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Developing Technology for Autonomous Control of Solar High-Altitude Balloons (SHABs)

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DEVELOPING TECHNOLOGY FOR AUTONOMOUS CONTROL OF SOLAR HIGH-ALTITUDE BALLOONS (SHABS)

1. INTRODUCTION

Vented Solar High-Altitude Balloons (SHAB-Vs) utilize a lightweight balloon envelope with ideal thermal properties for absorbing direct solar radiation and heating the envelope and internal ambient air through conduction and convection. These balloons therefore do not require a lifting gas to generate lift, and are a simple, inexpensive, passive form of high-altitude balloon flight. Until recently, SHABs have not had venting capabilities and been strictly free floating for high altitude science missions. We design, develop, and evaluate novel hardware, software, and guidance navigation and control (GNC) algorithms for autonomous solar high-altitude balloons (SHABs). The ability to change the altitude of the SHABs can lead to more sophisticated maneuvers in the future such as station-keeping or waypoint trajectory following by leveraging opposing winds at various layers of the atmosphere.

2. SOLAR BALLOON BACKGROUND

Vented Solar High-Altitude Balloons (SHAB-Vs) are a specialized type of lightweight hot air balloon that is heated by the sun. Direct solar radiation heats the balloon envelope, and then through conduction and convection, the ambient air inside the balloon envelope is heated which generates lift. SHABs do not require a fuel source and are therefore a completely passive form of flight, other than the powering of electronics in the gondola. The overall system, even with the vent, is much simpler and less expensive than other balloon platforms such as hot air balloons or buoyancy-controlled super pressure balloons. Because these balloons do not require a lifting gas, they have been proposed as viable platforms for planetary exploration on Mars and Venus; simulations show that SHABs would perform well on Venus due to the highly reflective cloud layer [1-3]. Montgolfière Infrarouge (MIR) balloons are similar to solar balloons but primarily use infrared radiation emitted from the Earth's surface rather than solar radiation to generate lift, and can therefore also fly at night, unlike solar balloons [4]. MIRs perform similarly to SHABs and we believe the vent technology and performance discussed in this manuscript would behave similarly on MIRs.

Recently, we designed and flew several experimental SHAB envelopes and gondolas which included various size and material combinations, as well as some initial vented flights [5]. The heliotrope design proved to be the most reliable and repeatable for incorporating a mechanical vent [6]. The heliotrope envelope is made of thin polyethylene plastic and then darkened with a fine pyrotechnic-grade charcoal powder to darken the envelope. This material combination results in a dark-gray envelope with a high absorptivity and low emissivity for converting direct solar radiation into heat to raise the temperature of the ambient air inside the balloon and generate lift.

SHAB-Vs fly as long as the sun is shining, which on average is approximately 8-12 hours at standard float altitudes (19-23 km), depending on geographic location and season. The float altitude can vary for a multitude of reasons including gondola weight, inconsistencies in the envelope manufacturing process, tears/holes during launch and ascent, high winds or turbulence, etc. These variables can cause identical balloons launched back-to-back to have different float altitudes as well; we've seen identical balloons have float altitudes up to 3 km off. Unvented SHABs also can fluctuate up to 1 km in altitude due to gravity

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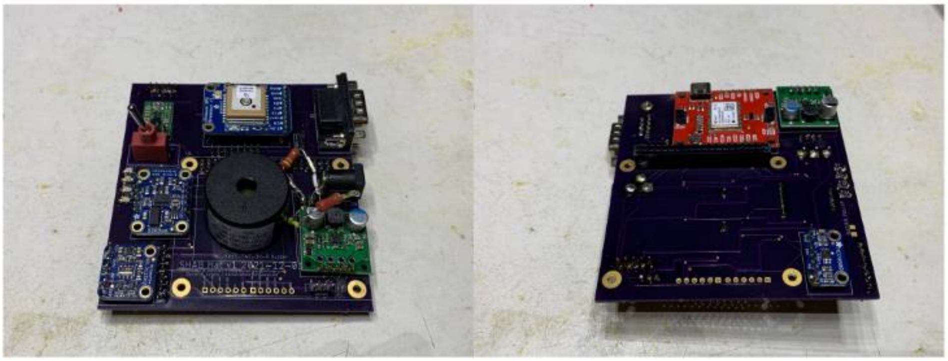
waves at the float altitude throughout the day [7]. The SHAB-V uses a mechanical butterfly-valve-like vent mounted to the top of the envelope to release hot air [5]. SHAB-Vs have demonstrated an altitude maneuverability range down to 9 km and can potentially go lower. However, lower altitudes aren't necessary for navigation and control applications.

3. SHAB-V GONDOLA HARDWARE DEVELOPMENT

We developed a custom gondola with COTS single board computer, sensors, and additional parts to power and control the vent to perform altitude maneuvers during the flight. Raspberry Pi 3s and 4s were used for the single board computer and then a custom PCB daughter board (SHABHat) was developed for power management and connecting the sensor suite; a SHABHat is shown in Figure 1. Table 1 shows the list of hardware components and technical parameters of each component. The update rates shown in Table 1 are the maximum rates of each sensor, not necessarily the rates used during each flight. The Raspberry Pi has a quad-core processor clocked at 1.5GHz and 8 Gb of RAM; it was selected due to its small form factor and strong computing power. The Raspberry Pi also allows for an onboard camera and the capability to use multiple programming languages for the flight software and autonomy. An Arducam Pi camera was used as the onboard camera, which has a 5 MP sensor and allows for a frame rate of 30 frames per second. The sensor suite includes an inertial measurement unit (IMU), GPS receiver, altimeter, and temperature sensor. In the event of a loss of GPS signal (which happened on SHAB13-V), the altimeter was used for altitude control. The raspberry PI and sensor suite are powered by 3 to 4 6V AA battery packs of Energizer Ultimate Lithium batteries connected in parallel, which perform well in cold environments and provide enough current for all the subsystems. Additionally, an independently powered satellite GPS transceiver is included in the gondola and an independently powered APRS transmitter connected to the flight line is included to track the balloon in real-time and recover the payload after landing.

The flight control software initiates and runs the sensors, logs the sensor data, and allows for control and autonomy for various missions. The activity diagram seen in Fig. 2 shows the functional flow of the flight control software. The camera, IMU, and 1 Hz sensors (GPS, altimeter, etc.) run as separate processes, utilizing the Pi's multiple cores. By running multiple processes, higher fidelity data from the sensors can be logged. The main program initializes the sensors, creates the separate processes, starts the processes, and creates data queues for each process to pass sensor data. Finally, the mission thread is started, which contains the autonomy and flight control for a specific flight. Throughout the flight, the main program reads each queue for flight data and logs the data onto the Raspberry Pi's SD card; the mission thread also uses the collected data in real-time.



(a) Top (b) Bottom

Fig. 1 — SHABHat, custom printed PCB daughterboard for Raspberry Pi with COTS sensors, voltage regulators, and additional parts for autonomous SHAB flights

Table 1 — COTS hardware components used with SHABHat for Raspberry Pi to conduct autonomous SHAB-V missions

Hardware Component	Power (W)	Mass (g)	Update Rate (Hz)
Raspberry Pi 4B Single Board Computer	15	50	N/A
Arducam Pi Camera	1	3	60
Adafruit BNO055 IMU	0.063	3	100
Adafruit Ultimate GPS	0.125	8.5	10
Adafruit GPS Antenna	0.083	100	N/A
Adafruit MPL3115A2 Altimeter	0.083	1.2	1
Adafruit MCP9808 Temperature Sensor	0.001	0.9	10
Anker 13000mAh Power Bank	N/A	240	N/A

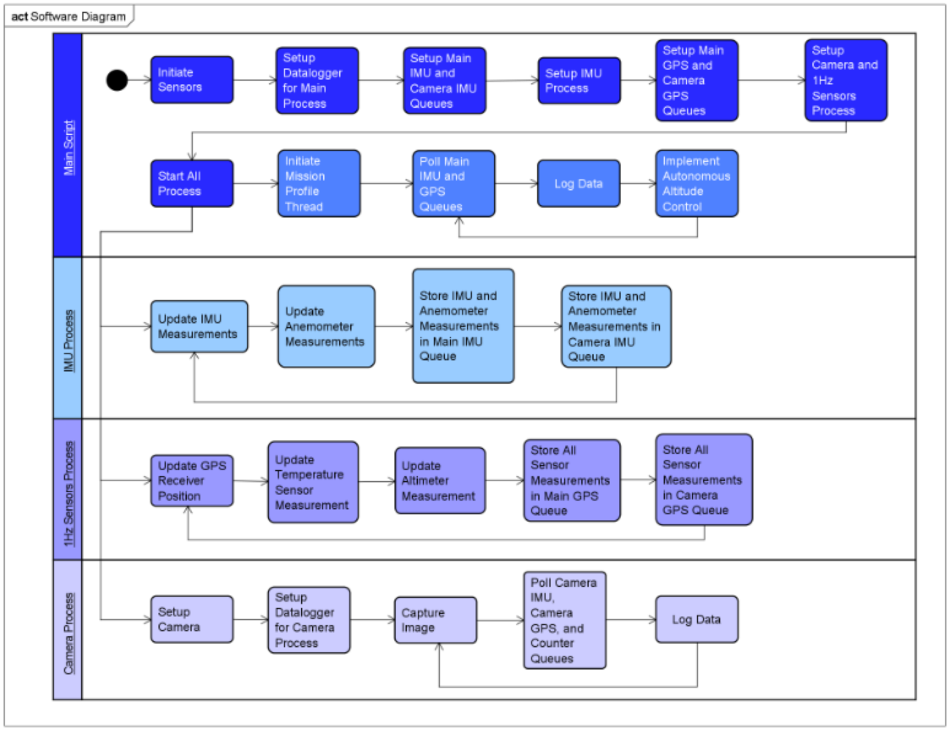


Fig. 2 — SHAB-V flight control software functional flow diagrams

4. FLIGHT EXPERIMENTS

4.1 Developing NRL’s High Altitude Balloon Testing Program

Until this project, the NRL did not have a procedure in place for launching High Altitude Balloons (HABs). Previous high-altitude balloon projects within NRL were launched by contractors. We worked with codes 1400, 5600, 1251/2 and more to ensure safe high-altitude balloon operations.

Although these balloons are under the FAA's 6-pound payload limit, making them unregulated, we still perform some additional safety measures. A Notice to Airmen (NOTAM) is filed directly with the FAA at least 24 hours prior to the launch of the balloon system after a launch site is determined based on the latest weather forecast. The SHAB-Vs are launched outside of major metro areas. Additionally, the balloons are launched at least 5 miles away from airports. The launch site can be updated 24 hours prior to flight depending on the latest weather (wind) forecast.

The total flight time of a SHAB-V is limited by the location of the launch site and the local sunrise and sunset times. SHAB-Vs fly as long as there is sunlight and will slowly descend after sundown until they land. The maximum flight time for a balloon launched is during the summer solstice. In Virginia, this would be approximately a 15-hour flight, however most launch durations were shorter than this.

Recovery operations are not time sensitive and can’t be precisely pre-planned. The time it takes to accomplish recovery operations is determined by a multitude of factors such as the location upon which the gondola lands, the weather conditions, the condition of the gondola and payload, the condition of the access roads, lodging availability, etc. Upon recovery of the payload, the recovery team will transport all recovery support equipment and recovered items back to the U.S. Naval Research Laboratory in Washington, DC.

4.2 Weather Balloon Flight Experiments

Before conducting SHAB-V flight experiments with our custom developed gondola hardware, we first tested it on 2 small, latex, helium-filled weather balloons. Weather balloons are much lower in complexity than SHAB-Vs and do not fly as long (1-2 hours typically), which makes recovery easier. Precise burst point can be calculated given the balloon size, payload weight, and volume of helium used. Upon recovery and analysis of the data from these flights, we made necessary changes to the hardware and flight software to prepare them for SHAB-V flight experiments.

5. ALTITUDE CONTROLLED SHAB-V FLIGHTS

The altitude controlled SHAB-V flights built on previous flight experiment collaborations and developments with the University of Arizona. The first vented SHAB flight conducted with University of Arizona was dubbed "SHAB3-V" after launching two non-vented flights. The balloon identifying numbers of each SHAB were then increased for each consecutive vented flight; we stick with this naming convention (for SHAB9-V through SHAB10-V) to remain consistent with our previous publications related to SHAB-Vs [1, 3, 5, 8]. Figure 3 shows a top-down view of a SHAB-V.

We settled on a standardized double flap design and vent size for SHAB9-V through SHAB15-V, with a mix of foam and basswood vents. Figure 4 shows time-synced altitude profiles for all of the SHAB-V flights that successfully vented for SHAB9-V through SHAB15-V. These flights were conducted over two separate flight campaigns in the Southwestern United States: Tucson and Albuquerque. Tucson and Albuquerque are ideal places to launch SHAB-Vs because they typically have low cloud cover and precipitation throughout the year. Additionally, Arizona and New Mexico are not densely populated and do not have many trees, which makes recovery easier. The Tucson flight campaign (9-11) took place in April and the Albuquerque flight campaign (12-15) took place in August, which provided a few additional hours of sunlight.

During the Tucson flight campaign, SHAB10-V and SHAB11-V were unsuccessful at altitude holding, but still produced other useful results. Both flights introduced new minimum controllable altitude ranges of 12.5 km and 9 km respectively. These 2 flights were also important for fixing bugs with the flight hardware and software going forward. These two flights are shown in Figure 4.

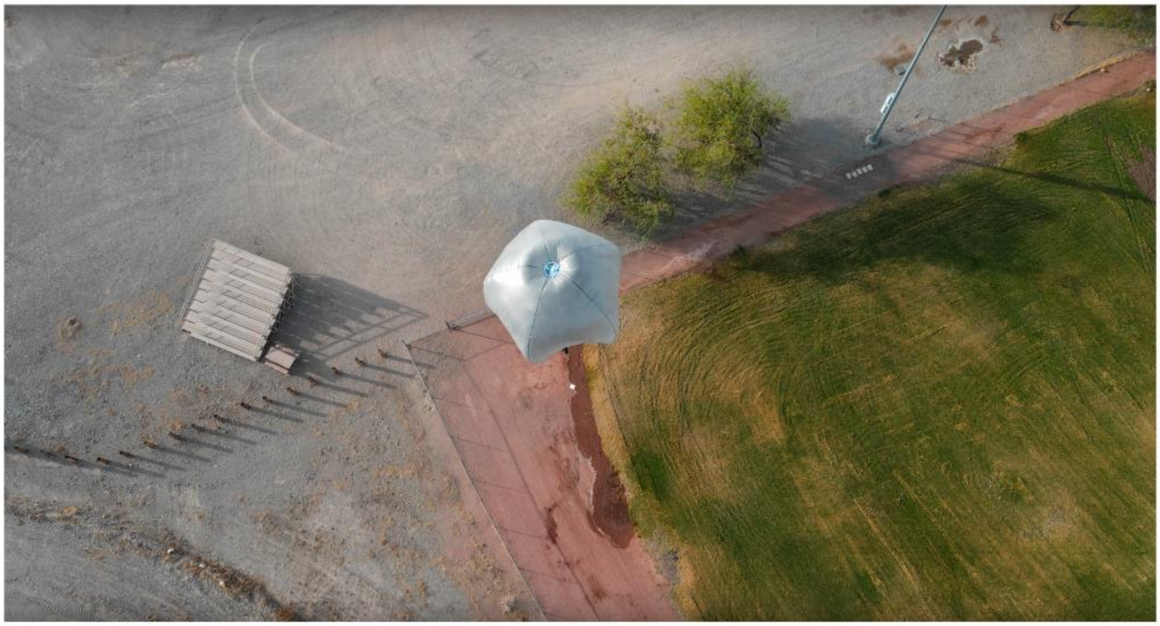


Fig. 3 — Aerial photo of a vented SHAB flight in Tucson with a Styrofoam (EPS) vent mounted to the top of the balloon

For the Albuquerque flight campaign, altitude control was successful on three out of four SHAB-Vs. SHAB14-V didn't vent due to hardware issues but acted as an unvented control balloon for the campaign. These four SHAB-Vs were launched 15 minutes apart on the same morning and were on a timed mission like previous flights but had an onboard proportional-derivative (PD) altitude controller with timed altitude set points rather than distinct vent opening percentages. SHAB12-V and SHAB13-V had proportional only control with a P-gain switch halfway through the missions. SHAB14-V and SHAB15-V had proportional derivative control with a PD-gain switch halfway through the missions as well. Throughout the day of the Albuquerque flight campaign, several distinct thunderstorms developed in regions the SHAB-Vs were flying, affecting venting maneuver performance.

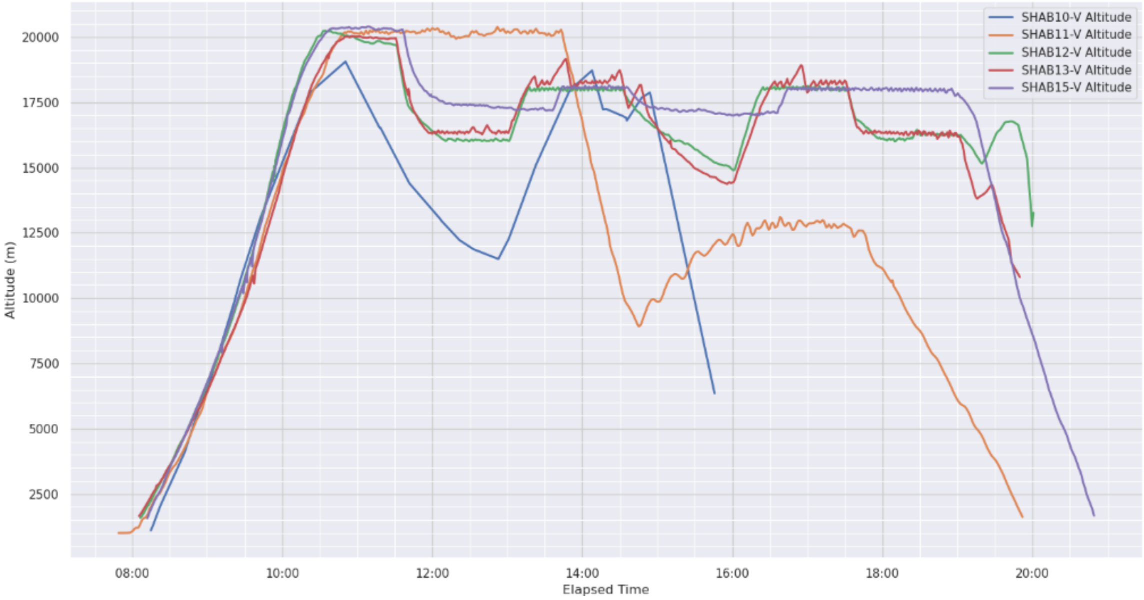


Fig. 4 — SHAB-V Altitude Profiles for all altitude-controlled flight campaigns

Figure 5 shows the altitude profile and venting from the best performing balloon during the Albuquerque flight campaign, SHAB12-V. SHAB12-V had 6 timed altitude set points throughout the flight, with the first being a very high value (changed to 20 km in the plot for visualization purposes) at the beginning to achieve float. Due to thunderstorms, and most likely increased albedo from the top of the cloud layer, as well as possible updrafts and downdrafts, SHAB12-V was unable to reach full descent velocity under 17.5 km like previous flights (See SHAB10-V and SHAB11-V in Figure 4). Each altitude set point was 1.5 hours in duration. SHAB12-V maintained altitude at the 16 km set points for 50+ minutes (the jump in altitude for the second 16 km set point was due to a loss of GPS signal and switching to the altimeter's altitude) and maintained altitude at both 18 km set points for an hour and 15 minutes. The 14 km altitude set point was unobtainable due to the thunderstorms.

The zoomed portion of Figure 5 shows that SHAB12-V oscillated between +/- 75 m on average at the various set points. Halfway through the mission, an 80\% reduction in the P gain was automatically triggered via a timer on the onboard computer. The smaller P gain produced similar altitude performance; however, the vent didn't oscillate between fully open and closed as frequently as the larger P gain. This suggests the P gain could be reduced even further to minimize the change in vent openings. Unvented SHABs naturally oscillate at float altitude and can have amplitudes of several tens of meters, which is similar in performance from the current venting maneuvers [6]. Therefore, +/- 75 m altitude oscillations are satisfactory for future guidance, navigation, and control (GNC) algorithm development, and minimizing the oscillations would mostly improve power efficiency.

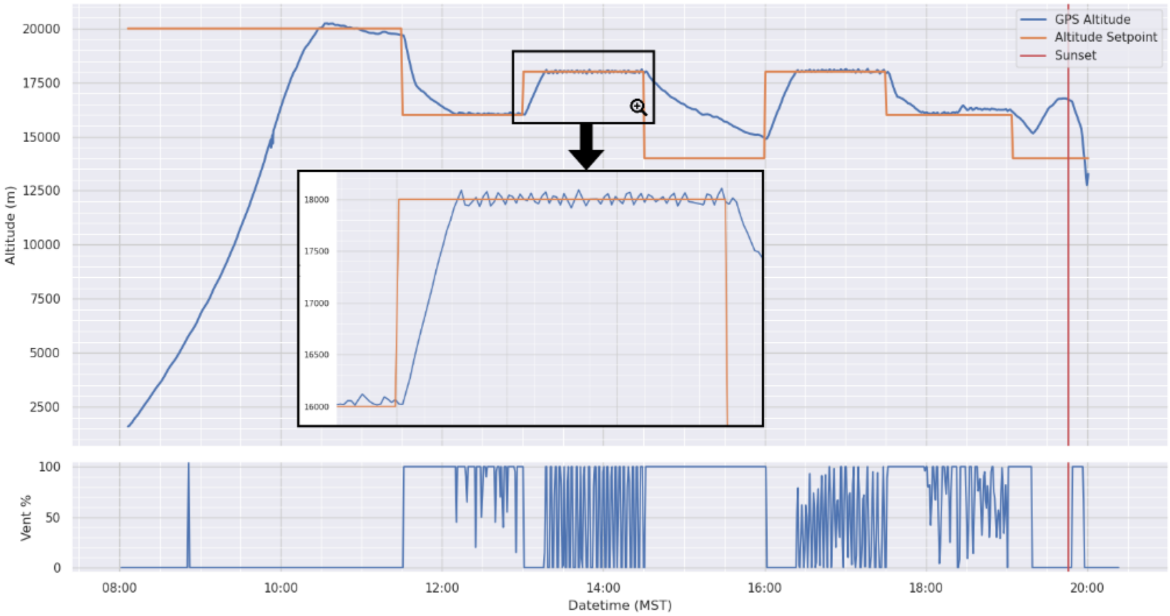


Fig. 5 — SHAB12-V Altitude Profile with venting

6. DISCUSSION

Table 2 shows key statistics from several of the most notable SHAB-V flights. SHAB3-V, the smallest and lightest SHAB-V was only able to descend 1 km. SHAB5-V had a large vent, 20% larger than the final standardized vent, and was able to descend to 13 km with a 1.1 kg payload. SHAB9-V through SHAB15-V all had the same size vent and total system mass however had much different altitude controllability performance. There were several distinct thunderstorms during the Albuquerque campaign that most likely contributed to some of these performance variations.

Table 2 — Key parameters and performance metrics from several SHAB-V flights

	Payload Weight (kg)	**Vent Weight (kg)**	**Total Weight (kg)**	**Max Vent Outflow area (m^2)**	**Average Float Altitude (km)**	**Lowest Altitude (km)**
SHAB3	0.85	-	1.5	0.12	21.5	20.5
SHAB5	1.1	-	2.75	0.3	21	13
SHAB10	1	0.3	3	0.24	19	11.5
SHAB11	0.85	0.35	3	0.24	20	9
SHAB12	0.9	0.35	3	0.24	20	15

There are numerous factors that make the SHABs deeply complex dynamic systems that presents challenges during analysis and simulation. Weather is a primary limiting factor in trajectory prediction and control. While NOAA's weather forecasts and the EarthSHAB simulation platform for predicting SHAB trajectories both incorporate many adjustable parameters, there is still a large degree of uncertainty in SHAB performance and trajectory, due to the influence of weather and other atmospheric anomalies on the balloons.

Another major factor that adds uncertainty to predicting vent performance is the extremely complex dynamics present in the balloon envelope-gondola-vent system. For free floating SHABs without venting, changes in weather and solar conditions throughout the day have minimal effect on the performance of the balloon. Adding venting adds another layer of complexity to the dynamics of the SHABs. In addition to the factors stated before, venting results in an outflow of heat air inside the envelope through the vent and an inflow of ambient air through the bottom hole, volume changes as internal air is released, changes in the radiation absorption and aerodynamic drag as the balloon changes shape, and aerodynamic forces from the descent/ascent further changing the shape of the balloon. These factors interact in hard to predict ways, which makes focused predictions a challenge.

To truly understand the details of these dynamics, we will need to conduct additional focused flight experiments that measure additional parameters throughout the flight. These flights would include detailed real-time data collection of the air volume within the balloon envelope, the air inflow and outflow, and the change in shape of the balloon. Additionally, a computational fluid dynamics (CFD) analysis would provide insight into the balloon dynamics. CFD analysis would need to account for solar and IR radiation sources, convective and conductive heat transfer, envelope flexibility, aerodynamic drag, and changing atmospheric conditions during all phases of the balloon's flight.

7. ADDITIONAL CONTRIBUTIONS

Key publications, presentation, and collaborations on all of the work discussed include:

- Journal publication in Acta Astronautica on Feasibility of SHABs on Venus [1]
- Conference publication and presentation at SciTech 2022 [5]
- Conference Poster and presentation AAS GNC 2022
- Conference publication at AGU 2021 [9]
- Conference publication and presentation at IEEE Aerospace Conference 2023 [10]

- Invited Speaker at Stratospheric Operations and Research Symposium (SOaRS)
- Invited Speaker at Pusan National University - Busan, Korea
- Member of joint force High Altitude Working Group (HAWG)
- Collaborations with Navy Information Warfare Center (NIWC) Pacific, Sandia National Laboratories, Air Force Research Laboratory (AFRL) - Kirtland, NASA Jet Propulsion Laboratory (JPL), University of Arizona, and Oklahoma State University

8. CONCLUSIONS AND NEXT STEPS

The purpose of SHAB12-V through SHAB15-V was to demonstrate altitude control with SHAB-Vs, which was successful. We also successfully developed the SHABHAT Raspberry Pi daughterboard to perform more autonomy on board for future flights. During the Albuquerque campaign, NOAA's global weather forecast also called for opposing winds at various altitudes. Therefore, altitude set points during the campaign were selected to demonstrate horizontal trajectory changes as a bonus. The resulting trajectories from the four balloon flights during the Albuquerque campaign are shown in Figure 6. Each of the balloons that vented went through several loop maneuvers, which resulted in full 360-degree maneuverability. These loop patterns typically happen in regions where the wind flow is transitioning between altitude levels and are usually a low velocity. These regions would be ideal for station-keeping, as there are low winds and full maneuverability to correct for drifting.

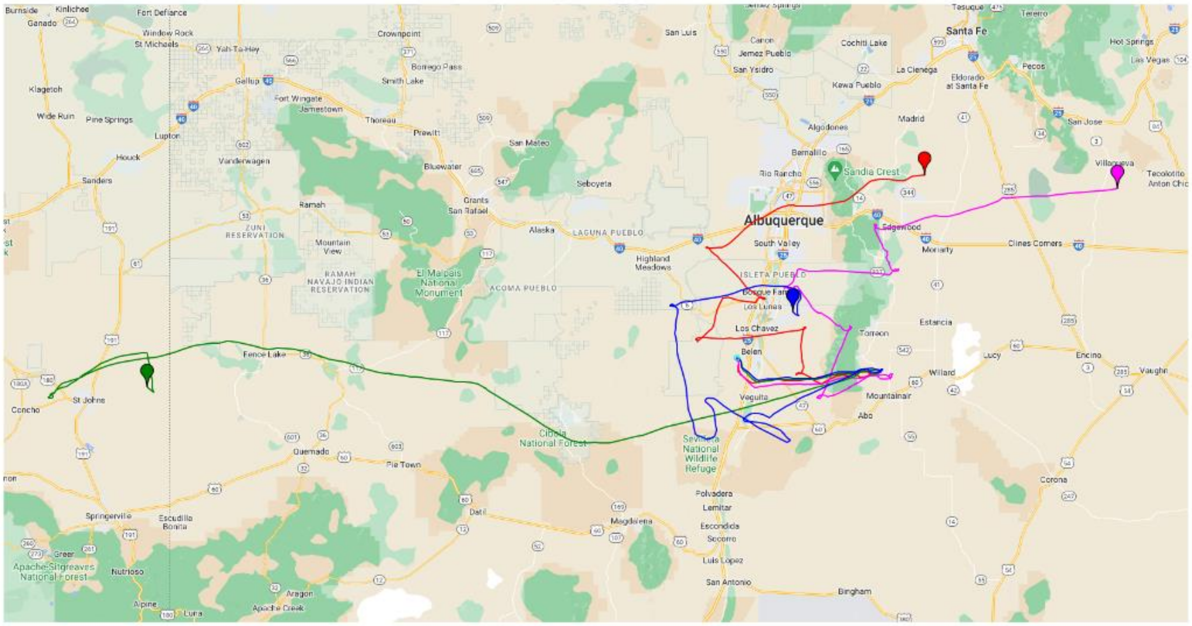


Fig. 6 — Map of four SHAB-V flights launched back-to-back 15 minutes apart, during the Albuquerque Flight Campaign. SHAB12-V is red, SHAB13-V is magenta, SHAB14-V is green (and did not vent), SHAB15-V is blue.

Horizontal navigation with high altitude balloons is non-trivial because opposing winds are not always available. When opposing winds are not available, station keeping will most likely be unobtainable, but some trajectories could be possible if they are along the direction of the prevailing winds. Additionally, global wind forecasts are frequently off, sometimes up to 180 degrees, and constantly dynamically changing in three dimensions as well as time. This makes path planning a very difficult challenge. For instance, Figure 7 shows the difference between the actual SHAB15-V trajectory and the post-processed forecasted trajectory using the altitudes from the SHAB15-V flight along with the last updated NOAA GFS wind forecast prior to launch.

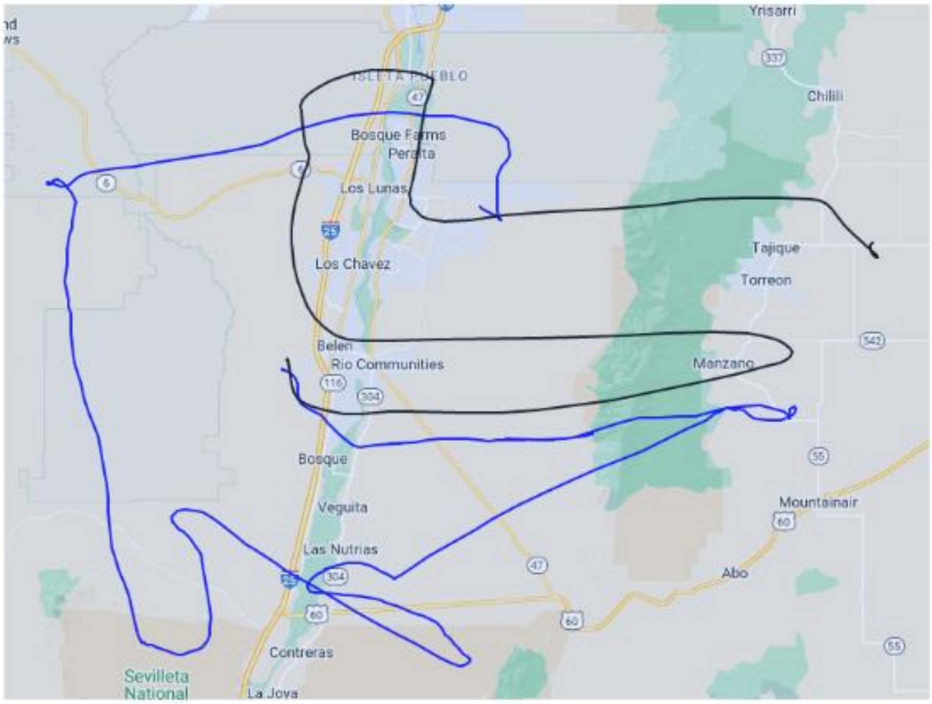
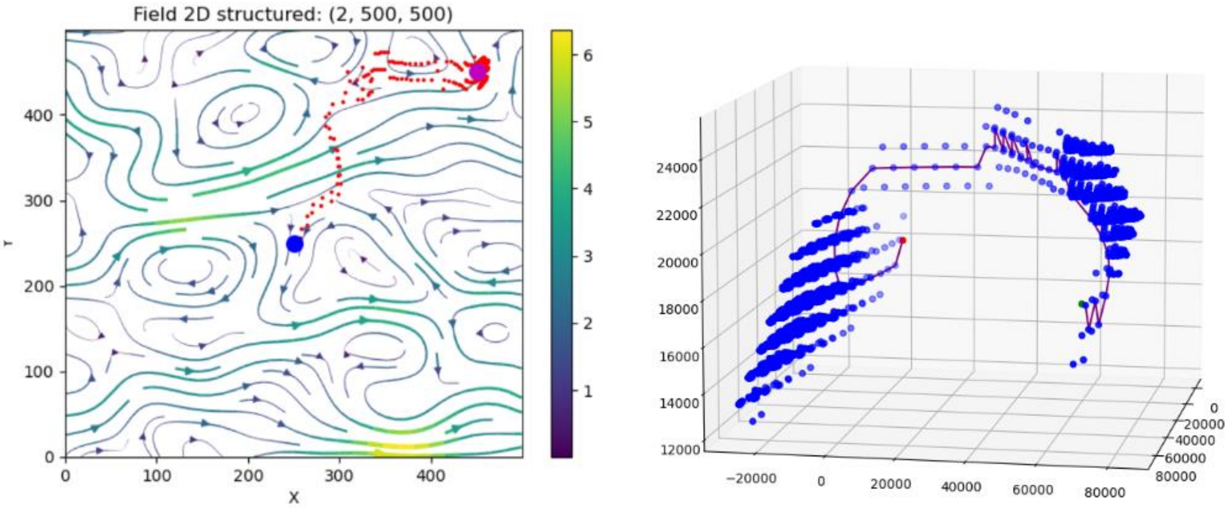


Fig. 7 — SHAB15-V trajectory (blue) vs post processed trajectory with NOAA GFS wind forecast and actual altitude profile (black)

With a perfect forecast, high altitude balloon trajectories could be found with graph search or ensemble trajectory methods [11, 12]. With dynamically changing winds throughout the flight the SHAB-V will have to adapt to the local winds in real-time to navigate. Google Loon successfully did this on super pressure balloons with deep reinforcement learning [13]. We plan to adapt these algorithms for SHAB-Vs and perform station keeping and trajectory following maneuvers. Some key differences between super pressure balloons and solar balloons include mission time frame (SHAB-Vs only fly during the day), ascent/descent rates, altitude holding oscillations, altitude maneuverability zone, and the option to do aerial launches with SHAB-Vs. Aerial deployment of unvented solar balloons has been demonstrated by dropping a SHAB from a higher floating weather balloon, knows as a "grand slam" launch [1].

We have begun developing simulation environments and exploring various algorithms and path planning techniques for horizontal navigation by leveraging opposing winds. Figure 8a shows a 2D "toy-simulation" environment for testing common reinforcement learning algorithms on a simpler problem before trying promising algorithms on a much more complex 3D environment. Figure 8b shows initial results of using a more deterministic path planning approach, in this case A*, to do path planning with a known wind forecast. This is an ongoing effort that will continue into 6.2 base funding to continue researching autonomous teams of SHABs to conduct persistent ISR, communications, and localized meteorological data collection missions.



(a) 2D Flow Field Reinforcement Learning Simulation

(b) 3D Flow Field A* path planning

Fig. 8 — Early Simulations for Navigating SHABs by leveraging opposing winds

REFERENCES

1. T. K. Schuler, D. C. Bowman, J. S. Izraelevitz, D. Sofge, and J. Thangavelautham, “Long duration flights in venus’ atmosphere using passive solar hot air balloons,” Acta Astronautica, vol. 191, pp. 160–168, 2022.

2. J. Jones and J. Wu, “Solar montgolfiere balloons for mars,” in International Balloon Technology Conference, p. 3852, 1999.

3. T. Schuler, S. Shkarayev, and J. Thangavelautham, “Altitude control of a solar balloon for mars exploration,” in AAS Guidance Navigation and Control Conference, pp. paper–20, 2020.

4. P. Malaterre, “Long duration balloon flights in the middle stratosphere,” Advances in Space Research, vol. 13, no. 2, pp. 107–114, 1993.

5. T. Schuler, M. Debbins, D. Bowman, D. Goolsby, J. Crest, I. Pimienta, S. Fitch, E. Roesler, L. Wheeler, D. A. Sofge, et al., “Solar high altitude balloons as a long duration controllable aerial platform,” in AIAA SCITECH 2022 Forum, p. 0282, 2022.

6. D. C. Bowman, P. E. Norman, M. T. Pauken, S. A. Albert, D. Dexheimer, X. Yang, S. Krishnamoorthy, A. Komjathy, and J. A. Cutts, “Multihour stratospheric flights with the heliotrope solar hot-air balloon,” Journal of Atmospheric and Oceanic Technology, vol. 37, no. 6, pp. 1051–1066, 2020.

7. V. Jewtoukoff, A. Hertzog, R. Plougonven, A. de la Camara, and F. Lott, “Comparison of gravity waves in the southern hemisphere derived from balloon observations and the ecmwf analyses,” Journal of the Atmospheric Sciences, vol. 72, no. 9, pp. 3449–3468, 2015.

8. T. Schuler, “Solar balloons-an aerial platform for planetary exploration,” 2020.

9. L. Wheeler, E. Roesler, D. Bowman, A. Glen, P. Miller, A. Sanchez, and T. Schuler, “Stratospheric sampling strategies for balloon-borne datasets of aerosols and gases,” in AGU Fall Meeting Abstracts, vol. 2021, pp. GC35E–0751, 2021.

10. T. Schuler, M. Debbins, M. Cobar, J. Thangavelautham, and D. Sofge, “Altitude control with vented solar high-altitude balloons (shab-vs),” in Proceedings of 2023 IEEE/AIAA Aerospace Conference, 2023.

11. R. R. Draxler, “Trajectory optimization for balloon flight planning,” Weather and Forecasting, vol. 11, no. 1, pp. 111–114, 1996.

12. L. Blackmore, Y. Kuwata, M. T. Wolf, C. Assad, N. Fathpour, C. Newman, and A. Elfes, “Global reachability and path planning for planetary exploration with montgolfiere balloons,” in 2010 IEEE International Conference on Robotics and Automation, pp. 3581–3588, IEEE, 2010.

13. M. G. Bellemare, S. Candido, P. S. Castro, J. Gong, M. C. Machado, S. Moitra, S. S. Ponda, and Z. Wang, “Autonomous navigation of stratospheric balloons using reinforcement learning,” Nature, vol. 588, no. 7836, pp. 77–82, 2020.