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Geophysical and Planetary Acoustics via Balloon Borne Platforms

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1 Introduction

Phenomena on planetary surfaces and atmospheres can generate acoustic waves. If these waves are of sufficiently low frequency (typically in the subsonic or "infrasound" range), they can travel for hundreds to thousands of kilometers. Ground-based microbarometer networks capture these signals, providing a window into geophysical and atmospheric activity on our planet. On Earth, natural infrasound-generating phenomena include lightning, bolides, volcanic eruptions, earthquakes, severe storms, colliding ocean waves, wind-mountain interactions, atmospheric turbulence, and the aurora. Infrasound waves from anthropogenic sources such as chemical and nuclear explosions, supersonic aircraft, industrial emissions, wind turbines, bridges, and spacecraft reentry are present as well (Campus and Christie, 2010). Wave propagation patterns can shed light on the wind and temperature structure of the atmosphere, particularly in the thermosphere and mesosphere where other measurements are scarce (Le Pichon et al., 2002). Infrasound waves also comprise a significant and sometimes dominant means of heating the upper atmosphere (Rind, 1977; Bowman and Lees, 2018).

Acoustic activity in the atmospheres of other planets is almost completely unknown. Possible sources on Venus include seismic activity (Cutts et al., 2016; Garcia et al., 2016b), volcanism (Shalygin et al., 2015), lightning (Russell et al., 2007), bolides, wind-mountain interactions, and atmospheric turbulence. Mars may experience acoustic waves from seismic activity (Taylor et al., 2013), bolides (Garcia et al., 2016a), and wind-mountain interactions; spacecraft entry into the planet's atmosphere may generate detectable signals as well. Lightning is known to occur on Jupiter (Brown et al., 2018) and thermal anomalies in the planet's upper atmosphere are thought to result from acoustic heating (O'Donoghue et al., 2016) Infrasound waves from a variety of processes in the atmospheres of Titan, Saturn, Uranus, and Neptune are also likely.

The vast majority of infrasound investigations have utilized ground-based instruments. However, planetary surfaces are not necessarily ideal for acoustic sensing. Aerodynamic "wind noise" often overwhelms all but the most powerful infrasound waves. Wind mitigation systems, which tend to be much larger than the sensor itself, improve but never entirely eliminate the issue (Walker and Hedlin, 2010). In addition, decreasing sound velocity with altitude in the troposphere causes acoustic waves to bend away from the surface, reducing the sensor detection range.

Free floating balloons offer certain advantages to ground based microbarometer deployments. They suffer very little wind noise because the flight system is advected at the mean wind speed (see Figure 1). Acoustic wave guides created by high altitude temperature and wind gradients can channel sound waves at balloon altitudes, in theory resulting in greater detection ranges. Prior to 2014, however, very little work has been done on this concept. Project MOGUL investigated balloon-borne microphones as a means to detect Soviet nuclear explosions and missile launches in the late 1940s (Weaver and McAndrew, 1995). A University of Michigan project measured background noise levels and acoustic events using sensors at up to 22 km altitude

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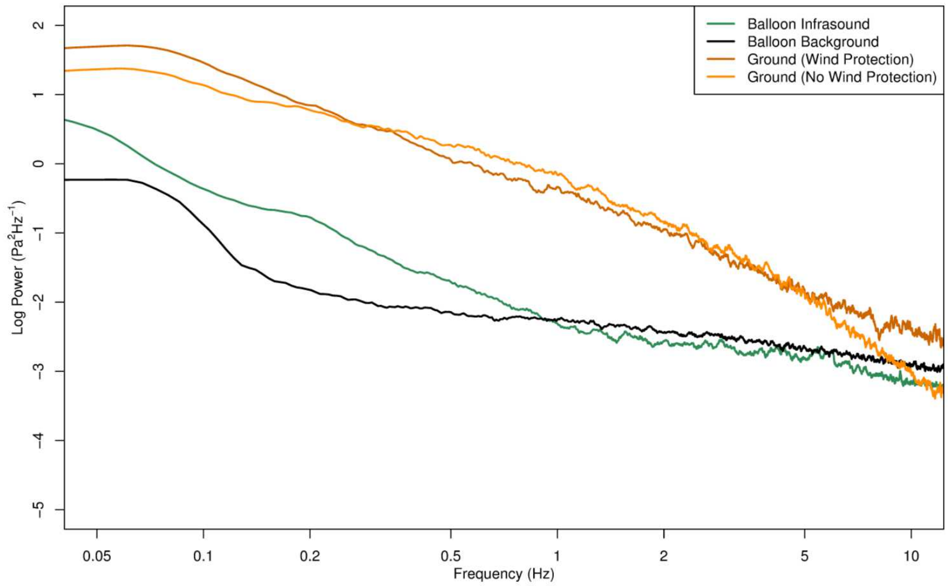

Figure 1: Pressure spectrum of a microbarometer set aboard the HASP 2016 flight compared to a ground station near the balloon's flight path. The balloon-borne sensors have much lower noise levels than the ground ones because of the lack of wind noise. Spectra have been adjusted for acoustic impedance and the high-altitude sensors denoised per Equation 1 in Bowman and Lees (2018).

in the early 1960s (Wescott, 1964). After that, no known balloon infrasound work was conducted for over half a century.

Balloon-borne infrasound research began again in 2014 with a small payload launched as part of the High Altitude Student Platform (HASP; Bowman and Lees (2015)). A larger payload was deployed through the same program in 2015. These proof of concept experiments demonstrated that balloon-borne microbarometers can capture the ocean microbarom (a pervasive infrasound signal generated by ocean waves) even when nearby ground sensors are not able to resolve them (Bowman and Lees, 2017). The following year saw infrasound sensors as secondary payloads on the 2016 Ultra Long Duration Balloon flight from Wanaka, New Zealand (Bowman and Lees, 2018; Lamb et al., 2018) and the WASP 2016 balloon flight from Ft. Sumner, New Mexico (Young et al., 2018). Another payload was included on the HASP 2016 flight as well. In 2017, the Heliotrope project included a four element microbarometer network drifting at altitudes of 20-24 km on solar hot air balloons (Bowman and Albert, 2018). At the time of this writing the Trans-Atlantic Infrasound Payload (TAIP, operated by Sandia National Laboratories) and the Payload for Infrasound Measurement in the Arctic (PIMA, operated by Jet Propulsion Laboratory) are preparing to fly from Sweden to Canada aboard the PMC-Turbo balloon. The purpose of this experiment is to cross-calibrate several different infrasound sensing systems and test whether wind noise events occur in the stratosphere.

Although the modern balloon-borne infrasound program is less than five years old, it has already yielded unique scientific dividends. Infrasound sensors flew directly over an ocean microbarom source region, resulting in the first direct measurement of up going acoustic energy flux from this phenomenon. These results confirmed that sufficient energy flows upwards to heat the thermosphere by several degrees Kelvin per day (Bowman and Lees, 2018). Overflight of thunderstorms in the Tasman Sea resulted in the first detection of infrasonic thunder from above (Lamb et al., 2018). Ground chemical explosions captured by balloon-borne microbarometers have given a unique perspective on infrasound propagation in the stratosphere. The SISE/USIE experiment showed that free floating sensors have a superior signal to noise ratio than ground ones (Young et al., 2018) and the Heliotrope campaign demonstrated that a multi-balloon sensor network can locate acoustic sources (Bowman and Albert, 2018). Both experiments also highlighted the role of gravity waves in defining acoustic propagation patterns.

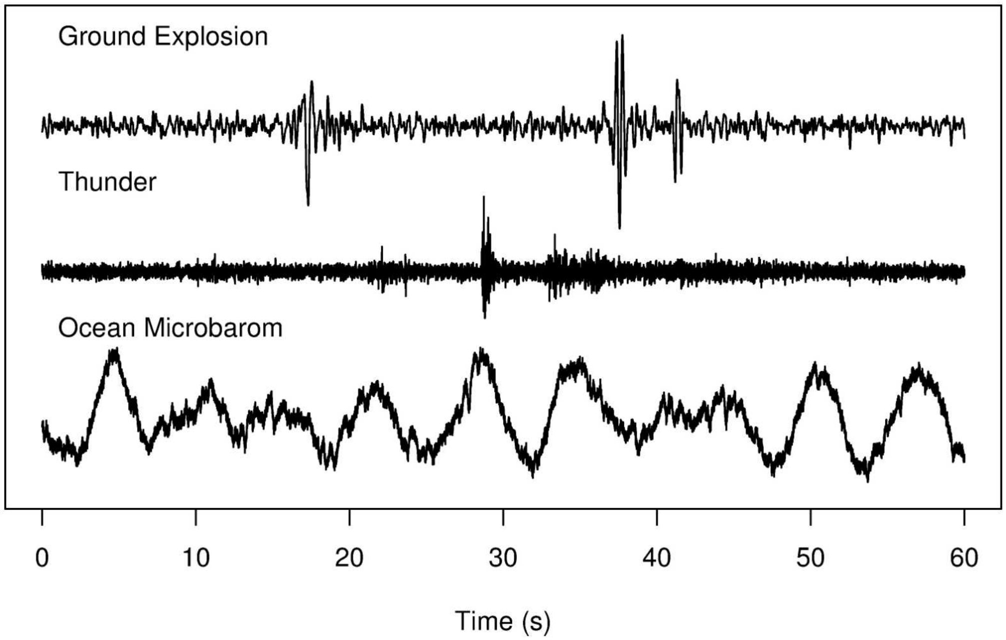

Figure 2: A ground explosion recorded over eastern New Mexico, USA (top), thunder above the Tasman Sea (middle) and the ocean microbarom southeast of New Zealand (bottom). All three traces have the same amplitude scale (approximately 0.03 Pa peak to peak).

2 Terrestrial Applications

Infrasound sensors and recording systems are very lightweight, ranging from several kilograms down to below 100 grams (e. g. the Gem Anderson et al. (2018)). This makes many of them compliant with the FAR 101 unmanned free balloon weight exemption, and several missions have already made use of this (Young et al., 2018; Bowman and Albert, 2018). Furthermore, they are a very attractive secondary payload on larger balloons because they are lightweight, simple to operate, generate minimal interference, and do not require pointing. Indeed, with the exception of the HASP flights and Heliotrope, all of the recent infrasound deployments have been secondary payloads.

Balloon-borne microbarometers are well suited to address a variety of scientific objectives, and are the only means of acquiring the required measurements in some cases. Floating sensors can delineate the dimensions of the acoustic "shadow zone", the width of which is often overestimated in acoustic propagation modeling (Hedlin and Walker, 2012). By capturing the up going direct and down going refracted acoustic waves from surface explosions, balloon-borne microbarometers can test the hypothesis that gravity waves in the middle stratosphere create the complex arrivals detected on the ground at ranges of 150 kilometers and greater. Energy from dissipating acoustic waves is a significant driver to upper-atmosphere heating (Rind, 1977). Ocean-microbarom derived energy flux has already been measured once from balloons (Bowman and Lees, 2018), but further observations from this source and others such as wind-mountain interactions (Semenov et al., 2012) and thunderstorms (Walterscheid et al., 2003) are needed to further constrain the magnitude of this effect. Furthermore, the possibility that anthropogenic infrasound is perturbing the upper atmosphere warrants investigation. The heightened sensitivity of balloons may make them very effective at capturing infrasound from meteors as small as golf balls. Underground explosions, earthquakes, and thunderstorms preferentially radiate infrasound vertically (Arrowsmith et al., 2012; Balachandran, 1983), implying that ground-based sensors only capture an incomplete picture of these phenomena. Infrasound may be an effective means of remotely detecting clear air turbulence; at present it is usually reported only when pilots encounter it directly. In this case, balloon-borne sensors could be used to validate models such as the NOAA ADDS Turbulence product. This is particularly important since clear air turbulence is predicted to increase as the climate warms (Storer et al., 2017). Finally, balloons can cross regions inaccessible to ground sensors, such as the open ocean. This can enhance missions such as that of the International Monitoring System, which is designed to detect nuclear explosions for the Comprehensive Test Ban Treaty Organization.

3 Planetary Applications

Balloons have been proposed for missions to Titan (Lorenz, 2008), the gas giants (Jones and Heun, 1997), and Mars (Jones et al., 1998). Helium balloons have been deployed on Venus already (Sagdeev et al., 1986). Balloon-borne microbarometers on these bodies should enjoy the same advantages as those on Earth. Their long-range detection ability would permit characterization of surface and atmospheric phenomena on geologically-active Titan. Balloons in the atmosphere of Jupiter are the equivalent of seismometers on the Earth; acoustic travel times through the planet's interior could give unprecedented detail on its inner structure. The exceptionally hostile surface of Venus does not permit seismic monitoring, but recent studies have indicated that floating microbarometers could capture acoustic waves from venusquakes (Cutts et al., 2016). Such detections could resolve long standing questions about the planet's tectonic activity and interior structure.

As noted above, microbarometers are an essential element for any lighter than air mission to another planet due to the extraordinary amount of information carried by acoustic waves. However, even the acoustic environment of Earth's stratosphere is just beginning to be explored. Lessons from terrestrial balloon campaigns, particularly with regards to event detection, discrimination, and attribution, will translate to sensor designs for extraterrestrial atmospheres. Thus, there is a strong short-term need for additional stratospheric deployments here on Earth.

4 Challenges

At present there are no infrasound sensors specifically designed for balloons. Existing micobarometers often encounter difficulty in the harsh thermal and pressure environments at high altitudes. While observed changes in sensor frequency response during actual missions are consistent with theory, only limited calibration data are available at stratospheric pressures (Bowman, 2016). Since acoustic amplitudes decrease as pressure drops, other noise sources such as electronic interference can be a problem if the sensors are not properly shielded (Bowman and Lees, 2015). Finally, the recorders must be recovered from the balloons, creating the risk of data loss if the payload is destroyed or inaccessible after landing.

Pressure measurements are scalar values. In order to get a direction of arrival vector for an acoustic wave, multiple sensors separated by several tens of meters are needed. It is thus impractical to capture signal azimuth on a single balloon, although elevation angle of arrival can be captured using sensors on tethers (Bowman and Lees, 2015). The Heliotrope experiment showed that multiple balloons could be used to locate an acoustic source (Bowman and Albert, 2018), although the network will eventually drift apart (Lally, 1967). Recent innovations in balloon stationkeeping (e. g. Project Loon, Stratollites) may provide a solution to this issue on Earth. However, fielding multiple balloons on another planet for the express purpose of acoustic source localization seems unlikely.

The majority of signals recorded on balloons are of unknown origin; this is true for campaigns in the mid twentieth century (Wescott, 1964) and recently (Bowman et al., 2019). This is both a challenge and an opportunity. Determining the provenance and significance of these signals remains an exciting avenue for future research.

5 Path Forward and Recommendations

At present, there is a need for infrasound sensors optimized and calibrated for high altitude environments. New concepts in array design, or even single-unit direction of arrival sensors (such as particle velocity rather than pressure measurements) are needed to discriminate between acoustic waves arriving from different azimuths. Single-station data analysis techniques for event discrimination and attribution need to be developed.

The field will benefit from more data collection over different altitudes, regions, and seasons to characterize background noise levels and signal sources. This is simple to accomplish – since microbarometers are lightweight and low power, they should be added to as many existing balloon missions as possible. The additional data volume, in tandem with dedicated high altitude sensors and new analysis techniques, will greatly advance the discipline.

Data telemetry is a challenge on Earth; on other planets it is even more restrictive. An extraterrestrial balloon infrasound mission will almost certainly not be able to continuously transmit data back to Earth. It is therefore critical to develop onboard processing methods that can flag signals of interest, determine direction of arrival, or even perform event attribution.

The Balloon Program Office could advance these objectives by

- Encouraging the principal investigators of large balloon missions to offer and advertise secondary payload opportunities
- Developing and advertising payload slots on the flight ladder and/or apex of the balloon envelope to permit vertically-oriented acoustic arrays
- Supporting single or multi balloon missions with very small (kilogram scale) payloads

6 Conclusions

Low frequency acoustic waves transmit information across vast distances, making them valuable records of surface and atmospheric phenomena hundreds to thousands of kilometers away. Recent work has shown that microbarometers on high altitude balloons can acquire these signals very effectively, offering a powerful alternative to traditional ground-based deployments. Since the data acquisition systems are lightweight and low power, they are easy to add as secondary payloads to existing terrestrial balloon missions. Furthermore, infrasound detectors could greatly add to the scientific impact of balloon payloads delivered to the atmospheres of other planets. Present technical research is focused on developing sensors optimized for high altitudes, investigating data telemetry methods, and discriminating between classes of events. Scientific questions such as the effect of middle stratosphere gravity wave activity on infrasound propagation, the magnitude of up going acoustic wave energy, and the existence of vertically-directed acoustic wave fields represent attractive targets for future balloon campaigns.

7 Acknowledgments

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