR(LEO) = 2\pi\big(1 - cos\lambda_0(LEO)\big)R_E^2 = \ 9.6e6\ km^2 \quad 1.11$$

Converting the area to a radius gives the effective horizon for each asset, which equates to 618km and 1,748km for the HAB and LEO assets, respectively. Assets in LEO orbits provide about eight times the coverage area as assets at stratospheric altitudes and extend the horizon almost three times further, which ultimately reduces the distance across which a single HAB could relay communications signals between users and limits the area in which it could collect remote sensing data or capture images. The same calculations at GEO altitudes results in a *FOR* over 181 times the area provided by the HAB or 13.5 times the effective horizon. The smaller *FOR* can be mitigated with a constellation of HABs, but that would also drive-up costs for operationalizing HABs.

Another disadvantage in utilizing HABs is the lack of solar access for photovoltaic power for longer durations compared to satellites. HABs rely on battery power for the duration of night (12 out of 24 hours on the equator during equinox), which varies based on latitude and time of year, then recharge with solar panels during the day. Higher latitudes have longer nights during winter months which can be mitigated with larger batteries to an extent. However, polar applications become impossible during winter months when HABs would not have access to sunlight for months. Conversely, satellites receive sunlight on every orbital pass, the length of which depends on the beta angle of the orbit. Beta angle is the angle between the orbit plane and the sun vector (see Figure 2). A beta angle of 0° results in the most time in eclipse, which would be half the orbit time for a theoretical orbit

[18] Wertz, Everett, and Puschell, 178.

on the earth's surface (42 minutes out of an 84-minute orbit). The time in eclipse decreases as the orbital altitude increases. A beta angle of 90° receives constant sunlight. The key point is that a satellite's time in eclipse depends on orbit parameters that are chosen based on mission requirements while HABs are subject to the variation of local diurnal rhythms, which can be irremediable.

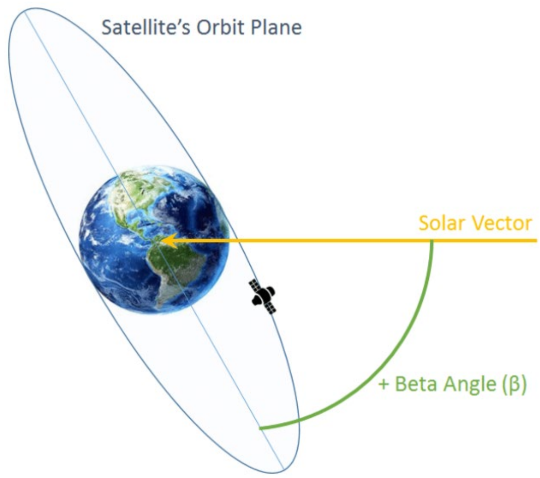

Figure 2. Beta angle is the angle between the orbit plane and the solar vector.[19]

Time of flight and weight limitations are another trade-off in operationalizing HAB systems. Google's helium balloon project, Loon, successfully demonstrated a flight lasting 300 days,[20] but there is not enough data to know the average lifetime of a HAB system. It is likely that solar radiation will damage the balloon materials and eventually cause failure. Additionally, payloads are limited to roughly 150 pounds. For comparison, the MILSTAR satellite weighs 10,000 pounds,[21] and orbits in geosynchronous orbit with a design life of

[19] Source: Pedro Nogueira, "Micro-Satellite Electrical Power Subsystem Design and Test for LEO Mission" (master's thesis, Beijing University, 2017), https://doi.org/10.13140/RG.2.2.29360.25603.

[20] Shah, "Google's AI Can Keep Loon Balloons Flying for over 300 Days in a Row."

[21] "Milstar Satellite Overview," Spaceflight Now, April 1, 2003, https://www.spaceflightnow.com/titan/b35/030401milstar.html.

10 years— he MILSTAR constellation is 25 years old and still operational.[22] HABs would need to operate in larger constellations to make up for their weight limitations, and their time restrictions limit their operational capacity to the supplemental role that this paper advocates.

Finally, HAB failure while operating over enemy territory could result in the loss of sensitive items to an adversary. For comparison, after a satellite fails it becomes orbital debris that poses little risk to informational operational security (OPSEC). If a satellite deorbits, it will burn up upon reentry before it can be exploited. Conversely, HAB-suspended payloads would land relatively close to where the balloon failure occurred, and sensitive components could survive for full exploitation if a slow leak results in a soft landing—in fact, an adversary could still garner useful information from the debris even if a complete rupture causes a hard-impact landing. Mitigation measures include self-destruction of the sensitive items following a catastrophic event to the HAB or utilizing a marsupial system for precision recovery of the items.

D. METHODOLOGY

The study approaches the research questions in three parts. The first part analyzes the strategic environment to determine the need for alternative network infrastructure to supplement space assets. The second focuses on designing the Bento Box and integrating payloads for operational use. The third part validates the Bento Box via payload commanding system-level tests and end-to-end system-level tests.

1. The Strategic Environment

To assess the risk to U.S. space-based assets, Chapter II of this study analyzes the progression of ASAT norms and weapons tests from the Cold War to today, concluding that the threat is increasing and the use of orbital assets is not guaranteed in future conflict. Orbital debris from ASAT tests, congestion from the commercialization of space, and

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22 Matthew Coleman-Foster, “Milstar Program Reaches 25 Year Milestone,” U.S. Strategic Command, February 6, 2019, https://www.stratcom.mil/Media/News/News-Article-View/Article/1760172/milstar-program-reaches-25-year-milestone/.

kinetic and directed-energy ASAT capabilities from great power competitors and other space-faring nations threaten the stability of the U.S. space infrastructure on which the military and economy have become so reliant. High altitude balloons can contribute to the U.S. space warfighting function with alternative means of communications, early warning systems, PNT, and reconnaissance. Additionally, by increasing the redundancy of the U.S. space-based warfighting network, HABs would help reduce any advantage an adversary would hope to gain by attacking satellite constellations, thereby decreasing the likelihood of a future attack. The premise for ASAT development by space-faring nations has changed from defensive to offensive behaviorism, signaled by the continuance of ASAT testing in the absence of orbital nuclear threats—fear of fractional and multiple orbit bombardment systems (FOBS and MOBS) during the Cold War initiated ASAT development. The United States must mitigate the increase in ASAT threats through alliance building that gives it access to additional space assets and launch locations, leveraging the commercialization of space, and developing alternative methods of providing capabilities normally provided by space-based assets (i.e., HABs).

2. Designing the Bento Box

Chapter III focuses on the design considerations and assembly of the Bento Box with modular payload plates to adapt three mission specific payloads. The Bento Box project is designed to evaluate the feasibility of utilizing HABs for SOF operations, focusing on modularity of the structure and payloads that increase situational awareness in the field as well as coordination between elements. Additionally, the Bento Box is designed to be utilized as a stand-alone structure under a HAB or as an integrated part of a marsupial system for precision recovery. The Bento Box makes use of existing CubeSat standards with a rail-based skeletal structure and achieves modularity through a system of adaptive plates designed to accommodate any payload board less than 1U (10cm) wide. Additionally, the adaptive plates can be used to attach multiple rail systems end-on-end or side-by-side to accommodate longer payload boards or to change the form factor of the Bento Box to fit various marsupial systems for precision recovery. The NPS SSAG developed avionics, primarily consisting of electrical power system (EPS) and command and data handling (C&DH) boards, specifically for this project. Iterating on a previous version of the SSAG HAB bus utilized by Pross (2019),[23] the advantage of the new EPS is the multi-voltage power connectors capable of providing power at 3.3V, 5V, and 12V to multiple payloads.

3. Validating the Bento Box

Chapter IV outlines the flight test of the Bento Box with three payloads to demonstrate the applicability of HABs during SOF operations. To preserve operational security of tactics, techniques, and procedures (TTPs) during the demonstration, the ground force in this study conducts a simple patrol. The HAB-suspended Bento Box supports the patrolling element with three payloads onboard: a software-defined radio (SDR) for RF signal relay between a drone, the joint operation center, and the ground force; an LED communications payload for alternate HAB telemetry, tracking, and command (TT&C); and an electro-optical (EO) sensor for overwatch of the patrol. The SDR performs as a bent-pipe communications system that can be remotely programmed to change transmit and receive frequencies. For the demonstration, the SDR switches between relaying video from a simulated artificial intelligence (AI) drone and video from an operator-worn body-camera. The LED payload is simple yet demonstrates the modularity of the Bento Box structure and bus system.

E. CHAPTER CONCLUSION

U.S. special operations forces and the military, writ large, are reliant on space assets for conducting modern warfare. The loss of satellite capabilities would severely threaten the ability of U.S.-forces to successfully find, fix, and finish targets; communicate between elements; and geo-locate friendly and enemy forces. High-altitude balloons offer the ability to provide capabilities similar to orbital assets with a variety of advantages and disadvantages. While a number of factors could cause a satellite-denied environment, one of specific concern is the international environment regarding ASAT weapons. The next

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[23] John W. Pross, "Filling the Gap: Rocket Delivered Short-Term Expeditionary Beyond Line-of-Sight Narrowband Communications Relay." (master's thesis, Monterey, CA; Naval Postgraduate School, 2019), https://calhoun.nps.edu/handle/10945/62697, 56.

chapter analyzes the changes in normative international behavior in the development and testing of ASATs and analyzes the resulting need to incorporate redundancy in the infrastructure of U.S. satellite capabilities.

II. THE STRATEGIC ENVIRONMENT

Recent events signal a change in the international norms concerning ASAT research, testing, and development. While there exist some international agreements that prohibit the use of specific types of ASAT weapons, they are inadequate and fail to address the necessary aspects of ASAT control—preventing both an arms race of ASAT weapons and the tests that result in orbital debris. The U.S. military and its allies are reliant on space-based assets for reconnaissance, communications, early warning systems, and position, navigation, and timing. Furthermore, the commercial use of space is increasing at an exponential rate. Disruption to space-based technologies, therefore, would cause economic repercussions on a global scale; commercial space programs will continue to increase the economic dependence on orbiting assets of all nations, regardless of economic status. The need for ASAT control goes beyond the security and prerogatives of the United States; preventing ASAT tests and proliferation is in the best interests of the entire international community. ASAT technology and its use should be regulated on the same scale as strategic nuclear weapons, considering the magnitude of their potential effects. Previous tests have had devastating results; nuclear tests in space resulted in disruption of non-targeted assets through electro-magnetic pulses and kinetic strike tests have left orbital debris that will continue to pollute space lanes and endanger manned and unmanned space flight for decades. However, ASATs are difficult to identify and their control would require significant cooperation between international entities. This chapter discusses a brief history of the ASAT programs during the Cold War, international agreements specific to ASAT technology, and disputed events that have negatively impacted ASAT norms. The chapter concludes with an overview of how to maintain space-based capabilities in the increasingly uncertain environment, such as with the operationally responsive space concept, strengthening alliances, and alternate methods of asset placement (HABs).

A. ASATS OF THE COLD WAR

The development of ASAT technology began as a countermeasure to the possibility of orbital nuclear weapons. During the Cold War period, in contrast to the development of

ASATs today, the driving factor to develop satellite-intercept technology was the perceived threat of death from above. The ongoing nuclear and space competition between the United States and the Soviet Union led many to believe that weaponizing space was the next logical step of progression in the ideological conflict. Additionally, satellite interceptor technology was important during the Cold War because it utilized the same launch and targeting methods as those required to intercept intercontinental ballistic missiles (ICBMs). This section provides a brief history on the progression of ASAT weapons and the lessons learned from the ASAT tests of the Cold War.

1. United States

The United States fielded and tested three variations of ASAT missiles from the early 1960s to 1975; the results should have sent a message to the world to avoid ASAT testing. Nuclear detonations in space caused indiscriminate damage to friendly satellites, and a kinetic strike against a spacecraft resulted in significant orbital debris. However, the U.S. drive toward ASAT technology originated from the fear that the Soviet Union would eventually use space as a domain for strategic warhead storage and delivery systems known as fractional and multiple orbit bombardment systems (FOBS and MOBS);[24] top officials and intelligence experts believed that the Soviets would be capable of threatening the United States with space assets.[25] Soviet reconnaissance systems were of little concern and were in fact desirable because their existence set space overflight precedence, resulting in international norms allowing freedom of overflight at orbital altitudes and de facto acceptance of Eisenhower's Open Skies plan of 1955, minus the aircraft component.[26] When ASAT programs began in earnest in 1963, the CIA did not believe that any foreign

[24] Director of Central Intelligence, *Soviet Capabilities and Intentions to Orbit Nuclear Weapons [Includes Table]* (Washington, D.C.: U.S. Intelligence Board, 1963), 17, https://search.proquest.com/docview/1679148872?pq-origsite=primo.

[25] Clayton K. S. Chun, *Shooting Down a "Star": Program 437, the U.S. Nuclear ASAT System and Present-Day Copycat Killers: CADRE Paper No. 6* (Maxwell Air Force Base, Alabama: Air University Press, 2012), 7.

[26] Johnson-Freese, *Heavenly Ambitions*, 35.

country's satellites posed a major threat; however, President Kennedy disagreed and ordered the development of an ASAT system as soon as possible.[27]

The simplest ASATs are nuclear tipped-missiles, and they are also the ones that result in the most collateral damage. Program 437, an Air Force nuclear ASAT program utilizing Thor missiles with a Mark 49 warhead, began in 1962 following the Starfish Prime and Fishbowl high-altitude nuclear-explosion tests, which proved overly effective and resulted in damage to untargeted spacecraft and terrestrial power grids.[28] Chun (2012) noted that the Secretary of the Air Force, Eugene Zuckert, and the Secretary of Defense, Robert McNamara, prioritized project 437 because the United States needed an ASAT program with instant reaction time; early systems required three days to launch. The Air Force also tested non-nuclear versions of the Thor system because the Pentagon and U.S. officials understood that a nuclear explosion in space targeting enemy satellites would likely damage U.S. satellites in the process.[29] The Defense Special Weapons Agency (DSWA) confirmed the assumption when it simulated a 50-kiloton nuclear explosion ~200km above New Delhi,[30] estimating that it would interfere with GPS and satellite communications for up to three hours and trap radiation in the Van Allen belts that would affect satellites up to 2,000 kilometers away.[31] Overall, neither the conventional nor nuclear versions of the Thor ASAT system proved useful, either due to lack of accuracy or potential of collateral damage, and the program diminished until its official dismantling in 1975.

Since there was no consensus on which branch should own ASAT development, the U.S. Army concurrently developed its own ASAT capability within the Nike-Zeus antiballistic missile system. The Nike-Zeus B ASAT, code-named Program 505, had a

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[27] Chun, *Shooting Down a "Star,"* 6.

[28] Chun, 5.

[29] James Clay Moltz, *The Politics of Space Security: Strategic Restraint and the Pursuit of National Interests*, 2nd ed. (Stanford, California: Stanford Security Studies, 2011), 143.

[30] Date of simulation not provided in source, but the study would have occurred between the launch of the first GPS satellite (1974) and the abolishment of the DSWA (1998).

[31] Chun, *Shooting Down a "Star,"* 68–69.

range of 250 miles with a 400-kiloton nuclear warhead. The Nike-Zeus showed promise during a demonstration in July 1962, in which it intercepted an Atlas D nose cone launched from Vandenberg Air Force Base (VAFB); the program had follow-on success the next year against an orbiting Agena-D.[32] While the system proved useful against orbiting craft, its radar system would be overwhelmed by any sizable attack with multiple weapons or decoys.[33] Furthermore, Program 505 was more costly, had less throw weight than the Thor system, and required the development and production of new missiles. Program 437 relied on spare Thors already in production. Finally, the Nike-Zeus program required non-military personnel from Bell Telephone Laboratories and the Western Electric Company whereas the Thor program could be conducted solely with military personnel. As a result, the U.S. government deactivated the Nike-Zeus B ASAT program and focused on Project 437.[34]

The United States later developed alternative methods of ASAT weapons to increase their viability for military use. The ASM-135 Direct Ascent ASAT (DA-ASAT) was a response to the Soviet Union's successful demonstration of a conventional warhead interceptor[35] and also a part of President Reagan's Strategic Defense Initiative.[36] On September 13, 1985, the U.S. Air Force conducted a successful test of the ASM-135 with the Miniature Home Vehicle (MHV) interceptor, which targeted and destroyed the Solwind (P-78) satellite creating extensive orbital debris, some of which remained in orbit until 2004.[37] It is worth noting that the Solwind event was the only time the United States destroyed a satellite with a missile prior to the highly debated 2008 event in which the

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[32] Chun, 8.

[33] Chun, 9.

[34] Chun, 10.

[35] Brian Weeden and Victoria Samson, *Global Counterspace Capabilities: An Open Source Assessment* (Washington, D.C.: Secure World Foundation, 2020), 3–8.

[36] Laura Grego, *A History of Anti-Satellite Programs* (Cambridge, MA: Union of Concerned Scientists, 2012), 5.

[37] Moltz, *The Politics of Space Security*, 202.

United States destroyed one of its own failed satellites.[38] Toward the end of the Cold War, the United States developed a directed-electromagnetic energy weapon called MIRACL (Mid-Infrared Advanced Chemical Laser) that could temporarily or permanently blind the sensors of an adversary's satellite without causing orbital debris, but Congress banned testing of the project after indications that Soviet directed-energy ASATs did not pose a threat to U.S. assets.[39] Ultimately, the United States turned its focus away from kinetic-kill (explosive) ASATs after recognizing that nuclear-tipped interceptors caused indiscriminate damage, kinetic strikes cause orbital debris, and the cost of maintaining a persistent direct-ascent ASAT capability was and remains extremely high.

2. Soviet Union

The Soviet Union began pursuing ASAT capabilities in 1963 for the same reasons as the United States—defense against potential orbital weapons.[40] In contrast to the United States, the Soviets conducted nearly two dozen ASAT tests between 1968 and 1982 with multiple successful intercepts of orbital craft.[41] Table 1, developed by Weeden and Samsom (2020), lists the known Soviet intercept attempts from 1963 to 1982; note that the interceptors successfully conducted strikes on twelve targets, three of which required multiple attacks.

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[38] Weeden and Samson, *Global Counterspace Capabilities: An Open Source Assessment*, 3–9.

[39] Grego, *A History of Anti-Satellite Programs*, 17.

[40] Weeden and Samson, *Global Counterspace Capabilities: An Open Source Assessment*, 2–3.

[41] James Clay Moltz, *Asia's Space Race: National Motivations, Regional Rivalries, and International Risks* (New York, NY: Columbia University Press, 2011), 97.

Table 1. List of ASAT tests conducted by the Soviet Union[42]

Date of Test	Target Object	Interceptor	Notes
Nov. 1, 1963	None	Polyot 1	Engine and maneuvering test
Apr. 12, 1964	None	Polyot 2	Engine and maneuvering test
Oct. 27, 1967	None	Cosmos 185 (IS)	First test launch of IS interceptor
Oct. 20, 1968	Cosmos 248	Cosmos 249, Cosmos 252 (IS)	Attacked twice: by Cosmos 249 on Oct. 20 and by Cosmos 252 on Nov. 1
Oct. 23, 1970	Cosmos 373	Cosmos 374, Cosmos 375(IS)	Attacked twice: by Cosmos 374 on Oct. 23 and by Cosmos 375 on Oct. 30
Feb. 25, 1971	Cosmos 394	Cosmos 397 (IS)	
Mar. 18, 1971	Cosmos 400	Cosmos 404 (IS)	
Dec. 3, 1971	Cosmos 459	Cosmos 462 (IS)	
Feb. 16, 1976	Cosmos 803	Cosmos 804, Cosmos 814 (IS)	Attacked twice: by Cosmos 803 on Feb. 12 and by Cosmos 804 on Feb. 16
July 9, 1976	Cosmos 839	Cosmos 843 (IS)	
Dec. 17, 1976	Cosmos 880	Cosmos 886 (IS)	
May 23, 1977	Cosmos 909	Cosmos 910, Cosmos 918 (IS)	Attacked twice: by Cosmos 910 on May 23 and by Cosmos 918 on Jun. 17 (both failures)
Oct. 26, 1977	Cosmos 959	Cosmos 961 (IS)	
Dec. 21, 1977	Cosmos 967	Cosmos 970 (IS)	Missed target, used as target itself in following test
May 19, 1978	Cosmos 970	Cosmos 1009 (IS)	
Apr. 18, 1980	Cosmos 1171	Cosmos 1174 (IS)	
Feb. 2, 1981	Cosmos 1241	Cosmos 1243, Cosmos 1258 (IS)	Attacked twice: Cosmos 1243 on Feb. 2 and Cosmos 1258 on Mar. 14 (both failures)
June 18, 1982	Cosmos 1375	Cosmos 1379 (IS-P)	

The Soviet ASAT program differed from that of the United States because it focused on conventional warhead systems to circumvent the Outer Space Treaty, which banned the use of nuclear weapons in space.[43] From Table 1, the Soviets utilized the Polyot missiles to conduct maneuvering and engine tests while the majority of the Cosmos interceptors utilized conventional warhead co-orbital methods, which maneuvered in orbit to collocate with the target satellite prior to detonating a cloud of pellets to damage nearby satellite components. Mowthorpe argues that the Soviet ASAT system was superior to the U.S. Thor system due to its "flexibility in its intercept trajectory, allowing attack from several directions and hence making countermeasures more difficult."[44] Additionally, some of the Cosmos tests did not include kinetic effects and demonstrated that the system

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[42] Source: Weeden and Samson, *Global Counterspace Capabilities: An Open Source Assessment*, 2–3.

[43] Matthew Mowthorpe, "The Soviet/Russian Antisatellite (ASAT) Programme during the Cold War and Beyond," *The Journal of Slavic Military Studies* 15, no. 1 (2002): 17–28, https://doi.org/10.1080/13518040208430510.

[44] Mowthorpe.

had multiple uses. For example, Mowthorpe notes that Cosmos 404 (interceptor) maneuvered to Cosmos 400 (target) and loitered briefly before de-orbiting back to earth, which suggests the Soviets intended to use the satellite for inspection or satellite-to-satellite reconnaissance missions—U.S. Project 437 also had an inspection version. The Soviet Union also attempted to develop directed-energy weapons (DEWs) at the Sary Shagan Laser-Ranging Facility in Kazakhstan. However, Mowthorpe notes that the Cosmos interceptors were limited to an altitude of 1,000 kilometers, posing no threat to U.S. communications and early-warning systems, and the directed-energy ASATs were hampered two-fold: they could not effectively track satellites and Earth's atmosphere diffused the laser beam to the point that it had no effect at higher satellite altitudes.[45] Ultimately, the Soviet ASAT programs reached a developmental standstill that could only target low-earth orbit (LEO) satellites with kinetic means.

B. CRAWLING START TO AN ASAT RACE

Following the Cold War, the original justification for ASAT development and testing no longer applied; the threat of nuclear war declined and widespread compliance with international treaties had long since prevented the placement of nuclear weapons in orbit. However, the United States had demonstrated the ability to target orbital assets, and other countries wanted to ensure they had the same capability. Although ASAT technology began as a defensive measure against the possibility of nuclear weapons in space, ASAT testing did not conclude with a treaty against the placement of nuclear weapons in outer space nor with the end of the Cold War. Since the turn of the century, the United States, China, and India have conducted successful ASAT tests or actions resulting in orbital debris, and Russia has conducted questionable co-orbital satellite operations. Chun notes that

> [a] nation may decide to fund an ASAT for a variety of reasons. The country may decide to acquire an ASAT as a political bargaining chip, as a deterrent, as a terrorist weapon, or as an offensive or defensive weapon; for prestige; or as a way to equalize its lack of a viable space capability relative to another

[45] Mowthorpe, 21.

> nation … the United States' reliance upon space systems for numerous military force applications is a tempting target to many nations.[46]

The most basic reason ASAT tests continue is that there are no official treaties to prevent them, and other nations, specifically the United States, China, and Russia, have already proven the capability.

The post-Cold War ASAT race began in 2007 when China conducted a successful kinetic strike against one of its own satellites. China launched the SC-19 ASAT missile with a conventional warhead on a two-stage DF-21 rocket targeting the inactive Chinese Feng Yun 1C (FY 1C) weather satellite as a capability demonstration, resulting in roughly 2,700 pieces of orbital debris larger than ten centimeters that will remain in orbit for at least 40 years based on the debris altitude of 525 miles.[47] No country had conducted a kinetic strike against an orbiting object since the U.S. MHV strike in 1985 prior to the end of the Cold War. While China did not publicly release its intention to conduct the test, some U.S. officials were aware of the effort based on previous proximity tests in 2005 and 2006; when asked why they did not try to prevent the test, one official stated simply, "we wanted to see if they could do it."[48] Weeden and Samson note that China is developing a wide range of capabilities including LEO/GEO direct ascent, co-orbital, directed-energy, electronic warfare, and Rendezvous and Proximity Operation (RPO) ASAT systems;[49] the Defense Intelligence Agency confirmed China's efforts on ground-based ASAT lasers in a report released in 2019.[50] China's recent advances and weapons development indicate that ASAT technology is a critical piece of China's future war strategy, especially considering the associated cost of developing, testing, and operating satellite interceptors.

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46 Chun, *Shooting Down a "Star,"* 62–69.

47 Moltz, *Asia's Space Race*, 96.

48 James Clay Moltz, "Space and International Security" (Class notes for NS4677: Space and International Security, Naval Postgraduate School, Monterey, CA, 2021).

49 Weeden and Samson, *Global Counterspace Capabilities: An Open Source Assessment*.

50 Bill Gertz, "DIA: China to Deploy ASAT Laser by 2020," Washington Free Beacon, February 15, 2019, https://freebeacon.com/national-security/dia-china-to-deploy-asat-laser-by-2020/.

Space-capable nations can be broken into four categories: limited, rising, spacefaring, and space power.[51] The new Chinese capability and continued drive for additional ASAT weapons sends a signal that states need an ASAT capability to be a space power nation, which has caused an international response of tests from the United States, Russia, and India.

The United States conducted its own post-Cold War satellite interception in 2008, known as Operation Burnt Frost, to destroy a National Reconnaissance Office (NRO) satellite (USA 193) that failed in orbit. The NRO satellite contained nearly 1,000 pounds of a highly toxic propellant called hydrazine and was deorbiting due to the inability to conduct orbit-management maneuvers.[52] Furthermore, the U.S. government could not guarantee the satellite would avoid populated areas on re-entry because it had no control of the dead asset. The United States reportedly intercepted and destroyed the satellite to prevent harmful exposure to the toxic hydrazine and did so at a very low altitude to reduce orbital debris. However, Richard Weitz, the director of the Center for Political-Military Analysis, noted that "Chinese, Russian, and other analysts interpreted the interception, which occurred a little more than a year following the Chinese ASAT test, as a warning to Beijing and others that the United States retained retaliatory ASAT capabilities."[53] Although the United Sates conducted the strike for safety reasons, the international community perceived the event as a potential trend toward a race for ASAT weapons.

To keep up with recent trends, Russia and India conducted their own ASAT tests. In 2017, Russia launched a "space apparatus inspector" that later released two smaller probes that "appear to be part of a Russian program not only to check in on Russian

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[51] B. Bahney, "Space Strategy at a Crossroads: Opportunities and Challenges for 21st Century Competition" (Livermore, CA: Lawrence Livermore National Lab, March 16, 2020), 44, https://doi.org/10.2172/1635784.

[52] Lucas Steinhauser and Scott Thon, "Operation Burnt Frost: The Power of Social Networks," *Academy Sharing Knowledge*, June 1, 2008, 18.

[53] Richard Weitz, "Arms Racing in Strategic Technologies: Asia's New Frontier - by Richard Weitz," Hudson Institute, May 3, 2015, http://www.hudson.org/research/11307-arms-racing-in-strategic-technologies-asia-s-new-frontier.

satellites, but understand what other countries are doing."[54] The inspector satellite, which has earned the nickname "Russian Doll Satellite" (RDS), could affect or gather information from another nation's asset by conducting an RPO on it. Though not kinetic, the RDS has ASAT potential. Russia also continues to test weapons that utilize electromagnetic pulses to disrupt satellites in orbit.[55] On the other hand, India's ASAT test was kinetic. India conducted the test due to "[concern] about a repeat of history with it being one of the ASAT 'have-nots' if there was ever a future ban on direct-ascent ASAT testing."[56] If current trends remain unchanged, ASAT development will continue to proliferate and threaten the free-use of outer space.

C. THE PHYSICS OF ASATS

Current international treaties are insufficient to address the negative effects of ASAT use because of the difficulty of orbital mechanics and the designation of space as a global commons. To prepare for the discussion on treaties, this section provides a general background of orbital mechanics and "free-space loss" to demonstrate the difficulty of ASAT weapons development and the issues of treaties looking to ban them. This study considers four types of ASAT weapons: direct ascent, co-orbital, RPO, and directed-energy. Direct ascent ASAT weapons target a satellite from the ground or aircraft and move directly toward an intercept with the intended target. Co-orbital ASATs first enter an orbit then conduct maneuvers to intercept with the target. RPO ASATs close with a target satellite to exploit or damage the craft or alter is orbital parameters. Directed-energy weapons send high amounts of energy (like lasers) toward a spacecraft with the intent of temporarily blinding the spacecraft or permanently damaging imaging components (i.e., mirror, camera sensor). All three types require an understanding of orbital paths; they are

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[54] McLeary, "Space Mystery."

[55] Mowthorpe, "The Soviet/Russian Antisatellite (ASAT) Programme during the Cold War and Beyond," 26.

[56] Brian Weeden and Victoria Samson, "India's ASAT Test Is Wake-up Call for Norms of Behavior in Space," SpaceNews, April 8, 2019, https://spacenews.com/op-ed-indias-asat-test-is-wake-up-call-for-norms-of-behavior-in-space/.

not intuitive and are made worse by the grossly inaccurate depiction of space in popular media.

Contrary to science fiction movies depicting spacecraft reaching a certain distance above earth, leaving gravity, and becoming weightless, satellites never "escape" gravity and their orbits are always governed by gravity. The perpetual freefall of a spacecraft in orbit gives the appearance of weightlessness, but the spacecraft is moving fast enough such that Earth's gravity pulls it in a continuous circle or ellipse around the planet. For example, we can use *Equation 2.1* to calculate the velocity of a satellite in low-earth orbit (LEO) at 300 kilometers altitude:[57]

$$v = \sqrt[2]{\frac{Gm1}{r}} = \sqrt[2]{\frac{\mu}{r}} = \sqrt[2]{\frac{398600km^3/s^2}{6678km}} = 7.73\,\frac{km}{s} \qquad 2.1$$

where G is the gravitational constant (6.67×10^{-11} $m^3/kg\ s^2$), m_1 is the mass of Earth (5.9722×10^{24}kg), and r is the radius of the satellite from the center of the Earth (300km altitude plus the 6378km radius of Earth). To stay in a circular orbit at 300 kilometers, a spacecraft must travel at 7.73 kilometers per *second,* tangential to the curvature of the earth. The U.S. ASAT Thor system had a five-second launch window in order to achieve the required accuracy for orbit interception; for comparison, the Apollo moon launches had a four-to-five-minute margin.[58] The difficulty of conducting ASAT operations cannot be overstated.

Satellite interception with direct ascent or directed-energy weapons is difficult based on the satellite velocity alone; the laws of physics further increase the difficulty of co-orbital weapons. Consider two spacecraft at the same altitude, traveling the same speed, on the same orbit path, with one spacecraft trailing the other by three kilometers. Intuitively, one would think that the trailing spacecraft needs to speed up in order to rendezvous with the lead craft; however, doing so would place the trail vehicle in an orbit with the further apogee (furthest orbital distance from Earth), which would effectively

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[57] Anil K. Maini and Varsha Agrawal, *Satellite Technology: Principles and Applications*, 3rd edition (Chichester, West Sussex: Wiley, 2014).

[58] Chun, *Shooting Down a "Star,"* 15.

increase the length of time required to orbit the earth, and the trail vehicle would fall further behind. In this example, the chase craft would need to slow down to catch up, which emphasizes that satellite interception involves complex operations and is not as simple as it may seem.

One important factor in the cost of ASAT operations is that it often requires more than one interceptor to destroy a satellite. Table 2, developed by Chun (2012), shows the estimated number of interceptors required to target a satellite based on the quality of the ASAT (columns) and the desired probability of success (rows). Note that very few instances result in one-for-one ASAT launch to satellite destruction. Additionally, ASAT launches require the same massive rockets and launch facilities as other orbital assets—they are extremely cost prohibitive.

Table 2. ASAT probability of kill and satellite probability of survival[59]

Probability of kill ⇨

Probability of survival ⇩

PK/ OPS	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1
0.01	2	3	4	6	7	10	13	21	44
0.05	2	2	3	4	5	6	9	14	29
0.10	1	2	2	3	4	5	7	11	22
0.15	1	2	2	3	3	4	6	9	19
0.20	1	1	2	2	3	4	5	8	16
0.25	1	1	2	2	2	3	4	7	14
0.50	1	1	1	1	1	2	2	4	7

Number of launches ⇨

Finally, directed-energy weapons are subject to free-space loss, which makes them difficult to utilize from ground-based systems. Recall the equation for free-space-loss (L_{fs}) of electromagnetic emitters:

$$L_{fs} = \left(\frac{4\pi R}{\lambda}\right)^2 \qquad 2.2$$

59 Source: Chun, 62.

where λ is the wavelength of the emission and R is the radius or distance from the emitter.[60] Note that free-space-loss has quadratic growth with the distance of travel, meaning that weapons would require extremely powerful emitters (most likely beyond current technology) to affect assets at an altitude of 300 kilometers. However, orbital assets armed with a DEW could make passes at altitudes slightly lower than the target vehicle and be within a range at which it could inflict permanent damage.

As this section has shown, ASAT technology of various types is difficult but not impossible. More importantly, the complexity of the space environment and the delivery method of ASAT weapons make it difficult to implement and enforce restrictions on their development on the international stage.

D. THE FAILURES OF CURRENT INTERNATIONAL AGREEMENTS

While some treaties exist, none focus on the prevention of ASAT weapons; the international system has relied heavily on cooperative norms,[61] hoping that mutual fear of razing orbital lanes would prevent a space war. Pursuant to a voluntary moratorium in 1986, the United States and the Soviet Union observed "contingent restraint"[62] not to engage each other's satellites with destructive means; other nations followed suit. However, emerging technologies threaten the stability of U.S. satellite constellations as great power competitors have conducted questionable demonstrations of potential ASAT weapons. Current treaties place the international system at the "Limited Treaties" phase on the Spectrum of International Space Governance (see Figure 3).[63] Currently, there are no legal repercussions for ASAT experiments that cause orbital debris, and the only existing treaties focus on nuclear weapons in space and non-interference with other nations' satellites. The international community needs to develop expanded treaties and a world

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[60] Maini and Agrawal, *Satellite Technology*.

[61] Cooperative norms are those that correspond to self-interest and do not require sanctioning. Gary Goertz and Paul F. Diehl, "Toward a Theory of International Norms," *Journal of Conflict Resolution* 36, no. 4 (December 1992).

[62] Johnson-Freese, *Heavenly Ambitions*, 47.

[63] Moltz, "Space and International Security."

space organization to implement repercussions for ASAT tests that cause orbital debris to ensure space is usable in the foreseeable future. This section covers current treaties, the issues of some of the proposed treaties, and recommendations for better results.

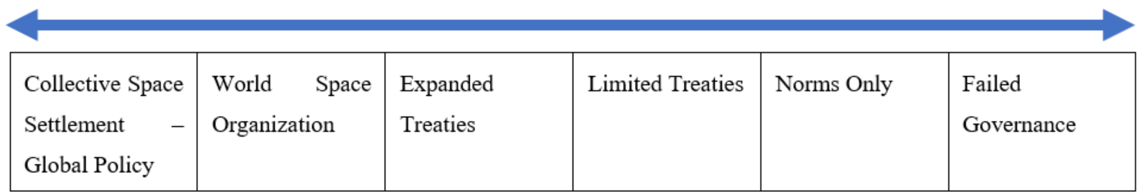

Figure 3. Spectrum of international space governance[64]

Nuclear ASATs are the easiest to create and are the most destructive, but they are also the easiest to control due to already existing treaties and international watchdogs on nuclear weapons development. Furthermore, Article IV of the *Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies* (referred to as the Outer Space Treaty) maintains that "States Parties to the Treaty undertake not to place in orbit around the Earth any objects carrying nuclear weapons or any other kinds of weapons of mass destruction, install such weapons on celestial bodies, or station such weapons in outer space in any other manner."[65] Currently, 111 nations are party to the treaty, including Russia and China, and there is no evidence to suggest any actors are working to develop modern nuclear ASATs—although any ICBM or SLBM could theoretically be repurposed as an ASAT.

For conventional warhead ASATs, the only limitation is a restriction on the interference of other nations' spacecraft. Article III of the *Convention on International Liability for Damage Caused by Space Objects* states that any launching state will be held liable if it damages another state's property or persons in space.[66] This does not prevent

[64] Moltz.

[65] United Nations, *United Nations Treaties and Principles on Outer Space* (Geneva, Switzerland: United Nations, 2002), 4.

[66] United Nations, 13.

testing because it gives states the ability to test on their own objects in orbit and does not account for the potential second order effects of ASAT tests; orbital debris from an interceptor test could damage another nation's asset. International agreements need to standardize repercussions for creating orbital debris through intentional destruction of orbiting objects, regardless of ownership (i.e., no kinetic ASAT tests).

In 2008, China and Russia presented the draft treaty on the Prevention of the Placement of Weapons in Outer Space (PPWT). The Sino-Russian treaty was unsuccessful because, among other reasons, the "United States [opposed it] due to its failure to limit China's ground-based ASAT weapons and its lack of verification mechanism."[67] Other criticisms of the treaty included: insufficient definition of space weapons, exclusion of ground and sea-based weapons, and a lack of verification mechanisms or bans on ground and sea-based weapons testing.[68] China and Russia presented a revised version of the PPWT in 2014, but according to Tronchetti and Hao, "the 2014 revision of the PPWT […] leaves substantially unchanged the most controversial aspects of its original 2008 version."[69] Essentially, the PPWT only creates restrictions that would prevent the United States from placing planned missile defense systems in orbit by agreeing to ban weapons technology that no country is knowingly pursuing. On the plus side, the PPWT would prohibit the "threat or use of force against outer space objects of States Parties,"[70] which would prevent ASAT testing and use during conflict. Conclusively, the draft PPWT attempts to include unnecessary restrictions targeting the goals of a particular actor, namely the United States; China and Russia should propose a treaty focusing solely on the prevention of the use of force in space before moving forward with the messy process of weapons restrictions.

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67 James Clay Moltz, "Brazil's Space Program: Dreaming with Its Feet on the Ground," *Space Policy* 33 (August 2015): 16.

68 Fabio Tronchetti and Liu Hao, "The 2014 Updated Draft PPWT: Hitting the Spot or Missing the Mark?," *Space Policy* 33 (2015): 40–41, https://doi.org/10.1016/j.spacepol.2015.05.004.

69 Tronchetti and Hao, 44.

70 Government of the Russian Federation and Government of the People's Republic of China, *Treaty on the Prevention of the Placement of Weapons in Outer Space, the Threat or Use of Force against Outer Space Objects (Draft)*, 2014, 2.

The one comforting aspect of ASAT technology is the extreme difficulty in achieving satellite interception. While multiple countries have demonstrated the ability to conduct interception and destruction of orbiting targets, it is an expensive endeavor, requiring significant fuel, advanced rockets, and substantial man-hours of preparation and calculations. Targeting and destroying an entire constellation of assets, such as the GPS constellation with 24 satellites, without affecting friendly assets, would be very difficult and very costly. Furthermore, the orbital debris remaining after a kinetic attack at an altitude of ~20,000km would leave that region unusable for centuries. A rational actor would quickly conclude that destroying U.S. and allied satellites on a massive scale would have lasting harmful effects against its own interests. But what if ASAT technology falls in the hands of an irrational actor? A single missile, theoretically, could cause a chain reaction with the potential to eradicate an entire constellation and leave space (or at least certain regions of it) an orbital wasteland devoid of useful assets. ASAT technology must be monitored and regulated with the same oversight as strategic missiles. Furthermore, counter-ASATs need to be developed and implemented by an international organization to protect the space environment and ensure the domain remains a global commons.

E. PROTECTING CRITICAL CAPABILITIES IN AN ANARCHIC SYSTEM

Considering the lack of expanded treaties and a world space organization, it is important for the United States to maintain space-based capabilities as a warfighting function without making aggressive maneuvers that would derail progress toward treaty establishment. Paul Meyer claims that the U.S. goal of space dominance and its shift to referring to space as a "warfighting domain" is destabilizing, increases threat perception, and is counter-productive to PAROS (Prevention of an Arms Race in Outer Space Treaty);[71] this is misguided and misinterprets the definition of a warfighting domain. The fact is that space, even without orbital weapons, has been a decisive warfighting domain since the Persian Gulf War of 1990–1991 when coalition forces utilized the Global

[71] Paul Meyer, "Washington Sparks a Space Spat at the United Nations," Bulletin of the Atomic Scientists, December 11, 2018, https://thebulletin.org/2018/12/washington-sparks-a-space-spat-at-the-united-nations/.

Positioning System for navigation[72] and the Defense Support Program warned troops of scud launches.[73] The U.S. focus on space dominance is neither destabilizing nor a drift from international norms but rather a continuation of the defensive and security measures required to maintain critical capabilities. Additionally, China and Russia have demonstrated the ability to threaten U.S. space infrastructure. The United States can protect space capabilities without increasing aggression in three ways: the development of quick asset replacement, increased asset maneuverability, and deterrence through denial.

First, the ability to replace assets quickly is tackled through the Operationally Responsive Space (ORS) initiative. The Department of Defense (DOD) developed the ORS initiative in 2006, focusing, in one aspect, on decreasing the requisite time to replace military satellites in orbit.[74] A study at NPS concluded that the asset replacement process could be shortened by creating common buses for all satellites, but that it still takes roughly six weeks from asset delivery to launch.[75] While this is a worthy endeavor, U.S. decision-makers must consider diverse methods to achieving the end goal: maintaining communications, remote sensing, and geolocation capabilities after catastrophic events to our space assets.

Second, space assets should be launched with extra propellant, which is admittedly costly, to increase their maneuverability in the event of an attack. Spacecraft require propellant while in orbit to maintain their orbital parameters to counter perturbations from the Moon, other planets, and the oblation of Earth's surface.[76] Considering the difficulty

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[72] Kaleb Dissinger, "GPS Goes to War - The Global Positioning System in Operation Desert Storm.," Army Heritage Museum, February 2008, https://www.army.mil/article/7457/gps_goes_to_war_the_global_positioning_system_in_operation_desert_storm_.

[73] Ellen Pawlikowski, Doug Loverro, and Tom Cristler, "Space," 32.

[74] Thomas M. Davis, "Operationally Responsive Space - The Way Forward," in *29th Annual AIAA/USU Conference on Small Satellites* (Logan, UT: AIAA/USU, 2015).

[75] Brian Anderson et al., *Operationally Responsive Space: Creating Responsive Space for America* (Monterey, CA: Naval Postgraduate School, 2008).

[76] Vincent L. Pisacane, *Fundamentals of Space Systems* (New York, NY: Oxford University Press, 2005), 125.

and extremely specific trajectory in direct-ascent interception, extra propellant on U.S. assets could be used to thwart an incoming missile immediately after ASAT launch detection. In the case of co-orbital ASATs, maneuvers could be made in-between each adjustment of the chase vehicle to move ahead or behind in the orbit stepwise until the attack vehicle runs out of fuel. Admittedly, spacecraft would run out of fuel after multiple attacks, but this could be mitigated with a spacecraft refueling program.

Finally, the United States should increase its security through deterrence by denial. According to Jeffrey W. Knopf, deterrence by denial is the "ability to resist and ultimately frustrate another actor's efforts…while still leaving it with the costs of its efforts."[77] Network reinforcement through alliances, commercial assets, and unconventional assets would frustrate hostile states' attempts to disrupt U.S. space infrastructure. Deputy Secretary of Defense Douglas Loverro noted in his 2017 statement to the House Armed Services Committee:

> The robust and burgeoning commercial space sector provides unmatched opportunity for the United States to augment and supplement traditional government-owned capabilities with U.S. commercial capabilities, with significant increases in resilience and mission capability, all while lowering overall cost … the strategic pursuit of partnerships with allied nations can simultaneously reduce the need for direct U.S. government investment, increase the complexity of the target set our adversaries must engage, diversify the means for us to support space missions, and create political hurdles for any adversary who might want to try to isolate the United States.[78]

In summary, the United States can increase the security of its space-based infrastructure by making it too large for an enemy to disrupt. Furthermore, the United States can reduce the cost of network reinforcement by leveraging commercial space programs, building mutually beneficial alliances with other space-faring nations, and implementing unconventional methods of asset placement.

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[77] Jeffrey W. Knopf, "Three Items in One," in *Complex Deterrence* (Chicago, Il: University of Chicago Press, 2009), https://www.press.uchicago.edu/ucp/books/book/chicago/C/bo6887686.html.38

[78] *Fiscal Year 2017 National Defense Authorization Budget Request for National Security Space Activities: Testimony before the Subcommittee on Strategic Forces, House Armed Services Committee,* 114th Cong. (2016)(Statement of Douglas Loverro, Deputy Assistant Secretary of Defense)

One unconventional method of reinforcing our space-based systems would be to remove the advantage of attacking United States satellites through non-standard network reinforcement via stratospheric assets. As previously noted, HABs have become operationally feasible. By operationalizing the stratosphere, the United States can reduce the significance of its satellite network or, more importantly, reduce the advantage a hostile nation would gain from its efforts to destroy U.S. orbital assets. Additionally, they can be utilized as a low-cost reinforcement or capability stop-gap after the loss of a spacecraft.

The use of stratospheric assets would reduce the reliance on assets in orbit and, more importantly, draw attention away from them. As detailed in Chapter I, they are cheap to put up and expensive to shoot down. Adding HABs to the military network architecture would induce a financial burden to any adversary wishing to disrupt U.S. capabilities, thereby increasing the overall security of space and near-space systems.

F. CHAPTER CONCLUSION

International norms on the development and use of ASAT weapons are trending in a perilous direction. The proliferation of ASAT development and lack of international regulatory bodies threatens the stability and security of space-based networks on which the U.S. military and its allies have become irreversibly reliant. Adversaries increasingly become more capable of disrupting space-based assets, and orbital debris continues to build up in the global commons of the space domain. The United States should lead efforts to develop international space-governing bodies to ensure the free and secure use of space and a means of ASAT control or, at a minimum, ASAT test regulation. In the absence of order in the international system, the United States must reinforce its space-based capabilities by strengthening alliances, leveraging commercial space programs, and developing unconventional methods of network reinforcement.

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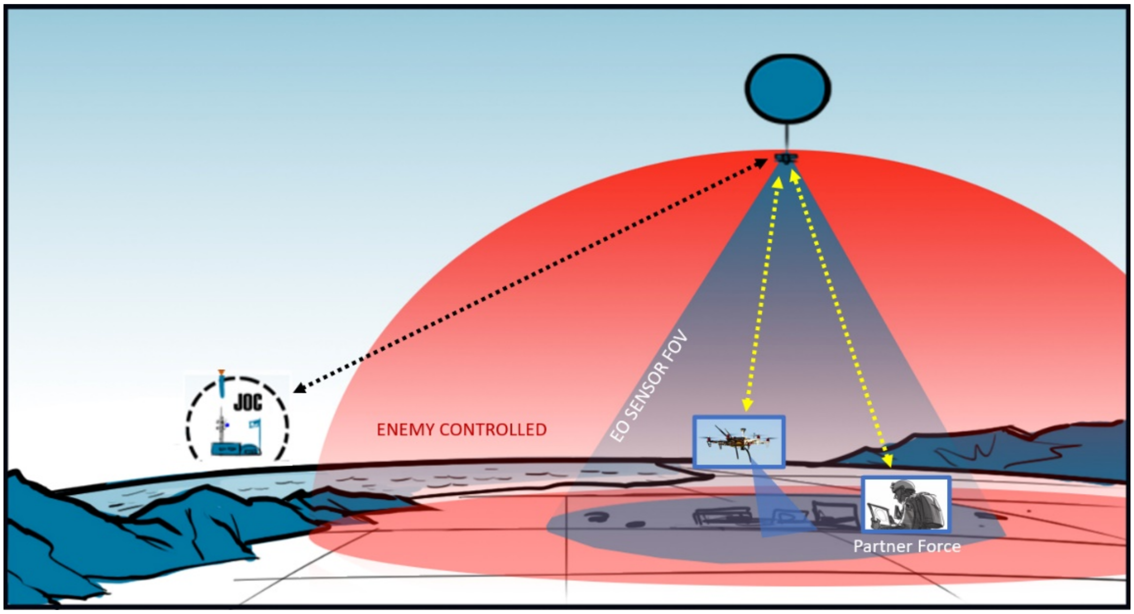
III. DESIGNING THE BENTO BOX

The previous chapters advocated the necessity to reinforce U.S. space-based infrastructure with alternative methods. The remainder of this study is a proof-of-concept experiment on enabling SOF with stratospheric systems—specifically, utilizing the Bento Box on a tethered HAB to reinforce network infrastructure for an operational scenario. The Bento Box is a modular HAB bus conceptualized by the author and MAJ Chris Gallegos and is designed as a payload integration system for stratospheric assets. The CONOP for the flight demonstration, shown in Figure 4, includes the Bento Box supporting a remote advise-assist (RAA) operation of a partner force (PF). The Bento Box enables the RAA by relaying video feeds (payload 1: drone relay) from the support drone and PF through the HAB back to the Joint Operations Center (JOC), providing overhead real-time video coverage of the target area (payload 2: EO sensor), and enabling alternative communications via LED (payload 3: LED comms). Additionally, the PF can access the video feeds via downlink from the HAB or directly from the drone, depending on proximity of the drone to the PF. Similar to space-based systems, the system architecture is broken into three mission segments: the ground segment (JOC), the "space" segment (Bento Box), and the user segments (drone and PF).



The Bento Box EO sensor provides overhead coverage of the operational area, the SDR relays the drone and PF video feeds to the JOC, and the LED payload represents alternative comms.[79]

Figure 4. CONOP overview

This research builds on the avionics developed by the Space Systems Academic Group of the NPS Graduate School of Engineering and Applied Sciences (GSEAS), the command and data handling (C&DH) and electrical power system (EPS) boards, and capitalizes on the standard CubeSat rails designed by Lawrence Livermore National Laboratory.[80] The Bento Box was designed, analyzed, and fabricated by the author, including the adapter plates that establish the modularity of this concept, which is intended for use on HABs as a standalone system or integrated as the modular component of a precision recovery marsupial system. If used, the recovery system would remain suspended under the HAB and detach in the event of a catastrophic failure or attack on the balloon. Additionally, with space-qualified components, the Bento Box structure and its adapter plates can be utilized on a LEO satellite.

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79 The LED payload is a simple representative payload that flashes a simple morse code message; however, students from the Space Systems Operations curriculum developed and tested a laser communications payload with high data rates that could replace the representative LED payload.

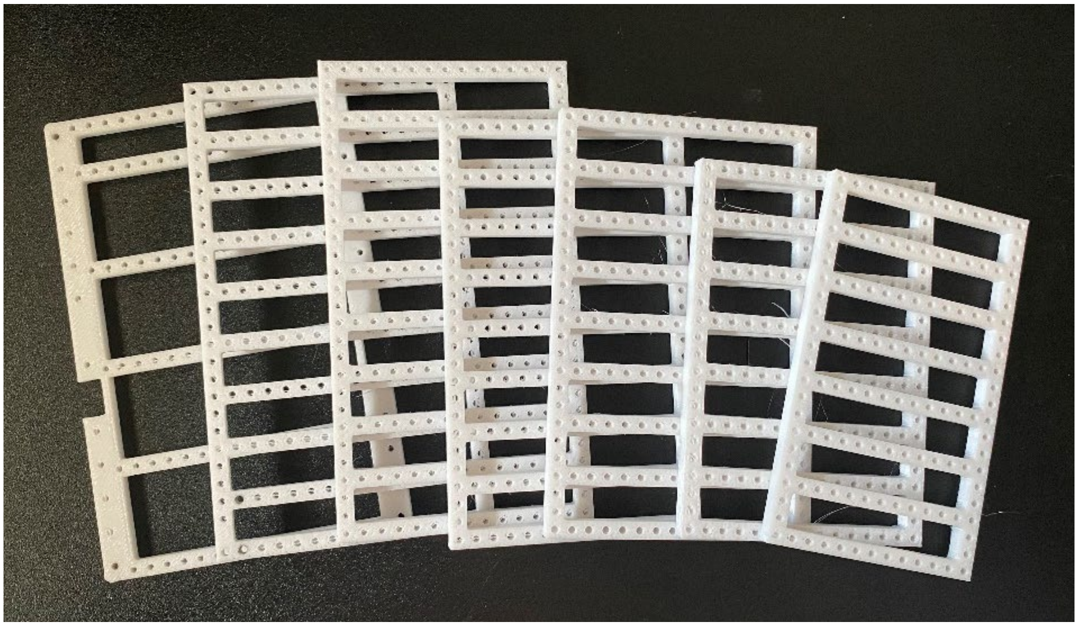
80 Jim Newman et al., "Government-Owned CubeSat Next Generation Bus Reference Architecture," in *28th Annual AIAA/USU Conference on Small Satellites*, SSC14-V-9 (Logan, UT: AIAA/USU, 2014).

A. DESIGN CONSIDERATIONS

The Bento Box design focuses on modularity, simplicity, operational relevancy, and structural integrity. Modularity for payload integration decreases the time required to adapt the Bento Box to changing mission requirements. Simplicity minimizes the need for specialized training for payload integration, and structural integrity ensures that the Bento Box will continue to function during the accelerations induced by HAB and marsupial system operations.

1. Modularity

The modularity of the Bento Box enables quick customization of the payloads to meet mission requirements. The Bento Box achieves structural modularity through adapter plates with various lengths and widths that allow for multiple configurations and accommodate payload boards of multiple sizes (see Figure 5). The adapter plates have tie-in points every 5 millimeters with holes for m2.5 screws. During the payload integration process of this study, components with existing attachment points easily connected to the adapter plates. Some components required custom casing (see Section B); the computer aided design (CAD) of the custom cases was simplified due to the various tie-in points and various sizes of the adapter plates. When developing payload attachment points, one can guarantee proper placement simply by maintaining an attachment point separation in multiples of 10mm in the x-axis (length) and 5mm in the y-axis (width). Appendix A contains the CAD drawings of the base adapter plate, the smallest adapter plate, and the custom parts for mounting the payloads.



Various plate sizes simplify payload integration; the plate on the far left is specifically designed as a base plate for the Lawrence Livermore CubeSat rails.[81]

Figure 5. Bento Box adapter plates

The plates fit within the payload compartment and stack upon each other via m2.5 hex male-female standoffs of various heights. Figure 6 shows the two adapter plates separated by hex standoffs with two payloads and their components distributed over the plates. The length of the stand-off is chosen based on payload clearance requirements.

[81] Adapter Plates designed, modeled, and printed by James Hansen, 2021.

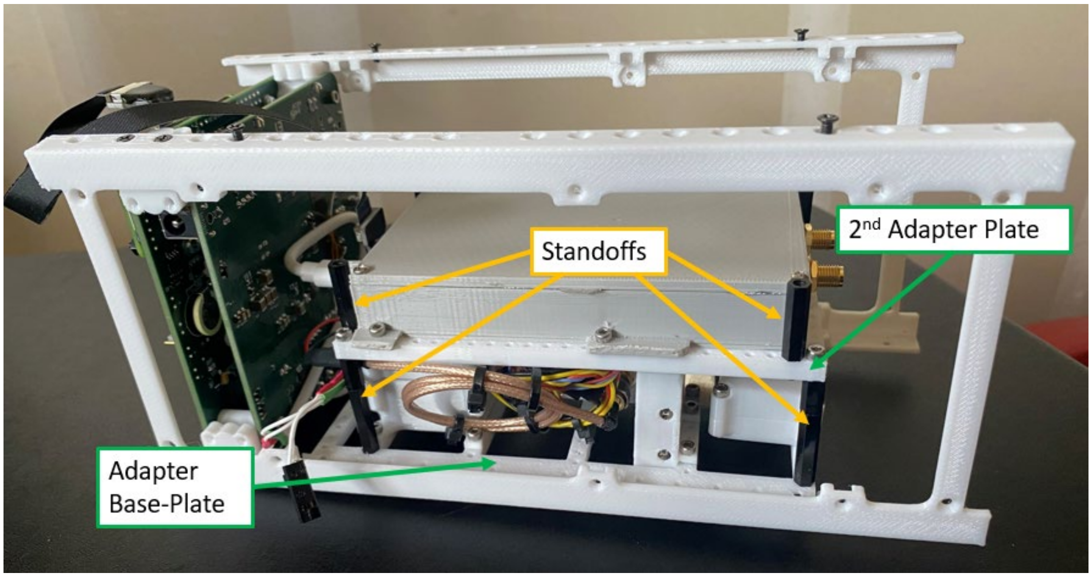
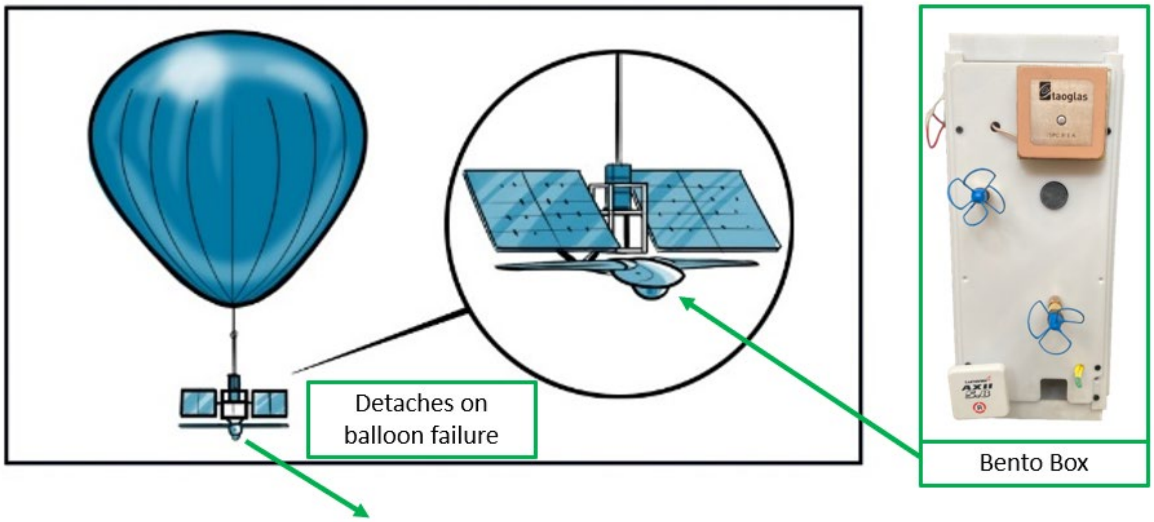


Figure 6. Payload adapter plates in Bento Box

2. Structural Integrity

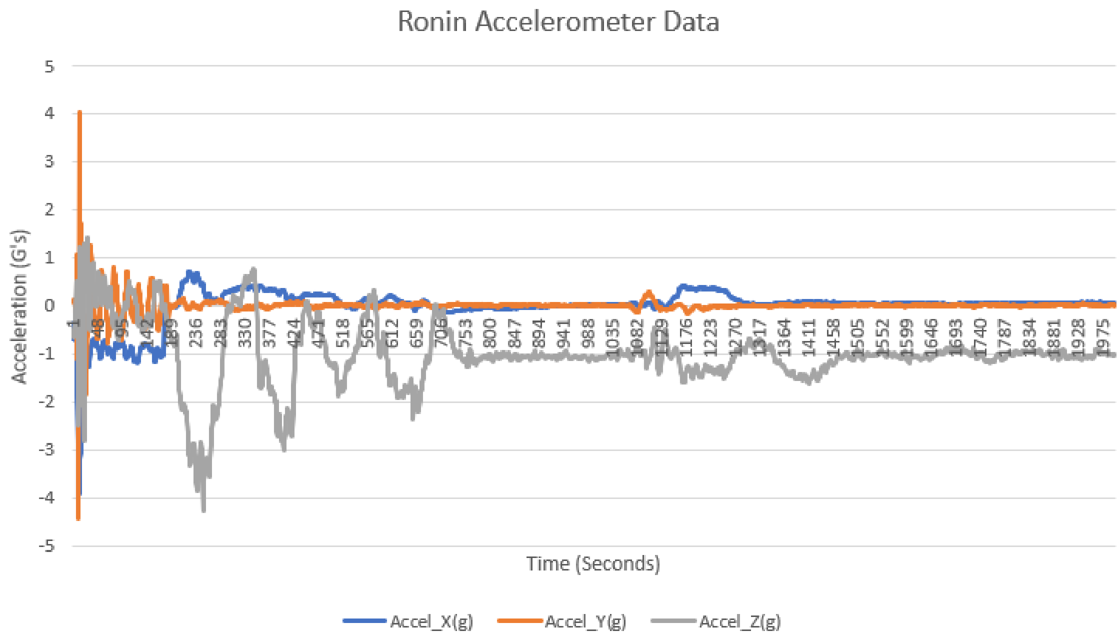
High altitude balloon operations induce accelerations on the structure, and the design must ensure survival of the bus and payloads. Precision recovery of the Bento Box back to friendly forces via a marsupial system induces additional accelerations. The concept of a marsupial system, as shown in Figure 7, is that a UAV would remain suspended underneath the HAB with all sensitive payloads and release in the event of HAB failure. Currently, there are two efforts in designing a HAB-dropped UAV that could perform as the marsupial system: the United States Air Force Academy (USAFA) Night Fury project and the Sierra Nevada Corporation (SNC) Ronin.



The UAV remains suspended under the HAB and releases for precision recovery in the event of a catastrophic incident to the balloon.

Figure 7. CONOP for a marsupial system UAV as precision recovery

SNC provided accelerometer data of a drop-test of the Ronin from 90,000 feet for analysis (see Figure 8). Considering that the max acceleration occurs during the ascent phase of the HAB launch, the structure needs to withstand accelerations up to 4.5 times Earth's gravity (g0), regardless of whether the Bento Box is in the standalone or marsupial configuration.



Note the max acceleration of ~4.5 Gs occurs during the HAB launch phase.

Figure 8. Accelerometer data from SNC Ronin[82]

Finite element analysis (FEA) in Siemens NX, a CAD modeling software package, confirms the structural integrity of the adapter plates.[83] The finite element model in Figure 9 focuses on one plate pinned at the four corners with a 12.25N load placed on the center two beams of the plate, which is equivalent to 0.6 pounds at 4.5 G's—much heavier than any payloads on this experiment. The maximum stress experienced by the plate is 2.17 megapascals (MPa), well within the 57 MPa tensile strength of 3D printable polycarbonate.[84] Even with the most conservative factor of safety for spaceflight, the adapter plates are structurally adequate.

[82] Derived from accelerometer data provided by Sierra Nevada Corporation.

[83] "FEA / Finite Element Analysis," Siemens Digital Industries Software, accessed May 11, 2021, https://www.plm.automation.siemens.com/global/en/our-story/glossary/finite-element-analysis-fea/13173.

[84] STRATASYS, *Characterization of Material Properties: Fortus Polycarbonate (PC)*, PC REPORT 01/11 (Eden Prairie, MN: Stratasys Incorporated, 2011).

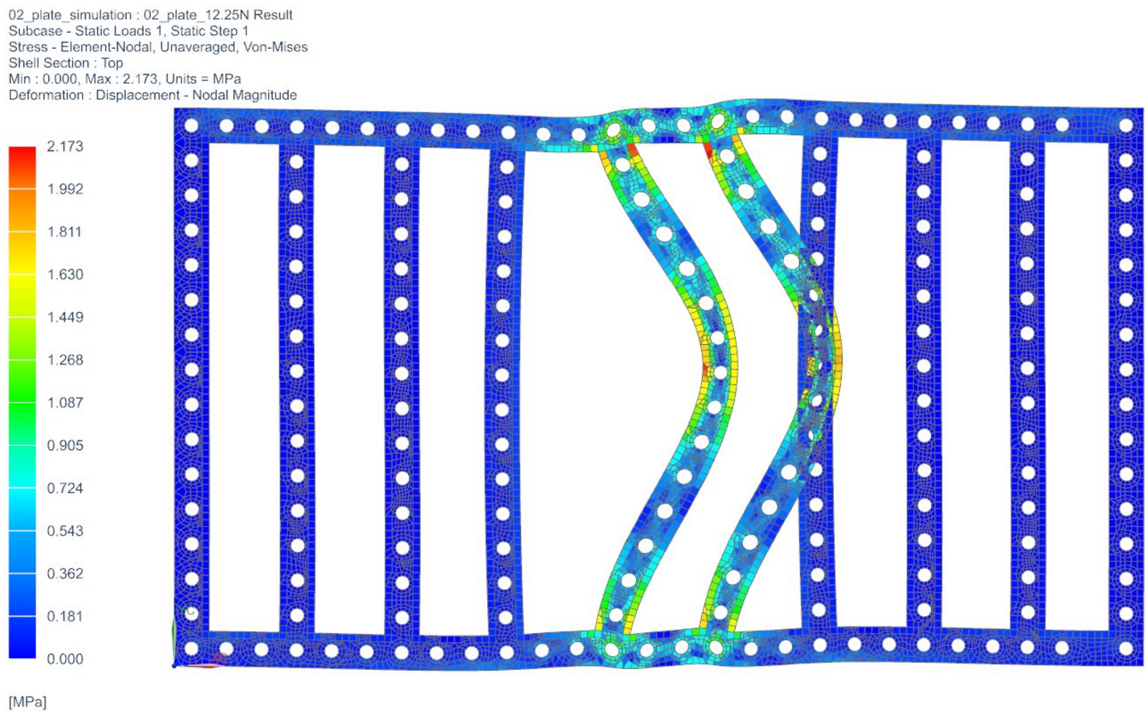


Figure 9. Stress results with 12.25 N load on center rails—plate pinned on the four corners

B. PAYLOAD INTEGRATION

The Bento Box incorporates payloads via modular adapter plates and multiple connectors from the EPS, providing a range of 3.3 to 12V of input power to the payloads. For the flight demonstration in this study, the Bento Box utilizes three payloads: a software-defined radio (SDR) video relay, an electro-optical (EO) sensor, and a light-emitting diode (LED) communications payload that sends messages in morse code. The EPS delivers 12V to the EO sensor and an amplifier for the SDR relay and 5V to the LED payload and an additional amplifier for the SDR. Figure 10 is a block diagram of the Bento Box bus components and integrated payloads.

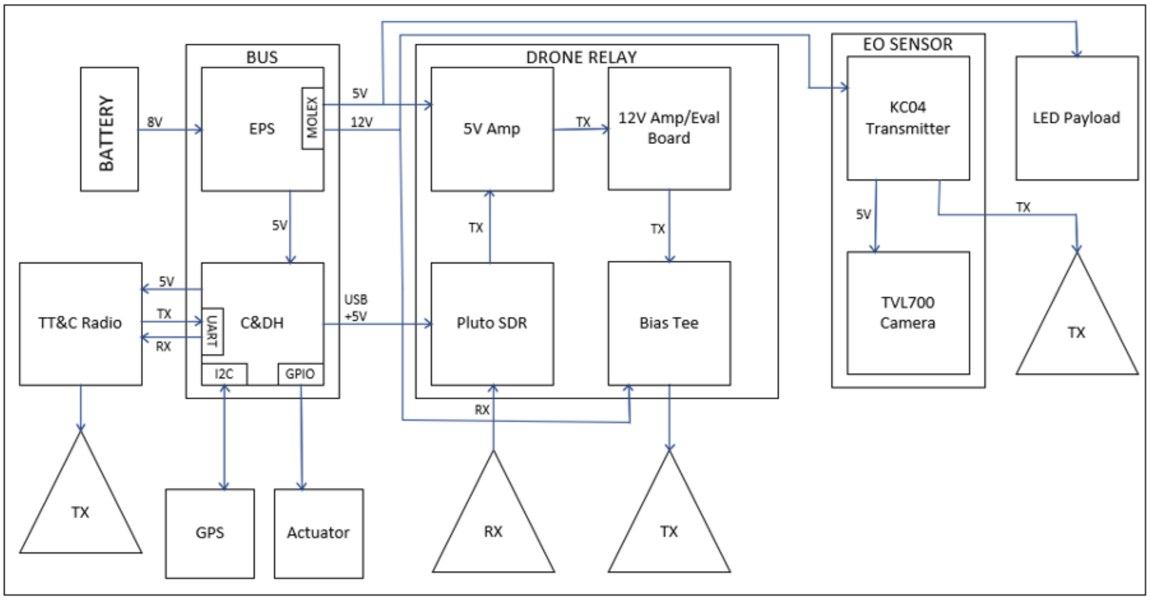


Figure 10. Block diagram: Bento Box with SDR drone relay, electro-optical sensor, and LED payload[85]

1. SDR Relay Payload

Students in the 2021 NPS Space Systems Payload Design course developed and tested the SDR drone relay payload. The relay is comprised of an Adalm Pluto SDR, controlled via Python code from the C&DH, and performs as a "bent-pipe" communications system. The Adalm Pluto is a full duplex SDR by Analog Devices Inc. that supports one transmit and one receive frequency with a measured transmit power of 2.24 mW at an occupied bandwidth of 2.29 MHz when utilizing the analog loopback function. Figure 11 shows the measurement and calculation for the transmit power of the Pluto—the occupied power is measured at -9.40 dBm, but accounting for the equipment attenuation, cable loss, and attenuator raises the actual value to 3.5 dBm. The SDR relay payload utilizes the loopback function to relay video feeds BLOS by switching frequencies and resending the received signal—the signal is not digitized.

[85] Overall design and integration of payloads created and implemented by James Hansen, 2021.

Figure 11. Adalm Pluto transmit power using analog loopback function

Figure 12 shows the first iteration of the SDR relay and an overview of the flight demonstration in March 2021.

Figure 12. SDR relay and overview of flight demonstration from March 2021

While the capability could be utilized to relay various RF signals (voice, data, etc.) in the 5.8 GHz range, the specific purpose of the relay is to backhaul live video feeds from drones utilizing artificial intelligence. The operational relevance of this payload is that it reinforces communications network infrastructure and aids in building situational awareness of a target area for decision makers. The SDR is situated on the second adapter plate of the Bento Box and connects to the C&DH via a USB cable as shown in Figure 13.

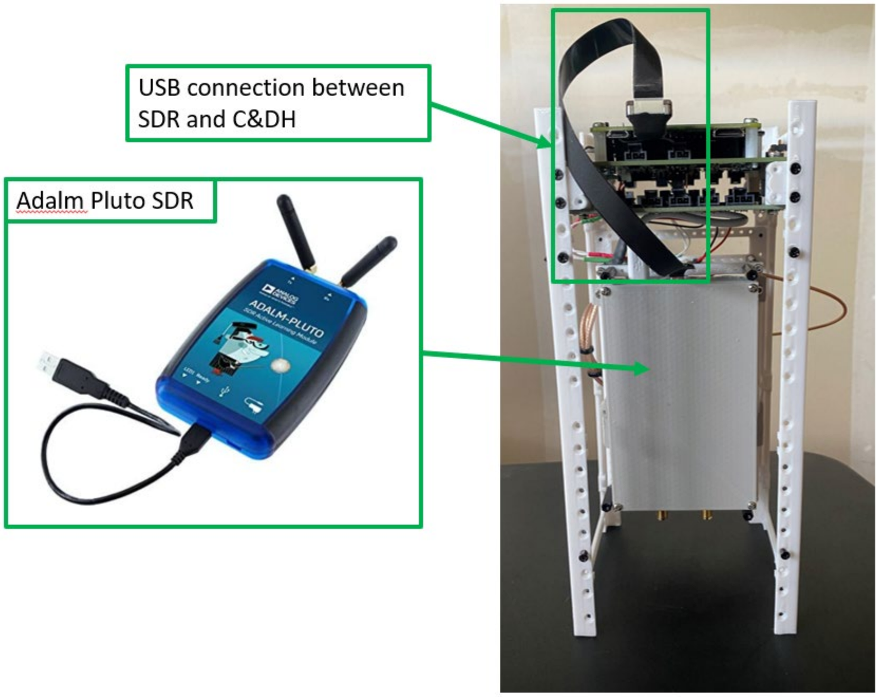


Figure 13. Adalm Pluto SDR placement in Bento Box—RF shielding coats the inside of the poly lactic acid printed case[86]

The first iteration of the drone relay in March 2021 successfully demonstrated link closure and usable video feed BLOS from the signal source. However, link closure intermittently failed due to a combination of weak signal strength and the instability in orientation of the HAB structure caused by the dynamics of a tethered balloon flight. The previous version of the SSAG boards flown for this demonstration only had the ability to power one 5V payload via the EPS, which limited amplifier options. With the anticipation for payloads that need more power, the Bento Box EPS supports payload voltage outputs of 3.3V, 5V, and 12V at maximum currents of 5A, 5A, and 3A, respectively. To amplify transmit power, the Bento Box utilizes an Analog Devices 12V ADPA9002 amplifier on an evaluation board in-line with a ZFBT-4R2G+ Bias Tee (shown in Figure 14) in addition to the 5V amplifier utilized in the March flight. The evaluation board has a maximum

[86] Adalm Pluto case created and printed by LT Mitchell Kempisty in the Naval Postgraduate School Space Systems Payload Design course of instruction.

operating temperature of 85 degrees Celsius[87] and quickly reaches 60 degrees Celsius running at 12V at 5.5 GHz.

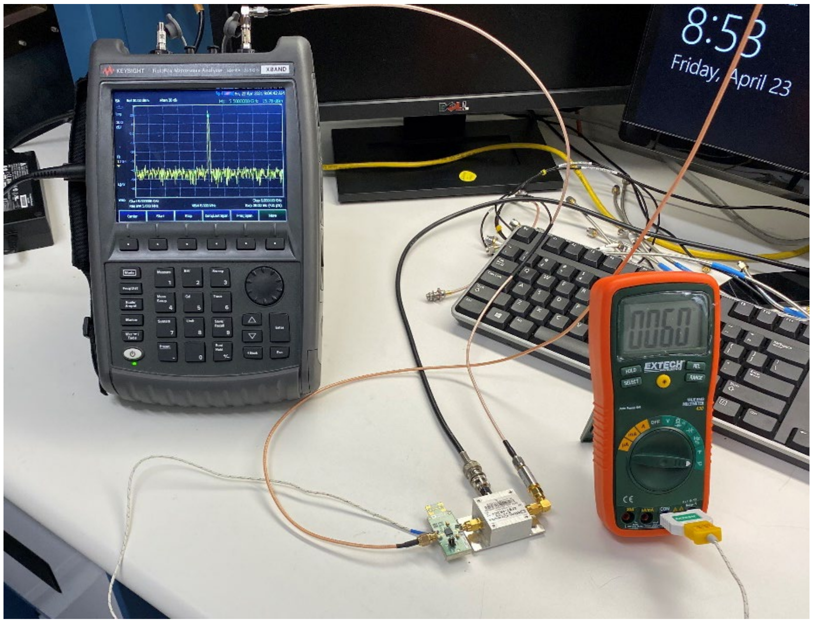


Figure 14. ADPA9002 evaluation board running at 12V and 350 mA reaches 60 degrees Celsius within one minute of operation

The ADPA9002 evaluation board includes a heat sink to dissipate heat but requires additional material contact to ensure conductive heat transfer from the device. A custom case developed in NX and printed with polycarbonate protects the evaluation board and ensures additional heat dissipation. Polycarbonate is thermally stable up to 135 degrees Celsius,[88] making it an acceptable material for housing the evaluation board. Additionally, NASA has approved polycarbonate for general use, and as an insulating material, on

87 "ADPA9002-EVALZ User Guide UG-1637," Analog Devices, October 2019, https://www.analog.com/media/en/technical-documentation/user-guides/ADPA9002-EVALZ-UG-1637.pdf.

88 Omnexus, "Polycarbonate (PC) Plastic: Properties, Uses, & Structure - Guide," Omnexus, 2021, https://omnexus.specialchem.com/selection-guide/polycarbonate-pc-plastic.

spacecraft.[89] Both the custom evaluation board case and standard bias tee case easily attach to the base adapter plate of the Bento Box, as shown in Figure 15.

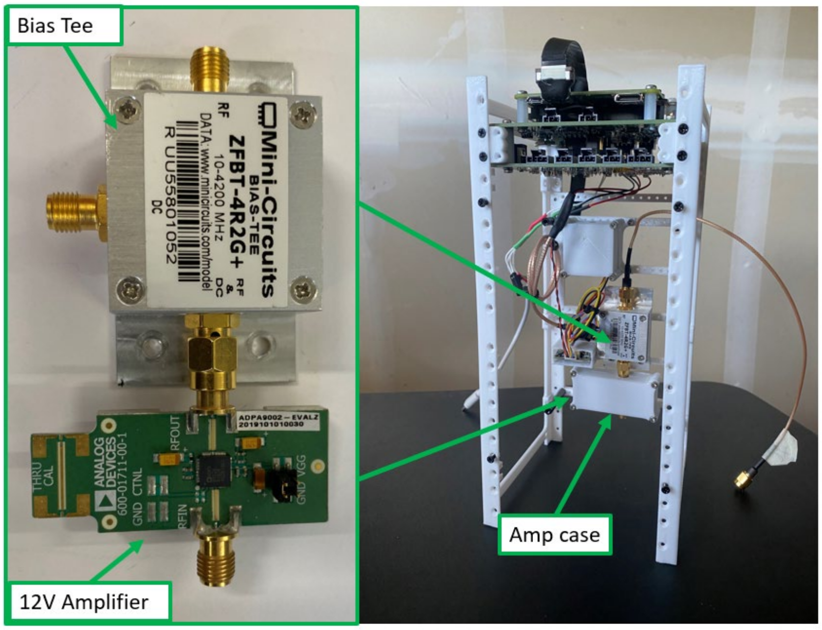


Figure 15. Placement of ADPA9002 amplifier evaluation board and ZFBT-4R2G+ bias tee in the Bento Box

Next, the Mini-Circuits ZX60-83LN-S+ low-noise amplifier (LNA) utilized in the March demonstration further increases the transmission signal. As noted, the transmission power of the Adalm Pluto is only 2.24 mW. However, the combination of the evaluation board, bias tee, and LNA significantly increases the strength of the transmission signal to adequate levels for BLOS video relay (see next section). Spectral analysis of the SDR relay transmission before and after the series of amplifiers and bias tee confirm improved performance of the relay. Figure 16 shows the placement of the 5V LNA in the Bento Box.

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[89] Jeremy T. Knipple, "Outgassing Data for Selecting Spacecraft Materials System," National Aeronautics and Space Administration, March 2017, https://outgassing.nasa.gov/.

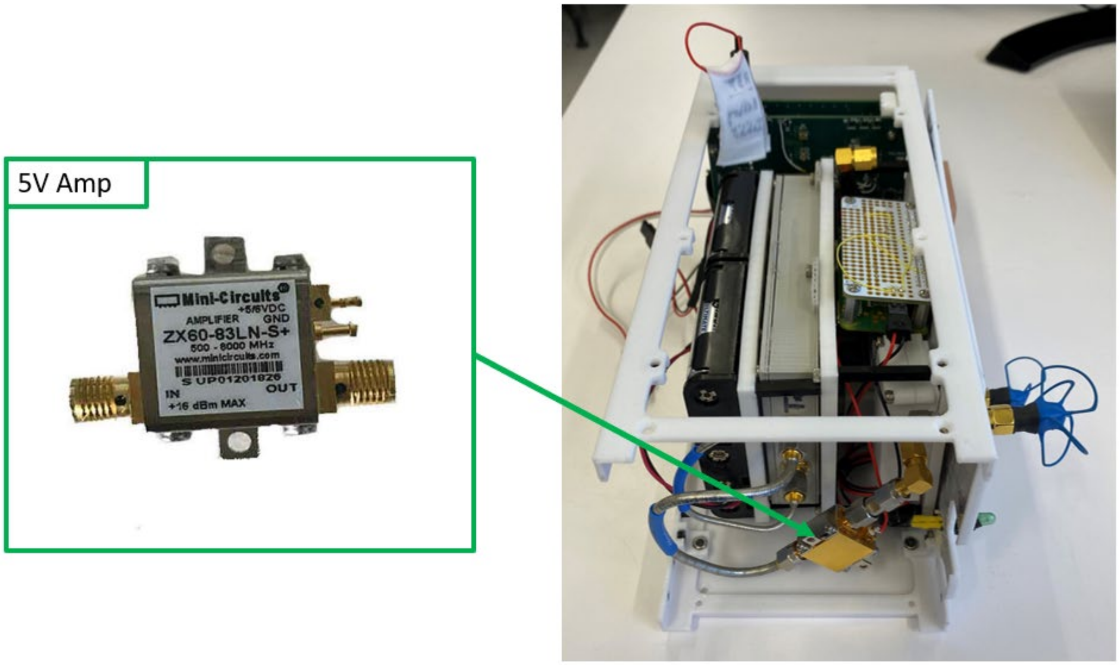


Figure 16. Placement of Mini-Circuits ZX60-83LN-S+ 5V low-noise amplifier in the Bento Box before the 12V amplifier evaluation board

a. SDR Relay Spectral Analysis

Spectral analysis reveals the benefits of the combination of amplifiers and the bias tee. This study utilizes two methods to conduct the spectral analysis of the RF signals associated with the payloads, drone, and plate carrier video transmitter. The first method uses a coax cable directly from the SDR relay amplification system to a microwave spectrum analyzer (Figure 17).

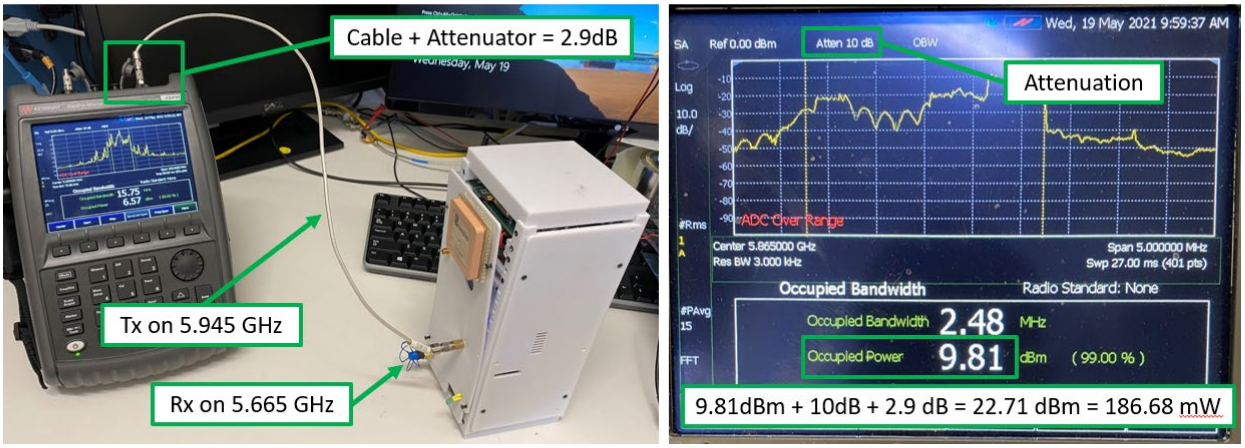


Figure 17. Power spectral density test for SDR relay integrated in Bento Box

The microwave analyzer indicates an occupied power of 22.71 dBm over an occupied bandwidth of 2.48 MHz when relaying a signal via the analog loopback function, which is an increase of 19.2 dB from the measured output without amplification. The second method of spectral analysis uses an additional Adalm Pluto connected to a computer running a Simulink program with the "Communications Support Package for Analog Devices ADALM-Pluto Radio,"[90] which provides a qualitative signal-to-noise ratio (SNR) of the received signal focused on the defined central frequency. Figure 18 shows the setup when utilizing the Pluto as a spectrum analyzer.

[90] "Spectral Analysis with ADALM-PLUTO Radio - MATLAB & Simulink Example," MathWorks, accessed May 3, 2021, https://www.mathworks.com/help/supportpkg/plutoradio/ug/spectral-analysis-with-adalm-pluto-radio.html.

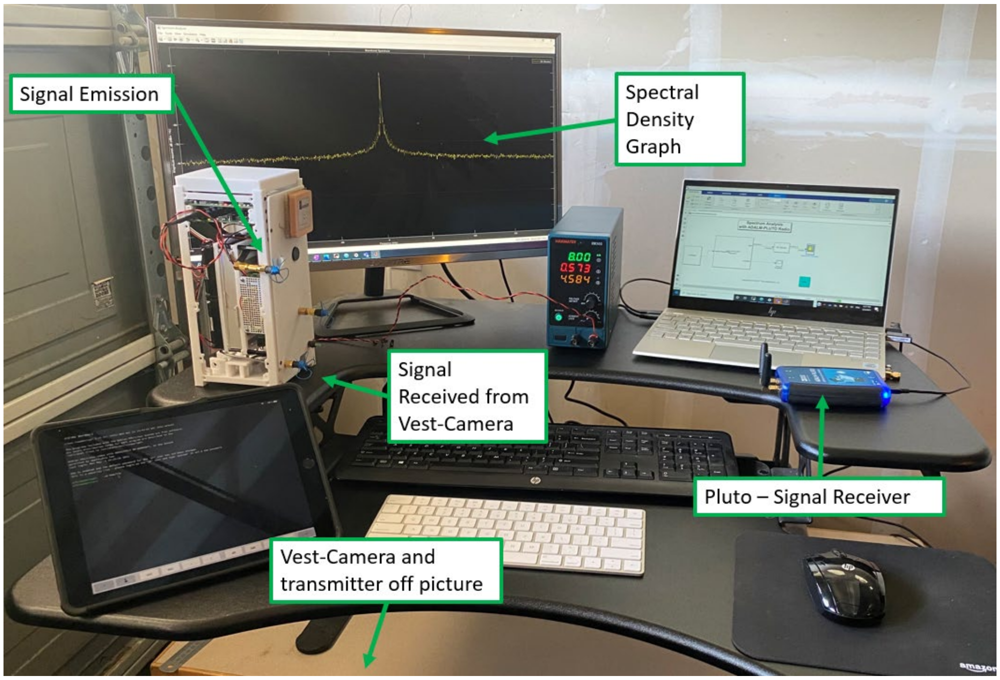
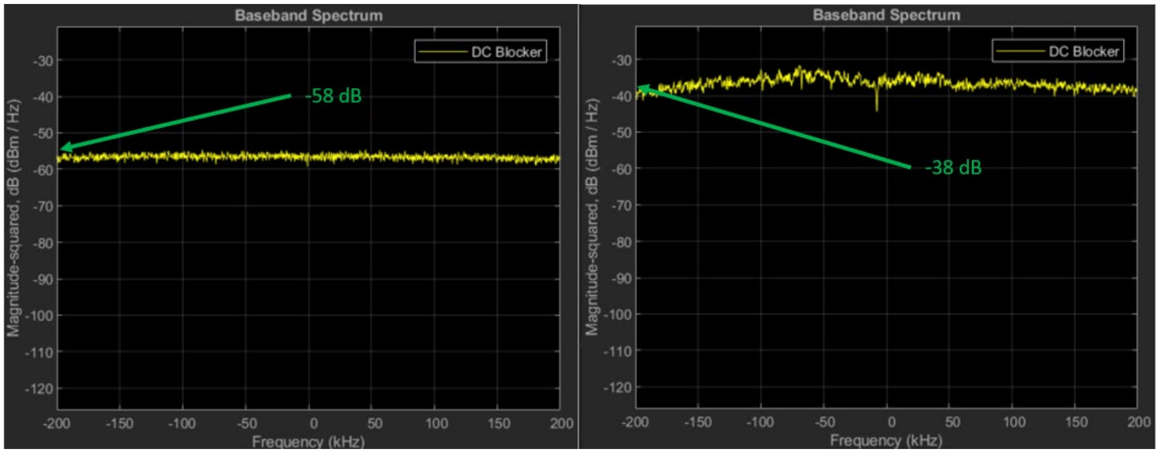


Figure 18. Spectral analysis of the Bento Box utilizing an Adalm Pluto and Simulink

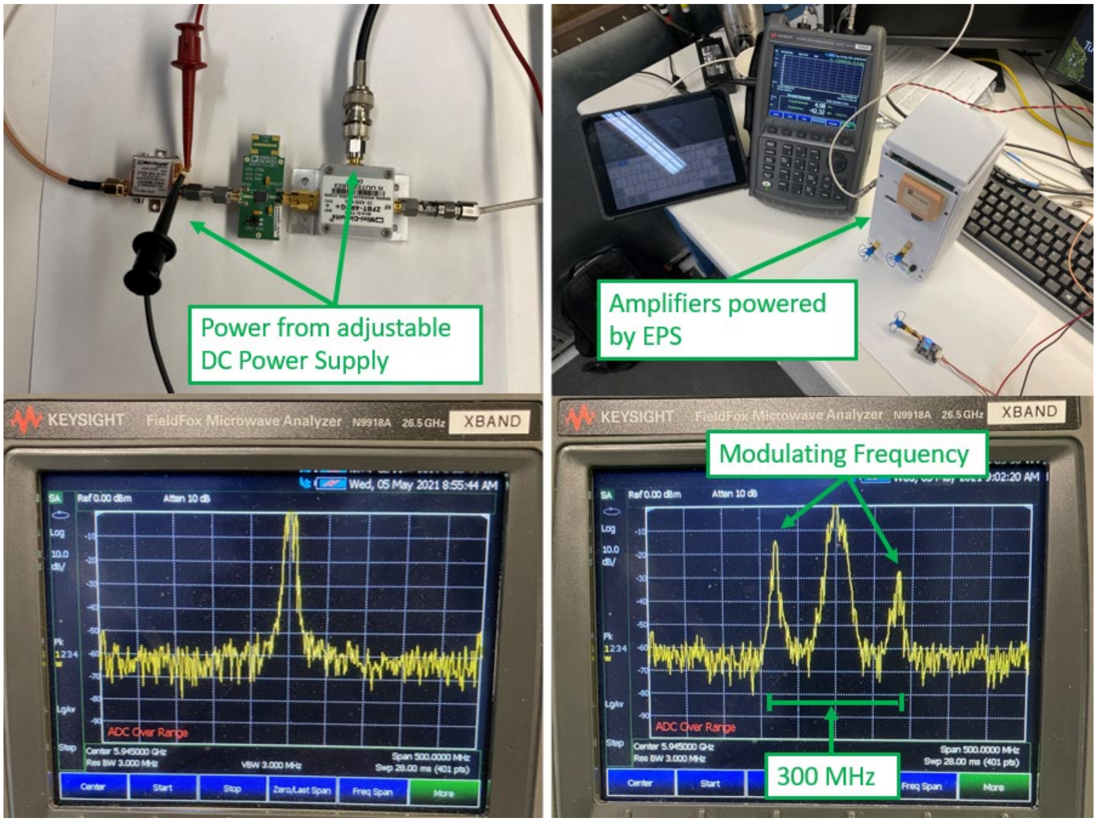
Again, the spectral data of the Pluto transmission without amplification provides data for comparing the performance of the amplification system. For both tests, the Adalm Pluto relayed a video feed from a video source transmitting on 5.745 GHz (channel A7) by retransmitting the signal on 5.945 GHz (channel E8). Figure 19 shows the results from the Pluto spectrum analyzer test. The spectral data indicate roughly 20 dB of gain generated by the series of amplifiers, which is corroborated by the previous test on the microwave analyzer. The assessment confirms both the quality of the amplification system and the use of the Adalm Pluto as a spectrum analyzer. The comparable results from both the microwave analyzer and the Adalm Pluto validated the viability of using a Pluto for the field systems tests in Chapter IV of this study.



Left: Power spectral density of Pluto SDR at 5.945 GHz without amplification. Right: Power spectral density of Pluto SDR at 5.945 GHz with 5V ZX60-83LN-S+ amplifier, 12V ADPA9002 evaluation board, and ZFBT-4R2G+ bias tee.

Figure 19. Spectral density comparison of SDR relay with and without amplification utilizing the Pluto spectral analyzer

Further analysis of the spectral data at a wider span utilizing the microwave analyzer reveals the effects of combining the EO sensor and 12V amplifier evaluation board on the same 12V power jack. Figure 20 shows the comparison of the amplifier system when powered by an adjustable direct current (DC) power supply versus the EPS, which results in significant distortion 150 MHz both above and below the center frequency.



Left: The spectral density of the SDR relay has one peak at a 500 MHz span when the amplification system is powered by an adjustable DC power supply. Right: The spectral density has three peaks when the amplification system is integrated in the Bento Box and powered by the EPS.

Figure 20. EO sensor transmitter modulating on the SDR relay signal

The EO sensor frequency, originally occupying 5.865 GHz, modulates the carrier frequency of the SDR relay and induces a second peak on the upper side-band of the signal. Figure 21 shows the process of a modulating frequency on a carrier frequency.[91]

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[91] Terry E. Smith, *Amplitude Modulation (AM)* (Monterey, CA: Naval Postgraduate School, 2020), 11.

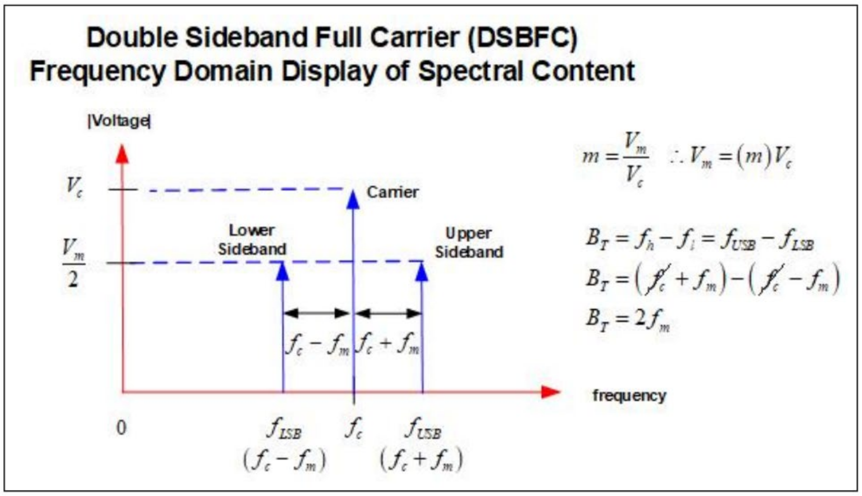

Figure 21. The effects of a modulating frequency on a carrier frequency[92]

Proper frequency allocation can help reduce the interference caused by the distortion, which is the method utilized in the flight test of this study due to time constraints. However, future use of the SDR relay should include reduction of the distortion by either allocating an independent power source for the amplifiers or adding a filter between power cables leading to the EO sensor and amplification system. The magnitude of the EO sensor signal and its proximity to the SDR relay center frequency may preclude filtering and an independent power source may result in a cleaner signal.

b. SDR Relay Link Budget

Utilizing the measured transmit power of the SDR relay, link budget calculations provide the estimated transmit distances of the SDR relay. Analog video signals require a 20 dB SNR at the receiver to reproduce the video feed.[93] First, the thermal noise power is required to establish the SNR at the source of the signal, which is calculated using *Equation 3.1* where P_N is the noise power, k is Boltzmann's constant, T_S is the system temperature, and B_N is the occupied bandwidth:[94]

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[92] Smith, *Amplitude Modulation (AM)*.

[93] Theodore S. Rappaport, *Wireless Communications: Principles and Practice*, 2nd ed. (India: Pearson Education, 1990), 343.

[94] Couch, *Digital & Analog Communication Systems*, 602.

$$P_N = kT_S B_N = \left(1.38 \times 10^{-23} J/_K\right)(290K)(2.48 \times 10^6 Hz) = 9.93 \times 10^{-15} W. \quad 3.1$$

The ratio of the measured occupied power of the SDR relay signal and the thermal noise power yield an SNR of:

$$SNR_{SDR\ relay} = \frac{186.68 \times 10^{-3} W}{9.93 \times 10^{-15} W} = 1.88 \times 10^{13} = 132.7dB. \quad 3.2$$

With a known SNR value at the source of the SDR relay, the link budget can be calculated to find the allowable free space loss L_{FS}.

Table 3. Link budget for the SDR relay

Link Budget	
Component	**Value (dB)**
SNR at source:	132.7
Tx Antenna:	1.4
Rx Antenna:	18
Receiver Cable Loss:	-6
Less the SNR required at receiver:	-20
Allowable L_{FS}	**126.1**

Finally, with an allowable L_{FS} of 126.1 dB (4.07x10^{12} - unitless), the operational distance of the SDR relay can be calculated with algebraic manipulation of the free-space-loss equation after calculating the wavelength of the electromagnetic wave at 5.8 GHz:[95]

$$\lambda f = c \implies \lambda = \frac{c}{f} = \frac{2.998E8\ ^m/_s}{5.8E9/_s} = 0.0517m = 51.7mm, \quad 3.3$$

$$L_{FS} = \left(\frac{4\pi R}{\lambda}\right)^2 \xrightarrow{implies} R = \frac{\lambda\sqrt{L_{FS}}}{4\pi} = \frac{0.0517m\sqrt{4.07 \times 10^{12}}}{4\pi} = 8.30 \times 10^3 m = 8.30km. \quad 3.4$$

95 Couch, 599.

With the amplification system, the expected operational distance of the SDR relay is **8.30km**, which is an acceptable distance for relaying video feeds BLOS for this experiment.

2. EO Sensor Payload

The EO sensor provides an overhead view of the operational area from the HAB. Both the ground force and joint operation center can view the video feed in real-time to maintain situational awareness and build a common operating picture (COP) throughout the duration of the operation. The EO Sensor payload is comprised of an AKK Technology Inc. KC04 transmitter and 700TVL 120-degree lens camera. The camera and transmitter are placed in the Bento Box via custom mounts that double as protective casings—the custom mounts were easily designed given the standardized spacing of mounting points on the adapter plates. The camera is mounted in the Bento Box in a nadir-view position to capture overhead video and imagery of areas of interest, as shown in Figure 22.

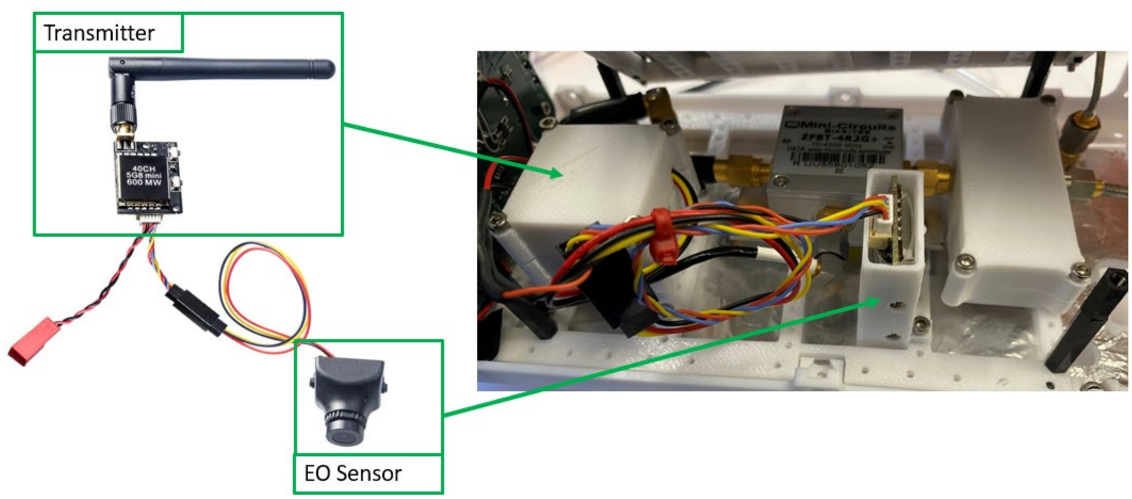
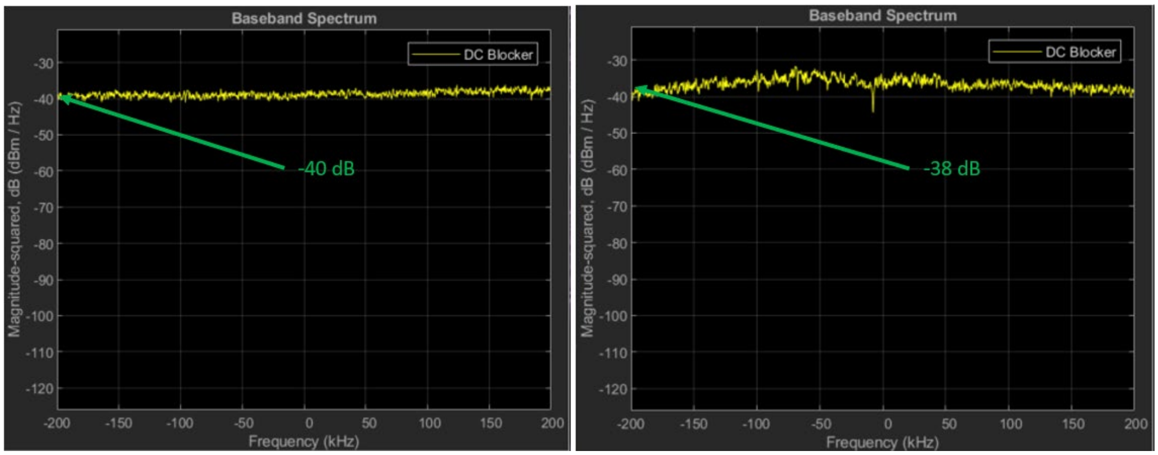


Figure 22. Placement of EO sensor in the Bento Box—cases custom made for the adapter plates

The power spectral density of the EO sensor is similar in amplitude to that of the SDR drone relay, which means the ground user should be able to receive video feeds from both payloads at roughly the same distance away from the HAB. Figure 23 shows a comparison of the RF signals of the EO sensor and SDR relay.



Left: Spectral density of EO sensor. Right: Spectral density of SDR relay with amplification.

Figure 23. Comparison of spectral densities of EO sensor and SDR relay

3. LED Payload

The LED payload is a simple device utilized as a representative payload to demonstrate the ability of the Bento Box and SSAG boards to integrate multiple payloads. The LED payload is comprised of a Raspberry Pi Zero and a Perma-Proto Bonnet that initiates on boot-up to flash serial data in Morse code. The payload is based on an LED communications payload developed by students from the Space Systems Operations curriculum, in summer of 2020, to send environmental data. However, the payload for this study only continuously and repeatedly transmits a simple message (“Bento Box”) because it is not a central focus of this study—its inclusion is merely to demonstrate the Bento Box’s capability of integrating multiple payloads. Figure 24 shows the placement of the LED payload in the Bento Box and the location of the LED on the antenna plate.

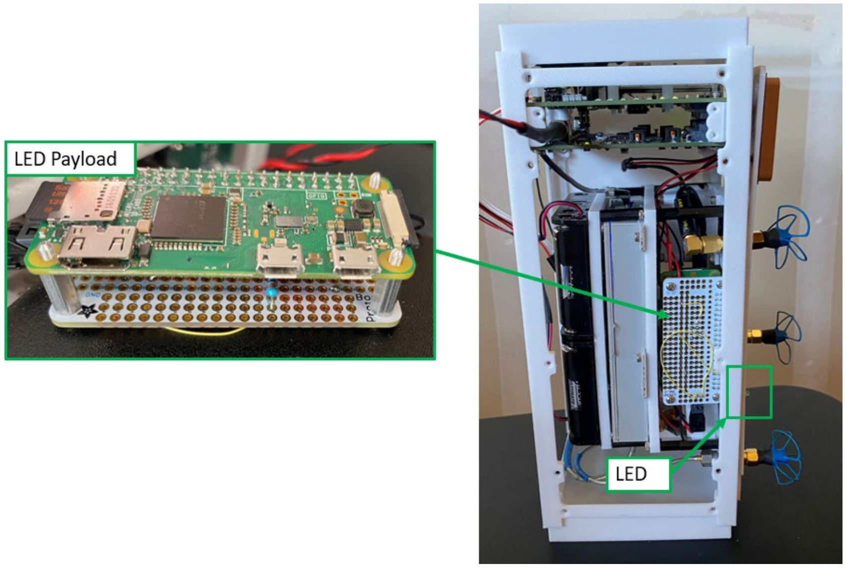


Figure 24. Placement of LED Payload into the Bento Box

C. RF MANAGEMENT

1. Frequency Allocation

The scenario of the flight demonstration requires four different frequencies with adequate separation in the amateur 5.8 GHz frequency range to avoid interference and must also avoid the distortion peaks caused by the EPS system. Analysis of the 5.8 GHz frequency chart created by Michael Niggel[96] (Figure 25) and multiple bench tests revealed the following allocation yielded the best results: drone video feed on E6 (5.905 GHz), on-board EO sensor on A1 (5.865 GHz), plate carrier camera on A3 (5.825 GHz), and downlink from the HAB on E3 (5.665 GHz). Placing the SDR relay transmit signal on the lower end of the amateur frequency range prevented interference from the modulated signal induced by the EO sensor.

[96] Michael Niggel, "Video Frequency Management: Keeping Multiple Quads in the Air," Propwashed, May 1, 2017, https://www.propwashed.com/video-frequency-management/.

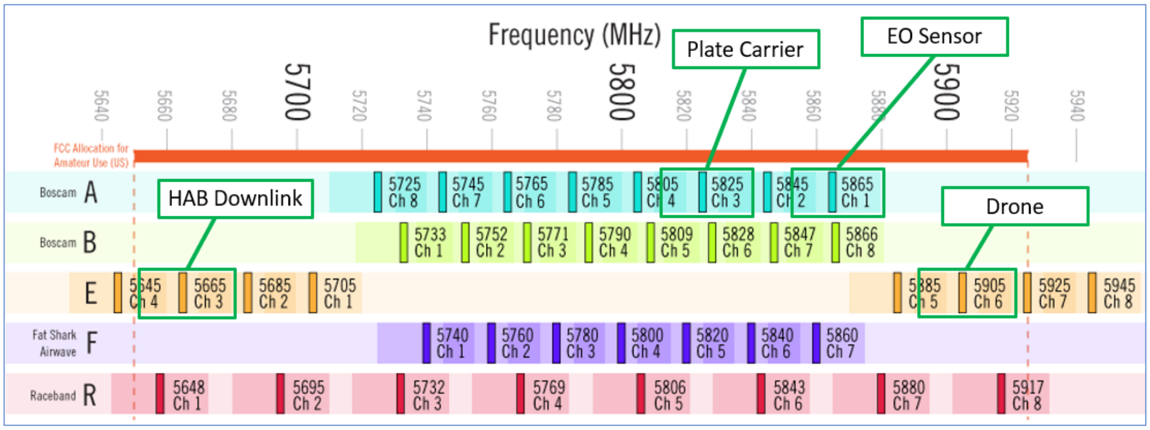


Figure 25. Visual aid of channel frequencies[97]

2. Antenna Placement

Considering that the Bento Box has four antennae, it is important to ensure their propagation will not interfere with each other. For optimal reception and transmission, antennae need to be spaced greater than one-quarter, and not at multiples of, the wavelength of the electromagnetic wave of the carrier frequency. All antennae on the Bento Box are greater than a full wavelength from each other and none reside at a multiple of the wavelength (as calculated in *Equation 3.3)* from another antenna, as shown in Figure 26.

[97] Niggel.

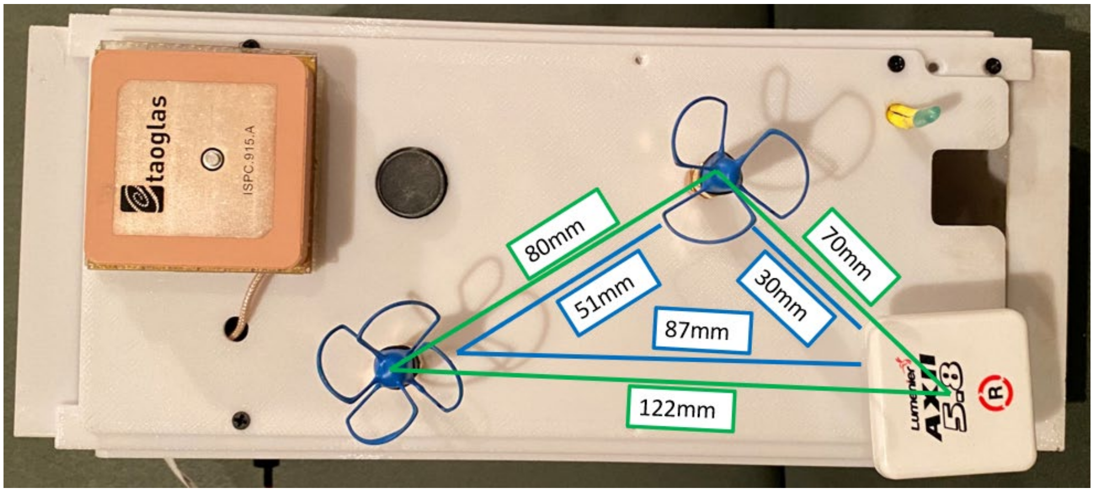


Figure 26. Antenna placement avoids multiples of the wavelength of the carrier frequency

Additionally, the multiple antennae have the potential to add noise to the payload electronics of the Bento Box. Figure 27 shows the layer of aluminum on the back of the antennae cover that helps to isolate the payload and bus components from the electromagnetic transmissions of the antennae.

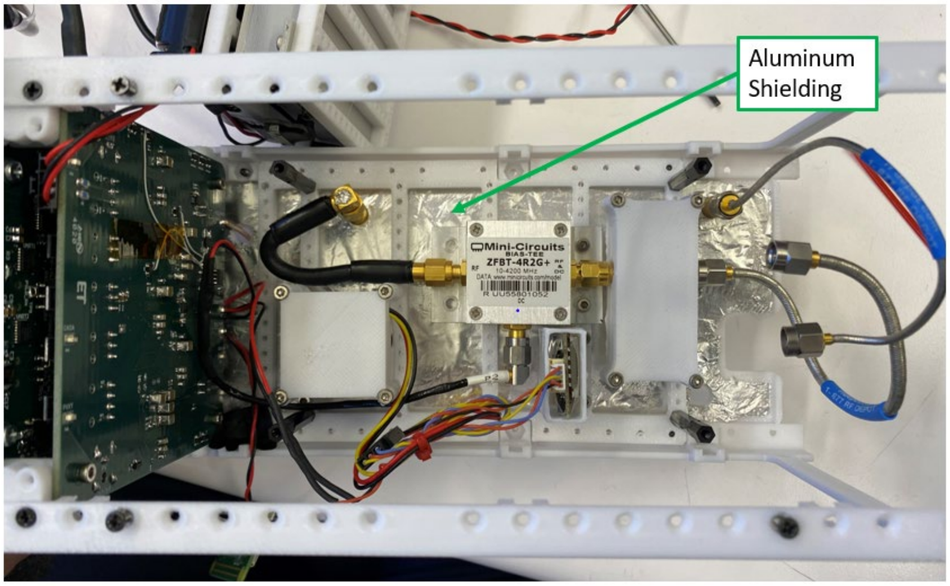


Figure 27. Aluminum shielding between the antennae and the components of the Bento Box

D. CHAPTER CONCLUSION

The modularity created by the adapter plates and multiple payload power sources of various voltages simplified the integration process of the three payloads. The Bento Box design is intended to facilitate quick and simple modifications based on mission-specific payload requirements. Confirmed by finite element analysis, the structural integrity of the adapter plates is adequate to support the forces generated by the masses of the payloads and expected accelerations. Spectral analysis shows that the additional amplification afforded by the increased power capabilities of the new EPS board improves the output signal of the SDR relay. Overall, the design of the Bento Box meets the desired qualities of modularity, simplicity, operational relevance, and structural integrity, and the integrated payloads meet the requirements for demonstrating network reinforcement in SOF operations. The next chapter captures the systems tests and flight validation of the Bento Box.

IV. BENTO BOX VALIDATION

Once all components were integrated and tested individually, the complete structure passed a series of systems tests prior to the flight demonstration on May 6, 2021. The systems tests ensured proper function of the Bento Box, its payloads, and the system architecture of the ground, space, and user mission segments. Following the systems tests, the flight demonstration met all success criteria of the Bento Box and validated the operational relevance of HABs in special operations.

A. SYSTEMS TESTS

The series of systems tests ensured complete functionality of the Bento Box bus and integrated payloads prior to the flight demonstration. There were two levels of systems that required validation: the Bento Box design and the mission architecture. The Bento Box systems tests ensured that the bus and payloads properly interacted to provide power to the payloads on command and that the bus C&DH initiated the drone relay program, with the correct frequencies, as designed. The architecture-level tests ensured that the ground station, Bento Box, drone video feed, and PF video feed were functioning properly.

1. Bento Box System—Payload Commanding

Following each payload integration into the Bento Box, testing confirmed the payload turned on and off via C&DH command and operated as designed. The Raspberry Pi Zero's Wi-Fi feature was utilized to establish a Secure Shell Protocol (SSH) connection, through MobaXterm client, with the C&DH to conduct the initial tests (see APPENDIX B). Utilizing SSH simplified the connection for testing and, more importantly, isolated the Bento Box from the ground segment components for troubleshooting any errors. The systems tests included a series of commands and expected responses from both the C&DH and payloads. Table 4 lists the C&DH commands and testing points during the integrated system-level test of the Bento Box with all three payloads and Table 5 lists the success criteria of the systems test. Validation required that the C&DH responded with the appropriate message listed in Table 4 and that the payload followed the given command as listed in Table 5. Note that the bus software is configured such that commands to turn on the payloads are to “turn off” P0, P1, and P2, which are associated with the 5V, 12V, and 3.3V power jacks on the EPS, respectively. Conversely, turning on P0, P1, and P2 turns off the payloads. P0 (5V) corresponds to the LED payload and MicroCircuit LNA, P1 (12V) corresponds to the EO sensor and 12V amplifier evaluation board, and P2 (3.3V) is not utilized in this experiment.

Table 4. Payload commanding testing procedure—use in combination with Table 5

Payload Commanding Testing Procedure		
C&DH Command	**C&DH Response**	**Action**
cd HAB/lib	pi@raspberrypi:~/HAB/lib $	Change directory to the C&DH library
sudo python PCA9536D.py 0 0	P0 OFF (load is ON)	Turn on 5V Payloads
sudo python PCA9536D.py 1 0	P1 OFF (load is ON)	Turn on 12V Payloads
sudo python PCA9536D.py 2 0	P2 OFF (load is ON)	Turn ON 3.3V Payloads
Perform multimeter tests on 3.3V, 5V, and 12V jacks		
sudo python PCA9536D.py 2 1	P2 ON (load is OFF)	Turn OFF 3.3V Payloads
Perform multimeter test on 3.3V jack		
Perform EO sensor and LED payload tests from Table 4		
cd /home/pi/Payload	pi@raspberrypi:~/Payload $	Change directory to the SDR relay library
sudo python3 Pluto.py #TX #Rx	16 1620668392 3 17 38	Start SDR Payload program and designate frequencies
(repeat as necessary)	17 1620668392 0 2	(Repeating command changes TX and RX frequencies)
Perform SDR relay tests from Table 4		
cd /home/pi/HAB/lib	pi@raspberrypi:~/HAB/lib $	Change directory to the C&DH library
sudo python PCA9536D.py 0 1	P0 ON (load is OFF)	Turn OFF 5V Payloads
sudo python PCA9536D.py 1 1	P1 ON (load is OFF)	Turn OFF 12V Payloads
sudo python PCA9536D.py 2 1	P2 ON (load is OFF)	Turn OFF 3.3V Payloads
Perform multimeter tests on 5V and 12V jacks		

Table 5. Success criteria for Bento Box payload commanding

Success Criteria - Payload Commanding		
Component	**Criteria**	**Method**
C&DH and Payloads	LED Payload on/off	Green light flashes (on) and off when payload turned off
	EO Sensor on/off	Test board on receiver/monitor
		Power received at KC04 transmitter
	SDR on/off and control	Video reception
		Spectral analysis
		C&DH response
EPS	Correct voltage at each jack	Multimeter tests

First, the systems test began by turning on each payload power connection, including cycling the 3.3V power jack to confirm functionality. Figure 28 shows the LED payload response after receiving power when the bus received the P0 OFF command; the payload automatically ran the Python code to flash “Bento Box” in Morse code, as designed. Additionally, the 5V LNA received power, which was confirmed via a reading of 5V on a multimeter.

Figure 28. LED payload confirmed after P0 OFF command

For the EO sensor test, the camera is facing a video test pattern; signal reception of the test pattern on a handheld 5.8 GHz receiver/monitor, as shown in Figure 29, confirmed operation of the EO sensor after sending the “P1 OFF” command, and a reading of 12V on a multimeter connected to the 12V power jack confirmed the EPS functioned as designed. Loss of signal and a reading of 0V at the 12V power jack following the P1 ON command at the end of the test confirmed that the 12V payloads can be toggled on and off.

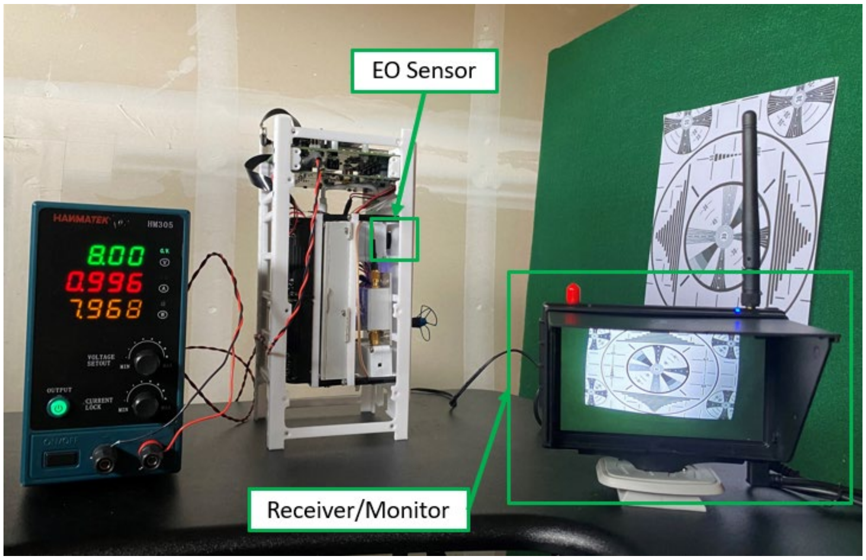
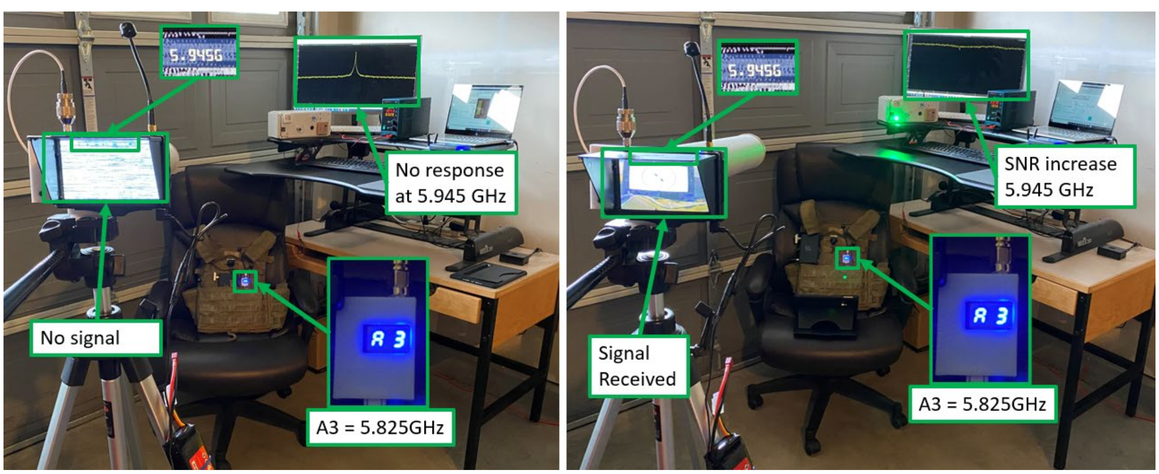


Figure 29. EO sensor confirmed after P1 OFF command

Proper performance of the SDR drone relay was confirmed via all three of the established success criteria: correct response from C&DH, receipt of live video feed on the receiver/monitor at the prescribed RX channel, and spectral analysis of the waveform on the central frequency. Figure 30 shows the setup of the SDR relay systems test—the spectral data is the same as presented earlier in Figure 19.

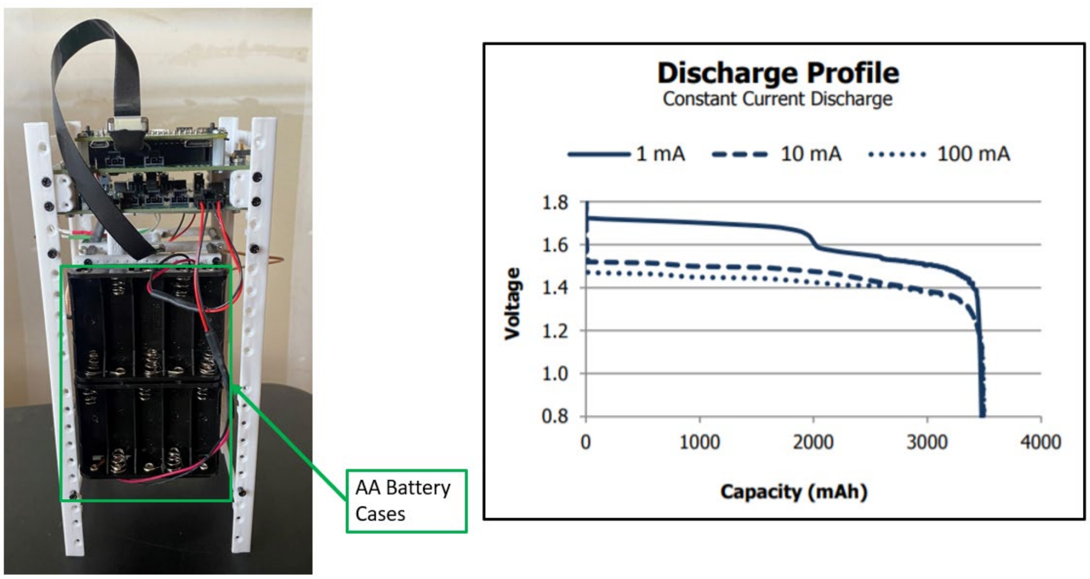


Left: Spectral analysis shows no signal reception at the center frequency of 5.945 GHz before the SDR program is initiated. Right: The SNR increases on the center frequency of 5.945 after the SDR program is initiated—Bento Box receiving plate carrier video feed on 5.825 GHz and transmitting on 5.945 GHz to receiver/monitor.

Figure 30. System test of SDR video relay

a. Integrated Bento Box, Power Budget

The Bento Box is powered by ten 1.6V lithium cells (AA) arranged in 2x5-battery slot holder cases (5S2P configuration). Ten lithium cells are required to meet the voltage and current requirements. The EPS requires an input voltage of 8V—five 1.6V cells in series generates the required 8V. Additionally, placing the battery cases in parallel increases the maximum current to 4A and doubles the Amp-hours of the supply. The ten 1.6V Energizer lithium cells have an advertised capacity of 3.0 Amp-hours at 1.6V, or the equivalent of 4.8 Watt-hours.[98] It follows that the ten lithium cells provide a total of 48 Watt-hours. Figure 31 shows the location of the lithium cell cases in the Bento Box and the discharge profile of the lithium cells. Note that the battery packs are located on an adapter plate and the placement can be modified, if needed.



Left: Location of the 10x1.5V lithium cells—the cells are arranged in 2 cases in parallel that each contain 5 cells in series. Right: Discharge profile of Energizer 1.5V lithium cells.[99]

Figure 31. Power supply location and discharge profile

[98] *Energizer L91 Product Datasheet*, Form No. L91GL1218 (St. Louis, MO: Energizer), accessed May 11, 2021, https://data.energizer.com/PDFs/l91.pdf.

[99] Source: Energizer.

The current of each component of the Bento Box was measured individually via an adjustable DC power supply with current readings as it was added to the structure. Table 6 shows the results, with a total maximum steady state power draw of 15.33 Watts with all payloads running. At a steady state of 15.33 Watts, the lithium cells can power the Bento Box for **3.1 hours**. For this study, the Bento Box needed to function for a minimum of 90 minutes to provide coverage for the PF patrol and to conduct all required in-flight tests; therefore, the battery packs provided 91 minutes of margin for the power requirements.

Table 6. Power budget (measured)

Power Budget			
Component	**Current (A)**	**Voltage (V)**	**Power (W)**
Bus	0.512	5	2.56
ZX60-83LN-S+ LNA	0.186	5	0.93
LED Payload	0.213	5	1.07
Pluto SDR	0.414	5	2.07
EO Sensor	0.34	12	4.08
ADAPA9002 Amp	0.385	12	4.62
Total Power Draw:			**15.33**

2. End-to-End System-Level Testing

The pre-flight mission architecture testing was conducted outdoors at NPS with adequate separation between system components; functional tests were conducted of each mission segment—the ground segment, the "space" segment (Bento Box), and the user segments (drone and PF)—once all systems were on and connected. Figure 32 shows the setup for the end-to-end systems test.

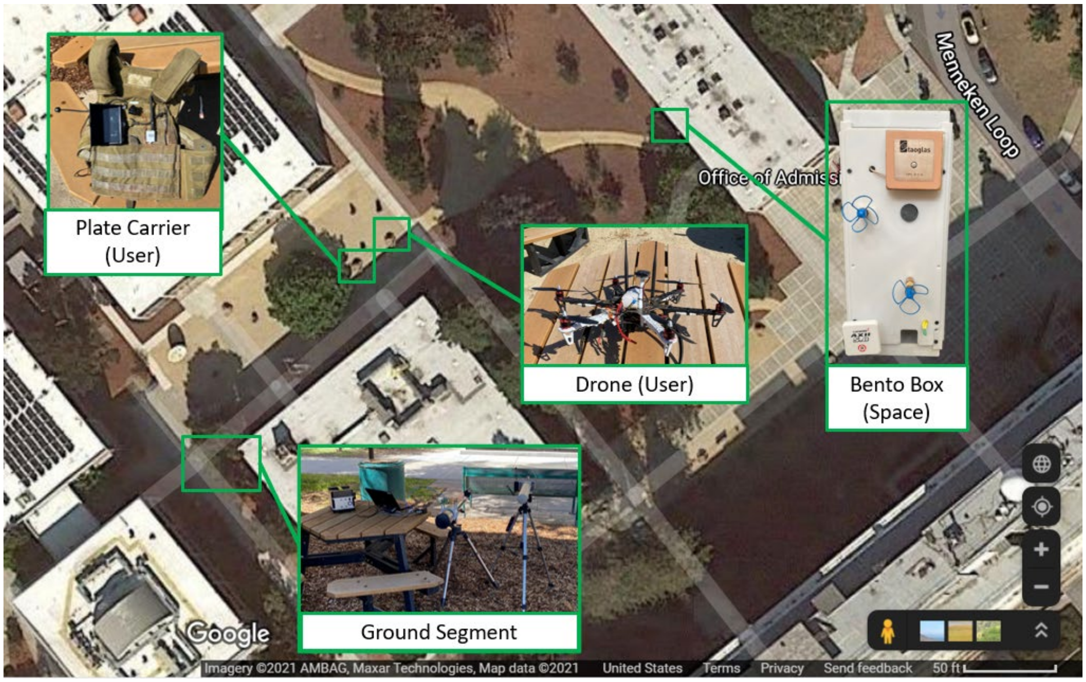


Figure 32. End-to-end systems-level test conducted on NPS campus

The ground segment, shown in Figure 33, consisted of a laptop computer running COSMOS connected to a Microhard Nano n920BD-ENC radio. The Microhard radio transmits TT&C data; COSMOS is open-source software that provides the graphical user interface (GUI) for the telemetry and commands. The ground segment components easily integrate into a mobile system with a power bank, which allowed the ground segment to maneuver to further distances and would also allow movement of USSOF to support the PF—see Section B.2 for the Mobile Ground Segment.

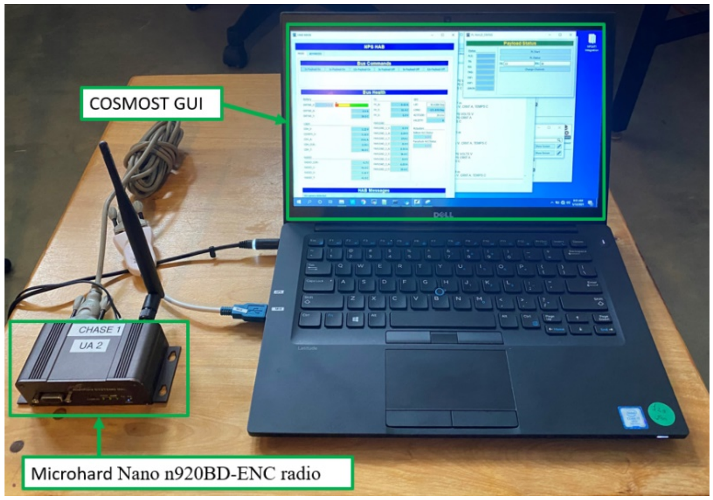
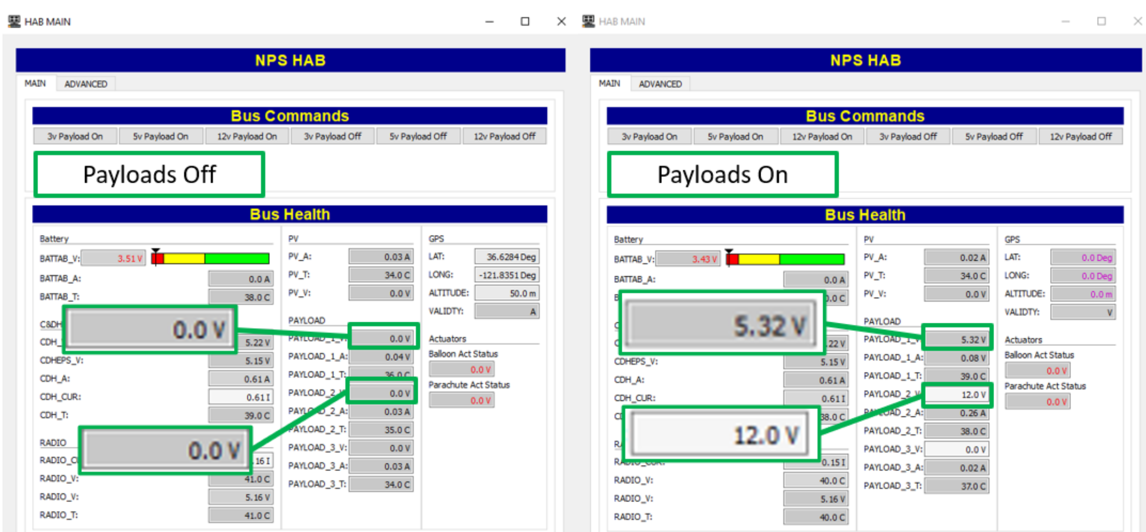


Figure 33. Ground segment

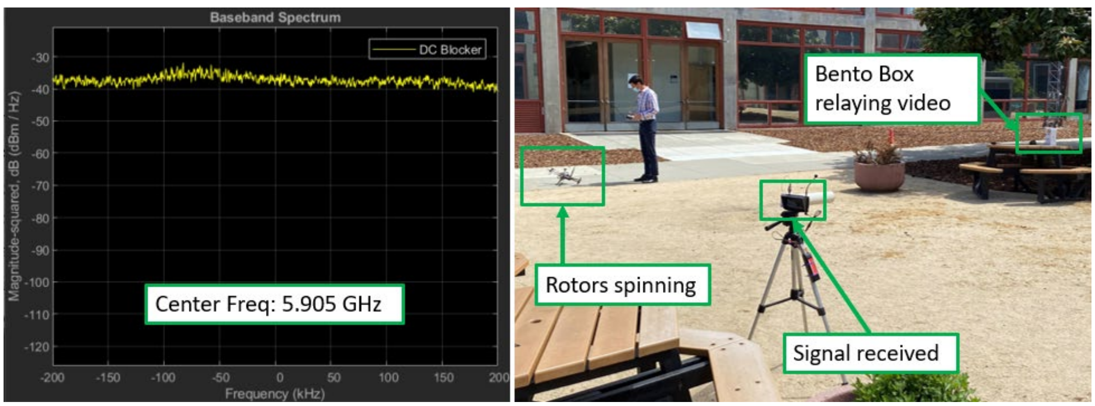
Telemetry reception and proper payload responses confirmed the desired interaction between the ground station and the Bento Box; an example is shown in Figure 34. The COSMOS GUI confirmed the correct payload response through telemetry data that provided the voltage of each payload, pre- and post-command.



Left: Payloads off—voltage at zero for all payloads. Right: Payloads on—voltage at 5V and 12V for the respective payloads.

Figure 34. COSMOS GUI indication of payload response

The aerial asset for the experiment was a hexa-blade drone, developed by Dr. Giovanni Minelli of the SSAG, with a KC04 transmitter and 700TVL 120-degree lens camera. The drone provided defensive coverage of the target area and PF patrol via HAB relay. The end-to-end level functional test between the drone, HAB, and ground station was similar to the test conducted with the plate carrier camera, but also required verification of signal reception while the drone was powered on with rotors spinning to ensure there were no unpredicted disturbances. Spectral analysis of the drone video feed and signal reception, as shown in Figure 35, confirmed functionality of the system between the drone, HAB, and ground station.



Left: Spectral analysis confirms adequate SNR of the relayed drone video feed. Right: Signal received via HAB relay during rotor test of the drone.

Figure 35. Drone signal test with rotors spinning

The final pre-flight end-to-end systems test verified appropriate function of all payloads when commanded by the COSMOS GUI while the Bento Box was running on battery power, representing a flight-like condition. The Bento Box was appraised to be ready for the flight demonstration on a tethered HAB.

B. FLIGHT TEST

The Bento Box team conducted the flight demonstration at the Monterey Bay Academy Airfield near Watsonville, CA, on May 6th, 2021. The purpose of the demonstration was to apply the Bento Box capabilities and HAB support during a representative operation while simultaneously testing the payloads and, more importantly, the C&DH and EPS boards while operating as part of an integrated system. The results of the demonstration indicate value added of high-altitude balloons in SOF operations.

1. Scenario

The scenario at the airfield was a small-scale representation of the overall concept of operation presented earlier in this study. As shown in Figure 36, the HAB was tethered over the target area, rather than free-flying, to provide persistent coverage equivalent to what could be expected from an advanced HAB system with station-keeping capability. The altitude of the tethered balloon was limited to 500 feet due to Federal Aviation Administration (FAA) regulations. Four PF role-players patrolled to the target area with support from the HAB, the drone, and lab support personnel located at the airfield. Both the ground segment (JOC) and user segment (PF) had access to the EO sensor payload and drone video feeds via the HAB. Additionally, the ground segment could switch the SDR relay payload between video footage from the drone and the PF plate carrier camera to receive ground-truth information on the PF status. The LED payload messages were not decoded, but the payload provided a visual indication of system status and demonstrated the ability of the Bento Box to support multiple payloads. The success criteria for this flight demonstration is outlined in Table 7. A secondary objective, once the stationary ground segment met the success criteria, was to gradually increase the distance between the ground segment and the target area to analyze the transmission capability of the SDR relay with the amplification system.

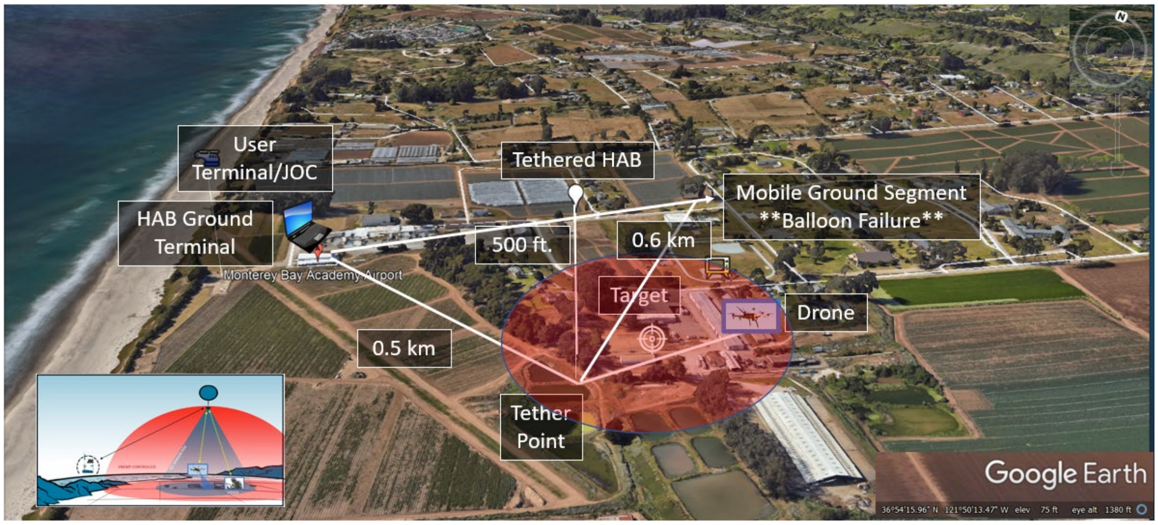


Figure 36. Flight demonstration geometry

Table 7. Success criteria of the flight demonstration

Success Criteria - Flight Demonstration		
Mission Segment	**Criteria**	**Method**
Ground	Receive BB telemetry	Telemetry Data Confirmed
	Receive SDR video feed	Video feed on monitor/spectral analysis shows positive SNR
	Receive EO sensor feed	Video Feed on Monitor
	Send payload on/off commands	Payload Power Telemetry/Payload response
	Change TX frequency of BB	Video feed changes from drone to plate carrier camera
Space	Sends Telemtry	Receipt at Ground Segment
	SDR converts TX/RX frequencies to relay video feeds	Video feed changes from drone to plate carrier camera
	EO sensor sends video feed	Ground and User Segments receive video feed
	LED functions on command	Green LED flashes after "5V Payload On" command
User	PF receives EO sensor and drone video feeds	Video feed on monitor
	Drone transmits video feed to HAB	Receipt at Ground Segment
	Plate carrier transmits video feed to HAB	Receipt at Ground Segment

The scenario began after the HAB reached approximately 482 ft in altitude, with the PF patrolling toward the target area. The PF did not have an operational objective and conducted the movement strictly to demonstrate the capabilities of the Bento Box. Figure 37 shows the HAB at altitude with a PF member, fitted with a plate carrier camera, preparing to start the patrol.

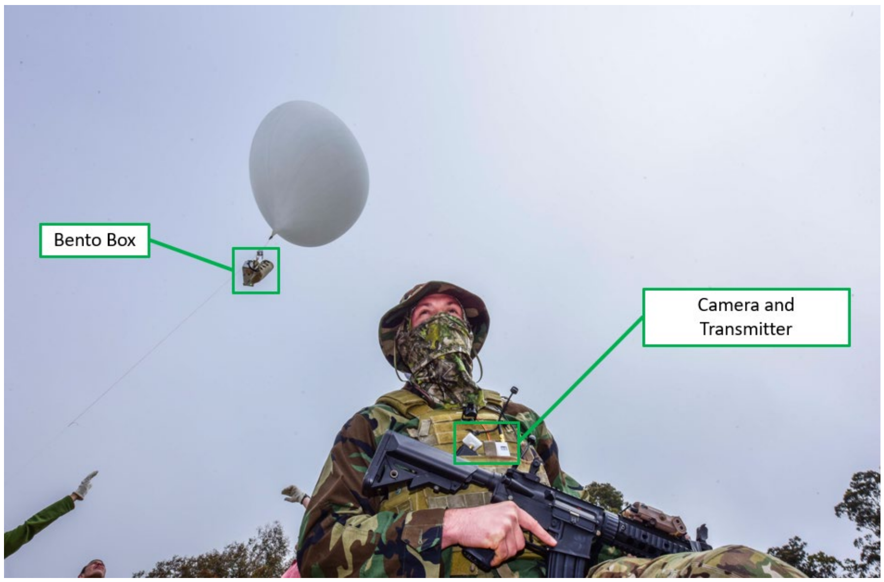


Figure 37. Launch of HAB—Partner Force preparing to start patrol

Throughout the PF patrol, the drone and HAB provided real-time video coverage of the target area to the PF (user) and the JOC (ground). The PF received the video feed via a receiver/monitor attached to the same plate carrier equipped with the transmitter and camera. Figure 38 shows the drone supporting the PF movement while the PF receives target updates in the form of video feeds via the plate-carrier-attached receiver/monitor.

Figure 38. Drone supporting Partner Force—PF receiving video feed from drone and HAB EO sensor

The ground segment, shown in Figure 39, was initially located 0.5 kilometers from the target area with the intent to increase distance once the success criteria was met. Although only half a kilometer away, the target area was beyond line-of-sight from the ground segment due to building structures, small hills, and a forested area.

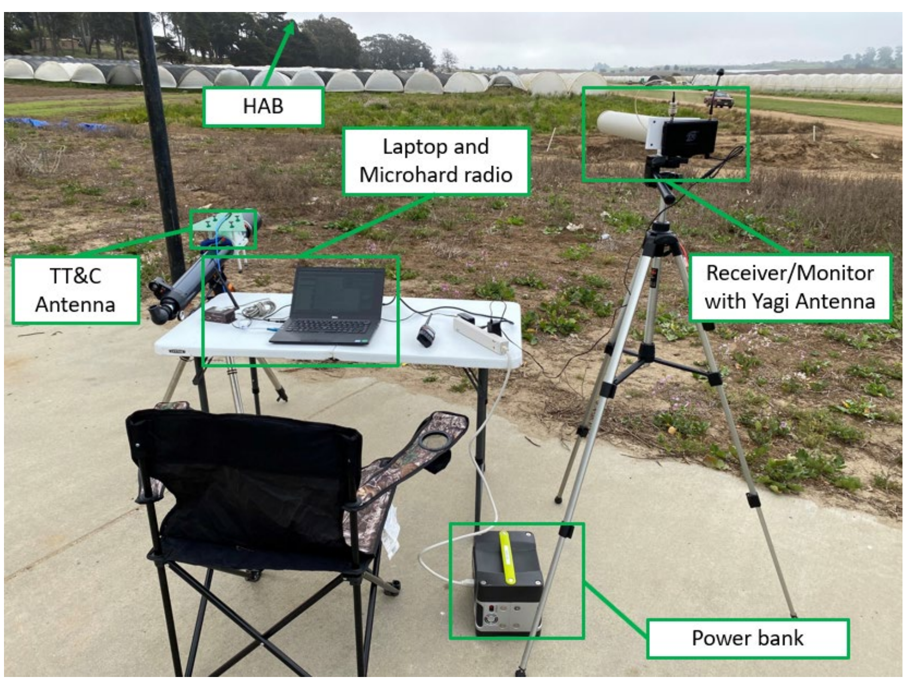


Figure 39. Ground segment located at Monterey Bay Academy Airport

2. Results

The Bento Box met all success criteria during the flight demonstration and validated the application of HABs in SOF operations by enabling a remote advise/assist operation of a PF. The Bento Box could be used in the same manner to enable USSOF during direct-action mission-sets in both land and maritime environments. The SDR relay showed improved performance as compared to the flight in March; with the addition of the 12V amplifier and an omnidirectional transmit antenna on the SDR relay, the relayed drone video feed remained constant throughout the experiment and was not affected by movements of the HAB and Bento Box. Both the JOC (ground) and PF (user) successfully received the video feed from the EO sensor payload, and the JOC was able to switch between viewing the drone and the plate carrier camera by remotely reprogramming the SDR relay payload. The EO sensor turned on and off on command and transmitted video of the target area. The LED payload functioned as designed, flashing after receiving the "5V Payload On" command and ceasing upon the "5V Payload Off" command.

The ground segment received telemetry data from the Bento Box throughout the duration of the demonstration and was able to send commands to control power to the payloads and change parameters of the SDR relay payload. Figure 40 shows the ground segment telemetry feed, Figure 41 shows SDR payload control with frequency change, and Figure 42 shows the COSMOS GUI with payload commands and telemetry data.

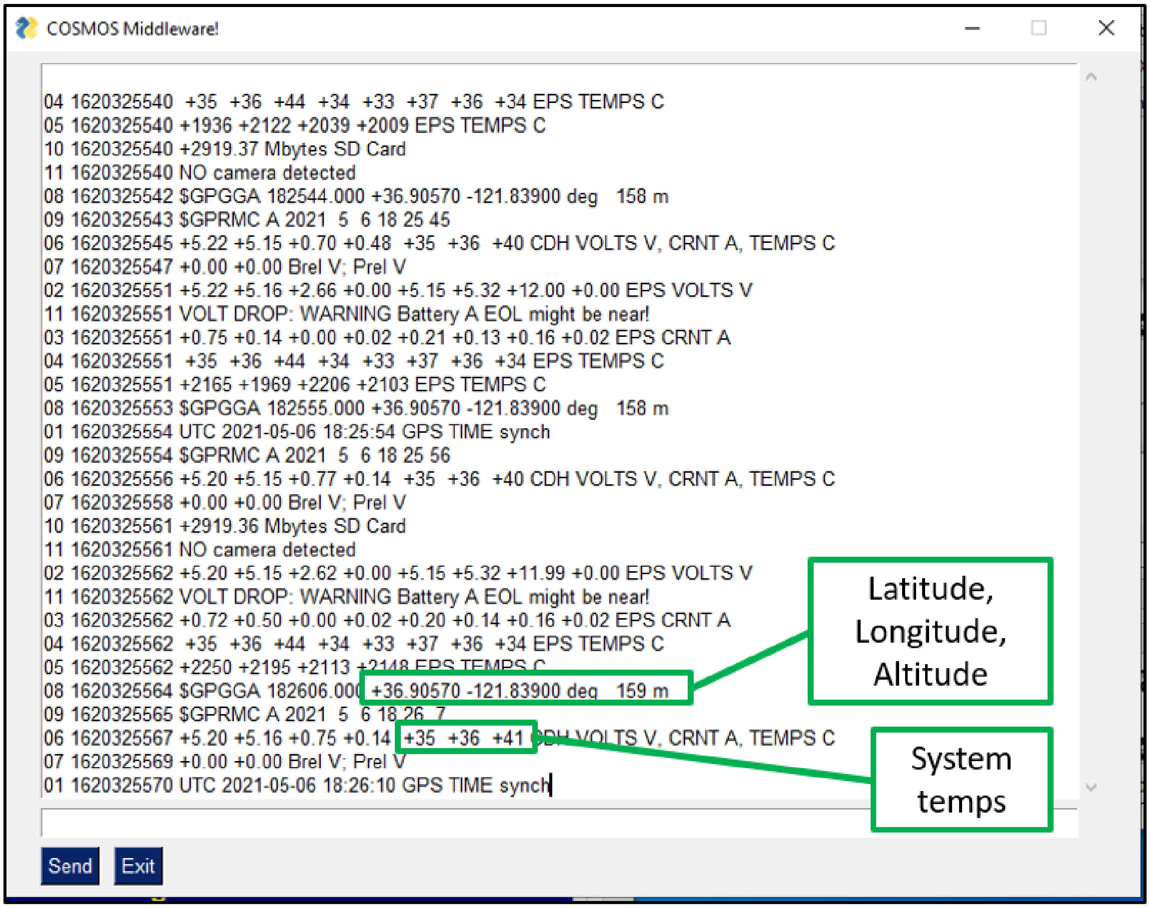


Figure 40. Telemetry data feed received at ground segment

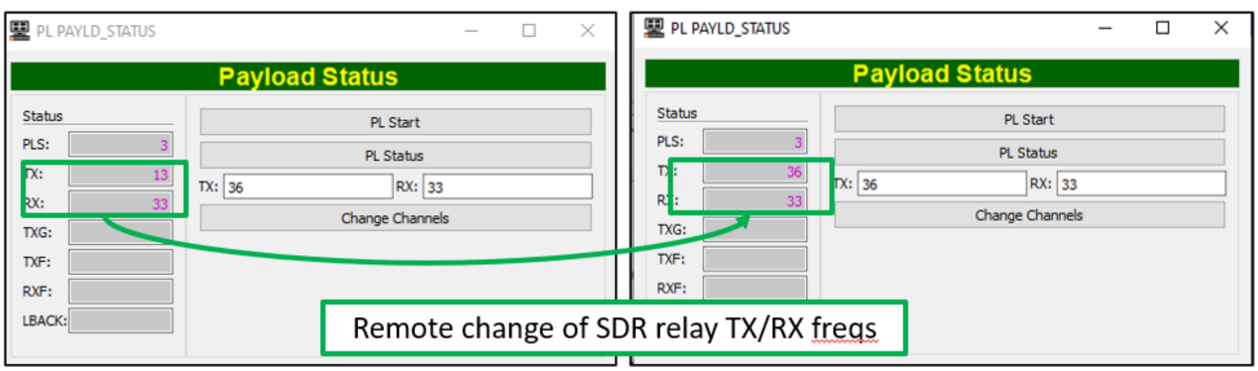


Figure 41. Payload command to change SDR relay frequencies

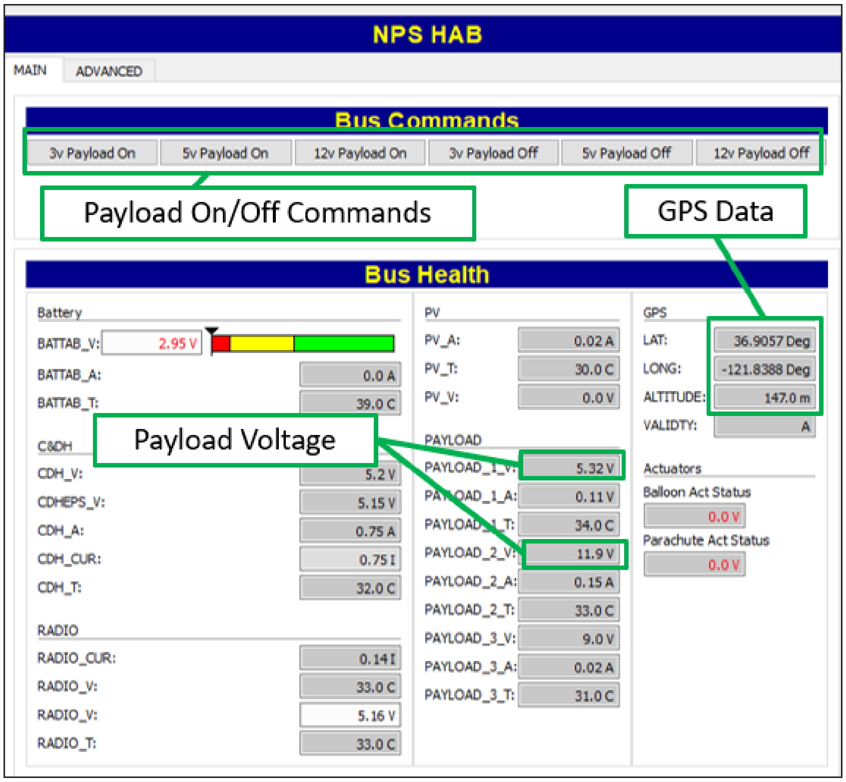


Figure 42. COSMOS GUI with payload commands, telemetry data, and payload voltage status

Sample images from the video feeds are presented to provide requirements verification evidence and are an example of the potential Bento Box capabilities that are applicable in SOF and remote advise/assist operations. The video feeds are not high quality but are on par with what is to be expected from low-cost, commercial off-the-shelf (COTS) video equipment. Military applications would require cameras with higher resolutions, but were not required for the purposes of this study. As shown in Figure 43, the Bento Box successfully relayed the video feed from the drone back to the JOC. The image of the PF patrol is taken from the video feed at the ground segment, received via HAB from the support drone.

Figure 43. Drone feed of the PF on patrol—relayed through the HAB to the ground segment

The EO sensor on the Bento Box transmitted real-time overhead video of the target area to the ground and user segments as designed. The PF was able to use the video feed to assess its position and the target area. Figure 44 is an image of the EO sensor video feed received at the ground segment. The combination of the relayed drone video and the EO sensor built a common operating picture of the target area and the PF status that improved the ability of the advisors at the JOC to assist the PF. Recall that the intent is to place the Bento Box on an advanced HAB that can maintain position for months at a time, offering persistent coverage of an area of interest.

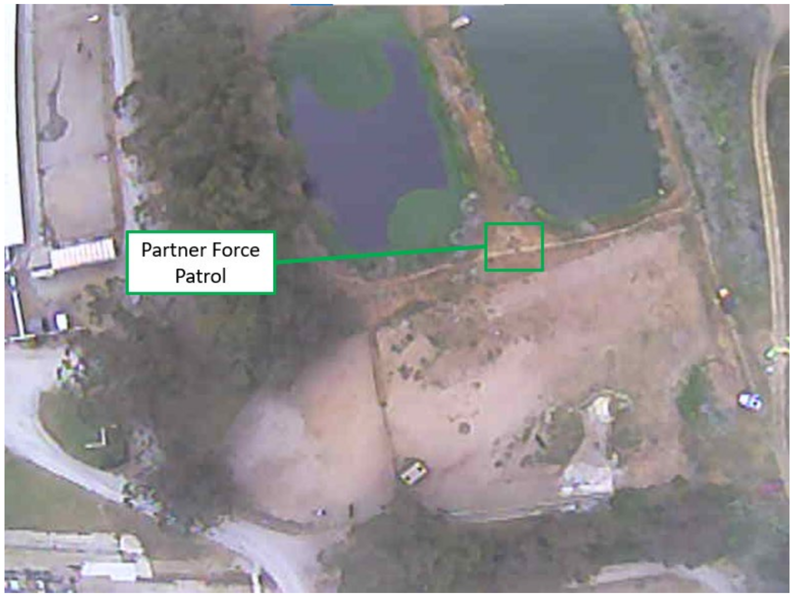
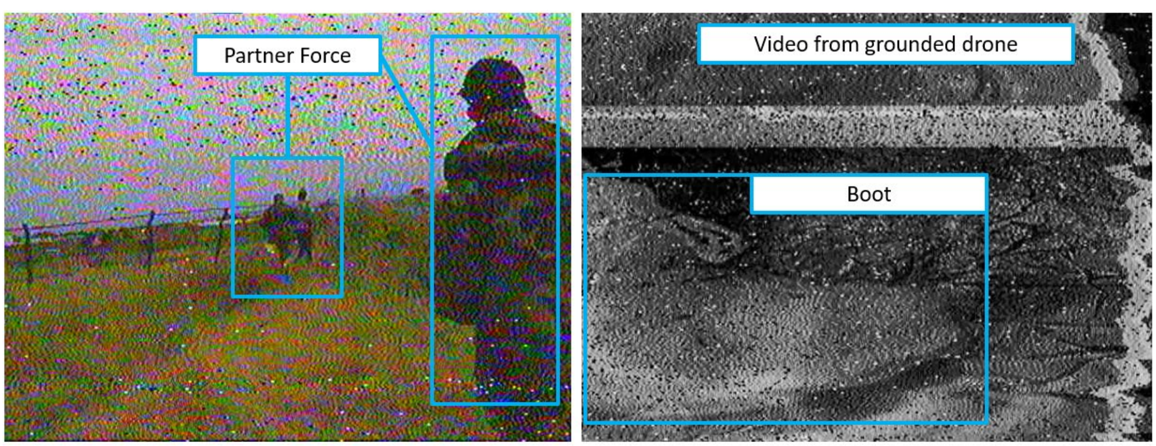


Figure 44. Overhead view of target area from EO sensor

After reviewing the video feeds of the EO sensor and drone via SDR relay, the ground segment remotely changed the frequencies of the SDR relay to receive the video feed of the PF plate carrier camera. The received video was grainy due to interference from the drone transmission, as could be seen from intermittent video from the drone feed transposed over the plate carrier video feed in Figure 45.



Left: Video from plate carrier camera relayed through the Bento Box. Right: The plate carrier camera feed was intermittently disrupted by drone video feed.

Figure 45. Plate carrier camera relayed through Bento Box

Following confirmation of success criteria at the stationary ground segment, a mobile ground segment increased distance from the target area to test the transmission limits of the SDR relay. Figure 46 shows the mobile ground segment in the back of a utility vehicle. The quality of received video signal remained consistent during transit away from the target area; however, the mobile ground segment only increased distance to 0.6 kilometers when the HAB experienced a malfunction and began to lose altitude, leading to immediate termination of the demonstration.

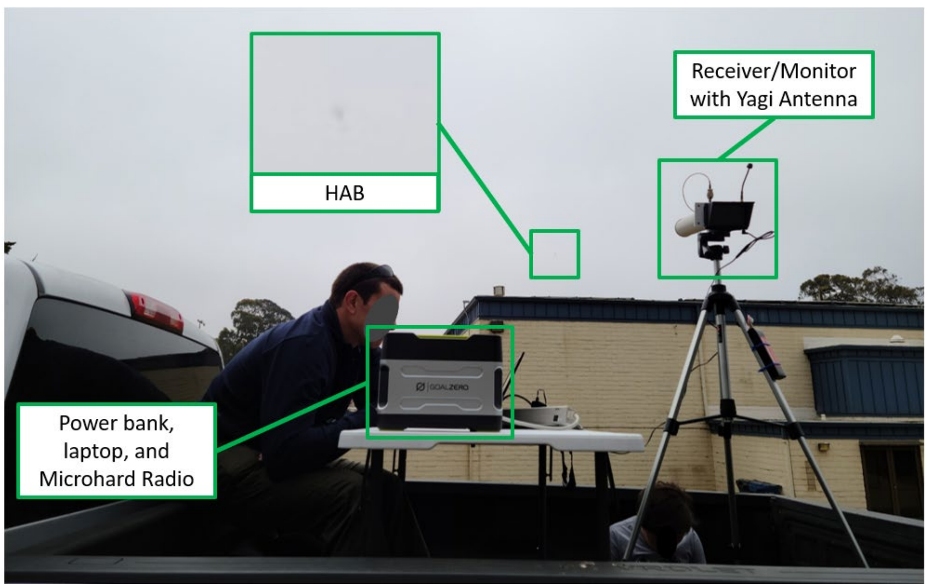


Figure 46. Mobile ground segment

C. CHAPTER CONCLUSION

Overall, the systems tests and final demonstration of the Bento Box was successful. The payload command systems test demonstrated proper function of the payloads, the EPS, and the C&DH, while the end-to-end systems test passed all success criteria for each mission segment. Although the demonstration ended early, all success criteria was met, and the SDR relay showed improvement in transmission distance, video quality, and consistency when compared to that of the March demonstration. Finally, the flight demonstration highlighted the operational relevance of the Bento Box and HABs, writ large. The successful tethered flight indicates that the Bento Box is ready for a free-flying HAB demonstration.

V. CONCLUSION

The U.S. military is highly dependent on space-based systems for coordination and security; the small element size of special operations forces (SOF) units further increases that dependence, especially in remote locations. The increase in antisatellite (ASAT) weapons testing and development in the 21st century and their potential use in future conflict increases the risk to U.S. orbital assets and, by extension, the United States at large. The increasing amount of orbital debris further compromises the safety of U.S. space systems. With a lack of international agreements preventing or regulating ASAT development, the U.S. military needs redundancy in space-based capabilities, which can be achieved through increasing alliances in space networks, diversifying current assets by utilizing commercial programs and smaller/cheaper satellites, and utilizing alternative methods of asset employment. HABs offer a unique, alternative solution to satellite infrastructure and can be used to place mission-specific payloads in the operational high ground to enable SOF operations for extended periods of time.

The research for this study included the development of a modular HAB structure to demonstrate and improve the effectiveness of HABs in special operations. Three payloads successfully flew on the Bento Box with various power and data requirements, which attached via a set of adapter plates designed for a standard CubeSat rail interface, demonstrating that the Bento Box achieves modularity and simplicity of integration. Finite element analysis confirmed the stability of the structure, and spectral analysis confirmed the performance of the SDR payload. The final validation of the Bento Box for this study was a flight demonstration that met all success criteria and creates a foundation for further research on the use of the Bento Box and HABs in special operations.

A. RECOMMENDATION FOR FUTURE WORK

In this study, the Bento Box demonstrated the ability to carry multiple payloads. The next step is to increase the performance of the Bento Box so that it can support more advanced payloads. For example, incorporating a chip-scale atomic clock (CSAC) would increase precision timing of the system and enable investigation of this system as a viable asset in alternative PNT applications.

For the SDR payload, the analog loop-back method of relaying the video feed is beneficial in its simplicity, but a version that digitizes the data would improve the performance because it would increase the link margin by filtering out noise in the on-board demodulation process. Additionally, an SDR with the ability to run multiple RF inputs and outputs would increase the operational suitability of the BLOS relay payload—it would be able to relay voice and video feeds simultaneously. The Analog Devices ADRV9361 is a higher-quality version of the Adalm Pluto SDR that can run four receive/transmit frequencies simultaneously, meaning a unit could receive three relayed feeds concurrently and still have a channel dedicated to voice communications.

Further research is required to identify how to optimize the RF signals when multiple sources require the same voltage in the Bento Box, like those of the EO sensor and SDR relay amplification system. An independent power source should improve the signal from the SDR. The recommended configuration with an independent power source, which was not used for this study, is shown in Figure 47.

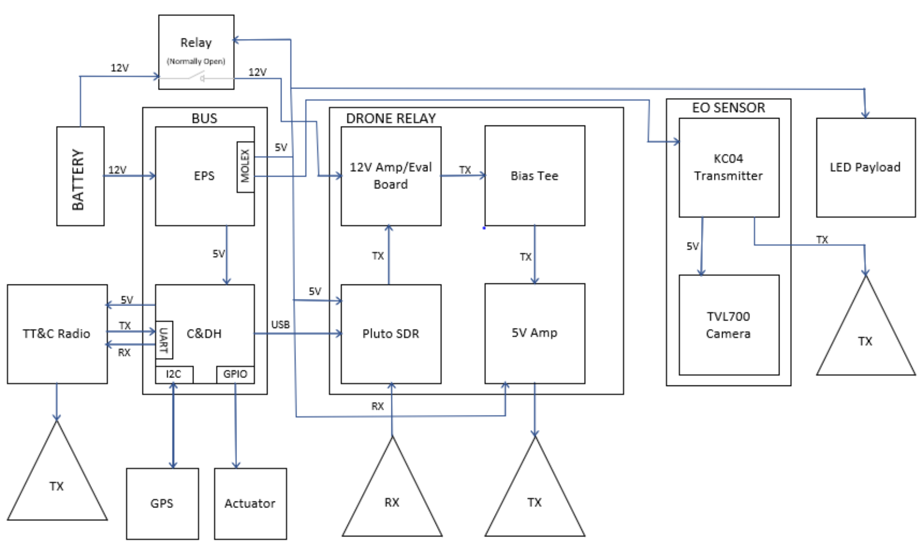


Figure 47. Bock diagram of using a relay to give the 12V amplifier an independent power source (not used for this study)

To increase the viability of the Bento Box for operational use requires improvement in the power source. In this study, the Bento Box utilized single-use AA 1.6V lithium cells, but the asset would benefit from a rechargeable, higher-capacity battery and photovoltaic cells. The photovoltaic cells, combined with the rechargeable battery, would increase the operation time of the Bento Box.

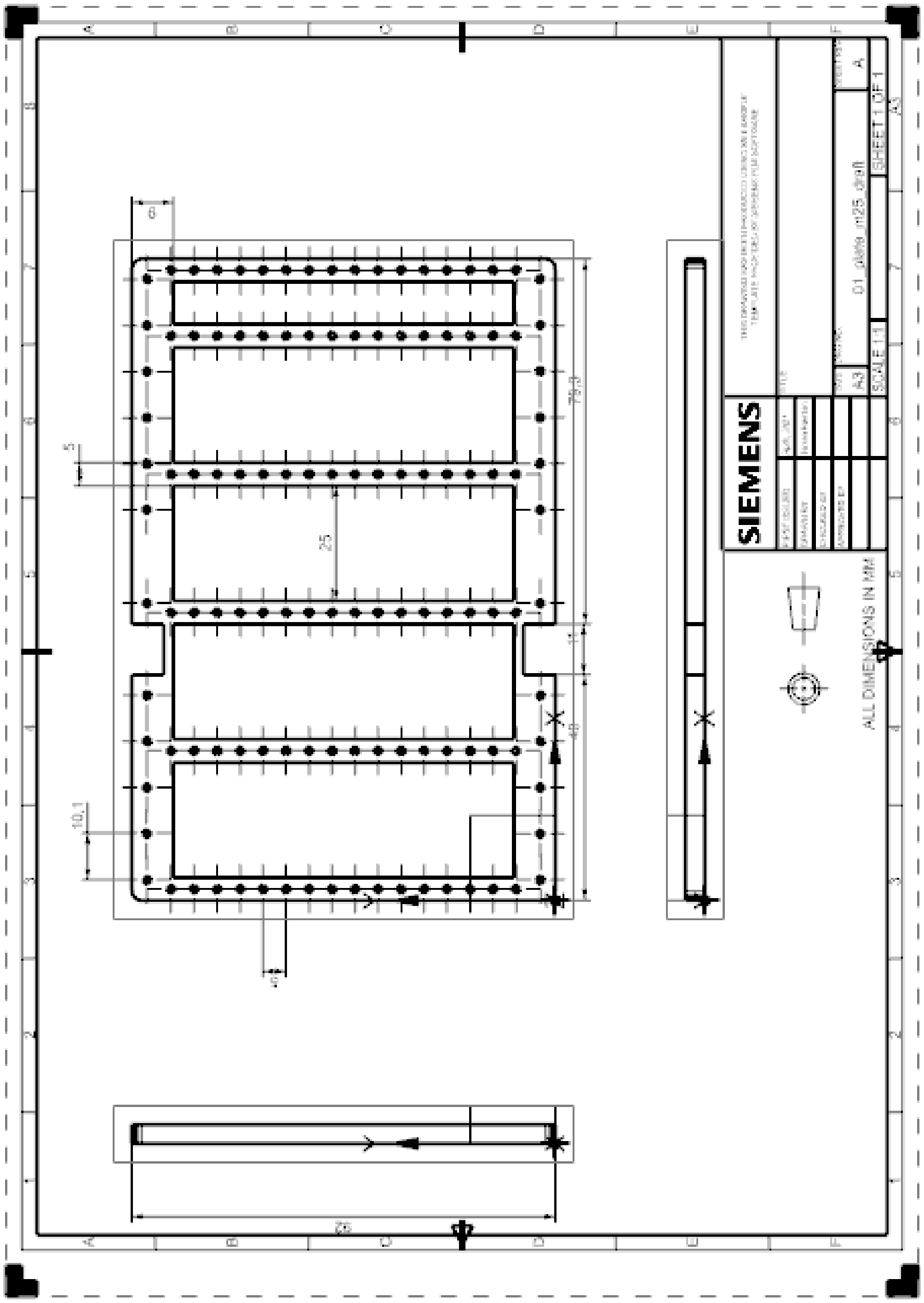
Gimbaled antennas on the Bento Box would increase the range of payloads like the EO sensor and SDR relay while also improving their viability in LPI/LPD applications. While gimbaled antennas would increase the SWaP of the Bento Box, the initial flight test could be done with a single payload to remain under the four-pound FAA restrictions before moving on to an advanced HAB with multiple payloads.

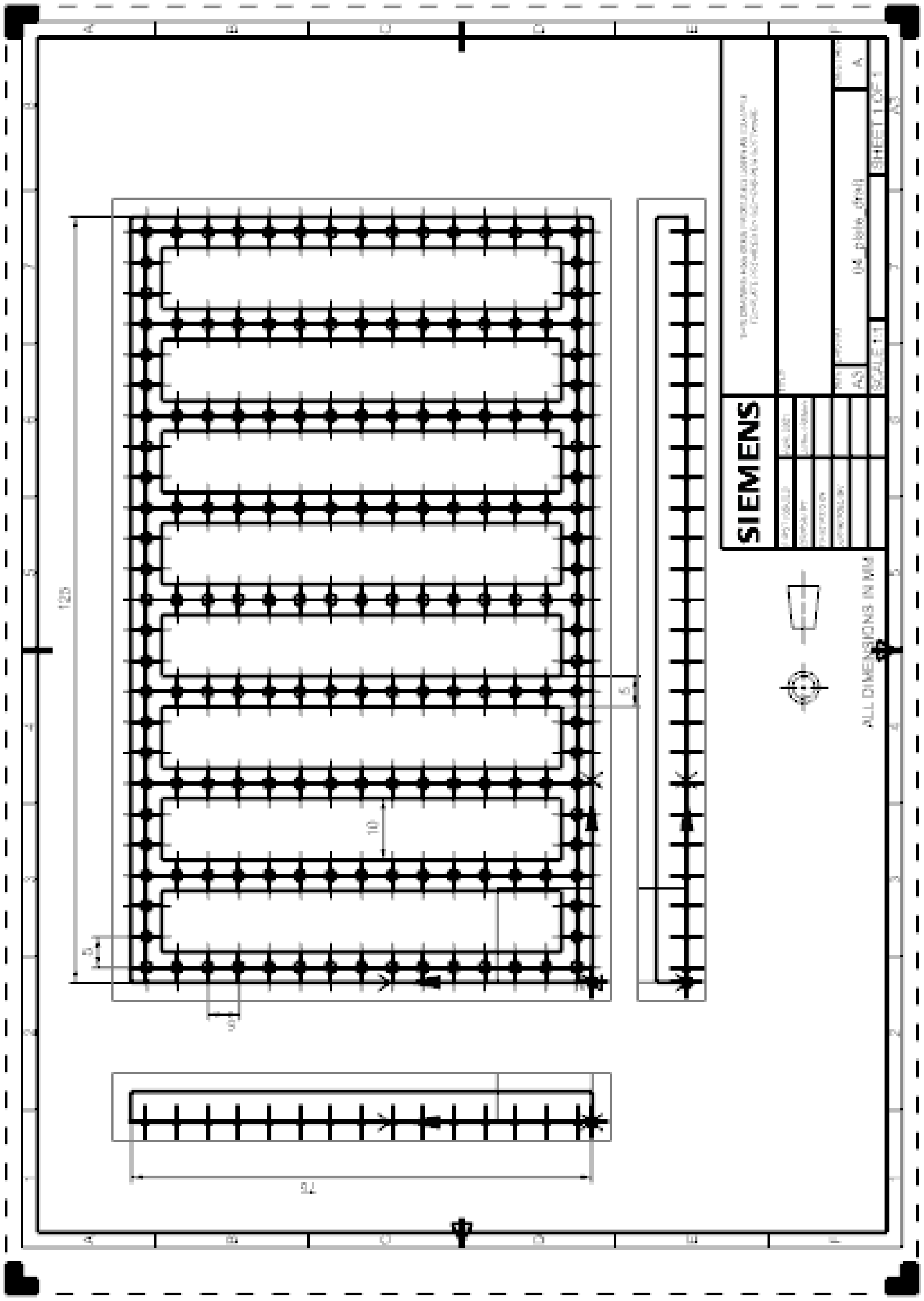
Finally, the Bento Box needs to be tested in a marsupial system on an advanced HAB with an auto-disconnect power connector. As shown by the HAB failure during the flight demonstration of this study, precision recovery of sensitive and/or expensive payloads is an important aspect of operationalizing stratospheric assets.

B. FINAL THOUGHTS

The nature of the next U.S. conflict is not known, and it is a mistake to think that it will look anything like recent or past wars. However, the need for communication between maneuver, command, and supporting elements is consistent throughout history. Space offers the ultimate high ground in collecting and relaying information. The next conflict involving a peer or near-peer adversary almost guarantees that U.S. space-based assets will be targeted and disrupted, or even destroyed. Investment in redundancy of U.S. space-based infrastructure is an investment in gaining and maintaining the informational advantage in future engagements. HABs are a relatively cheap and effective way of supplementing space-based systems that can mitigate the loss of assets during conflict. Additionally, HABs would offer a layer of protection to U.S. space infrastructure through deterrence by denial—from an adversary's perspective, it does not make sense to conduct an expensive attack against a space-based asset when redundancy will prevent any disruption of the capability. USSOF may not need this capability right now, but it could make the difference between success and failure in the future. The U.S. military should consider developing and testing HABs for military operations and establishing TTPs for their use, in advance, to make them capable of mitigating future space-based asset loss. Much like the dictum that SOF cannot be created after emergencies occur, neither can this capability.

APPENDIX A. CAD DRAWINGS

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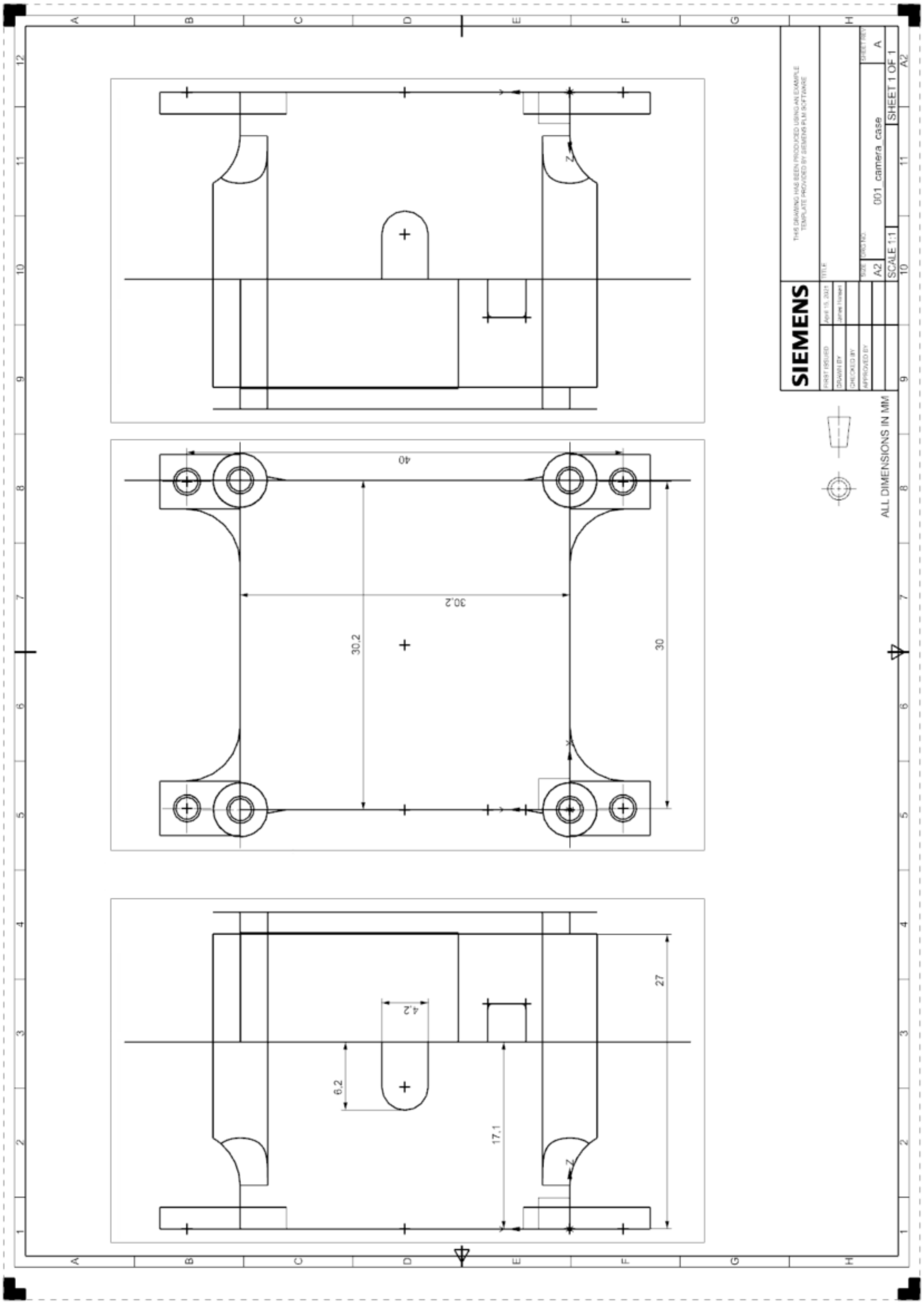
A3
125
10
5


SIEMENS
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A2
SCALE 1:1
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A
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30,2
30,2
30
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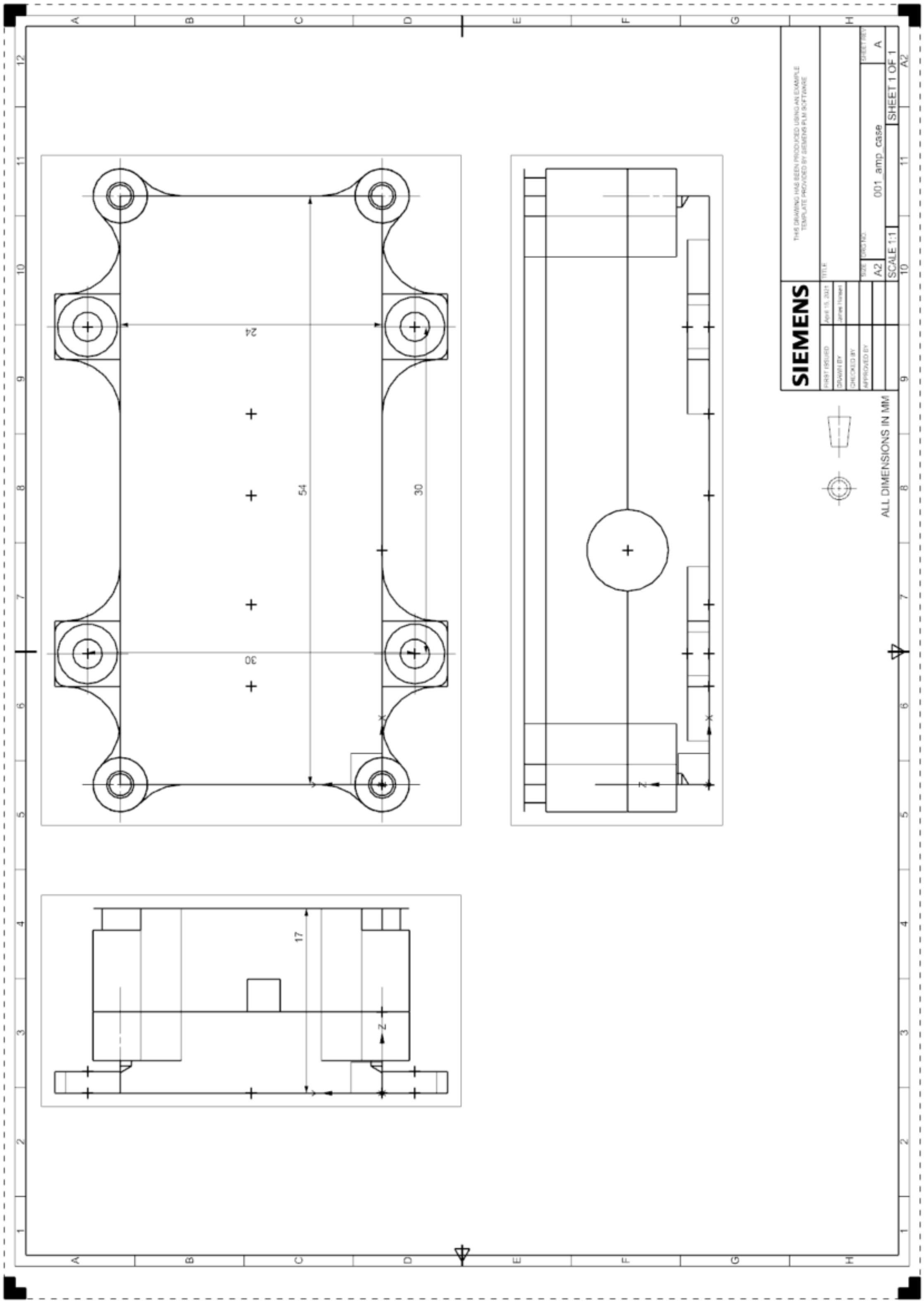
4,2
6,2
17,1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ALL DIMENSIONS IN MM
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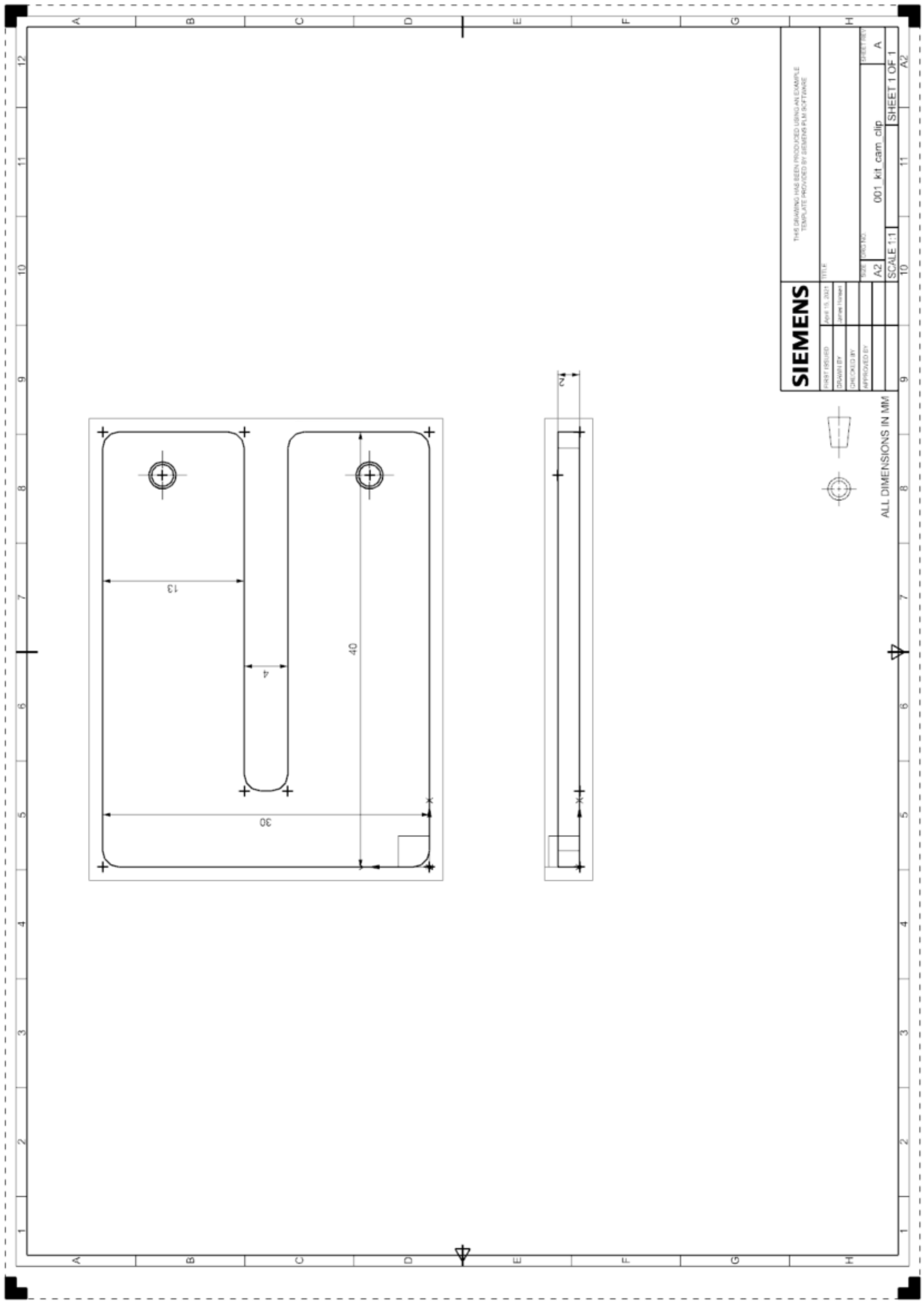
54
30
30
17



SIEMENS
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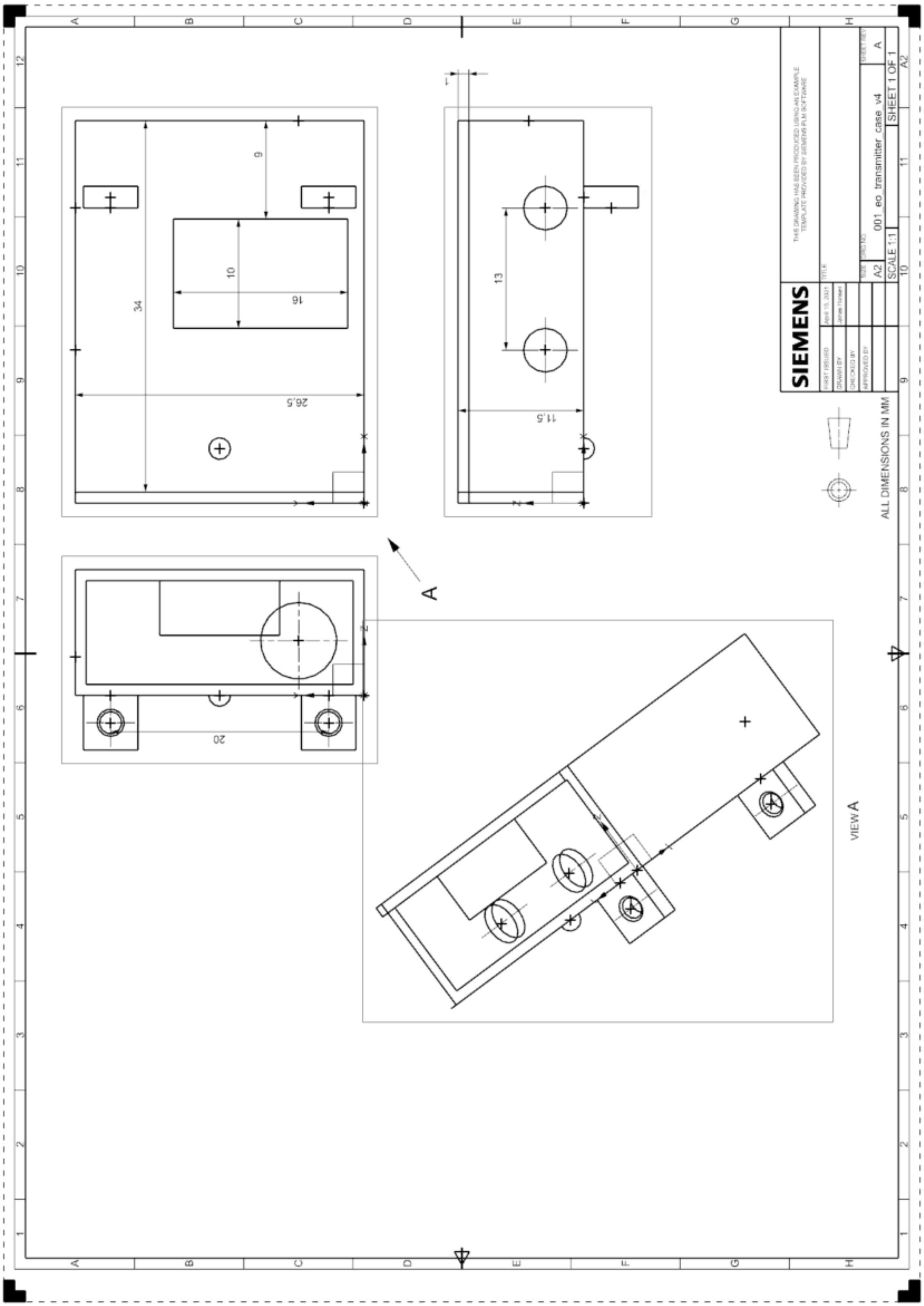
SHEET 1 OF 1
SCALE 1:1
A2
ALL DIMENSIONS IN MM
13
4
40
30
2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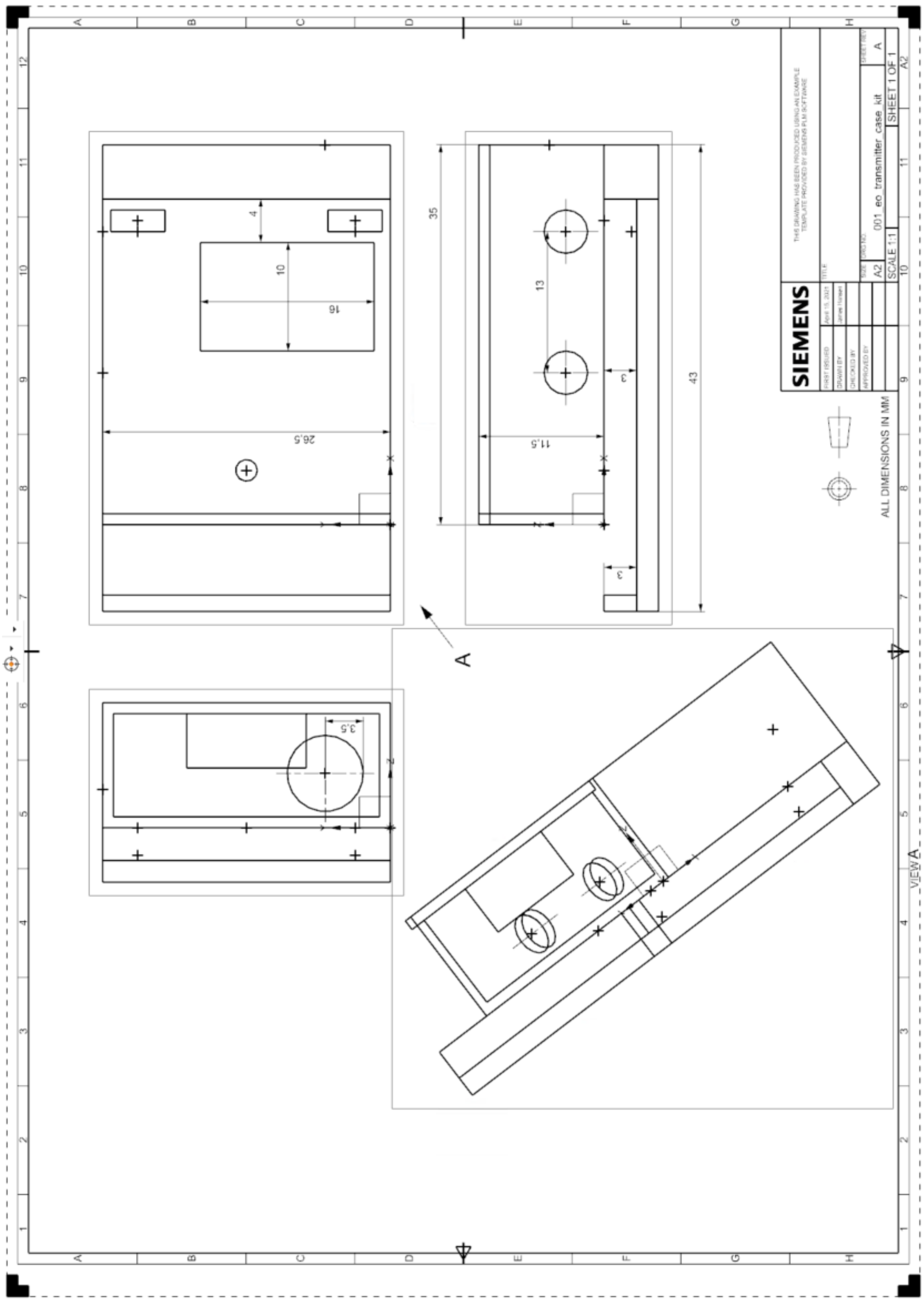
A2
ALL DIMENSIONS IN MM
VIEW A
A
34
26.5
16
10
9
13
11.5
20



SIEMENS
THIS DRAWING HAS BEEN PRODUCED USING AN EXAMPLE TEMPLATE PROVIDED BY SIEMENS PLM SOFTWARE
001_eo_transmitter_case_kit
A2
SCALE 1:1
SHEET 1 OF 1
A
ALL DIMENSIONS IN MM
VIEW A
35
43
13
11.5
3
3
26.5
16
10
4
3.5

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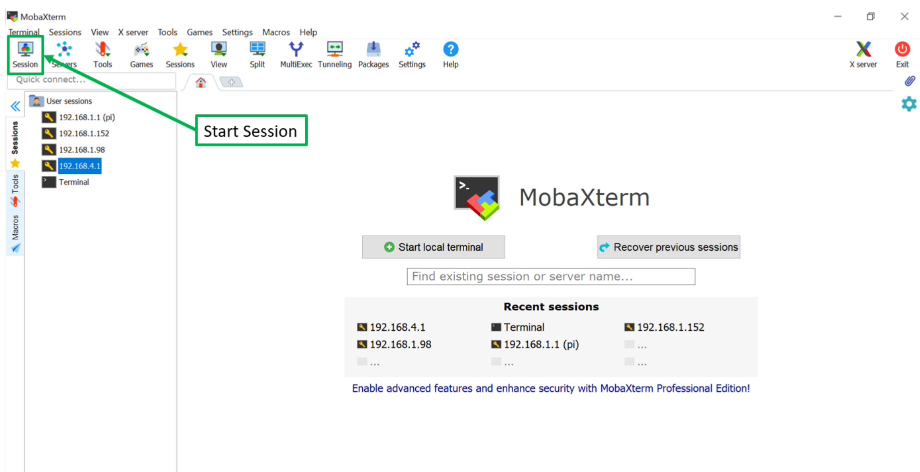
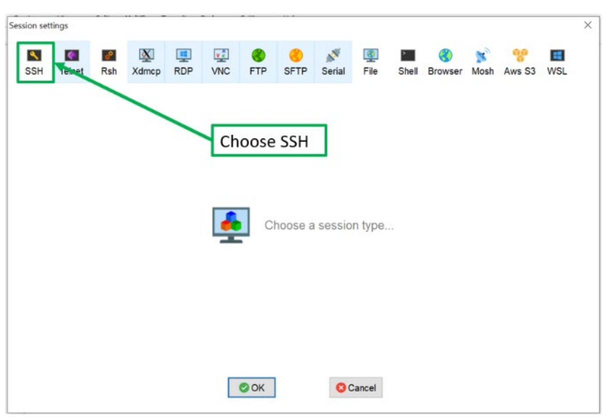
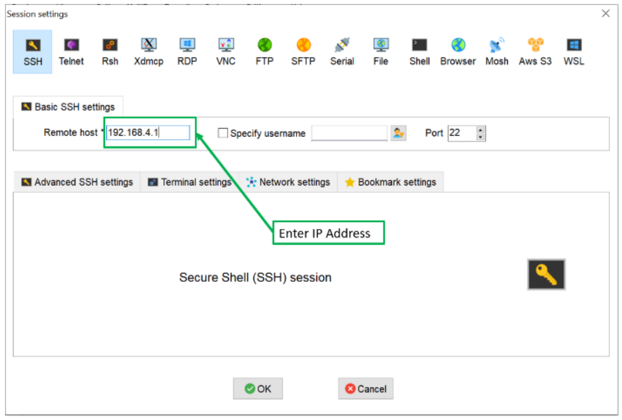
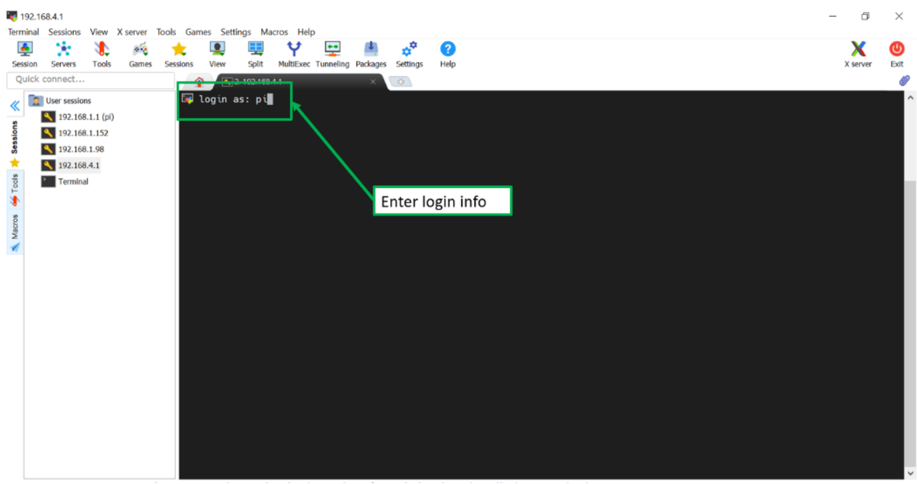
APPENDIX B. SSH CONNECTION TO BUS VIA MOBAXTERM

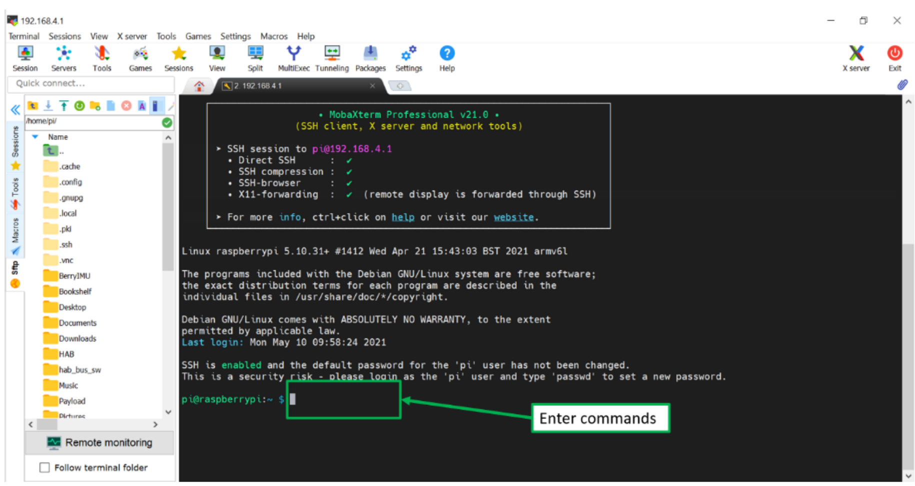
Connecting to the bus via MobaXterm (or other similar remote terminal program) requires a computer with Wi-Fi connection to the bus. The Bento Box C&DH Wi-Fi is programmed to function as a wireless access point using the “hostapd” installation, meaning that other devices can connect directly to it as the host. After connecting to the bus via Wi-Fi, start the terminal software and connect to the IP address (192.168.4.1) via an SSH session. Then enter the commands in the command window as if connected directly to the C&DH.






Session settings
SSH
Telnet
Rsh
Xdmcp
RDP
VNC
FTP
SFTP
Serial
File
Shell
Browser
Mosh
Aws S3
WSL
Basic SSH settings
Remote host * 192.168.4.1
Specify username
Port 22
Advanced SSH settings
Terminal settings
Network settings
Bookmark settings
Enter IP Address
Secure Shell (SSH) session
OK
Cancel


192.168.4.1
User sessions
192.168.1.1 (pi)
192.168.1.152
192.168.1.98
192.168.4.1
Terminal
login as: pi
Enter login info


192.168.4.1
• MobaXterm Professional v21.0 •
(SSH client, X server and network tools)
➤ SSH session to pi@192.168.4.1
• Direct SSH : ✓
• SSH compression : ✓
• SSH-browser : ✓
• X11-forwarding : ✓ (remote display is forwarded through SSH)
➤ For more info, ctrl+click on help or visit our website.
Linux raspberrypi 5.10.31+ #1412 Wed Apr 21 15:43:03 BST 2021 armv6l
The programs included with the Debian GNU/Linux system are free software;
the exact distribution terms for each program are described in the
individual files in /usr/share/doc/*/copyright.
Debian GNU/Linux comes with ABSOLUTELY NO WARRANTY, to the extent
permitted by applicable law.
Last login: Mon May 10 09:58:24 2021
SSH is enabled and the default password for the 'pi' user has not been changed.
This is a security risk - please login as the 'pi' user and type 'passwd' to set a new password.
pi@raspberrypi:~ $
Enter commands
Remote monitoring
Follow terminal folder

APPENDIX C. SDR PYTHON CODE

```
# Pluto.py

#Pluto SDR Relay
#Kyle Decker
##https://analogdevicesinc.github.io/pyadi-iio/guides/examples.html


# Channel callout functions for
# column index numbers are:
#    0       1    2    3
# Chan Act, Freq, FR#, CH#
# Chan Act is the actual channel number when read out (1-32)
# Freq is the associated frequency for the channel
# FR# is the Frequency Range number (1-4)
# CH# if the Channel Frequency associated with the Freq range (1-8)
import sys
from CHdict import channel

#Error Logging
import traceback

#This line opens a log file
with open("log.txt," "w") as log:

   import time

   #Initialize Payload Message Values
   epoch=round(time.time())
   payloadstatus=0
   txfr=0
   txch=0
   txfq=0
   rxfr=0
   rxch=0
   rxfq=0
   txg=0
   lback=0


   try:

       if len(sys.argv)==1:
           # Transmitter prompt
           ch_tx=34  #Default for max spectrum spread
           freq_out_tx         = channel [ch_tx]['freq']
           freq_range_out_tx   = channel [ch_tx]['FR']
           channel_freq_out_tx = channel [ch_tx]['CH']
#            print("The frequency for the Video Receiver is:  ,"
freq_out_tx , "Hz")
#            print("Use the FR button to select a Frequncy Range of:
," freq_range_out_tx)
```

```
#            print("Use the CH button to select a Channel of:
," channel_freq_out_tx)

           # Receiver Prompt
           ch_rx=58 #Default for max spectrum spread
           freq_out_rx         = channel [ch_rx]['freq']
           freq_range_out_rx   = channel [ch_rx]['FR']
           channel_freq_out_rx = channel [ch_rx]['CH']
#            print("The frequency for the Drone Transmitter is:  ,"
freq_out_rx, "Hz")
#            print("Use the FR button to select a Frequncy Range of:
," freq_range_out_rx)
#            print("Use the CH button to select a Channel of:
," channel_freq_out_rx)

       elif len(sys.argv)==2:
#            print("Requires 2 Arguments, VidRx and DroneTx Channels")
           rxfq="No Rx Arg"
           print(f'16 {epoch:<10} {payloadstatus} {rxfr}{rxch}
{txfr}{txch}')
           print(f'17 {epoch:<10} {txg} {lback} {rxfq:<10} {txfq:<10}')
           exit()

       elif len(sys.argv)>3:
#            print("Requires 2 Arguments, VidRx and DroneTx Channels")
           rxfq="2 many Arg"
           print(f'16 {epoch:<10} {payloadstatus} {rxfr}{rxch}
{txfr}{txch}')
           print(f'17 {epoch:<10} {txg} {lback} {rxfq:<10} {txfq:<10}')
           exit()

       else:
           ch_tx=int(sys.argv [1])
           freq_out_rx         = channel [ch_tx]['freq']
           freq_range_out_rx   = channel [ch_tx]['FR']
           channel_freq_out_rx = channel [ch_tx]['CH']

#            print("The frequency for the Drone Transmitter is:  ,"
freq_out_rx, "Hz")
#            print("Use the FR button to select a Frequncy Range of:
," freq_range_out_rx)
#            print("Use the CH button to select a Channel of:
," channel_freq_out_rx)

           ch_rx=int(sys.argv [2])
           freq_out_tx         = channel [ch_rx]['freq']
           freq_range_out_tx   = channel [ch_rx]['FR']
           channel_freq_out_tx = channel [ch_rx]['CH']
#            print("The frequency for the Video Receiver is:  ,"
freq_out_tx , "Hz")
#            print("Use the FR button to select a Frequncy Range of:
," freq_range_out_tx)
#            print("Use the CH button to select a Channel of:
," channel_freq_out_tx)
```

```
        #
========================================================================
=========== #

        #The following is a workaround to utilize the libiio library
        #that only installs on $python and not $python3 libraries.
        #iio is required to import adi which defines the radio.
        #Must have preinstalled libiio and pylibiio prior to executing.

        try:
            import iio
        except:
            # By default the iio python bindings are not in path
            sys.path.append('/usr/lib/python2.7/site-packages/')
            import iio

        import adi

        # Create radio
        #sdr = adi.ad9361(uri="ip:analog")
        sdr = adi.Pluto()   #Only works in Thonny; Not from Command
Prompt
        #sdr = adi.FMComms5(uri="ip:192.168.2.1")        #"usb:1.4.5")
#ip:192.168.2.1") IP not working on monitor hub

        # Configure properties
        sdr.rx_lo = freq_out_rx
        time.sleep(1)
        sdr.tx_lo = freq_out_tx
        sdr.rx_rf_bandwidth =18000000  #56MHz max
        sdr.tx_rf_bandwidth =18000000
        sdr.tx_cyclic_buffer = True
        sdr.tx_hardwaregain_chan0 = 0 # attenuation applied to transmit
path
        sdr.gain_control_mode_chan0 = "slow_attack"
        sdr.loopback=2 #0=Disabled,1=Digital,2=RF
        sdr.sample_rate=61440000 #max

        # Read properties
#         print("")
#         print("Relay Properties Running on SDR")
#         print("")
#         print("SDR Tx Freq (Hz): %s" % (sdr.tx_lo))
#         print("SDR Tx BW (Hz): %s" % (sdr.tx_rf_bandwidth))
#         #print("Tx HW Gain (dB):," sdr._ctrl.attrs
["out_voltage0_rssi"].value)
#         #print("Tx HW Gain (dB): %s" % (sdr.tx_hardwaregain_ch0))
#         print("")
#         print("SDR Rx Freq (Hz): %s" % (sdr.rx_lo))
#         print("SDR Rx BW (Hz): %s" % (sdr.rx_rf_bandwidth))
#         #print("Rx HW Gain (dB): %s" % (sdr.rx_hardwaregain_ch0))
#         print("")
#         print("Sample Rate: %s" %(sdr.sample_rate))

        if abs(freq_out_tx/sdr.tx_lo-1)<1e-9:
```

```
#             print("")
#             print("SDR Tx Config Sat")
            tx=1
        else:
#             print("")
#             print("SDR Tx Config Failed")
            tx=0

        if abs(freq_out_rx/sdr.rx_lo-1)<1e-9:
#             print("SDR Rx Config Sat")
            rx=2
        else:
#             print("SDR Rx Config Failed")
            rx=0

#         if tx+rx==3:
#             print("")
#             print("Configuration Has Been Verified!")
#             print("")
#             print("Your Pluto SDR is now a Bent Pipe Relay")
#         else:
#             print("")
#             print("System Configuration Is NOT Set. Retry
Configuration")


        payloadstatus=tx+rx
        txfr=freq_range_out_rx
        txch=channel_freq_out_rx #ch_rx
        txfq=sdr.rx_lo
        rxfr=freq_range_out_tx
        rxch=channel_freq_out_tx #ch_rx
        rxfq=sdr.tx_lo
        txg=sdr.tx_hardwaregain_chan0
        lback=sdr.loopback

        print(f'16 {epoch:<10} {payloadstatus} {txfr}{txch}
{rxfr}{rxch}')
        print(f'17 {epoch:<10} {txg} {lback} {txfq:<10} {rxfq:<10}')

    except Exception:
        traceback.print_exc(file=log)
#         print("")
#         print("Execution Failed, See log.txt")
        print(f'16 {epoch:<10} {payloadstatus} {txfr}{txch}
{rxfr}{rxch}')
        print(f'17 {epoch:<10} {txg} {lback} {txfq:<10} {rxfq:<10}')

# END SCRIPT #




# CHdict.py
```

```
#Chan Act,Freq,FR,CH

channel =  {11: {'freq': 5865000000, 'FR': 1, 'CH': 1},
          12: {'freq': 5845000000, 'FR': 1, 'CH': 2},
          13: {'freq': 5825000000, 'FR': 1, 'CH': 3},
          14: {'freq': 5805000000, 'FR': 1, 'CH': 4},
          15: {'freq': 5785000000, 'FR': 1, 'CH': 5},
          16: {'freq': 5765000000, 'FR': 1, 'CH': 6},
          17: {'freq': 5745000000, 'FR': 1, 'CH': 7},
          18: {'freq': 5725000000, 'FR': 1, 'CH': 8},
          21: {'freq': 5733000000, 'FR': 2, 'CH': 1},
          22: {'freq': 5752000000, 'FR': 2, 'CH': 2},
          23: {'freq': 5771000000, 'FR': 2, 'CH': 3},
          24: {'freq': 5790000000, 'FR': 2, 'CH': 4},
          25: {'freq': 5809000000, 'FR': 2, 'CH': 5},
          26: {'freq': 5828000000, 'FR': 2, 'CH': 6},
          27: {'freq': 5847000000, 'FR': 2, 'CH': 7},
          28: {'freq': 5866000000, 'FR': 2, 'CH': 8},
          31: {'freq': 5707000000, 'FR': 3, 'CH': 1},
          32: {'freq': 5685000000, 'FR': 3, 'CH': 2},
          33: {'freq': 5665000000, 'FR': 3, 'CH': 3},
          34: {'freq': 5645000000, 'FR': 3, 'CH': 4},
          35: {'freq': 5885000000, 'FR': 3, 'CH': 5},
          36: {'freq': 5905000000, 'FR': 3, 'CH': 6},
          37: {'freq': 5925000000, 'FR': 3, 'CH': 7},
          38: {'freq': 5945000000, 'FR': 3, 'CH': 8},
          41: {'freq': 5740000000, 'FR': 4, 'CH': 1},
          42: {'freq': 5760000000, 'FR': 4, 'CH': 2},
          43: {'freq': 5780000000, 'FR': 4, 'CH': 3},
          44: {'freq': 5800000000, 'FR': 4, 'CH': 4},
          45: {'freq': 5820000000, 'FR': 4, 'CH': 5},
          46: {'freq': 5840000000, 'FR': 4, 'CH': 6},
          47: {'freq': 5860000000, 'FR': 4, 'CH': 7},
          48: {'freq': 5880000000, 'FR': 4, 'CH': 8},
          51: {'freq': 5658000000, 'FR': 5, 'CH': 1},
          52: {'freq': 5695000000, 'FR': 5, 'CH': 2},
          53: {'freq': 5732000000, 'FR': 5, 'CH': 3},
          54: {'freq': 5769000000, 'FR': 5, 'CH': 4},
          55: {'freq': 5806000000, 'FR': 5, 'CH': 5},
          56: {'freq': 5843000000, 'FR': 5, 'CH': 6},
          57: {'freq': 5880000000, 'FR': 5, 'CH': 7},
          58: {'freq': 5917000000, 'FR': 5, 'CH': 8},
          59: {'freq': 467637500, 'FR': 'Walkie Talkie Rx', 'CH': 11},
          60: {'freq': 462562500, 'FR': 'Walkie Talkie Tx', 'CH': 1}}

# END SCRIPT #




# status.py
```

```
import sys

#Error Logging
import traceback

#This line opens a log file
with open("statlog.txt," "w") as log:

   import time

   #Initialize Payload Message Values
   epoch=round(time.time())
   txfq=0
   rxfq=0
   txg=0
   lback=0

   try:

       #
======================================================================
=========== #

       #The following is a workaround to utilize the libiio library
       #that only installs on $python and not $python3 libraries.
       #iio is required to import adi which defines the radio.
       #Must have preinstalled libiio and pylibiio prior to executing.

       try:
           import iio
       except:
           # By default the iio python bindings are not in path
           sys.path.append('/usr/lib/python2.7/site-packages/')
           import iio

       import adi

       # Create radio
       #sdr = adi.ad9361(uri="ip:analog")
       sdr = adi.Pluto()   #Only works in Thonny; Not from Command
Prompt

       txfq=sdr.rx_lo
       rxfq=sdr.tx_lo
       txg=sdr.tx_hardwaregain_chan0
       lback=sdr.loopback

       print(f'17 {epoch:<10} {txg} {lback} {txfq:<10} {rxfq:<10}')

   except Exception:
       traceback.print_exc(file=log)
#        print("")
#        print("Execution Failed, See statlog.txt")
       print(f'17 {epoch:<10} {txg} {lback} {txfq:<10} {rxfq:<10}')
```

```
# END SCRIPT #
```

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