University of Colorado
Department of Aerospace Engineering Sciences
Senior Projects – ASEN 4018

ASTERIA

(**A**loft **S**tratospheric **T**estbed for **E**xperimental **R**esearch on **I**nfrasonic **A**ctivity)

Conceptual Design Document

September 29, 2014

1.0 Information

1.1 Project Customer

ELIOT YOUNG
Southwest Research Institute, Boulder
Phone: (720) 432-2333
Email: efy@boulder.swri.edu

1.2 Group Members

KERRY WAHL (303) 885-1494 kerry.wahl@colorado.edu	EMMA YOUNG (719) 641-1747 emma.young@colorado.edu	KYLE GARNER (720) 837-6379 kyle.garner@colorado.edu
CONNOR DULLEA (303) 524-4295 connor.dullea@colorado.edu	IAN THOM (303) 927-9981 ian.thom@colorado.edu	MARTIN HEANEY (720) 326-6831 martin.heaney@colorado.edu
MICHAEL VON HENDY (303) 505-0111 michael.vonhendy@colorado.edu	COURTNEY BALLARD (303) 746-9379 courtney.ballard@colorado.edu	EMILY DAUGHERTY (719) 221-4612 emily.daugherty@colorado.edu

2.0 Project Description

The ASTERIA team, in conjunction with Southwest Research Institute (SwRI), will design and build a high-altitude balloon payload capable of measuring sound waves between 0.1 and 20 Hz. The payload will later be used by SwRI to measure infrasonic activity in the stratosphere. The following sections outline the project purpose, objectives, and concept of operations of the payload.

2.1 Project Purpose

Infrasonic waves are shock waves with a frequency of less than 20 Hz that are generated by a number of natural sources[1]. One particular source of interest is bolides – meteors that enter the Earth's atmosphere and disintegrate before impacting the surface. The disintegration of bolides creates a large explosion that generates infrasonic waves. Due to the low frequency of infrasound waves, they are able to propagate long distances and can be detected by ground-based stations around the world.

The existing Comprehensive Nuclear-Test-Ban Treaty International Monitoring System (CTBT-IMS) network, which is used to detect infrasound on Earth, is currently only capable of sensing approximately 30% of 0.1-kiloton explosion events[2]. Some events are missed due to the presence of noise, mostly from wind, and to atmospheric ducts that channel infrasound upwards; vertical wave guides in the lower atmosphere greatly increase the amount of vertical infrasound propagation relative to horizontal propagation.

There exists a need to detect a greater percentage of these events to improve the understanding of the near-Earth object population. There is interest in expanding the current network of detection to include sensors located within the stratosphere. It is proposed that using an infrasonic sensing platform within the stratosphere could reduce sources of noise and capitalize on vertical atmospheric ducts, permitting more accurate and precise detection of infrasonic events by increasing the probability of event detection.

The purpose of this project is to develop a high-altitude balloon payload, the Aloft Stratospheric Testbed for Experimental Research on Infrasonic Activity (ASTERIA), which is capable of measuring infrasonic events. ASTERIA will consist of a microphone system capable of measuring infrasonic waves and a support package to store data, and provide thermal control, power, and a structural housing for approximately 24 hours – the duration of an average balloon mission. ASTERIA will be verified for operation in the stratosphere through testing in controlled temperature and pressure environments.

2.2 Project Objectives

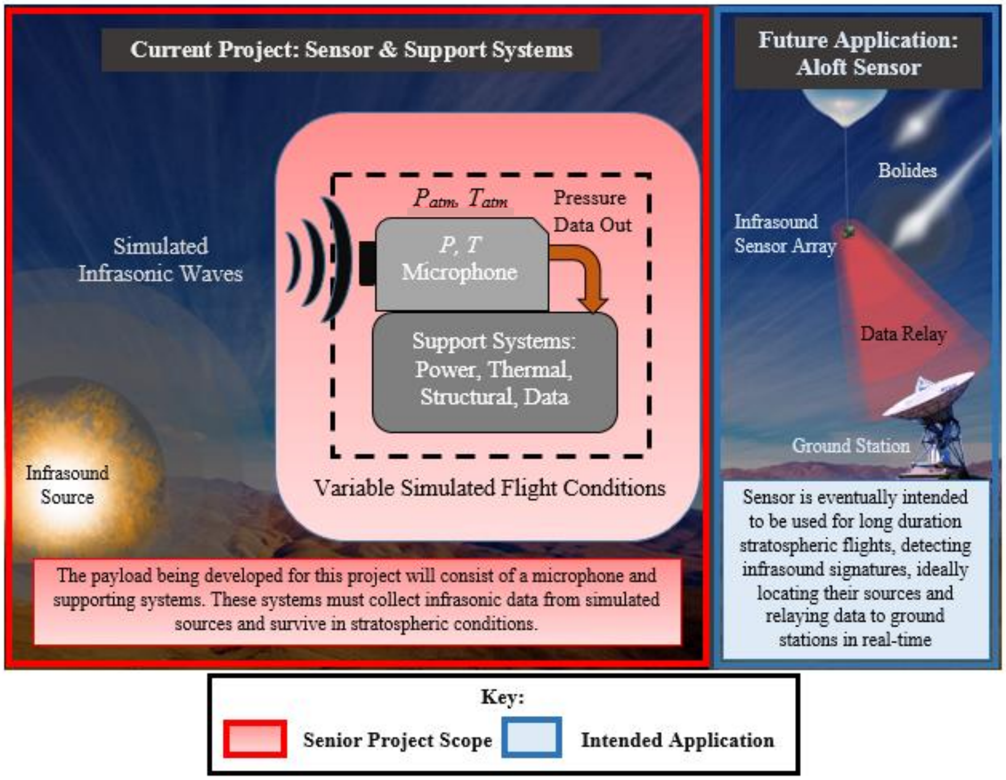
The primary goal of the project is to deliver a functionally tested payload, designed for 18 to 30.5 kilometer balloon flights, capable of measuring and storing infrasonic wave data. Infrasonic measurements have not yet been attempted in the Earth's stratosphere, so the objective of this project is to provide SwRI with a payload that will:

- Measure infrasonic waves between 0.1 and 20Hz frequencies, and an amplitude of 0.1 Pa.
- Survive and operate autonomously from 18-30.5 km. This includes autonomous operation of the instrument suite, Command & Data Handling, Power, Thermal, and Structural subsystems.
- Record and store data for payload subsystem temperatures and sound pressure.

The payload will be tested on its ability to detect infrasonic waves in a low pressure, low temperature environment, as well as survive the flight termination and ground impact events of the mission. The actual balloon flight is considered to be outside the scope of this project, so payload testing will be performed at the subsystem level with resources available on campus and at the NOAA facility.

2.3 Project Concept of Operations (CONOPS)

The scope of this project encompasses the building and testing of an infrasonic sensor balloon payload and ground test equipment for the infrasonic sensor. Figure 1 illustrates the goal of the current project as well as the intended future applications of the infrasound payload.



The payload being developed for this project will consist of a microphone and supporting systems. These systems must collect infrasonic data from simulated sources and survive in stratospheric conditions.

Sensor is eventually intended to be used for long duration stratospheric flights, detecting infrasound signatures, ideally locating their sources and relaying data to ground stations in real-time

Figure 1. ASTERIA Project Concept of Operations

This project requires a microphone capable of detecting simulated infrasonic signals during testing, which will be done by recording voltages produced due to a pressure differential; the infrasound will be produced using a low frequency generator – most likely a Helmholtz generator. The microphone must also be capable of surviving in the harsh environment of the stratosphere. Thus, supporting systems will provide thermal regulation, power, structural support, and data storage capabilities. When operating, the payload will be a self-contained unit, collecting and saving data with no outside support.

Eventually the payload will be modified, by SwRI, to collect data for extended flights and relaying this data instead of simply storing it. While the initial payload itself will save data to solid-state memory, the future payload would be modified to contain a communications system so that information and instructions can be transferred between the payload and ground stations. The aloft sensor’s intended purpose is the detection of bolides through their infrasound signatures. This purpose could be expanded to explore other significant sources of infrasound in the upper atmosphere, gather data on the propagation of infrasound waves above the atmospheric boundary layer, and fully validate whether an upper atmospheric bolide detection platform provides better infrasonic data than its ground counterparts.

2.4 *Functional Block Diagram*

The orange box in Figure 2 is the designed infrasound detection payload. A microphone on board the payload measures propagating infrasound waves, producing an analog signal. This analog signal is conditioned – amplified and filtered – and converted to a digital output, which is stored in on board memory. To collect useful data, a spatial filter system will be added to attenuate noise due to wind. Spatial filters are physical attachments mounted to the exterior of the pressure sensor that increase the sampling surface area, thereby creating a spatially averaged measurement. All of these components require both power to remain functional and thermal control to stay within their operational temperature ranges. The thermal control is based upon onboard temperature readings of the various components

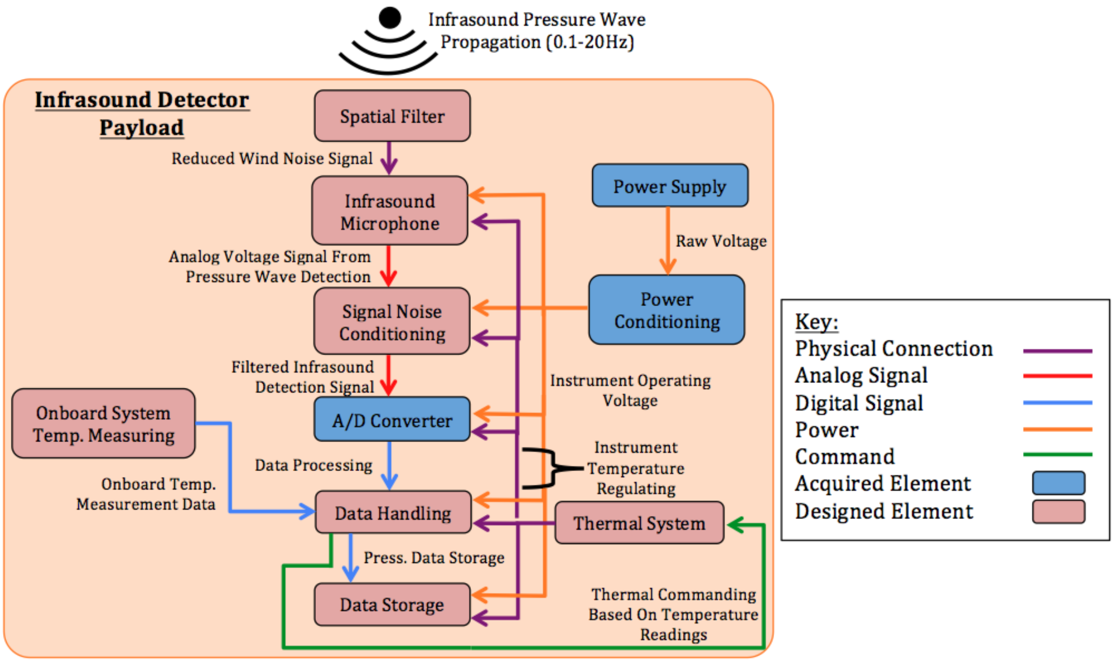


Figure 2. Functional Block Diagram

2.5 Functional Requirements

The functional requirements of a project define its ultimate goals and objectives; functional requirements are either defined specifically by the customer or set by the engineering team to accomplish the project goals. The functional requirements for the ASTERIA mission are outlined in Table 1.

Table 1. Project Functional Requirements

Requirement Designation	***Description***	***Parent Requirement***	***Verification***
FR.1	ASTERIA shall collect pressure measurements from simulated infrasonic sources between 0.1 and 20 Hz, with a sensitivity of 0.1 Pa.	Customer	All lower level requirements are fulfilled.
FR.2	ASTERIA shall be housed and operate on a balloon that travels to 18 to 30.5 km.	Customer	All lower level requirements are fulfilled.
FR.3	ASTERIA shall operate autonomously for the duration of the mission flight.	Customer	All lower level requirements are fulfilled.

3.0 Design Requirements

The first functional requirement (FR.1) specifies collection parameters for the pressure data due to infrasonic waves. Collection implies both taking measurements and storing data. These two tasks require a microphone system capable of taking pressure measurements, a signal conditioning circuit to condition the microphone's measurement into one useable by a microprocessor, a microprocessor to format physical measurements into a useable data type, and a data storage device to record the measurements. To collect useful data, a spatial filter system will be added to attenuate noise due to wind. Spatial filters are physical attachments mounted to the exterior of the pressure sensor that increase the sampling surface area, thereby creating a spatially averaged measurement. The design requirements in Table 2 below outline the parameters required to accomplish FR.1.

Table 2. Design Requirements for Functional Requirement FR.1

FR.1: ASTERIA shall collect pressure measurements from simulated infrasonic sources between 0.1 and 20 Hz, with a sensitivity of 0.1 Pa.

Requirement Designation	***Description***	***Parent Requirement***	***Verification***
DR.1	The microphone system shall measure pressure changes of magnitude 0.1 Pa (74 dB SPL) at a minimum sample rate of 40 Hz (twice the maximum frequency to avoid aliasing).	FR.1	Testing – Infrasonic waves will be generated to produce pressure changes with a controlled, predictable frequency signature at 10 Hz.
DR.2	The spatial filtering system shall reduce wind noise within the 0.1 to 20 Hz frequency range with minimal artificially generated false infrasound signatures.	FR.1	Testing – Noise reduction will be tested in the ITLL wind tunnel. False signal generation will be analyzed via post-processing of wind tunnel pressure data.
DR.3	The configuration shall reduce signal attenuation due to sensor array directionality.	FR.1	Testing - The configuration will be verified by performing multiple infrasound tests from various incident angles.
DR.4	The output voltage from the microphone shall be filtered with an analog low-pass filter to reduce sound pressure measurements with a frequency above 20 Hz.	FR.1	Testing – The filter will be verified using an ITLL function generator and oscilloscope.
DR.5	The output voltage shall be amplified from the microphone output to the microprocessor's voltage. Typical microprocessor voltages range from 0 to 5 volts.	FR.1	Testing- The amplifier will be verified using an ITLL function generator and multimeter.
DR.6	The amplified output voltage shall be converted from analog to digital signal using a resolution to accurately represent the pressure changes. Typical resolutions are 24 - 32 bit.	FR.1	Testing – The A/D converted will be verified with an ITLL function generator and oscilloscope.
DR.7	All onboard measurements shall be handled by a microprocessor then recorded on a removable data storage device.	FR.1	Testing – The data handling system will be tested with a function generator in the ITLL to simulate incoming pressure data.

The second functional requirement (FR.2) addresses the need for the payload to operate in a stratospheric environment (18-30.5 km). This requirement encompasses the functionality of the payload in low pressure and low temperature environments, as well as the structural survivability of the payload during descent.

Table 3. Design Requirements for Functional Requirement FR.2

FR.2: ASTERIA shall operate between altitudes of 18 and 30.5 kilometers.			
Requirement Number	***Design Requirement Description***	***Parent Requirement***	***Verification and Validation***
DR.8	ASTERIA mass and volume of the payload shall remain as small as possible – not to exceed 20 kg or 5 m^3 respectively.	FR.2	Inspection – the payload mass and volume shall be weighed and the dimensions measured.
DR.9	ASTERIA shall be capable of operating under stratospheric pressure conditions: 300 to 500 Pa.	FR.2	Testing – the microphone sensor, and support electronics, will undergo testing in a vacuum chamber.
DR.10	ASTERIA shall be capable of operating under stratospheric temperature conditions: -60° to 40° C.	FR.2	Testing – the microphone sensor, and support electronics, will undergo testing in a vacuum chamber with sufficient thermal capabilities.
DR.11	ASTERIA shall maintain structural integrity under launch and landing loads: approximately 1400 to 1600 N.[9]	FR.2	Modeling – the structural survivability of the payload will be verified using load simulation software.

The third functional requirement (FR.3) addresses the need for ASTERIA to operate autonomously for a minimum typical balloon flight of 24 hours. The design requirements that dictate thermal, power, and data storage capabilities to support FR.3 are described in Table 4.

Table 4. Design Requirements for Functional Requirement FR.3

FR.3: ASTERIA shall function autonomously for a minimum of 24 hours.			
Requirement Number	***Design Requirement Description***	***Parent Requirement***	***Verification and Validation***
DR.12	ASTERIA shall measure the temperature of payload components to a minimum of 1° C resolution.	FR.3	Demonstration – Collect temperature data and verify that data is taken at a resolution of 1° C.
DR.13	ASTERIA shall maintain the temperature of payload components to a range that is 10 ± 1° C below the maximum and above component minimum specifications.	FR.3	Testing – ASTERIA will be exposed to the maximum (+40 ± 1° C) and minimum temperatures (-60 ± 1° C) and verified to maintain temperature within the specified range
DR.14	ASTERIA shall provide necessary power as dictated by component specifications for a minimum of 24 hours.	FR.3	Testing – All systems will be powered on and sample pressure data will be collected to simulate flight for 24 hours
DR.15	ASTERIA shall be capable of storing a minimum of 24 hours worth of pressure and temperature data onboard.	FR.3	Analysis – Run simulation to determine necessary data storage volume Testing – Perform a ground test to verify all pressure and temperature data collected is able to be stored onboard

4.0 Key Design Options Considered

4.1 Methods of Infrasound Detection

Currently, there are various methods for ground-based infrasound collection. The purpose of this project is to take those methods and adapt them for use in the stratosphere. Figure 3 outlines the various methods considered for an infrasound measurement instrument. The primary design consideration focused on the infrasound microphone system because the subsystems specified by FR.3 are readily available in a commercial off-the-shelf format; whereas the infrasound microphone system must be redesigned for operation in the stratosphere.

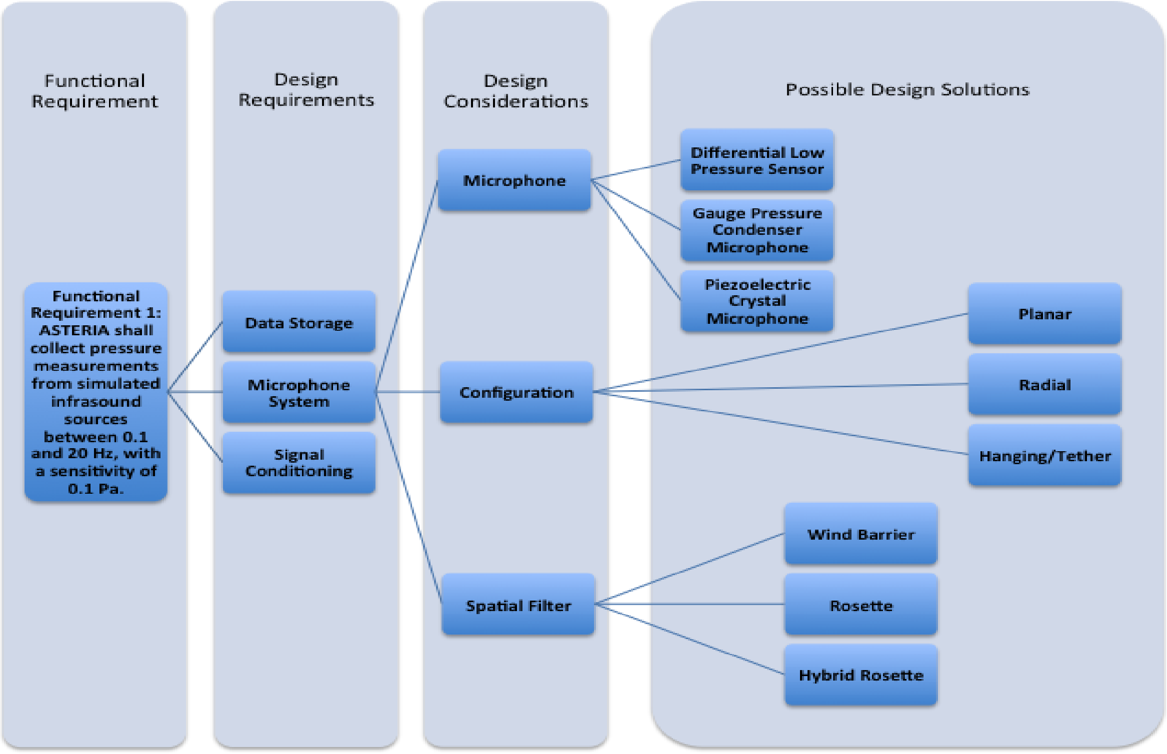


Figure 3. Functional Requirement Flow Down

4.2 Microphone Detector Design

Detecting pressure changes is the fundamental principle behind both pressure sensors and microphones; however the methods used by each differ. Microphones commonly use a capacitive or current induction system to detect pressure as decibels of sound pressure level (SPL), measured relative to the lower level of human hearing, which is 0.00002Pa and 0 dB SPL.[6] Frequency response, decibel range, and decibel sensitivity are the quoted specifications for microphones. Pressure sensors commonly use a strain-gauge methodology, including piezoelectric systems. The sensitivity and the survivable pressure levels are given in units of pressure, not decibels.[8] These are both broad categories however, and there is significant cross-over in capabilities. Both types were considered in this document, and potential differences accounted for in their respective sections.

All of the detector designs considered in this document utilize either differential or gauge pressure measurements. Differential sensors are designed to measure changes in pressure between two points, where the conditions or inputs at both points can be determined by the user. Gauge pressure sensors measure the pressure at one point relative to the local atmospheric pressure. These designs allow for the best resolution, since there is often a very small difference in pressures, and a properly designed sensor will be able to resolve small fluctuations relative to this difference.[3]

The other main category of pressure measurement is the vacuum-referenced absolute pressure. Absolute pressure devices identify the true pressure relative to a vacuum, and are not designed to detect small changes in local pressure. Though they have the broadest ranges of any pressure-based sensor, their resolution is diminished.[8] The diaphragm, the element that must contain the reference pressure and measure the pressure relative to it, must be more rigid than in a differential sensor, which limits how much it can flex in response to small disturbances. For this application, absolute pressure was not needed, and giving up the resolution of the other types for that measurement was unnecessary. Thus, no absolute pressure sensors were carried through to this point.

4.2.1 Amplified Very Low Pressure Sensor

This microphone concept relies on the use of a low cost differential pressure transducer to detect low frequency (1-20 Hz) sound waves. Specifically, this section considers sensors based on a capacitive measurement system, as seen in Figure 4. When the pressure in one of the volumes changes relative to the other, a capacitor in the diaphragm is compressed and a voltage difference is registered; the capacitor in this case is a pre-polarized, or electret, capacitor so it does not require a large voltage input to retain capacitance levels.[4] These sensors allow the user to determine what pressures are being compared, and for this project the reference would be $P_{ambient}$ to minimize the danger of the membrane bursting and increase sensitivity. An increase in differential pressure would occur if P_1 increased or decreased relative to $P_{ambient}$, as in the case of a sound wave entering Volume 1 while Volume 2 remained at ambient pressure; the sound wave would not affect Volume 2 because of the opposing directionality of the ports leading to Volume 1 and Volume 2. It is important to note that with differential pressure sensors there is no sealed area, both volumes are open to the ambient environment, so the possibility of rupturing the diaphragm during the ascent or float phases decreases. Because both volumes are open to the ambient pressure, noise due to changes in temperature is also reduced because both sides heat and cool at approximately the same rate.

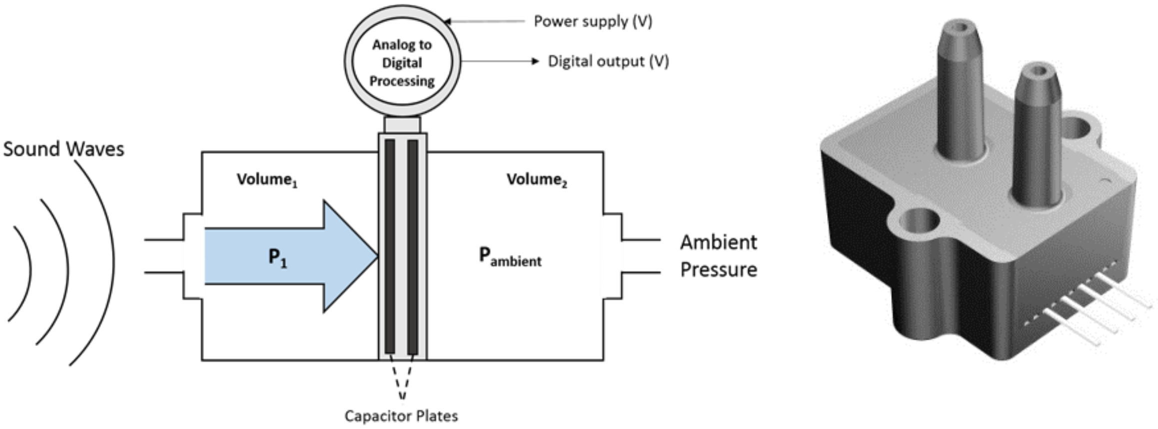


Figure 4. Differential Pressure Sensor[8]

Equation 1 is used to determine the change in capacitance, while Equation 2 determines the corresponding change in voltage:

$$\Delta C = \frac{\epsilon A}{\Delta d} \tag{1}$$

$$\Delta V = Q \Delta C \tag{2}$$

Here, C is the capacitance, V is the voltage across the sensor, Q is the charge on the two plates, A is the area of each plate, ϵ is the permittivity of the material separating the two plates, and d is the distance between them. This shows that there is a linear relationship between the displacement and voltage measured, which can be calibrated to pressure through linear calibration constants provided with the sensors. Table 5 shows the benefits and issues with using a differential pressure sensor.

Table 5. Differential Pressure Sensor Pros and Cons[4]

Advantages	Disadvantages
Able to detect minute pressure changes, on the order of 0.5-1 Pa (88-94dB SPL) fluctuations	Temperature range of -25 to 85°C means these sensors will require insulation
Small profile and low mass, on the order of 16 cm^3 and <0.1kg	Strongly unidirectional, only able to sense pressure waves traveling parallel to the direction the inlet is pointed
Durable diaphragm, takes no damage up to 25kPa differential pressure	Compensation for noise due to temperature only calibrated for values between 5 and 50°C
Low cost, under $100 and available through general electrical distributors	Requires significant signal amplification
Resists condensation, made from plastic materials with no exposed metal	

4.2.2 Piezoelectric Crystal Microphone

This detection system would use commercially available piezoelectric microphones to collect pressure data. These sensors use a thin diaphragm that moves based on the pressure difference across them. This motion is then converted to voltage using a piezoelectric crystal, as seen in Figure 5. The crystal generates a voltage in response to strain. By fixing one end to the case and connecting the other end to the diaphragm, this voltage correlates to displacement and in turn, can be correlated to pressure on the sensor.[8] These sensors have near-linear responses to pressure and come calibrated, so converting from voltage to pressure requires only simple algebra. They commonly require a specific preamplifier that can be purchased with the sensor. They also require an excitation voltage or current to energize the crystal.[7] The crystals are affected by other types of strain as well, so adjustments would need to be made for motion of the sensor. These sensors can pick up pressure waves from the field in front of them, making them mildly directional. The benefits and issues with using these sensors can be seen in Table 6.

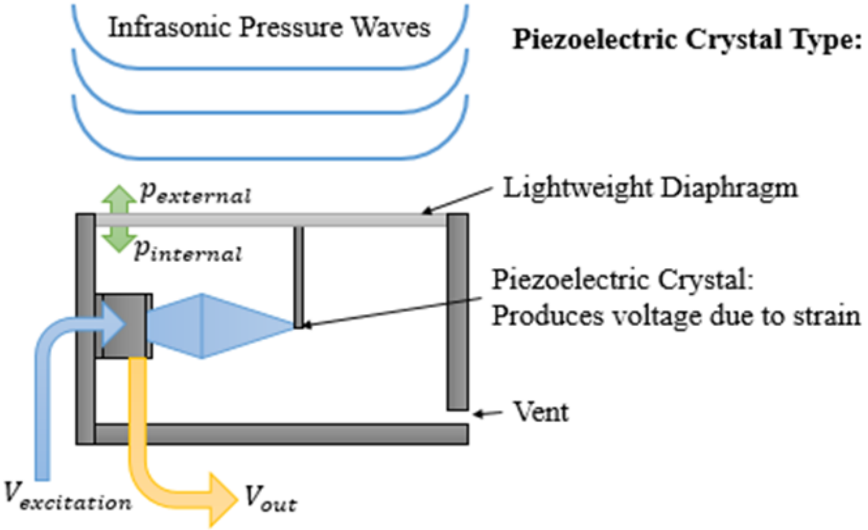


Figure 5. Piezoelectric Crystal Sensor

Table 6. Piezoelectric Crystal Sensor Pros and Cons[7]

Advantages	Disadvantages
Thin diaphragm allows for detection of pressure changes on the order of 0.1 Pa (74 dB SPL)	Frequency responses tend to be cut-off at 5 Hz, which is high for this project
Small profile and low mass on the order of 16 cm^3 and <0.1kg	Expensive and require specialized equipment to function properly, which increase cost, mass, and volume
Resistant to temperature and pressure, able to operate as low as -73°C with a maximum differential pressure of over 1000kPa	Require voltages of 20-30V for excitation, increasing cost, mass, and volume further
Resistant to shocks and impacts due to sturdy sensing material	Sensitive to vibrations and motion of sensor

4.2.3 Gauge Pressure Condenser Microphones

This detection system would use commercially available gauge condenser microphones to collect pressure data. As opposed to the sensor outlined in Section 4.2.1, these microphones do not allow the user to set the reference pressure, instead being vented to the local atmosphere. Another difference is that only one plate in these sensors moves, instead of both. As seen in Figure 6, the capacitance changes as the lightweight plate exposed to the target waves moves relative to the fixed back plate, causing the voltage across the sensor to be modulated.[5] Equations 1 and 2 in Section 4.2.1 illustrate the basic principles behind these sensors. These sensors have linear responses to pressure and are calibrated by the manufacturer, so converting from voltage to pressure is a matter of simple multiplication. They require a preamplifier, like the other sensors, however they also require a large polarization voltage, commonly 200V, to maintain charge between the plates.[5] The top plate is also highly sensitive to motion in the axis perpendicular to the plates, as any motion of the top plate is registered as a voltage. This could be accounted for using an accelerometer, though this is an additional element required for its use. Finally, these sensors detect a pressure field in front of them, making them mildly directional. The benefits and issues with using these sensors can be seen in Table 7.

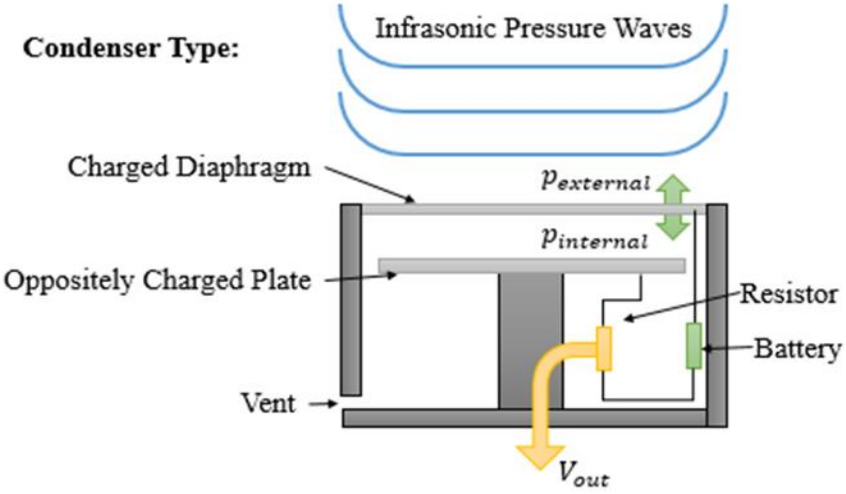


Figure 6. Gauge Pressure Condenser Sensor

Table 7. Gauge Pressure Condenser Sensor Pros and Cons[5]

Advantages	Disadvantages
Thin diaphragm allows for detecting pressure changes on the order of 0.1 Pa (74 dB SPL)	High amplitude signals and rapid pressure changes can damage the diaphragm in spite of venting, as the vents are small and the diaphragms thin and fragile
Can be optimized for low-frequency signals, as low as 0.07 Hz with a 0.01 Hz -3 dB point.	Expensive and require specialized equipment to function properly, which increase cost, mass, and volume
Lightweight and small profile, on the order of 16 cm^3 and <0.05kg	Requires a 200V supply, increasing cost, mass, and volume further
Resistant to temperature, humidity and shock.	Sensitive to vibrations along axis perpendicular to diaphragm

4.3 Spatial Filtering Design

To achieve FR.1, the sensitivity of the infrasonic microphone system must detect pressure changes of approximately 0.1 Pa. However, the winds seen in the stratosphere can cause a dynamic pressure that can introduce noise into the system. Wind speed models of the stratosphere predict maximum wind speeds of approximately 67 m/s. Because this speed places the flow within the compressible flow regime, the dynamic pressure can be predicted using the NASA standard atmosphere model and Bernoulli's equation, given by Equation 3.

$$\frac{1}{2}\rho V^2 + \rho g z + p_0 = Const. \tag{3}$$

Where ρ is the local density at altitude, V is the wind speed, g is the acceleration due to gravity, z is the altitude, and p_0 is the static pressure at altitude. Bernoulli's equation predicts that wind speeds of 1.3-3.4 m/s will exceed the microphone's sensitivity as defined in section 4, if the wind is unfiltered. At altitudes of approximately 25 km and above, applying a 15dB spatial filter decreases the dynamic pressure imparted by wind disturbances to below 0.1 Pa, the microphone sensitivity threshold. Figure 7 below shows a plot of the wind speeds that cause a 0.1 Pa disturbance relative to altitude. For example, at an altitude of approximately 18 km, the microphone with a 15dB spatial filter could withstand wind speeds up to 48 m/s before it begins to register the wind as noise. This plot confirms the necessity to provide filtering for the microphone.

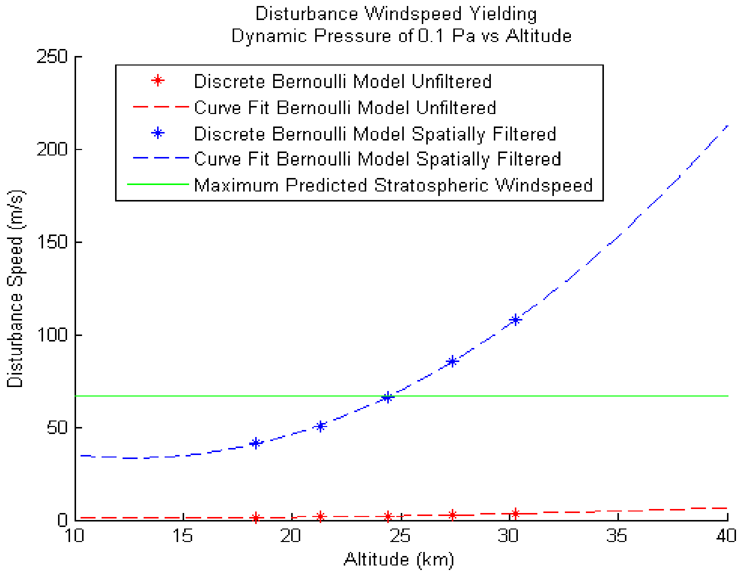


Figure 7. Wind speed disturbance vs altitude for microphone

4.3.1 Wind Barrier

Wind noise reduction during infrasonic signal measurement can be achieved using a physical wind-screening method, known as a barrier. Barriers function to reduce noise from wind pressure by both deflecting incoming small scale turbulent bursts of wind and distributing incoming pressure increases over the exposed surface area. Although barriers attenuate sudden, large magnitude pressure changes, they are permeable enough to permit the ambient, low pressure differentials resulting from infrasound to pass. The barrier wind noise reduction concept is outlined in Figure 8 below.

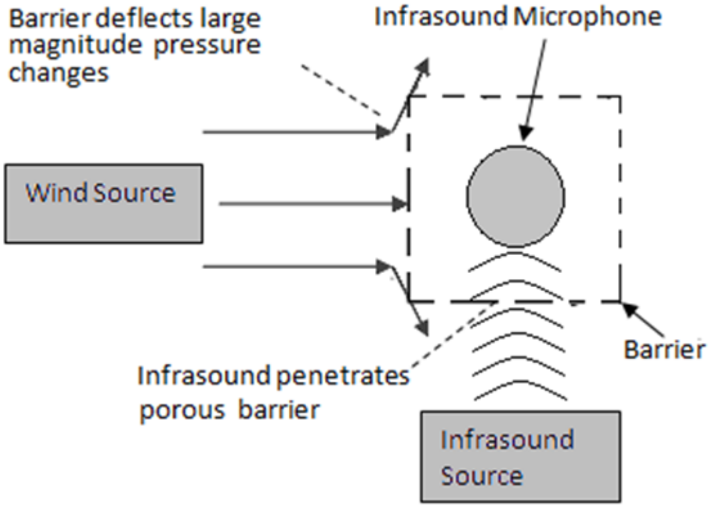


Figure 8. Barrier functionality scheme for wind noise reduction

Barrier design permits several configurations and sizes. The shape of a barrier is only constrained by frame construction and material weight limitations. Selection of barrier material is driven by the need for porosity; a material must be permeable enough to permit sufficient ambient pressure detection while still providing the microphone shelter from wind disturbances. Porous materials have the advantage of mass reduction relative to a solid material spatial filter. Furthermore, these materials, such as polyethylene or polyurethane foam, are readily available and easy to incorporate into a barrier design.

Barriers possess ideal noise reduction properties. The reduced corner frequency represents a normalized frequency at which the filter's relative noise reduction ratio drops to the half power point. The reduced corner frequency of a barrier can be determined as the product of the incoming signal frequency with the ratio of the characteristic size to the disturbance wind speed, as given below by Equation 4:

$$R = f * \frac{L}{v} \tag{4}$$

In this equation, R is the reduced corner frequency, f is the frequency, L is the barriers characteristic size, and v is the wind speed.

For wind disturbances below the corner frequency of the barrier, an ideal design attenuates approximately 90% of the wind noise, or about 20 dB of relative reduction.[11] Wind disturbances exceeding the corner frequency of the barrier are still attenuated by about 4 dB relative to the background noise. Furthermore, barriers have a functional operating range in which they reduce wind noise from frequencies as low as 0.05 Hz to frequencies well above the infrasonic spectrum.[11] Finally, due to the non-isotropic nature of porous materials, pressure propagation through a barrier is unlikely to cause resonance since the material properties vary throughout.

Table 8. Pros and Cons of Wind Barrier

Advantages	Disadvantages
Barrier shape is adaptable	Requires additional mass and volume added to payload, dependent on shape, size, and material.
Large operational frequency range: ≥0.05 Hz	Material versatility causes uncertainty in manufacturability.
20-25 dB noise reduction relative to the background wind noise for wind disturbances below reduced corner frequency, otherwise 17-18 dB reduction.	Barrier spatially averages falsely detected signals, yielding a constant bias in pressure data from wind disturbances.
Non-isotropic material reduces resonance and reduces temperature dependence with respect to noise reduction.	

4.3.2 Spatial Filtering - Rosette

Rosettes reduce signal noise due to wind by collecting average pressure measurements over a large area, relative to the area of the microphone. A rosette, seen in Figure 9, consists of attaching long tubes to the microphone with small inlets drilled along the length. Capillaries are placed inside the tube at the junction connecting the tubes to the microphone. These capillaries are a semi-permeable material that prevents sudden variations in pressure from entering the microphone, which helps to prevent damage from occurring to it. Three primary factors go into selecting the tube lengths: the resonant frequency of the tube, the desired pressure sample area, and the overall size of the structure. Equation 5 shows how the resonance frequencies are characterized by the tube length. In this equation F_n is the frequency of the nth harmonic, a_0 is the speed of sound, and L is the tube length.

$$F_n = \frac{a_0}{2L}n \quad \text{for n=1,2,3,…} \tag{5}$$

Table 9 shows the first two harmonics for various tube lengths. In this table, the values shown correspond to the two temperature extremes of the flight, -60º C and 40º C. It is desirable to have a resonant frequency outside of the frequency range being observed to avoid amplification of noise. For this project resonant frequencies should fall outside the range of 0.1 to 20 Hz.

Table 9. Rosette Resonance for Various Lengths

Rosette Tube Length, m	1st Harmonic at -60ºC, Hz	2nd Harmonic at -60ºC, Hz	1st Harmonic at 40ºC, Hz	2nd Harmonic at 40ºC, Hz
30	4.915	9.830	5.932	11.863
20	7.373	14.745	8.898	17.795
10	14.745	29.490	17.795	35.590
5	29.490	58.980	35.590	71.180
2	73.725	147.450	88.975	177.950

Having multiple inlets exposed to the ambient conditions along a tube's length averages the pressure. A gust of wind striking the filter may vary the pressure readings over a section of the tube, but having multiple inlets reduces resulting noise. However, these tubes must remain in a plane orthogonal to the Earth's gravitational field to prevent various erroneous pressure readings due to density induced pressure gradients. This method of reducing wind noise has been well researched and observed to reduce noise in the range of 0.1 to 10 Hz, making it a viable option for spatial filtering.[10]

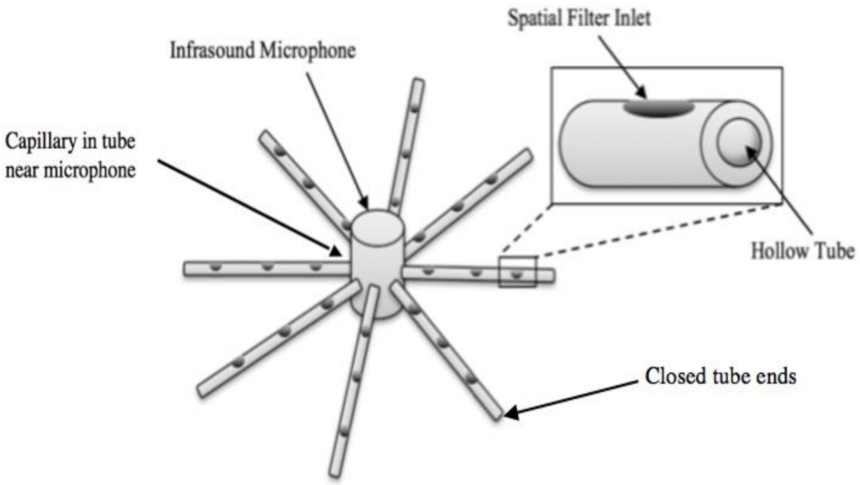


Figure 9. A rosette attached to an infrasound microphone

Table 10. Pros and Cons of Spatial Filter

Advantages	Disadvantages
Resistance to noise from wind due to pressure from 0.1 to 10Hz at various wind speeds.	False signal detection when the structure has sudden movements.
Currently being used by the CTBT-IMS sensor network	Resonates at distinct frequencies, thus amplifying noise. These frequencies are dependent on the tube length, see Table 9
	Can only collect pressure data in the direction that the holes are pointing.
	Tubes take up a large volume with respect to the microphone; each tube has a length ranging from 2-30m.
	Long tubes risk bending and breaking during flight; possible safety hazard.
	Prone to condensation and freezing in the tubes, preventing wave propagation.

4.3.3 Hybrid Spatial Filter

Since both spatial filter designs of interest are able to attenuate wind and other infrasonic noise substantially, a third design option is a hybrid of these two, combining the directional capability of a rosette with the significant wind reducing effects of a barrier. While a rosette uses capillaries to emulate a semi-permeable material, a barrier uses a porous material to reduce the presence of undesirable pressure disturbances so that low frequency pressure fluctuations can be detected and isolated.

The premise is to take the advantages of both types of filters that have been tried on the ground, and come up with a spatial filter that is conceivably less bulky for a balloon borne payload but just as effective as their ground counterparts. This entire configuration will either be connected to one or many infrasound sensors, or to a cavity open to one or many sensors in a summing junction. The external design is shown in Figure 10, with the internal structure pictured and a table of pros and cons of the design are given the following table.

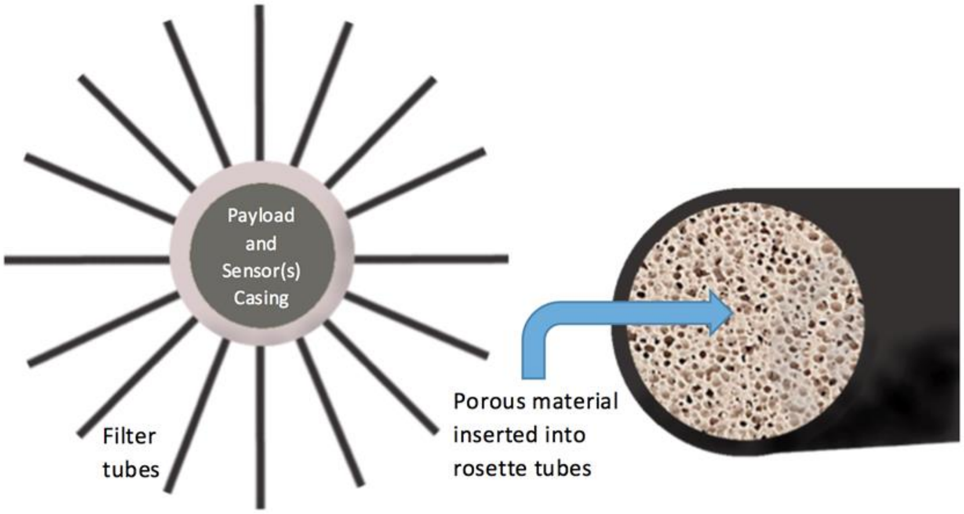


Figure 10. Hybrid spatial filter specifics, with rosette configuration and porous tube design

Table 11. Pros and Cons of Hybrid Spatial Filter

Advantages	Disadvantages
Directional wind noise issues reduced with many inlets in all different directions	Still requires bulky structure
Prevents against wind gusts inside tubes	Unknown moisture effects on porous material could potentially lead to freezing inside and loss of infrasound detection ability
Summing junction effect of rosette combined with barrier advantages	Unknown vibration and resonance responses
Reduction below corner frequency[10]	Payload balance issues, where the structure may not be aligned perfectly parallel to the payload
	Unknown propagation effects due to porous material inside

4.4 Microphone Array Configuration Design

4.4.1 Radial Configuration

A radial configuration of microphones allows for the detection of infrasound waves coming from a wide range of locations relative to the payload. Inspired by submarine sonar transducer arrays[17], a radial configuration accommodates *n* number of infrasound microphones, distributed radially around a spherical, ellipsoidal, or cylindrical surface (Figure 11). As the number of microphones increases, the collective "field of view" of the microphones increases and the array will be able to pick up incoming infrasound sources from an increasing number of directions. For an ellipsoidal or spherical design, as the number of microphones *n* approaches the maximum that can physically be accommodated on the structure, the equivalent "field of view" of the array approaches 360 degrees in any direction around the structure minus any blockages due to the balloon or gondola. For the cylindrical array, as the number of microphones reaches its maximum that can be physically accommodated, the equivalent "field of view" approaches 360 degrees around the perimeter of the cylinder. Sensors could be placed on the top and bottom surfaces of the cylinder, or they could be omitted to mount other hardware on those surfaces such as attachment hardware for a tether.

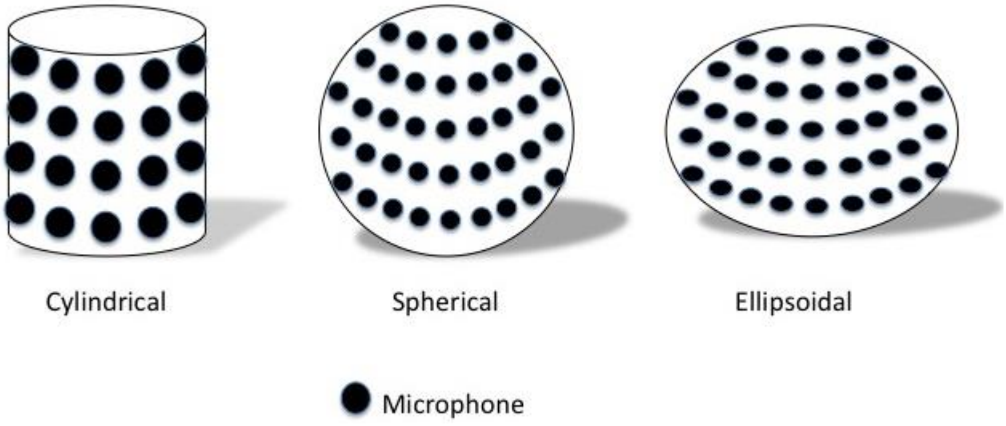


Figure 11. Radial Configuration Microphone Distribution

Figure 12 below shows the geometry of the microphone field of view and the incoming infrasound waves. The infrasound microphones under consideration are unidirectional, meaning they can best detect incoming infrasound signals from the direction in which they are pointed. However, an attenuated signal can still be detected if the angle perpendicular to the incoming infrasound wave front is greater than 15° from the microphone local horizontal for frequencies greater than 1 Hz; for frequencies less than 1 Hz, any incoming angle can be detected without severe signal attenuation.[10]

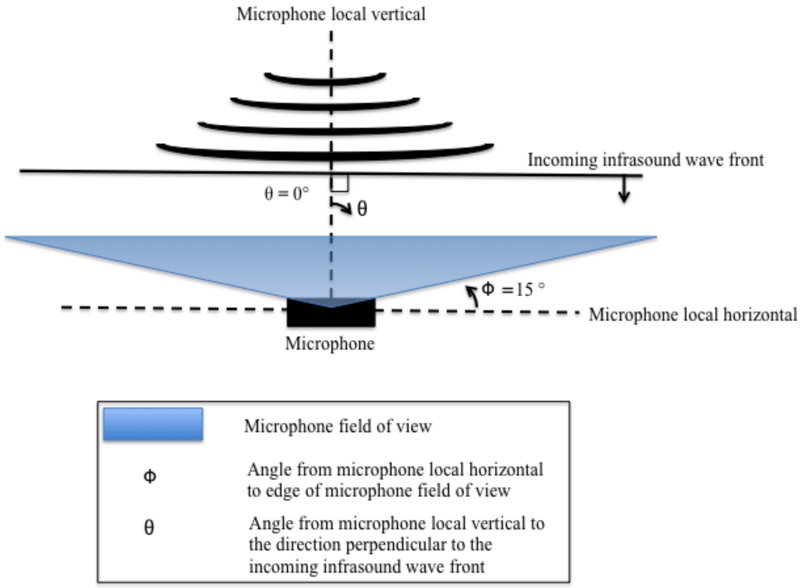


Figure 12. Microphone Field of View Geometry

Complete coverage can be achieved with only 5 microphones distributed around the surface of a radial configuration. Shown in the Figure 13 are the cones of field of view for each microphone; the five cones extend from the spherical surface, each facing a different direction and overlapping to achieve full coverage.

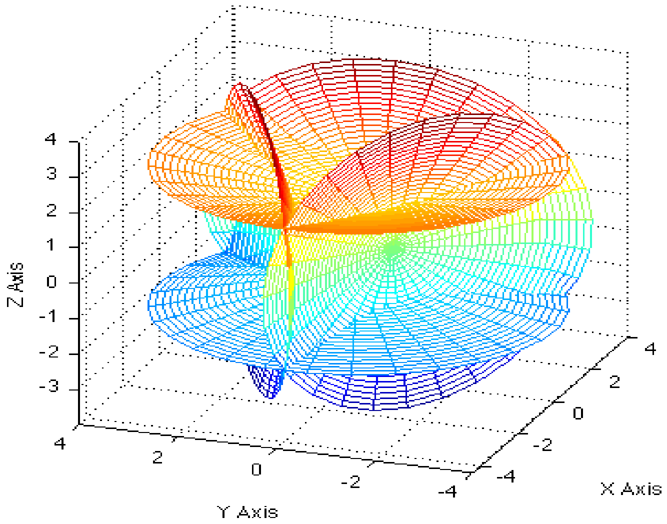


Figure 13. Microphone Field of View Coverage - Sphere

Due to the curved geometry of the structure and the large number of microphones used to cover the surface, it is difficult to accommodate rosette-type spatial filters.

Structurally, these radial configurations would include a support frame. This frame could be made up of truss-like beams to define the radial shape and provide support for the microphones, or the frame could be made of a solid material with a hollow interior to accommodate the microphones and support hardware. The structural support would be rigid, keeping the microphones stationary relative to each other and allowing for greater survivability of the structure during a balloon flight and during recovery events such as balloon popping, parachute deployment, and touchdown upon the ground. This array could be designed to be mounted on the gondola, or could be hung either between the balloon and gondola or from the base of the gondola.

Table 12 below overviews the advantages and disadvantages for a radial microphone array configuration.

Table 12. Radial Microphone Array Pros and Cons

Advantages	Disadvantages
Complete microphone field of view coverage resulting in optimal signal detection is achieved with only 5 microphones	Difficult to accommodate rosette-type wind filters due to their large volumes.
Improved signal-to-noise ratio (SNR) of detected infrasound signals due to likelihood of multiple sensors detecting incoming waves.	A spherical or ellipsoidal frame structure could be difficult to manufacture due to curved surface, depending on chosen materials.
Relative locations of microphones is always known due to the rigid array structures	
Rigid structure in a cylindrical, spherical, or ellipsoidal configuration increases survivability of arrangement when encountering sudden acceleration changes during a balloon flight	
Hollow interior and potential for adding additional padding around structure accommodates support hardware and electronics needed for microphones and protects them from impact upon landing	

4.4.2 Planar Configuration

This configuration assumes the pressure sensors would be mounted on flat panels that could be positioned on the gondola in different ways. The orientation of the planes relative to one another and their position relative to the gondola could have a significant impact on the coverage pattern of the overall sensor suite. For example, the panels could be joined together to form various prisms, pyramids, and platonic solids depending on the pointing restrictions of the pressure sensors, although a cube is assumed to be the most likely shape. The entire arrangement could then be suspended from the gondola to create a self-contained package, separate from the gondola.

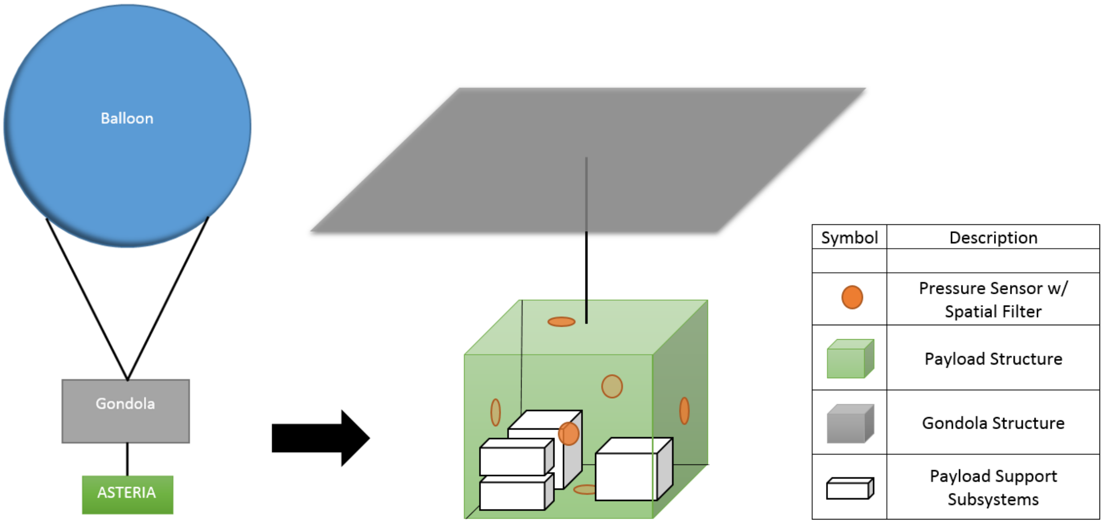


Figure 14. Planar Configuration Array

For the same microphone field of view geometry as described previously in Figure 14 (in Section 4.3.1 above), six sensors are required to achieve full microphone field of view coverage. Figure 15 below shows the field of view cones extending from a cube configuration; the cones overlap to be able to detect infrasound waves from any incoming direction and to improve the signal-to-noise ratio when more than one sensor detects pressure changes due to the infrasound waves.

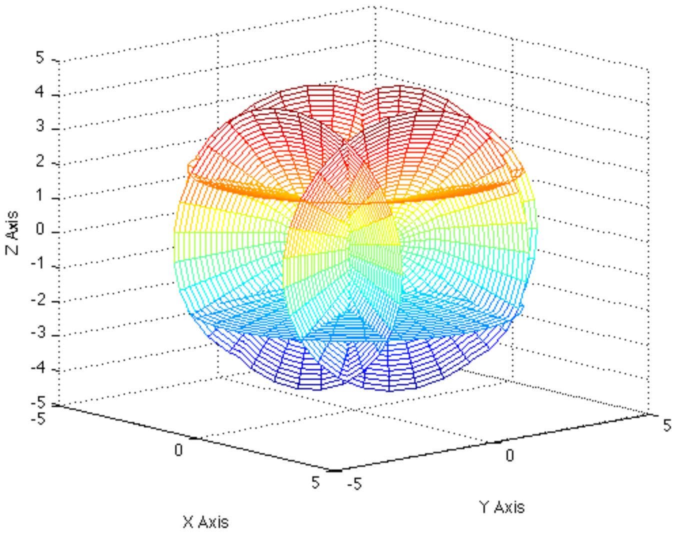


Figure 15. Planar Configuration Microphone Coverage - Cube

This configuration scheme would be able to accommodate pressure sensors using both barrier and rosette style spatial filters. In the case of barrier filters, the filter size is on the scale of the pressure sensor itself, meaning the that presence of the filter would not have a significant impact on the number of sensors mounted on a panel, nor their arrangement relative to one another. They can also be used on a panel regardless of its orientation to other panels or the gondola. If rosette style filters are used, there may be restrictions as to their use on vertically mounted panels, since some of the rosette tubes would be oriented vertically and be subject to pressure gradient effects on the air mass within the tube, skewing the pressure readings. Horizontally mounted panels would not experience this effect because none of the rosette tubes are vertically mounted. This imposes some constraints on the ability of the payload to detect signals approaching from the side. The length of the tubes may also impose some limitations regarding the mounting of sensors relative to one another, potentially reducing the number of pressure sensors that can fit on a given panel.

Table 13. Planar Configuration Pros and Cons

Advantages	Disadvantages
Using a collection of attached panels suspended from the gondola creates the opportunity for a self-contained payload	Coverage pattern is highly dependent on the type of microphones used as well as the number of panels and their orientation to one another.
Complete microphone field of view coverage resulting in optimal signal detection is achieved with 6 microphones,	Using a collection of attached panels suspended from the gondola could make the payload susceptible to blocking of incoming signals, depending on the payload's proximity to the gondola.
Relative locations of microphones is always known due to the rigid array structures	
Rigid structure in a planar configuration increases survivability of arrangement when encountering sudden acceleration changes during a balloon flight	
Hollow interior and potential for adding additional padding around structure accommodates support hardware and electronics needed for microphones and protects them from impact upon landing	

4.4.3 Hanging Tether Configuration

A hanging array is comprised of numerous microphones with several meters of spacing between them, hung separately from ASTERIA. The hanging configuration has two variations, one being hung beneath the instrument support package and the other attached to the balloon tether. Both configurations are shown in Figure 16.

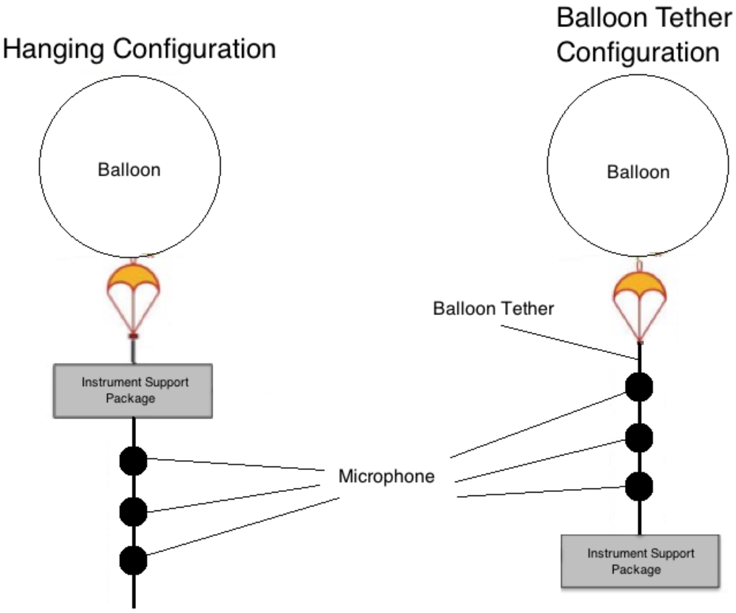


Figure 16. Hanging Tether Microphone Configuration

This configuration allows a variety of customization for rosette and barrier filtering as it allows for large boom arrays, like those currently used on ground stations, to be stored during ascent and deployed once the target altitude is reached. The key disadvantage of the tether design is the inability to install sensors in a configuration that can measure pressure waves from infrasonic activity in all directions. Three microphones can provide at best full-coverage in a single plane, and at worst coverage equivalent to approximately only one microphone when they are all pointing the same direction (assuming the microphones are only able to be mounted in a plane perpendicular to the tether). Figure 17 and Figure 18 below show the best-case scenario from top and side views, respectively, while Figure 19 show the worst-case scenario also from top and side views, respectively. Each figure shows the field of view cones for microphones in the tethered configuration.

This disadvantage is fully explained with the "Number of Microphones for Optimal Signal Detection" metric in the trade study definition, Table 22. Further, this design also introduces problems with designing a mechanism to deploy the array once the target altitude is reached, difficulties being easily interfaced to a variety of different balloon platforms, and a possibility that the configuration would not survive under significant G-loading, particularly during free-fall and landing.

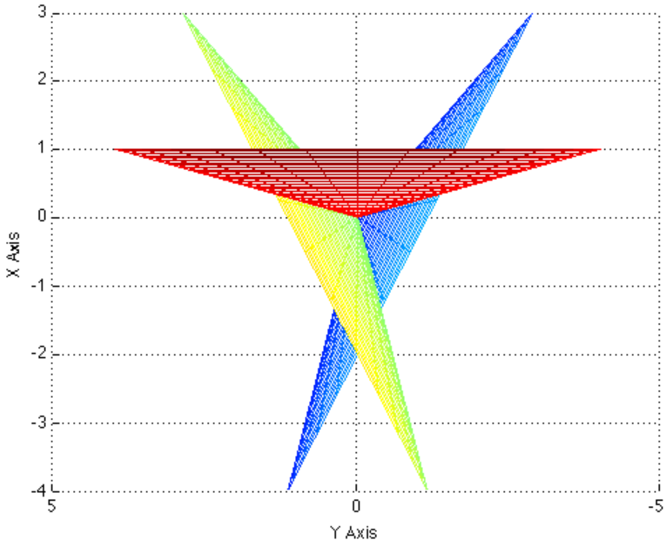


Figure 17. Top View, Three Microphones Provide Single Plane of Coverage

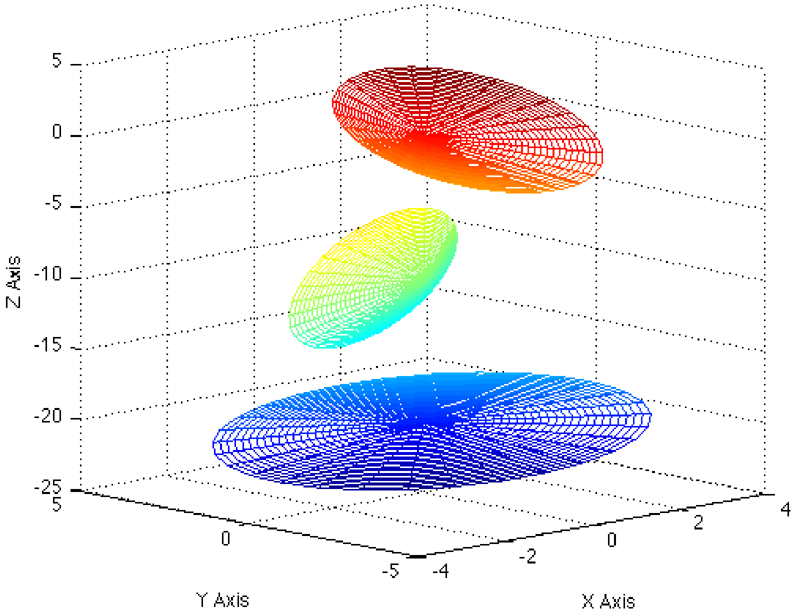


Figure 18. Side View of Three Microphones Placed Along a Vertical Tether

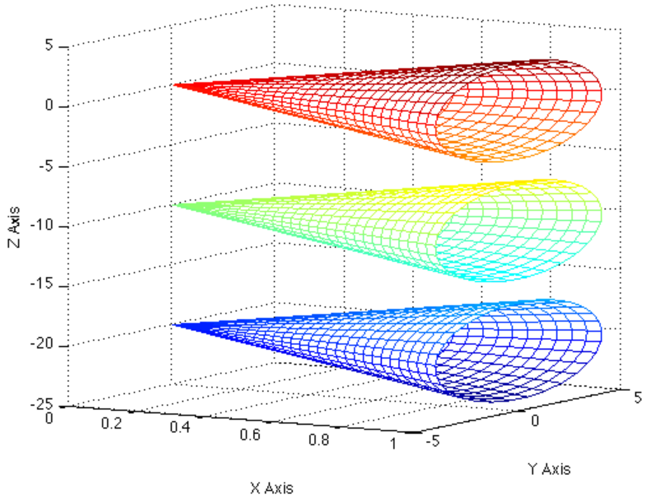


Figure 19. Side View, Three Microphones Orientated in a Single Direction on a Tether

Table 14. Pros and Cons of Tether Configuration

Advantages	Disadvantages
Compatible with a variety of large spatial filters, including those currently used on ground stations	May need to design additional mechanism to release and deploy array at altitude
Easy to reconfigure microphones (number, type, arrangement on array)	Limits the number of balloon platforms to fly on (interfacing requirements, not all allow tether/hanging configurations)
	Possibility that configuration may not survive balloon flight (separation from balloon, descent, landing)
	Tether is susceptible to bending and twisting from the wind, making optimal signal detection difficult

5.0 Trade Study Process and Results

5.1 Microphone Detector

Table 15 is a description of the major metrics considered in the trade study performed on the microphone detector design options. The table outlines each metric's weight, along with a description of the metric. Metrics not included in the table, such as Technology Readiness Level (TRL), were not considered because they were either not critical to the design, or had the same value for each design. An example of the latter would be TRL: as none of the microphone designs have been tested for stratospheric environments, they all would have received the same TRL rating. Another metric that was not selected was sensitivity to acceleration. Though some sensor types may have marginally higher susceptibility, all the sensors considered were given as having similar effects that could be handled in the same way: using an accelerometer to account for the motion.

Table 15. Microphone Detector Metrics

Metric	Weight	Description
Cost	13%	This metric is derived from a limited budget. The customer has offered to donate additional funds if the sensor selected is above budget, reducing the weight of this metric, but staying below budget is preferable. This metric also incorporates the cost of supporting systems required for the sensor type being considered.
Mass/Volume	8%	This metric is derived from the customer request for a small, light-as-possible payload; the balloon platform options increase as the volume and mass of the payload decrease. This metric also incorporates the mass and volume of supporting systems required for the sensor type being considered. Other systems require the majority of the overall mass budget, so this metric is less important.
Frequency Response	25%	This metric is derived directly from customer requirement FR.1, which states that the microphone must detect frequencies in the 0.1-20 Hz range. The frequency response is a key element of the project, so it receives a high weighting.
Operational Pressure Range	25%	This metric is derived from the requirement (FR.2) that the payload must operate in stratospheric conditions (a pressure range of 300-500 Pa). The sensor must maintain structural and functional integrity in near vacuum conditions. Since ASTERIA must operate in the stratosphere, this metric is critical to that requirement.
Temperature Sensitivity	12%	This metric is also derived from the requirement (FR.2) that the payload operate at altitudes between 18 to 30.5 km. Changes in temperature cause changes in pressure that are detected by the microphone. ASTERIA must operate in the stratosphere but temperature control is possible, so this metric is less critical.
Pressure Sensitivity	17%	This metric is derived from the need to measure waves from distant, or low amplitude sources. The microphone diaphragm must be sensitive enough to register pressure changes on the order 0.1 Pa to detect low amplitude (0.1 Pa) waves on the order of 74 dB SPL. Although the target amplitude is set, different resolutions still meet minimum levels of success, reducing the weight for this metric.

To evaluate the different types of microphone detectors, a five-level scale was developed for each of the microphone detector metrics. These are laid out in Table 16, where level one is the worst and level five is the best.

Table 16. Microphone Detector Score Definitions

Metric	Score 1	Score 2	Score 3	Score 4	Score 5
Cost	Costs more than $5000	Costs $1000 to $5000	Costs $500 to $1000	Costs $100 to $500	Costs less than $100
Mass/Volume	Mass over 5 kg Larger than 442 cm^3	Mass between 1 to 5 kg Fits within 442 cm^3	Mass between 0.25 to 1 kg Fits within 131 cm^3	Mass between 0.05 to 0.25 kg Fits within 16 cm^3	Mass under 0.05 kg Fits within 2 cm^3
Frequency Response	Detects frequencies of >20Hz	Detects frequencies of >10Hz	Detects frequencies of >5Hz	Detects frequencies of >1Hz	Detects frequencies of >0.1Hz
Operational Pressure Range	Operates at pressures down to 80kPa (1.80 km)	Operates at pressures down to 30kPa (9.15 km)	Operates at pressures down to 7kPa (18.3 km)	Operates at pressures down to 1kPa (30.5 km)	Operates in near-vacuum conditions (~0kPa)
Temperature Sensitivity	Operates with or without pressure corrections due to temperature down to 0ºC	Operates with pressure corrections needed due to temperature down to -30ºC	Operates with no pressure corrections needed due to temperature down to -30ºC	Operates with pressure corrections needed due to temperature down to -60ºC	Operates with no pressure corrections needed due to temperature down to -60ºC
Pressure Sensitivity	Detects pressure changes of 10Pa (114 dB SPL)	Detects pressure changes of 1Pa (94 dB SPL)	Detects pressure changes of 0.1Pa (74 dB SPL)	Detects pressure changes of 0.01Pa (54 dB SPL)	Detects pressure changes of 0.001Pa (34 dB SPL)

For cost, the levels were based on the budget for this project, using the maximum $5000 as the worst level. Level three was taken as a single sensor target, where the detector would be 10-20% of the budget. Level one was taken as under 2% of the budget to allow for a multitude of sensors. Intermediate ranges were given as levels two and four.

The mass and volume levels had two elements, where the mass requirements came from the target total mass of the payload. The worst case was taken as a single microphone limit of 25% of the total, while the best case was near-negligible and would allow for many microphones to be used. The volume requirements came from a similar line of reasoning.

The frequency response levels were selected based on the requirements given by the customer and the definition of infrasound. 20 Hz is the upper edge of infrasound, so was made the lowest level. The top level was given as the customer's target minimum frequency, and the other three levels were selected as intermediate values.

The levels for the pressure range were obtained from the requirements for altitude. The top level score would be the best case scenario where the pressure sensor can operate independent of altitude and pressure. The next levels come from the target range for future use of the payload. The lowest level was based on a worst-case scenario where the sensor can only operate on the ground.

For temperature sensitivity, two criteria were considered. The first was whether or not the sensor could collect data at the required temperatures, which determined the three temperature levels. -60° C is the minimum temperature seen between ground level and the maximum altitude of 30.5 km, and was selected as the top level. The other was if the data would have to be adjusted after collection due to the temperature of the sensor, and determined the splits between the levels with the same temperatures. Sensors with no corrections needed are better as they would need less supporting instrumentation.

Pressure sensitivity levels were given as orders of magnitude since there are many factors that could affect the amplitudes of signals. Since amplitude changes with distance and size of the events being measured, more resolution would help to detect more events at larger distances, and ensure the signal can still be found through any filtering applied.

The results of the microphone detector trade study are shown in Table 17, below.

Table 17. Microphone Detector Trade Study

	Weight	Amplified Low Pressure Sensor	Piezoelectric Crystal	Condenser Microphone
Cost	13%	5	3	2
Mass/Volume	8%	4	2	2
Frequency Response	25%	4	3	5
Operational Pressure Range	25%	4	4	4
Temperature Sensitivity	12%	3	4	2
Pressure Sensitivity	17%	3	3	4
Total	**100%**	**3.84**	**3.29**	**3.59**

The microphone detector trade study found the amplified low pressure sensor to be the highest scored design. The piezoelectric crystal design scored the lowest and was eliminated. The amplified low pressure sensor and condenser both had similar scores. However, the amplified low pressure sensor was chosen as the base design. The rationale behind choosing it, even though the condenser had a close score, was that the cost, mass and volume are low enough to allow for multiple sensors to be integrated onto the overall design. The microphone array design is therefore not limited and any array design is feasible. With a larger and more expensive microphone, such as the condenser, the array is limited by the amount of microphones that can be purchased with the budget as well as the total mass. Another rationale is the amplified low pressure sensor's flight heritage. This sensor has already successfully been flown on a balloon payload to measure infrasound.

5.2 Spatial Filtering

To aid in the selection of a noise filter for the infrasound microphone, a trade study involving three different options was used. To perform this study, several metrics deemed the most important for the operation of the noise filter were selected. Table 18 shows these selected metrics, along with their associated weight in the trade study.

Table 18. Spatial Filtering Metrics

Metric	Weight	Description
Noise Attenuation	30%	This metric is derived from the requirement (FR.1) to make accurate pressure measurements of infrasound, 0.1 to 20Hz, with an amplitude sensitivity of 0.1 Pa (74 dB SPL). Reducing noise produced from a variety of sources of pressure changes, such as wind and temperature fluctuations, is necessary to ensure an adequate signal to noise ratio. This metric was assigned the highest weight because it is the primary purpose of the noise filter.
Mass	10%	This metric is derived from the customer request for a payload less than 20kg; the balloon platform options increase as the mass of the payload decreases. This was assigned a lower weight because it is not as critical to mission success.
Detection Reliability	26%	This metric is derived directly from the requirement (FR.1) to measure pressure from infrasound waves. There is a possibility that the microphone will register a false detection due to pressure changes within the filter. A high weight was given to this metric because false detections could decrease the reliability of the collected data.
Volume	16%	This metric is derived from the customer's request to have a portable, easily deployed payload. A large filter can make the payload more difficult to transport and deploy. This was assigned a lower score because it is not as critical to mission success, but is more so than mass.
Temperature Sensitivity	18%	This metric is also derived from the requirement (FR.2) that the payload be able to operate at altitudes from 18-30.5 km. Variations in temperature cause pressure changes and material expansion or contraction that shifts the frequency response of the filter. This was assigned a weight between the other four because it is very important to mission success, but less so than noise attenuation and false detections.

In this trade study many other metrics were considered but not selected because they were not deemed critical to the achievement of the functional requirements. Two other metrics that were considered but not selected were manufacturability and cost. Manufacturability was considered because all of the design options considered required some form of machining. However, the manufacturing required was determined to not be complicated enough for any of the designs to be a primary element in a component selection. Many different noise filters are made from foam or PVC piping, both being relatively cheap materials so cost was not included as one of the critical metrics.

Table 19. Spatial Filter Score Assignment

Metric	1	2	3	4	5
Noise Attenuation Ratio	< 5 dB	5-10 dB	10 – 15 dB	15 – 20 dB	>20 dB
Mass	> 80 kg	12 - 16 kg	8 - 12 kg	4- 8 kg	< 4 kg
Detection Reliability	Cannot filter false detections	-	Some false detections can be filtered	-	All false detections easily filtered
Volume	> 1.5 m^3	-	0.001 – 1.5 m^3	-	< 0.001 m^3
Temperature Sensitivity	Large change in filter response due to temperature changes.	-	Medium change in filter response due to temperature changes.	-	Small change in filter response due to temperature changes.

The first metric and most important metric of spatial filtering is noise attenuation. This metric's score was assigned based upon the ambient noise reduction, measured in dB. The highest score corresponded to a noise reduction of 20dB or greater; this is based upon research indicating the greatest measured reduction from 0.1 to 10Hz was slightly larger than 20dB.

The second metric, Mass, was based off the customer's preference to minimize the system mass; all of the values are based on the assumption of a payload less than 20 kg. The highest score is assigned to a filter system that takes up less than 20% of the total mass value, approximately 4 kg or less. The other categories are rated based on increments of 4 kg, where the lowest score of 1 was a system that had a mass of 16 kg or more, since this accounted for more than 80% of the customer mass value and would be undesirable.

Detection reliability is difficult to quantify because it is based on the ease of isolating a true infrasound signal from false detections due to the design of the spatial filter. While no research currently exists on the types of false detections associated with each filter, the scoring is based on the predicted ease of removal of false detections from the total signal. Based on fundamental aerodynamics, a rosette is prone to short duration, large magnitude false detections, while barriers due to their spatial averaging effect induce bias due to wind gusts. This metric determines which type of induced error is most acceptable. Due to the lack of quantifiable data on this matter, further testing (see DR.2) will be required to verify the above assertions.

The volume metric was based on research of the sizes of existing barriers and filters. In this category, the highest score was given to the smallest volume, a cube of approximately 0.1 m in length. The middle level consisted of increasing the size of this filter cube design space by increasing all three dimensions linearly to 0.5 meters. The lowest score was given to a cube volume with 1.1 m in length or more, resulting in a volume of 1.5 m^3 or more.

Temperature sensitivity, like detection reliability, is an important metric but the impact of temperature on spatial filter materials is still relatively unknown. Scores are based on whether or not the temperature induces a large change in the filter response, ranging from the highest score where the filter is barely effected to the lowest where the temperature has a large impact on how the filter responds. Scores were assigned to each filter based on the understanding of the predicted spatial filtering behavior. This metric would also require testing to gain a better understanding of the filter response and gain quantitative data to support the choice of a certain design.

Table 20. Spatial Filter Trade Study

	Weight	Barrier	Rosette	Hybrid Filter
Noise Attenuation	30%	4	3	5
Mass	10%	5	3	2
Detection Reliability	26%	3	1	3
Volume	16%	3	1	1
Temperature Sensitivity	18%	3	2	2
Total	**100%**	**3.5**	**1.98**	**3.00**

Previous tests of two foam barriers, one being 180mm in diameter and the other 90mm, have shown noise reductions of 18dB on average for wind speeds of about 4.8 m/s in the frequency range of 0.1 to 10Hz.[10] This research was the basis for assigning a score of 4 to the barrier for noise attenuation. The barrier was assigned the highest score on mass due to the fact that is it will most likely be constructed from foam and be a relatively small volume, thus remaining below 4kg. It is predicted that a spherical barrier will cause a relatively constant pressure bias when wind strikes it. This is based upon knowledge that spheres have the property of averaging pressure gradients across their surface area, therefore a wind disturbance would appear as a constant increase in pressure for the duration of a gust. Based on aerodynamics constant pressure biases for a sphere are easier to filter out for short duration, large magnitude spikes in pressure. The barrier received a score of 3 for volume because, although the smallest known barrier in use falls within a ranking of 5 at 0.001m^3, alternative barrier designs require more volume. The barrier received a 3 for temperature sensitivity because the porous nature of the material necessary for a functional barrier—approximately 50% porous according to the study by Hedlin—provides a multitude of pathways through which pressure can propagate. Material expansion or contraction due to temperature changes will not prevent air from passing through the barrier.

To have noticeable filtering effects while maintaining both portability and a reasonable volume, a tube length of 2m was assumed in this trade study. According to studies conducted by Michael Hedlin on spatial filters for scaled frequencies, a filter with 2m long tubes at wind speeds of 5.25m/s reduces noise in the frequency range of

0.1 to 10Hz by on average 15dB, thus resulting in a score of 3[10]. Using typical spatial filter systems, with a standard number of 8 tubes for a rosette, a mass of 8 kg per spatial filter would be necessary. This mass corresponds to a score of 2, but could possibly be a score of 1 if the tube length or number of tubes was increased from these minimal values. If wind hits the rosette and causes it to move from its current orientation, the air inside the tubing will exert a pressure force on the sensor due to the conservation of momentum. This pressure force has the possibility of resulting in a false infrasound detection consisting of short duration, high magnitude spikes in pressure. Experimental tests would need to be conducted to quantitatively analyze this property. Since a minimal length of 2m tubes was assumed, the diameter of the system would total 4m, making it not very portable and difficult to deploy. Inside the tubes used for the spatial filter, small capillaries are placed near the microphone sensor. These capillaries will most likely expand and contract during the temperature changes experienced by the payload. The hybrid rosette received a score of 2 because there are only a few tubes, any single capillary expanding and contracting will distort the experimental data. This would require experimental testing to determine a score quantitatively.

The hybrid spatial filter combines both aspects of the rosette and the barrier. From this it can be predicted that the noise attenuation from this type of filter would likely either match that of the barrier, and possibly exceed it considering there would be extra attenuation due to the rosette configuration. Because of this, the hybrid was given a score of 5 for noise attenuation. However, further testing would have to be implemented to confirm this assumption. The weight and volume, however, were more quantifiable since most of these values could be based off the rosette study. The hybrid would have more mass than a rosette due to the extra porous material, so it received a score of 2. Its volume would not change from the rosette, since it occupies the same space, meaning it also received a score of 1 in volume. The temperature sensitivity and the detection reliability were metrics that were hard to quantify, and their scores were based off the predicted behavior of each separate filter. From this, it was predicted that the hybrid would be as sensitive to temperature as a rosette due to the porous material being in a fairly long and linear volume, thus being given a 2 in this category. For false detections, the hybrid spatial filter will perform similarly to the barrier and produce an averaged pressure offset during a gust of wind or an induced oscillation of the payload. These have the potential to be filtered or accounted for by tracking the acceleration of the payload. Therefore it received the same score as the barrier, a 3.

5.3 Microphone Array Configurations

Table 21 below describes each metric used in the trade study, the weighting assigned, and a description.

Table 21. Microphone Array Configuration Trade Metrics

Metric	Weight	Description
Number of microphones for optimal signal detection	40%	Using the explanations in section 4.4.1 this metric measures the number of microphones required for optimal infrasound signal detection regardless of the incoming angle of the wave. The first metric, number of microphones for optimal signal detection, received the highest rating of all the metrics at 40%. This is the most important of the metrics because it directly relates to FR.1 and is essential for payload success in detecting pressure changes due to incoming infrasound waves.
Accommodation of support hardware	25%	Measuring pressure differences due to infrasound waves requires support electronics and hardware in addition to a microphone. This metric evaluates how complex mounting the microphone and its supporting hardware and electronics is based on the configuration design. Under consideration for this metric is how difficult it is to mount and connect the supporting hardware and electronics to the microphone based on the configuration geometry. This metric was assigned 25% because the accommodation of support hardware is an important consideration in complexity of the design. A design that accommodates the support hardware and electronics near the microphones themselves is more compact and portable, while a design that spreads the support hardware and microphones out over a distance is more difficult to transport and store, and introduces more complexity, mass, and risk of damage to the structure.
Survivability	25%	This metric indicates the likelihood that the structure would survive the entirety of the balloon flight, particularly during changes in acceleration such as parachute deployment, free-fall, and the impact upon landing. Also considered with this metric is the ability of configurations to accommodate additional structural reinforcements or padding to absorb the impact of landing to protect the sensors and data storage devices, and the likelihood of the configuration being dragged or getting caught in trees, bushes, or other ground-based hazards during landing due to its long length. This metric was given a weight of 25% because it is important to mission success because if the payload is damaged during flight or landing, its ability to successfully detect pressure changes due to infrasound waves or store collected data for retrieval, respectively, is made much more difficult or even impossible.
Compatibility with spatial filters	10%	Due to the configuration geometries, certain spatial filters (such as the rosettes and the hybrid filter with their large volumes) may be very difficult to integrate. This metric rates how compatible the configuration is with the spatial filter designs under consideration. This metric was assigned a weight of 10% because the compatibility of the configuration with wind filters is important because it allows the team to consider design options that combine various configurations with wind filter designs; a configuration that cannot accommodate any of the considered wind filters is not desirable.

Several metrics were considered for the trade study, but ultimately only those that that had the most significant impact on determining the best configurations were used. Some trade metrics that were determined to be important for design, but not important for the trade study, included manufacturability, cost, and mass. These metrics will be considered after selection of a baseline design and discussed further in the Preliminary Design Review.

To evaluate the different types of configurations, a three-level scale was developed for each of the microphone configuration metrics. These definitions are outlined in Table 22, with a score of 1 being the worst and a score of 3 being the best.

Table 22. Microphone Array Configuration Score Definitions

Metric	Score 1	Score 2	Score 3
Number of microphones for optimal signal detection	No number of microphones results in full coverage	6 or more	5 or fewer
Accommodation of support hardware	Very difficult to mount and connect support hardware and electronics to microphones	Moderately difficult to mount and connect support hardware and electronics to microphones	Simple to mount and connect support hardware and electronics to microphones
Survivability	Low probability of configuration surviving balloon flight	Medium probability of configuration surviving balloon flight	High probability of configuration surviving balloon flight
Compatibility with Spatial Filters	Configuration is compatible with one filter type	Configuration is compatible with two filter types	Configuration is compatible with all three filter types

The first metric of interest is the number of microphones needed to obtain optimal signal detection, which is full field of view coverage surrounding the configuration. The minimum number of microphones required to achieve this between the considered options is 5, receiving a score of 3. The lowest score is for the case where full coverage is not achievable with any number of microphones.

The accommodation of support hardware metric was based on issues concerning mounting microphones a large distance from the instrument support package. The lowest score was given to a configuration that would be more complex in wiring due to microphones being far from the instrument support package, as in the hanging design. The highest score was given to those designs that were compact and contained all of the microphones within a centralized location, thereby eliminating the need for excess wiring and deployment mechanisms.

Survivability was an important metric to consider, albeit difficult to quantify. Because there is no data downlink, the ability of the configuration to survive landing and protect the data storage device is critical to mission success. The highest score on this metric was given to designs that would have a higher probability of surviving the harsh conditions experienced on balloon flights, particularly after the payload is released from the balloon, during descent, and landing. Descending scores were given to those designs that had a lower probability of surviving the flight and landing.

The last metric, compatibility with spatial filters, was the least important metric considered of the four. A score of 3 was given to those configurations that were compatible with all three spatial filter types, while a score of 2 was given to those only compatible with two of spatial filter designs.

Table 23. Microphone Configuration Trade Study

	Weight	Hanging Configuration	Planar Configuration	Radial Configuration
Number of microphones for optimal signal detection	40%	2	2	3
Accommodation of support hardware	25%	1	3	3
Survivability	25%	2	3	3
Compatibility with spatial filters	10%	3	2	2
Total	**100%**	**1.85**	**2.5**	**2.9**

The microphone configuration trade study resulted in the radial configuration being the highest scored design. The hanging tether configuration scored the lowest by a large margin and was eliminated. While the planar configuration did score lower than the radial configuration, the two scores are similar and so additional analysis and trade studies will be performed to evaluate which of these two methods is best. This additional analysis, which will involve trade studies on material selection, structure, and manufacturability, will be completed prior to the Preliminary Design Review.

6.0 Selection of Baseline Design

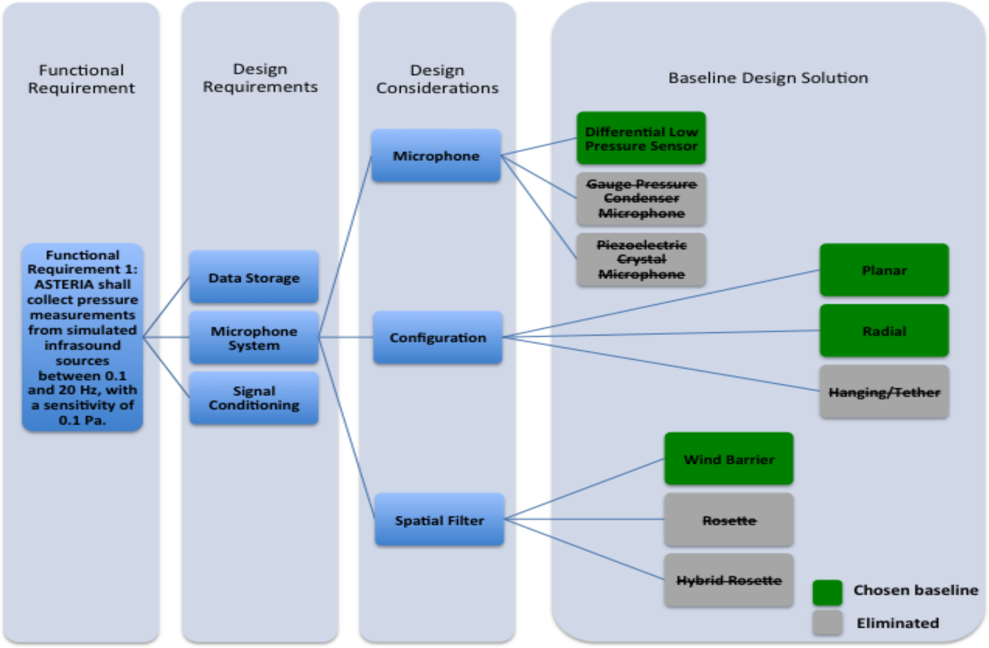


Figure 20. Baseline Design Selection

A baseline design was selected using the results obtained from conducting trade studies for several of the most critical project components. An Amplified Low Pressure Sensor was selected as the best microphone design choice. Despite this microphone type and the condenser microphone type having similar scores from the trade study, the ability to have multiple sensors integrated into the overall design became the deciding factor; the cost of the condenser microphone ultimately ruled it out as an option. Based on the results of the configuration trade study, having multiple microphones allows for systems that cover a wider field of view, thus increasing the likelihood of infrasound wave detection. Even though the trade study yielded the Amplified Low Pressure Sensor as the best choice, it still presents design problems such as thermal insulation and signal amplification.

Although the barrier and hybrid rosette scored similarly, the barrier was selected as the baseline design choice. Ultimately, any configuration involving multiple microphones would not be very practical with the hybrid rosette due to the required mass and volume. For each microphone, a minimum of 9kg of filter material would be needed; 8kg of PVC tubing and an additional 1kg of porous material. If a configuration required four or six microphones this would correspond to 36kg and 54kg, respectively greatly exceeding the customer requested maximum 20kg mass limit. In addition, the volume required would make it difficult to transport and deploy. Since a configuration including multiple microphones is desirable, the wind barrier was selected as the spatial filter that will be used for each microphone. Despite the barrier being the design choice, testing will be necessary to confirm that false signal detections can be removed.

From the microphone configuration trade study, the radial and planar designs have been selected to move on for further testing and design considerations. Both of these designs have similar field of view coverage, increasing the likelihood that infrasound waves will be detected. To select a design, further analyses will have to be conducted considering the material costs, manufacturability, microphone placement, and other traits deemed important to the overall design. Since both of these designs require multiple microphones, the usage of the Amplified Low Pressure Sensor microphone and a barrier spatial filter are both justified.

7.0 References

[1] Nave, R., "Infrasonic Sound," Georgia State University Department of Physics and Astronomy – HyperPhysics, 2014, [http://hyperphysics.phy-astr.gsu.edu/hbase/sound/infrasound.html. Accessed 09/04/2014]

[2] Young, Eliot et al. "Infrasound Detection from Balloon-Borne Platforms." Southwest Research Institute, Boulder, CO. 26 Aug. 2014.

[3]"Differential Pressure Sensor", 2014, First Sensor, *first-sensor.com*. Web. 25 Sept. 2014. http://www.sensortechnics.com/en/products/pressure-sensors-and-transmitters/pressure-types.html

[4]"Amplified Very Low Pressure Sensors", All Sensors, DS-0032 Rev B. Web. 24 Sept. 2014. http://www.allsensors.com/datasheets/DS-0032_Rev_B4.pdf

[5]"Product Data: 1/2" Pressure-Field Microphone – Type 4193", 2008, Brüel & Kjær, BP 2214-11. Web. 19 Sept. 2014. http://www.bksv.com/doc/bp2214.pdf

[6]Pender, George A. "Microphone Talk." Meggitt, July 2008. Web. 19 Sept. 2014. <https://www.endevco.com/news/archivednews/2008/2008_07/f2_tp278.pdf>.

[7]"Acoustic ICP® Pressure Sensor", 2013, PCB Piezotronics, 40794 Rev. C. Web. 19 Sept. 2014. http://www.pcb.com/contentstore/docs/PCB_Corporate/Pressure/Products/Specsheets/103B01_C.pdf

[8]"Microphone Handbook." National Instruments, February 2012. Web. 19 Sept. 2014. http://www.ni.com/white-paper/7059/en/

[9]Marcillo, Omar, and Jeffrey Johnson. "Implementation, Characterization, and Evaluation of an Inexpensive Low-Power Low-Noise Infrasound Sensor Based on a Micromachined Differential Pressure Transducer and a Mechanical Filter." *Atmospheric and Oceanic Technology* Vol. 29 (2012): pp. 1275-284. American Meteorological Society. Web. 22 Sept. 2014. <http://journals.ametsoc.org/doi/abs/10.1175/JTECH-D-11-00101.1>.

[10]Hedlin, Michael. "Infrasonic Wind-noise Reduction by Barriers and Spatial Filters." *Acoustical Society of America* Vol. 114. (2003): pp. 379-386. Web. 1 Sept. 2014. <http://l2a.ucsd.edu/pub/Infrasonic_wind-noise_reduction_barriers_spatial_filters.pdf>.

[11]"Storms and Infrasound." *All About Heaven.* Web. 1 Sept. 2014. <http://www.allaboutheaven.org/science/248/121/storms-and-infrasound>.

[12]Bedard, Alfred, and Thomas Georges. "Atmospheric Infrasound." Physics Today, Vol. 53, March 2000, pp 32-37. Print.

[13]Smith, I. Steve. "Low Cost Access to Near Space." Southwest Research Institute, San Antonio, TX. 11 Sep. 2014.

[14]"Symposium on Atmospheric Acoustic Propagation." 20 June 1963, White Sands Missile Range, New Mexico, United States

[15]Bowman, Daniel, and Jonathan Lee. "HASP Student Payload Application for 2014." (2013). *LASPACE*. Web. 21 Sept. 2014. <http://laspace.lsu.edu/hasp/groups/Payload.php?py=2014&pn=02>.

[16]Franco, Hugo. "Structural Requirements and Recommendations for Balloon Gondola Design." OM-220-10-H Rev. A (2013). *Nasa.gov*. National Aeronautics and Space Administration. Web. 1 Sept. 2014.

<http://www.nsbf.nasa.gov/documents/gondola/OM-220-10-H-A Structural Requirements Gondola Design.pdf>.

[17] *Sea Wolf Bow Sonar*. N.d. *U.S. Submarines since 1945: An Illustrated Design History*. Ed. Norman Friedman. Annapolis: U.S. Naval Institute, 1994. 208. Print.