Space Variant Report for Honeywell Atmospheric Winds Campaign for Space (HAWCS)

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1. Executive Summary

The HALAS system has proven capable of delivering timely weather information from high-altitude atmospheric lidar measurements in both ground and aircraft-based variants. A space-based HALAS represents the next frontier for technological development that would expand the geographical footprint and benefit the earth observing network, while adding valuable data to the predictive modeling mission of NOAA. Modeling of a HALAS space-based system could achieve the requirements for 3D wind measurements from measuring the atmospheric wind profile: Call for Studies and Field Measurement Campaigns Broad Agency Announcement (BAA-NOAA-3DWinds-2022).

The modeling study indicated that technological changes are recommended for a successful HALAS space-variant, most importantly a detector with minimal background noise. A 3D wind measurement from a lidar requires 3 or more lines-of-sight (LOS), and several strategies are proposed: multiple satellites, multiple telescopes, a single telescope continuously moving about the nadir, and a combination thereof. Size, weight, and power (SWAP) estimates for a HALAS space-variant capable of 3D Wind Measurement were benchmarked against the European Space Agency's (ESA) Aeolus-1 satellite. In comparison to Aeolus-1, the HALAS space-variant SWAP estimation concluded that the scientific payload could be significantly reduced in volume with slight reduction in mass and further reductions were possible. The key technical challenges to achieve a BAA-NOAA-3DWinds-2022 performant wind measurement with a HALAS space-variant are discussed along with the ongoing, planned, and proposed technological improvements. Overall, a potential HALAS space-variant can achieve the BAA-NOAA-3DWinds-2022 minimum requirements with a reduced SWAP compared to the Aeolus-I satellite but will require investment to achieve the required technological enhancements, engineering SWAP, and ruggedization for the space environment.

2. HALAS Technology Today

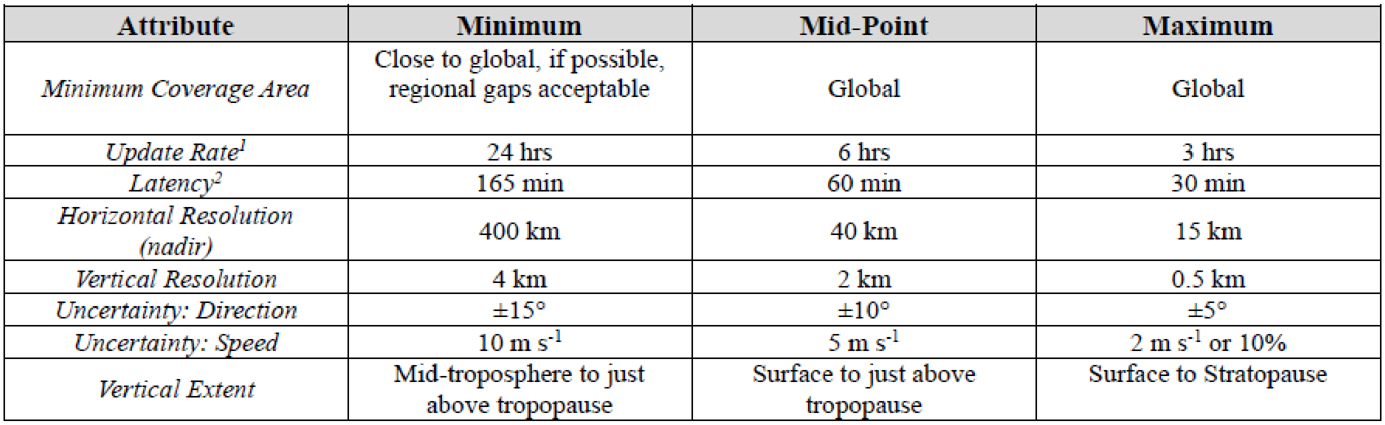
2.1 Introduction

Honeywell's HALAS technology enables the delivery of accurate, localized, and timely atmospheric data to end users for a variety of applications. All HALAS systems use ultraviolet (UV) direct detection lidar, which leverages both aerosol and molecular scattering to achieve performance at altitude ranges exceeding the competing remote-sensing technologies. Currently fielded HALAS systems include multiple ground-based variants housed in shipping containers (HALAS-ground) and the second-generation airborne variant onboard a high altitude unmanned aircraft (HALAS-Airborne).

All HALAS systems use the same underlying principles of measurement and share their core hardware and software for detecting and analyzing the light returned by aerosol and molecular scattering. Key differences between systems are platform- and application-specific transceivers and infrastructure designed to enable measurements in various environments. The HALAS technology offers distinct advantages over competing technologies achieving wind measurement in low-aerosol environments. Honeywell has demonstrated flexibility and adaptability in designing and deploying the HALAS core instrument technology to achieve atmospheric measurements from different platforms and for different applications. The next frontier for HALAS may be space, to enable NOAA to meet its objective of closing the current wind data gap in the earth observation system and thereby improving the performance of the global numerical weather prediction models.

This report provides information on the modeled performance of a satellite-based HALAS system in reference to the needs described in NOAA's 3D Winds Broad Agency Announcement (BAA), which are summarized in Table 1. Other physical and logistical considerations and constraints for the satellite-based HALAS system will be explored, particularly size, weight, and power (SWAP); orbits and satellite configurations; and technological challenges.

Table 1: Trade ranges for 3D Wind Measurements from Broad Agency Announcement



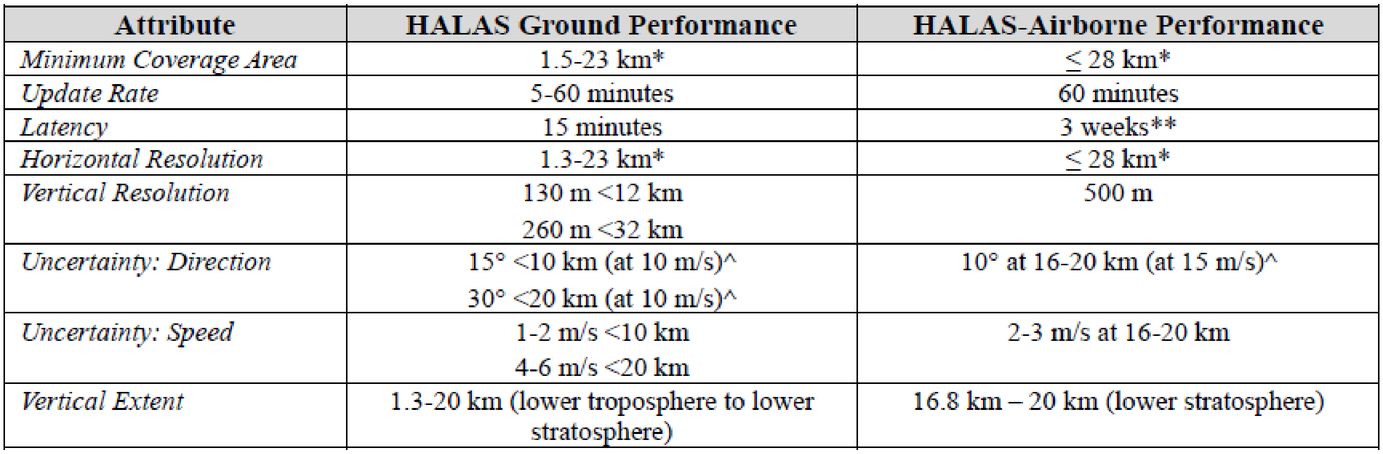
Attribute	Minimum	Mid-Point	Maximum
Minimum Coverage Area	Close to global, if possible, regional gaps acceptable	Global	Global
Update Rate[1]	24 hrs	6 hrs	3 hrs
Latency[2]	165 min	60 min	30 min
Horizontal Resolution (nadir)	400 km	40 km	15 km
Vertical Resolution	4 km	2 km	0.5 km
Uncertainty: Direction	±15°	±10°	±5°
Uncertainty: Speed	10 m s^{-1}	5 m s^{-1}	2 m s^{-1} or 10%
Vertical Extent	Mid-troposphere to just above tropopause	Surface to just above tropopause	Surface to Stratopause

[1] *Update rate is the time interval between successive collections of data from the same geographical point on, or above, the surface of the earth.*

[2] Data Latency is defined as the period from the time of observation of all requisite data by the satellite until the data product produced from those date is available to the user at the distribution system.

The previous HAWCS Instrument Report described the existing HALAS-ground and HALAS-Airborne technologies, including how HALAS-ground met various BAA-NOAA-3DWinds-2022 requirements. Table 2 provides the typical HALAS-ground performance for attributes in Table 1.

Table 2: HALAS Ground and HALAS-Airborne System' Performance for Key Attributes.



Attribute	HALAS Ground Performance	HALAS-Airborne Performance
Minimum Coverage Area	1.5-23 km*	≤ 28 km*
Update Rate	5-60 minutes	60 minutes
Latency	15 minutes	3 weeks**
Horizontal Resolution	1.3-23 km*	≤ 28 km*
Vertical Resolution	130 m <12 km 260 m <32 km	500 m
Uncertainty: Direction	15° <10 km (at 10 m/s)^ 30° <20 km (at 10 m/s)^	10° at 16-20 km (at 15 m/s)^
Uncertainty: Speed	1-2 m/s <10 km 4-6 m/s <20 km	2-3 m/s at 16-20 km
Vertical Extent	1.3-20 km (lower troposphere to lower stratosphere)	16.8 km – 20 km (lower stratosphere)

**Varies with altitude.*

***During the initial data analysis, a significant portion of this time was spent updating code to handle the laser anomaly.*

^Varies with wind speed.

From the HAWCS campaign, the initial performance of HALAS-Airborne is also included in Table 2.

***Note:** The HALAS-Airborne laser performed below peak performance during the campaign but is provided for initial hardware demonstration.*

3. Introduction to Space Variant Requirements

3.1. BAA Table II: Required Performance for Space

BAA-NOAA-3DWinds-2022 outlines the desired performance requirements for a 3D wind measurement platform, shown in Table 1. To achieve the global coverage area with a HALAS system with a minimum of 400 km resolution, either a comprehensive combined ground- and airborne-based approach or a satellite-based approach is required. Due to the scale, a satellite-based approach is the most likely to succeed. The European Space Agency Aeolus program has demonstrated a variant of a wind Doppler profiler, which acts as a good reference point for a space-based HALAS system.

Meeting all the requirements in Table 1 for a satellite-based HALAS system highly depends upon the orbit chosen for the sensor. A sun-synchronized dawn-dusk polar orbit, like the Aeolus program, is an attractive setup for a lidar-based sensor due to its stable solar power availability, consistent solar background, and very consistent global coverage. While other orbits are also possible, the sun-synchronous polar orbit will be used to briefly discuss the measurement requirements below.

- *Minimum Coverage Area* – Depending upon the orbit, a low-earth orbit (LEO) satellite-based HALAS system would naturally meet the desired global coverage.

- *Update Rate* – Depending upon the orbit, a single satellite-based HALAS system should provide the minimum update rate of 24 hours. To achieve a faster update rate and global coverage, multiple satellites would need to be operated.

- *Latency* – Current data collection from a ground-based HALAS system is approaching ~15 minutes. A similar processing time may be expected for a satellite-based system although it is important to note that any changes in the technology may alter latency and additional time for transmission of data to ground stations should be considered.

- *Horizontal Resolution* – The horizontal resolution of a line-of-sight wind Doppler measurement is dependent upon two quantities; 1) the movement of the satellite over the course of the measurement, and 2) the use of multiple lines-of-sight to determine the 3D wind profile. Due to the high ground speed of the satellite (~400 km/min), the measurement dwell time must be ~1 min to reach the minimum requirement in Table 1 and ~2 min to reach the maximum requirement.

- *Vertical Resolution* – The vertical resolution is currently set by a hardware limitation requiring minimum range bins of 150m, which translates to 130m in altitude space when pointing at a 60° elevation angle. This is far below the Table 1 requirements, and multiple range bins would be combined during analysis to minimize uncertainty while still meeting vertical resolution requirements.

- *Uncertainty* – The HALAS measurement uncertainty will depend upon instrumental design, mission characteristics, and will be described further in Section 4.0 below.

- *Vertical Extent* – The HALAS measurement vertical extent will depend upon instrumental design and mission characteristics. Additionally, any obscuring clouds may limit the measurement capability to altitudes above the cloud layer.

These baseline performance characteristics for a space-based HALAS instrument will change depending upon the precise mission characteristics. Many of the unique characteristics and challenges posed by this space-based wind measurement will be discussed in greater depth below.

3.2 Challenge Overview of Space-Based Operation

The current HALAS instrumentation has undergone many advances for the implementation on both ground and airborne systems. While some of this work can easily be leveraged, there are many unique challenges to a space-based system.

Many of the requirements for a HALAS-space system are shared requirements with most satellite systems including ruggedization, power consumption, thermal dissipation, radiation hardening, and others. Other stringent requirements stem from the need of a high-performance optical system with strict alignment capabilities of both a transmit and a receive optical path in addition to the optical analysis instrumentation. These pose substantial challenges for maturation of the current HALAS technology for robust space operation, but in no way poses an insurmountable challenge.

Some of the specific requirements stem from the nature of the lidar Doppler wind measurement itself. This includes necessary signal strengths for robust measurements, use of multiple pointing directions to determine the wind vector from Doppler measurements, and handling hard-target ground return on optical sensors. Careful consideration and optimization of these instrument characteristics have strong implications on the design of the final sensor.

The most important requirements to meet and understand are those relating to the performance of the HALAS instrument as will be analyzed in the following section.

4. Performance in Space

A HALAS-space system was modeled, and its characteristics were selected to meet BAA minimum requirements for LOS wind speed uncertainty. The HALAS-space system design recommended by the modeling would improve upon the HALAS-Airborne system in three key areas: a 24-inch telescope (HALAS-ground telescope size), double the laser power to 14W (achievable by laser supplier), and a photon detector with background reduced 500× (demonstrated in preliminary testing of new prototype detector). The modeling methodology used to arrive at this recommendation is described in the subsections below.

Key parameters in the lidar equation that impact performance was adjusted to determine how they affected the LOS wind uncertainty within the HALAS modeling framework. Through this modeling exercise, the key area in which the HALAS-space system needed improvement was identified as reduction of background noise on the interferometers' detector. A realistic detector solution based on preliminary testing was modeled, and other parameters of the laser and telescope were adjusted to achieve the ruggedization and size/weight required by a satellite system.

4.1 The Lidar Equation

The signal detected by HALAS is dependent on multiple factors from design of the transmitter/receiver optics to the optical properties of the atmosphere. This behavior of the HALAS signal is described by the lidar equation (Wandinger 2005):

$$P(r) = \underbrace{P_0 A\eta \frac{c\tau}{2}\frac{O(r)}{r^2}}_{\substack{Instrument\\ Properties}} \underbrace{\beta_\pi(r)\exp\left(-\int_0^r \alpha_{\lambda_{Laser}}(r')\,dr'\right)\exp\left(-\int_0^r \alpha_{\lambda_{scatter}}(r')\,dr'\right)}_{Atmospheric\ Properties} \qquad 1$$

Where $P(r)$ is the power of the signal received back by telescope, r is the distance between the telescope and the target area, A is telescope area, P_0 is the average power of the laser, τ is the integration time of the detector, c is the speed of light, η is the overall optical collection efficiency,

$O(r)$ is the overlap function between the laser beam and telescope field-of-view, $\beta_\pi(r)$ is the backscattering coefficient, $\alpha_{\lambda_{Laser}}$ and $\alpha_{\lambda_{scatter}}$ and are the extinction coefficients at the laser wavelength and scattering wavelength, respectively. Through examination Eq. 1 can be split into atmospheric properties and instrument properties.

The total number of photons detected, $N(r)$, from range *r* over a dwell time *T* is given in Eq. 2,

$$N(r) = \frac{\lambda_{scatter}}{hc} P(r) T \qquad 2$$

where $\lambda_{scatter}$ is the scattering wavelength and *h* is Planck's constant. The random uncertainty,

$\sigma(r)$, associated with the signal has been found to be Poisson limited, thus the uncertainty is related to the photon count through Eq. 3 with the signal-to-noise ratio (SNR) by Eq. 4.

$$\sigma(r) = \sqrt{N(r)} \qquad 3$$

$$SNR = \frac{N(r)}{\sigma(r)} = \sqrt{N(r)} \qquad 4$$

Equations 1–4 indicates the instrumental design characteristics can be adjusted to improve results. These include laser power output (P_0), telescope size (A), overall optical collection efficiency (η), integration time (τ), and the distance to the target altitudes.

- *Laser Power* – Improving laser power has a direct impact on SNR with $\mathrm{SNR}{\sim}\sqrt{P_0}$. While a more powerful laser is often desired, this comes with technological and SWAP limitations. Typical laser strengths in HALAS systems already use high pulse energies of 100–800 mJ generating 5–15 W of laser power. While laser technology steadily improves, stronger lasers will likely be power and size limiting.

- *Telescope Size* – Size is a direct relationship with $\mathrm{SNR}{\sim}\sqrt{A}$. Larger telescopes have sizeable consequences for SWAP. Current HALAS technology uses telescopes measuring 14–24”in diameter, while larger telescopes are available with the Aeolus program using a 59” telescope (1.5 m), further gains quickly become size limiting.

- *Optical Efficiency* – Yields a direct relationship with $\mathrm{SNR}{\sim}\sqrt{\eta}$. Current HALAS systems use fiber-optic coupling of the signal to enable modularity, maintainability, and independent movement of the transmit/receive system and science equipment. These qualities are not required in a space-based application, potentially yielding up to 2–3× more signal.

- *Integration Time* – Integration times has a direct relationship with $\mathrm{SNR}{\sim}\sqrt{\tau}$. This quantity directly relates to the vertical resolution with requirements shown in Table 1 through the term $\Delta r = c\tau/2$ with Δr as the integrated range bin. Current HALAS systems use small altitude bins of 130–260m. Going to the minimum requirements in Table 1 (4000m) would generate 15–30× increase in signal, while going to maximum requirements (500m) would only generate a 2–4× increase in signal. The integration time is a parameter that is configured during data analysis and not in the instrument, allowing for flexibility.

- *Distance to Target* – The distance to target has an inverse relationship to SNR, with $\mathrm{SNR}{\sim}1/r$. This distance is set by the orbit of the satellite-based system. A higher orbit increases the satellite lifetime while a shallower orbit reduces the satellite lifetime. Estimates and past satellite performances suggest an altitude between 300–500 km is realistic.

- *Dwell time* – The dwell time *T* is related to the total number of photons and has relationship $\mathrm{SNR}{\sim}\sqrt{T}$. Practically the dwell time will be limited by the minimum requirement horizontal resolution from Table 1 to 1 minute.

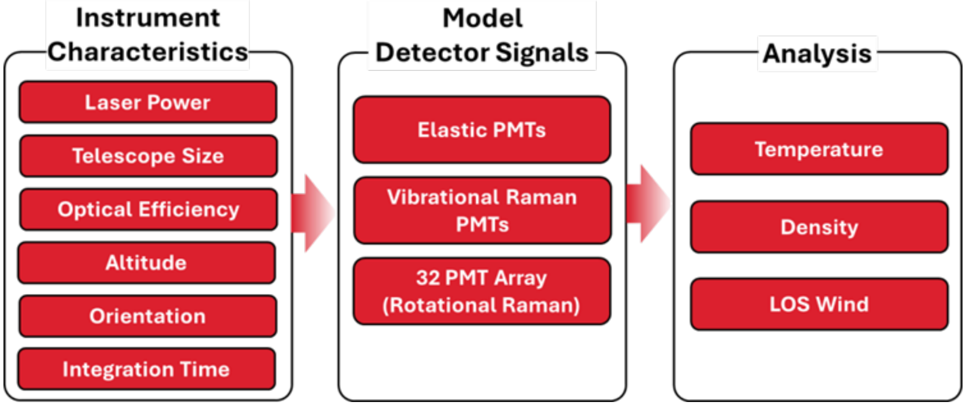
The overlap function, $O(r)$, should reach unity at long range and does not influence the SNR.

Together, these instrumental parameters represent the adjustable parameters for increasing performance for the current HALAS technology. Finding the correct solution of these parameters should yield a performant HALAS-space system. These parameters are inputs from Eqs. 1 and 4 and are modeled in the HALAS modeling framework to help understand the parameter space for a HALAS-space system. As noted, additional considerations important to this parameter space are SWAP and sensor lifetime.

4.2 Description of HALAS modeling framework

The Honeywell HALAS software suite includes a modeling framework that simulates the HALAS system's performance. After some capabilities were added to its flight planning algorithms under the Honeywell Atmospheric Winds Campaign for Space (HAWCS) to enable satellite orbital flight paths, this modeling tool can now predict the fidelity of atmospheric measurements in a hypothesized satellite flight scenario. The model provides a profile of line-of-sight (LOS) wind measurement uncertainty (defined as one standard deviation error bounds on measurements). The schematic in Figure 1 provides a general overview of the HALAS modeling framework, and its key stages are described below.

Figure 1: HALAS modeling framework flow from instrument characteristics to model detector signals to the analysis.



The inputs to the modeling framework include the instrumental parameters described in Section 4.1. Specifically, instrumental parameters are scaled from existing HALAS systems (ground and airborne) with known performance. For example, the HALAS-ground system has a 24-inch telescope. To model the characteristic performance of a HALAS-ground system with a 30-inch telescope $\sigma(r)$ would increase by 25%. Similar methodologies are applied to both the laser power and optical efficiency. The altitude and orientation of the instrument are used to define a specific LOS through the atmosphere, which will have different characteristics accordingly. For example, an LOS pointing at an elevation angle of 90° will travel through the atmosphere to the surface more quickly than a LOS at an elevation angle of 60°.

In addition to these instrument characteristics, a model atmosphere is needed as an input to the HALAS model. The 1976 standard atmosphere (Sissenwine et al. 1976) was chosen to generate typical pressure, temperature, and density profiles. While more complex atmospheric models can be used with spatially and temporally varying profiles, this negligibly changes model results while increasing modeling time to account for different atmospheric profiles. Different aerosol models can also be used to model lidar signal intensity and attenuation in different conditions. In this study, a relatively low loading of aerosols was used to ensure that a robust signal could be generated in that scenario. It is important to note that heavy aerosol loadings can easily attenuate signals below usable levels making atmospheric measurements beyond the aerosols impossible. Due to the UV nature of the HALAS laser, ozone was included to ensure any absorption is appropriately captured. Lastly, a wind profile can be chosen to generate LOS Doppler shifts and LOS wind velocity for an instrumental configuration.

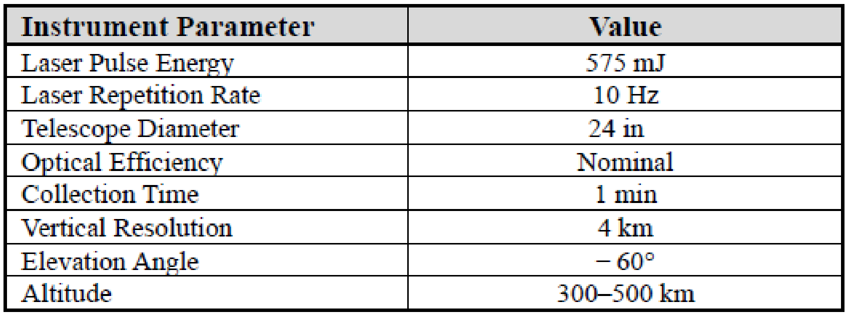
The instrument characteristics and atmospheric model are input into Eq. 1 (along with additional factors specific to each detector type) to create modeled detector signals. These modeled detector signals are then used to calculate atmospheric parameters using the same algorithms analyzing real world HALAS data. Random uncertainties for each data product are determined by propagating

$\sigma(r)$ and SNR of the associated modeled detector signals through the analysis. Furthermore, systematic errors for each data product are determined by comparison to the atmospheric model. Sources of systematic error include both instrumental and detector characteristics.

4.3 Baseline Satellite Performance

The baseline performance of a HALAS-space system is based on the nominal performance of the HALAS-ground system (Table 2), but uses modified instrumental characteristics, defined in Table 3.

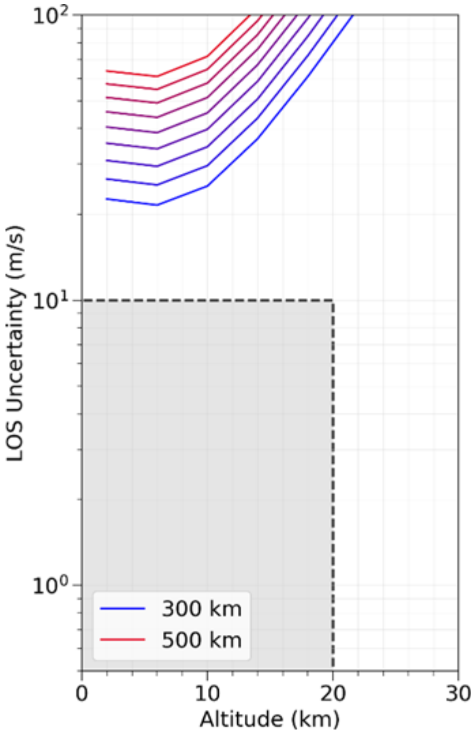
Table 3: Baseline HALAS Instrumental Characteristics.



Instrument Parameter	Value
Laser Pulse Energy	575 mJ
Laser Repetition Rate	10 Hz
Telescope Diameter	24 in
Optical Efficiency	Nominal
Collection Time	1 min
Vertical Resolution	4 km
Elevation Angle	− 60°
Altitude	300–500 km

These parameters represent a minimal change from the current implementation of the HALAS-ground system accounting for the change in initial altitude, pointing direction, vertical resolution, and collection time. Specifically, various initial altitudes between 300–500 km were modeled to examine the performance from different orbits. The pointing direction was changed to be downward facing at an angle of 60° from tangent to Earth’s surface. The vertical resolution was altered to meet the minimum requirement of 4 km from Table 1. Lastly, the collection time was altered to meet the minimum spatial requirement of 400 km, roughly equating to 1 min of data collection for a satellite with a ground speed of 400 km/min. Together these parameters yielded the single LOS wind velocity measurement shown in Figure 2. The resulting uncertainty of this baseline case does not meet the minimum uncertainty requirements in Table 1. The resulting uncertainty at the lowest altitude (300 km) was > 20 m/s at all altitudes.

Figure 2: LOS Wind Uncertainty for the baseline system.



The next task for modeling a HALAS system that will be performant for Table 1 wind uncertainty requirements is to augment the existing instrumental parameters from the ground system. To meet these minimum uncertainty requirements the simplest instrumental parameter to adjust is the power-area product (P_0A)*.* In other words, to increase the return signal through the increases to the laser power and/or the telescope area. The amount of signal can be arbitrarily increased by a scalar which is equivalent to increasing the power-area product. In this way, the amount of signal increase required to meet the requirements can be determined. To meet the requirements for different satellite orbital altitudes, a larger scalar signal enhancement value is required as the distance to target increases for higher orbital altitudes. Figure 3 demonstrates the increased signal strengths of 8×, 15×, and 25× enables HALAS to achieve the minimum LOS wind speed uncertainty requirements from Table 1 (< 10 m/s uncertainty) at 300, 400, and 500 km, respectively.

The minimum improvement at a 300 km altitude requires an 8× improvement to the power-area product. Using the Aeolus project as a reasonable benchmark, the 1.5m telescope (~60 in) can only provide a 6.25× improvement, requiring additional 1.3× laser power increase to a ~750 mJ pulse energy laser. While these estimates meet the desired result, the practical implications of these improvements lay out the need for alternative improvements. Notably, these improvements barely meet the minimum requirements whereas some performance margin is highly desired. The flight altitude of 300 km would likely mean a shorter satellite lifetime or heavier spacecraft mass to accommodate more propellant, so higher altitudes are preferable. Lastly, this laser pulse energy would be difficult to achieve with a rugged space-based laser.

Modeling was used to investigate possible increases to laser power for the two types of HALAS lasers currently in use. HALAS-ground systems use a flashlamp-pumped Nd:YAG laser, whereas

HALAS-Airborne uses a ruggedized diode-pumped Nd:YAG laser. Ruggedized lasers are typically diode-pumped, but diode-pumped lasers typically have lower pulse energy. For HALAS-Airborne, the lower pulse energy is offset by having a higher repetition rate. shows nominal values for HALAS-Airborne lasers. A modest increase to these nominal values will allow a HALAS-ground style laser to achieve the 8× signal increase scenario described above, meeting minimum performance requirements, see Figure 4. A ruggedized HALAS-Airborne style laser at the same hypothetical power does not meet requirements, but this modeling illuminates the impact of ruggedizing the laser. The impact to performance stems from background sources in the measurement and is discussed further in following section. Importantly, understanding these limitations may provide a pathway to overcome them if the current technological gaps are addressed as discussed in Section 7.

Figure 3: Uncertainty reduction with increasing signal strengths

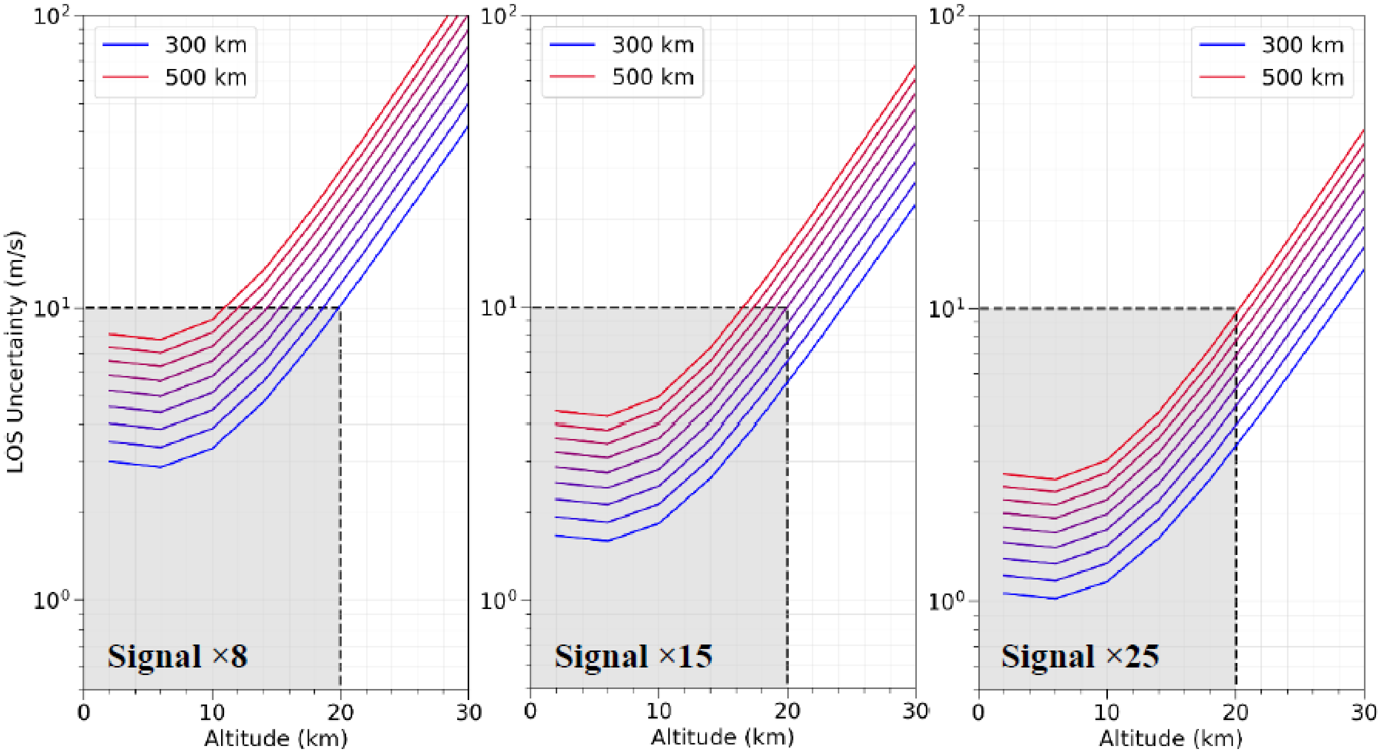


Figure 4: LOS wind uncertainty comparison between a hypothetically improved HALAS-ground (blue) and HALAS-Airborne (AB) lasers (orange) with parameters from at 300 km altitude.

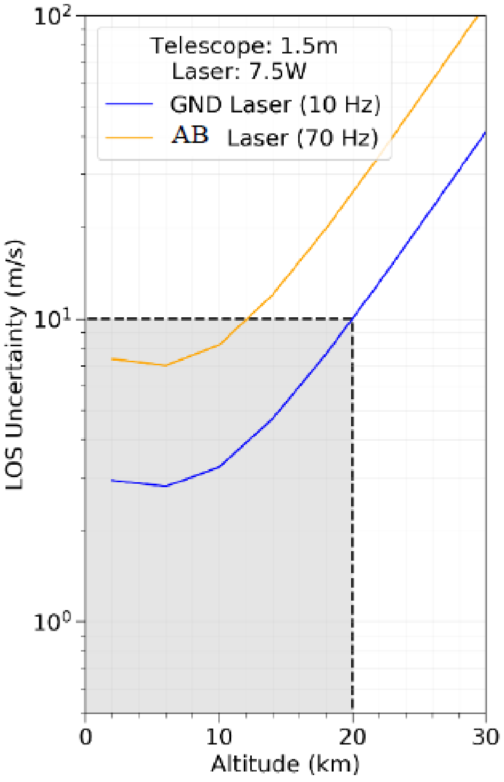


Table 4: Laser characteristics for nominal operational conditions of HALAS-ground and HALAS-Airborne systems and for hypothetically improved conditions for Figure 4

	Nominal		Hypothetical Improved (Figure 4)	
	HALAS-ground	**HALAS-Airborne**	**HALAS-ground**	**HALAS-Airborne**
Laser Type	Flashlamp	Diode	Flashlamp	Diode
Pulse Energy	575 mJ	100 mJ	750 mJ	107 mJ
Repetition Rate	10 Hz	70 Hz	10 Hz	70 Hz
Power	5.75 W	7 W	7.5 W	7.5 W

4.4 Performance with Low Measurement Background

Eq. 4 gives the SNR of the lidar equation in the absence of additional signals. There are many sources of background that can complicate the measurement of the relatively small atmospheric lidar return. Two prominent sources, however, are solar background and detector noise. Eq. 3 & 4 can be rewritten to account for the background level (*B*):

$$\sigma(r) = \sqrt{N(r) + B} \qquad 5$$

$$SNR = \frac{N(r)}{\sigma(r)} = \frac{N(r)}{\sqrt{N(r) + B}} \qquad 6$$

The atmospheric wind measurement is recorded using a Fabry-Perot interferometer and streaking an electron multiplying charge-coupled device (EMCCD) camera. Using this technique the Doppler shift of the backscattered return is readily measurable when compared to a reference measurement of the outgoing laser light. This technique has proved highly successful with the deployment of the HALAS-ground system, but it has not been extensively tested in the HALAS-Airborne systems. This implementation of the EMCCD camera in the HALAS instrument yields a high detector read noise background, due to the high-read speed, spread of the lidar signal across many camera pixels, relatively high collected photon rate, and a large dynamic range. While in practice, the EMCCD camera performs well in high signal levels, the current detection system with its low gain, high resolution EMCCD camera demonstrated worse performance in low signal level than a high gain detector when modeled in preceding section. A high gain detector for low light levels is currently being tested, and its idealized performance as part of a HALAS-space system is modeled below.

In comparison to the detector noise, the HALAS-ground system does not collect sufficient solar background photons to alter the performance. However, the amount of collected solar background between a ground-based and a space-based instrument could be substantially different. In the HALAS-ground system the solar background arises from the number of scattered photons in the atmosphere that are both within the field of view of the telescope and within the spectral bandwidth of the collection filters. For a space-based system, photons reflected from the surface of the Earth are also collected by the telescope, which can potentially increase the solar background. The increased solar background level is difficult to estimate as it depends upon several unknown factors including, orbital trajectory, telescope size, telescope field of view, and telescope pointing direction. Nonetheless, it is unlikely to be large enough to dominate the detector’s read noise. Due to its less substantial impact and the potential ability to mitigate the solar background level through various technical improvements, solar background was not included separately in the HALAS model.

The actual implementation of reducing this instrument background is harder and likely takes the form of a substantial hardware change, e.g., different detector selection or different optical setup. The HALAS modeling framework offers a convenient tool for examining the effect of different background levels on a space-based HALAS system. Specifically, the scenario of interest is taking the limit of no background, shown in Figure 6. The current implementation of the HALAS-ground sensor with parameters shows in Table 3 and with no background meets the minimum requirements for the wind measurement at all orbital altitudes. Upon comparison to the nominal performances in Figure 2, there is a substantial improvement, and, upon comparison to the hypothetically improved signal strengths in Figure 3, the “no-background” case (Figure 6) attains the minimum wind speed uncertainty requirement (10 m/s) up to altitudes higher than the 25× more signal case. Similarly, in Figure 5 the “no-background” case for the HALAS-ground laser substantially outperforms the HALAS-ground laser case with background, even with its 8× signal increase, by achieving the minimum uncertainty requirement up to higher altitudes. Importantly, Figure 5 also demonstrates that a lower-background detector changes the slope of the uncertainty falloff with altitude, enabling a shallower slope and therefore more reliable measurements to be made across a larger altitude range. Importantly, this finding suggests that a considerable amount of effort in the design of a space-based HALAS system should focus on the reduction of the detector read noise.

Figure 5: LOS wind uncertainty under different laser and background (BKG) configurations at 300 km altitude.

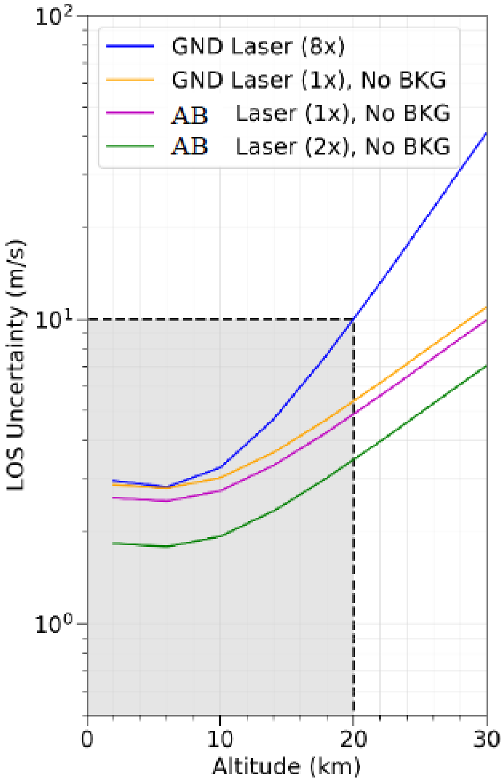
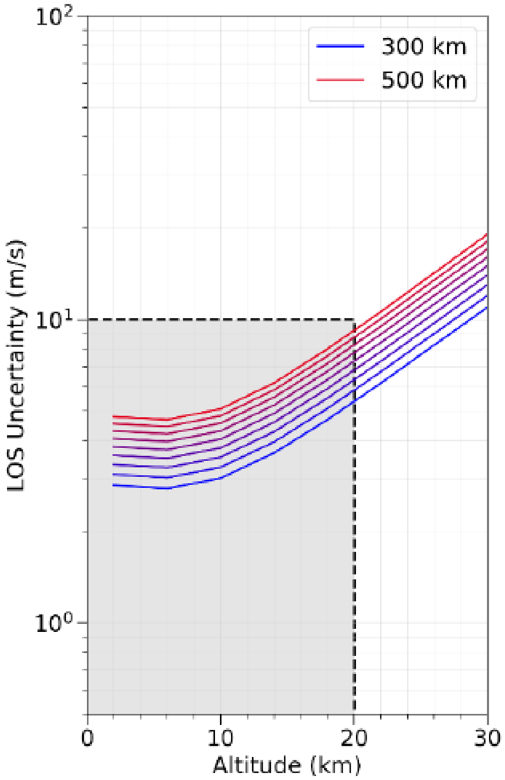


Figure 6: LOS wind uncertainty with the background removed using the nominal HALAS ground system parameters.



Lower background not only increases effective performance, but it also allows the flexibility of the lower pulse energy, ruggedized lasers including the HALAS-Airborne variant. This is readily demonstrated by Figure 5, where the HALAS-Airborne laser outperforms the HALAS-ground laser due to a small increase in laser power (). Figure 5 starkly contrasts Figure 4, where the HALAS-Airborne laser underperforms. The inclusion in Figure 5 of a HALAS-Airborne laser with 2× the signal strength is important due to the known capabilities of the laser manufacturer to produce a laser with twice the pulse energy. With the inclusion of this laser, the < 10 m/s uncertainty extends to ~35 km, and < 5m/s uncertainty extends up to ~25 km meeting the mid-point requirements Table 1 with some margin.

The complete absence of background, however, is unrealistic. At minimum, a small amount of detector noise along with solar background will limit system performance. The HALAS-model allows for the quantification of the background reduction required to meet minimum wind measurement requirements. For the HALAS-Airborne at 2× power (200 mJ) it would necessitate a background level of 1% of nominal and at 0.5% for the HALAS-Airborne at normal power (100 mJ). Figure 8 shows how decrementing background levels improve performance. Importantly, recent experiments of a high-gain detector have found solar-limited background at 0.2% of nominal levels (500× decrease). While applying such a detector for HALAS technology is still in progress, this shows a promising direction and the ability to reach highly desirable performance levels.

Lastly, the ability to meet these requirements with substantial margin is important. The uncertainty estimates shown in Figure 2–7 are associated with a single-LOS measurement and not a 2D wind vector measurement. As with other HALAS systems, multiple LOS measurements are required to retrieve the full 2D wind vector measurement. While a few different strategies can achieve the desired measurement, all come with the cost of sacrificing signal levels to make multiple measurements or launching additional satellites. These different strategies are discussed in Section 5.

4.5 Model-based HALAS Recommendations for Satellite Variant

Based on the modeling described in preceding sections, the optimal options for the HALAS-space system parameters, to meet Table 1 requirements, are provided in Table 5. The main difference from Table 2's baseline parameters is the inclusion of an improved HALAS-Airborne laser, which will include a 2× laser power improvement that was discussed with the manufacturer. This results in a 14W laser with a 20mJ pulse energy and a repetition rate of 70Hz. The HALAS-Airborne laser was chosen due to its lower SWAP and higher degree of ruggedization than the HALAS-ground laser. However, as Figure 4 demonstrates, the laser itself is unable to meet Table 1 requirements for uncertainty without additional changes. As presented in Figure 6, removal of background sources (*B* in Eq. 5 and 6) enables the HALAS-Airborne laser to meet uncertainty requirements. While removal of all background is unrealistic, methods are being tested to maximize the reduction impact of the background components, the detector background with an expected reduction down to 0.2% of current background levels. This high-level reduction was previously demonstrated in early testing of a different HALAS system and would be targeted for a space-based variant. System improvements to address both detector and solar background more effectively are discussed in Section 7.0. Figure 7 depicts the best performance of the proposed HALAS-Airborne system for the case of this 0.2% background level. One improvement to overall performance not modeled here is the potential improved optical efficiency from avoiding fiber coupling in the HALAS-space variant which requires more collaboration with suppliers to determine its impact on performance and/or tradeoffs for SWAP and cost. Overall, while technological gaps exist to attain the performance modeled herein (Figure 7), these are assessed as low to medium risk as technology development continues.

Figure 7: LOS wind uncertainty for the recommended HALAS-space variant.

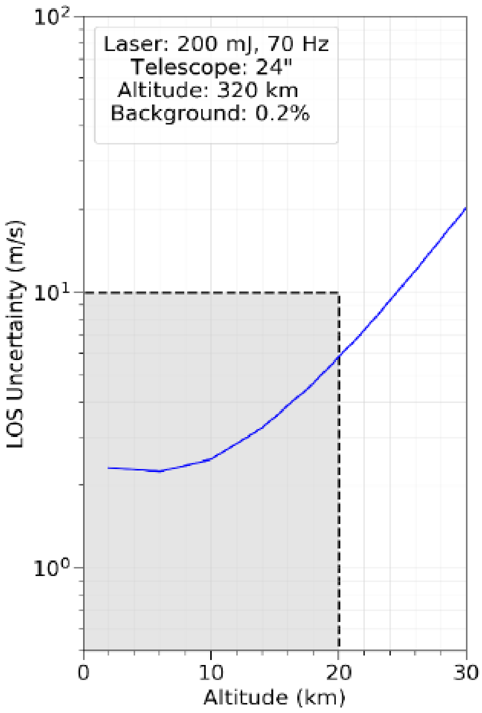
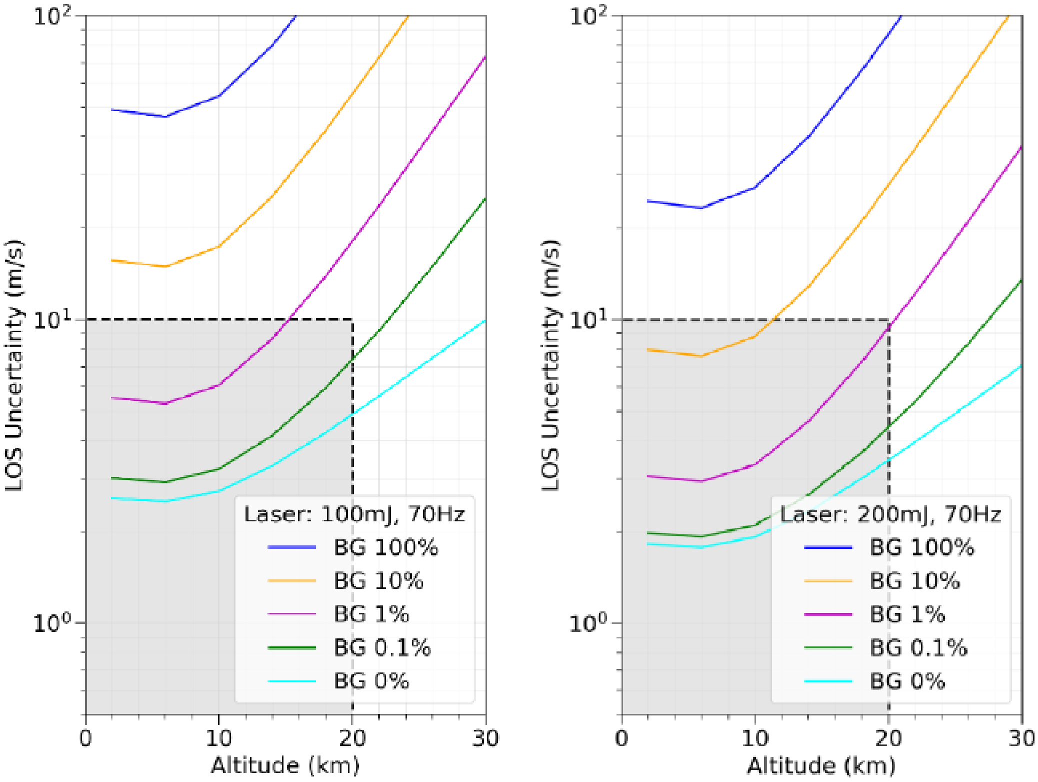


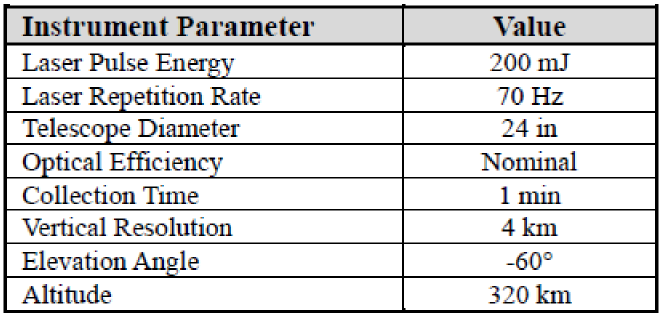
Figure 8: Background Level Influence on Wind Uncertainty.



5. 3D Wind Measurement Strategies

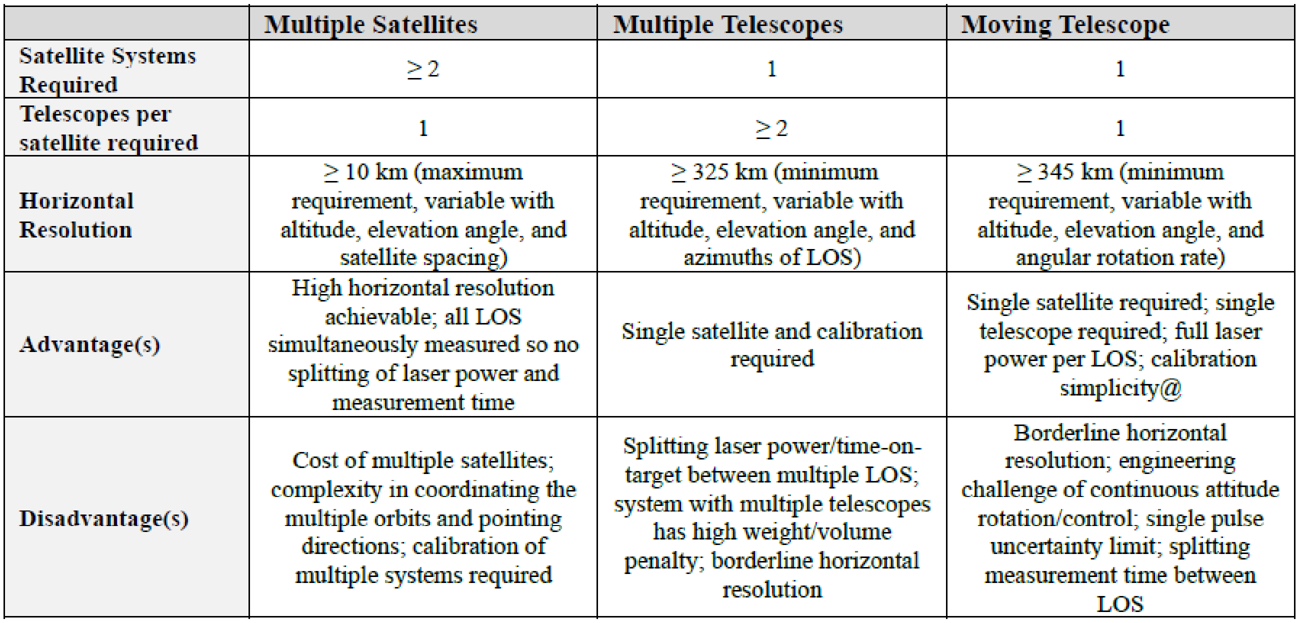
The Doppler shift measurement nature of the HALAS systems requires the combination of multiple pointing directions (i.e. Line-of-sight/LOS) to determine a wind vector. For the HALAS-ground system, this requires pointing the transmit/receive optics at different azimuth and elevation angles in the hemisphere above the horizon. For the HALAS-Airborne system this requires directing the aircraft to perform circular maneuvers to examine many different pointing directions around a localized position. For a HALAS-space system, an entirely different approach must be developed to handle the challenges associated with the fast-moving orbital trajectory as it crosses the surface of earth. Table 6 provides an overview of the various 3D wind measurement strategies proposed in subsections below.

Table 5: Recommended HALAS-space Characteristics.



Instrument Parameter	Value
Laser Pulse Energy	200 mJ
Laser Repetition Rate	70 Hz
Telescope Diameter	24 in
Optical Efficiency	Nominal
Collection Time	1 min
Vertical Resolution	4 km
Elevation Angle	-60°
Altitude	320 km

Table 6: Satellite 3D Wind Measurement Strategies Summary

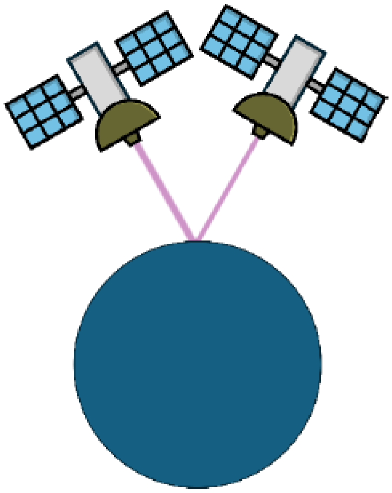


	Multiple Satellites	Multiple Telescopes	Moving Telescope
Satellite Systems Required	≥ 2	1	1
Telescopes per satellite required	1	≥ 2	1
Horizontal Resolution	≥ 10 km (maximum requirement, variable with altitude, elevation angle, and satellite spacing)	≥ 325 km (minimum requirement, variable with altitude, elevation angle, and azimuths of LOS)	≥ 345 km (minimum requirement, variable with altitude, elevation angle, and angular rotation rate)
Advantage(s)	High horizontal resolution achievable; all LOS simultaneously measured so no splitting of laser power and measurement time	Single satellite and calibration required	Single satellite required; single telescope required; full laser power per LOS; calibration simplicity@
Disadvantage(s)	Cost of multiple satellites; complexity in coordinating the multiple orbits and pointing directions; calibration of multiple systems required	Splitting laser power/time-on-target between multiple LOS; system with multiple telescopes has high weight/volume penalty; borderline horizontal resolution	Borderline horizontal resolution; engineering challenge of continuous attitude rotation/control; single pulse uncertainty limit; splitting measurement time between LOS

5.1 Multiple Satellites

Multiple pointing directions are possible by having multiple HALAS-space systems that point in different directions. A constellation of satellites would follow closely, each pointing in a different direction. The advantage of this scenario is ach pointing direction has an independent transmit/receive system collecting LOS data with a dedicated laser, full telescope aperture, and full integration time. In this scenario, the estimates above are a true representation of performance. Due to the ability to choose the orbital trajectory of each satellite independently, it may be possible and advantageous to position the satellites in such a way to minimize the horizontal resolution of the wind measurement. For instance, in a configuration with 2–3 satellites orbiting at 400 km altitude and spaced 450 km horizontally, with a −60° elevation angle (Table 5), the horizontal resolution in the region of highest interest below ~20 km altitude would be ≤ 10 km. Figure 9 shows a schematic illustration of the proposed satellite arrangement in which the different satellites' LOS intersect in the troposphere. Given that the satellite is moving at 400 km/min and requires one minute of data averaging to achieve adequate SNR, realistically, that limits the resolution to 400 km, the minimum requirement. However, because both LOS are interrogating the same approximate region of Earth's atmosphere simultaneously, the assumption of spatial homogeneity is more correct than in other strategies discussed below.

Figure 9: Multiple satellite constellation strategy with 2 satellites oriented to point near same location on Earth's surface for maximum horizontal resolution (not-to-scale).

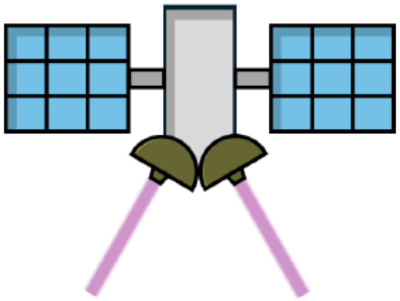


The disadvantage of this scenario is the increased complexity and size of such a system. The need to launch multiple satellites and position these satellites in a coordinated constellation increases the difficulty. Additionally, these space-based HALAS systems may not be cubesats, minisats, or smallsats as has been achieved with other satellite constellations but larger. Section 6 provides more information on the estimated size and weight of these systems. Finally, calibration of multiple instruments relative to one another may become a technical challenge with biases potentially accruing from differing calibrations.

5.2 Multiple Telescopes

The next methodology to achieve multiple LOS directions is to package multiple telescopes onto a single satellite. Figure 10 provides a schematic illustration of a multiple telescope satellite. In this implementation, multiple telescopes can be oriented examining different LOS with the single laser split between the 2–4 LOS either simultaneously or sequentially. The advantage of this scenario is the simplicity to launch a single instrument to achieve the wind measurement. Calibration of a single set of science instruments may be easier and provide more robust wind measurements.

Figure 10: Multiple telescope satellite strategy with 2 telescopes oriented to point separate at LOS to different points on Earth's surface (not-to-scale).



The disadvantages of this scenario are decreased performance and potentially increased instrument size. To make a 2D wind measurement, at least 2 LOS are required, however, to ensure adequate bias cancellation, HALAS systems usually require an additional LOS, increasing the total to 3. This suggests splitting the laser intensity across each LOS, reducing the effective laser power by 2–3× and degrading the performance. To reduce the complexity on the science equipment, each laser pulse or set of laser pulses is sent to each telescope sequentially. In addition to the laser power reduction, the telescopes may also have to be reduced in size since including at least three 24-inch telescopes may prove to be prohibitively large.

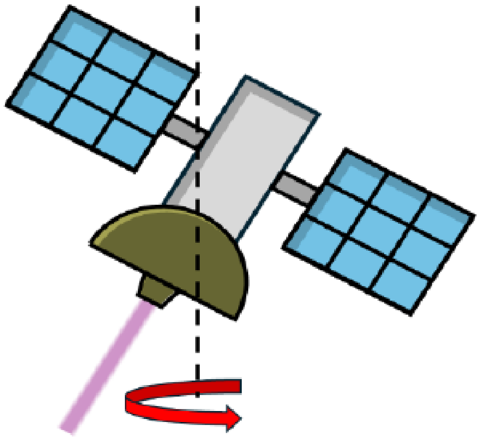
Another disadvantage would be the limitation on horizontal resolution since this method requires pointing telescopes at different azimuth angles from a high altitude, which results in interrogating air masses that are horizontally separated by substantial distances. For a satellite with two telescopes oriented at −60° elevation angle and azimuths separated by 90°, the separation of the interrogated regions is a horizontal ground distance of ~325 km. As more telescopes are added, this horizontal resolution increases. Since the satellite is moving at ground speed of ~400 km/min, each LOS will have a 400 km horizontal resolution over the assumed 1-minute measurement (Table 3), and this horizontal distance of ~325 km would be added to make the functional resolution ≥ 725 km for the 3D measurement, not meeting minimum requirements.

An alternative approach to multiple telescopes is the design of a wide-field telescope that has the capability to measure all 3 LOS simultaneously, allowing for a large-aperture measurement without additional equipment. The current HALAS systems use a Cassegrain telescope, which typically has a small field-of-view. Implementing a wide-field telescope would require the tradeoff of increased solar background which the current small field-of-view telescope has minimized. A different telescope design would be necessary to implement this alternate LOS strategy.

5.3 Moving Telescope

Another methodology involves moving the telescope to point in multiple LOS directions throughout the measurement. In this implementation, the telescope or the whole satellite is rotated about its axis such that multiple LOS are captured in sequence. Figure 11 illustrates this strategy schematically.

Figure 11: Moving telescope satellite strategy with 1 telescope rotating about an axis (nadir in this case) to achieve multiple LOS either continuously or in sequence throughout a measurement period (not-to-scale).



The advantages of this scenario are the requirement of a single instrument to achieve the wind measurement, the simplified calibration of a single set of science instruments, and the ability to use a single telescope and laser to perform the measurement. The potential to use satellite motion control to perform these maneuvers limits the need for additional dedicated equipment (e.g., multiple satellites, multiple telescopes, or a motorized gimbal).

The disadvantage of this scenario is the necessary reduction in performance, difficulty meeting horizontal resolution requirements, and potential source of bias. Each LOS measurement must be measured sequentially, thus like the previous methodology, the laser intensity is spread across each LOS effectively reducing the signal strength by 2–3×. The need to adjust the satellite position to each LOS, necessitates accommodation of the movement time between LOS. This unnecessarily creates difficulty to move between disparate LOS rapidly. The wind measurement produces the best wind vector measurement when azimuths of LOS are spaced equally, preferably with the 3 LOS equally separated by 120° in azimuth. For the minimum horizontal resolution requirement in Table 1, this full 360° rotation needs to be completed in ~1 min, and this type of rotational speed is difficult to achieve. There are two different operational conditions; 1) continuous rotation where each laser pulse observes a different LOS and 2) stop and stare movement where the data is integrated into three static LOS. The first methodology allows for a constant rotational speed which is simpler to produce and maintain, but with the generation of many LOS for each individual pulse, each LOS uncertainty is limited by the pulse energy of the single laser pulse. With estimated maximum angular rotating rates of 2 degrees per second, the second approach would account for substantial downtime within the measurement window (a full minute per LOS with 120° separation), reducing performance. Additionally, to start/stop the movement of the telescope rapidly is an engineering challenge. The horizontal resolution limitations of moving the telescope are plagued by similar limitations as the multiple telescope method, and for a satellite rotating 120° in the 1-minute measurement window, the horizontal separation of the points on Earth's surface being interrogated by the laser beam is ~345 km with the possible need to consider the satellite ground speed reducing the horizontal resolution below the minimum requirement.

5.4 Hybrid Approaches and Final Recommendation

More complex strategies are available to minimize the number of satellites to two while ensuring an adequate measurement of the 2D horizontal wind vector and limiting the impacts of bias. These will not be presented in detail, but are mentioned to indicate that solutions are not limited to those discussed above, of which moving telescope and multiple telescopes present challenges in meeting horizontal resolution requirements and would require significant engineering. A multiple satellite or hybrid approach, if the latter is studied in more detail, is the final recommendation based on these investigations in Sections 5.1-5.4 and the BAA requirements.

5.5 Single Line-of-Sight (LOS)

The requirement for multiple LOS presents a significant technological challenge, and all solutions presented above come with trade-offs in key areas of cost and SWAP. Moreover, two of the strategies may not meet the minimum horizontal resolution requirement. A single LOS satellite would avoid these pitfalls of adding a second satellite and/or telescope to the mission while potentially meeting the minimum needs of the numerical weather prediction community. Ample evidence exists from the deployment of Aeolus that a single LOS satellite can provide improved short-range forecasting (Rennie et al. 2021). A single LOS strategy would be the simplest, but it would not meet NOAA's requirements for a 3D wind measurement. In addition, the technological challenge of bias would need to be addressed for a single LOS measurement from a HALAS-space system to be effective. The HALAS technology team has active plans to address this bias challenge for a reliable single LOS measurement independent of the HALAS-space system development.

6. Satellite System SWAP

The Size, Weight, and Power (SWAP) of a HALAS-space system would drive launch cost and complexity which motivates its minimization while maintaining performance and reliability, which is an important element of this feasibility study. Many of the components will require redesign for any space-based system, which makes estimation of SWAP difficult. Compared to the airborne or ground-based HALAS systems, a space-based system will have higher requirements, including radiation hardening, launch survivability, and increased reliability. A best-effort estimation of a space-based system SWAP was made by scaling current equipment estimates. Many of the SWAP estimates were increased to obtain a best-effort conservative estimate for the overall space-based HALAS SWAP. Table 7 summarizes the estimate by component and includes justifications to explain the scaling.

Table 7: Current airborne and scaled satellite mass estimates

Component	Current Airborne Estimate (kg)	Scaling	Explanation	Satellite Estimate (kg)
Transmit/Receive	30	150%	Larger telescope + Ruggedization	45
Laser	30	133%	Alteration of Thermal Control	40
Science Equipment	65	150%	Ruggedization and Space-based Optimization	100
Thermal	40	200%	Radiative Cooling Adaptation	80
Monitoring	5	200%	Additional Sensors and Ruggedization	10
Computer	8	200%	Real-Time Processing	16
Mechanical	100	150%	Ruggedization	150
Total	**286**			**441**

6.1 Estimated vs. Recommended SWAP Target for HALAS-SPACE

The type of satellite mission targeted by NOAA for a future space-based 3D Wind lidar falls within the category of small satellite (“smallsat”). This is a broad category covering anything under 600kg (Federal Aviation Administration, 2018), but NOAA has recommended the mass of 500kg for a HALAS space-variant. The Atmospheric Laser Doppler Instrument (ALADIN) instrument on the Aeolus satellite had a mass of ~450kg, so the current airborne HALAS SWAP falls significantly below this limit. However, conservative estimates of increased SWAP requirements for space-worthiness bring the estimated weight in line with ALADIN at 441kg, as shown in Table 7. These mass estimates are for the scientific sensor payload onboard a satellite. The non-payload components of the satellite would add significant weight and impact launch vehicle requirements and cost. For the Aeolus mission, the satellite platform dry weight supporting the ALADIN was 650kg, with an additional 266kg of propellant (wet weight), increasing the mass payload by 200%. With the estimated HALAS-space variant mass from Table 7, and the added satellite platform dry and wet mass assumptions as Aeolus, the launch mass would be just over 1300 kg, slightly less than Aeolus but well beyond the mass recommended by NOAA for the “smallsat” definition. There are options for optimization that will be discussed below.

Importantly, this mass figure is derived using the conservative assumptions about the increased mass of various components in Table 7. The biggest components driving SWAP have a large degree of uncertainty (e.g., thermal and mechanical) as the requirements for space may vary significantly. Additionally, some mechanical/thermal support can be provided by the spacecraft rather than the HALAS payload and thus could be double counted in the conservate estimate provided here.

A key parameter driving the volume of a HALAS-space system is the telescope diameter. For the baseline HALAS telescope, a diameter of 24 inches (0.61 m) was used in the modeling above. This telescope is 40% of the 1.5-m diameter ALADIN telescope and 16.5% of its cross-sectional area resulting in significantly reduced volumetric requirements for the spacecraft. The overall spacecraft dimensions for Aeolus were 1.9×2.0×4.6 ($L \times W \times H$) m^3 which added approximately 33% to the diameter in the $L \times W$ dimensions to support the telescope and protect it from radiation, space debris, etc. With the HALAS baseline telescope, the estimated spacecraft cross-section would have a diameter of 0.81 m, giving the HALAS-space variant a volume much closer to a large refrigerator, a typical benchmark for a “smallsat.”

The power for ALADIN was 800W, so the current estimated HALAS power draw of 1kW would be a reasonable expectation from a satellite. Power would be supplied by an array of solar panels extending from the spacecraft just as in Aeolus and many other satellite systems. To achieve 1kW power, approximately 20kg of solar panels would be required based on mean and median specific power ratios of ~50 W/kg (NASA 2025). This is a relatively small portion of the overall mass and is assumed to be a part of the spacecraft mass and thus not included in Table 7. The spacecraft would also require a battery for energy storage, since the polar orbit will pass it through Earth’s shadow each orbit. Also, note that the 2× laser power selected in Section 4.0 would likely require a power draw ~1.3kW and exact requirements should be provided by the laser supplier. Overall, while reducing the power requirements for a HALAS-space system would benefit a future “smallsat” mission, it is not as critical as mass reduction and is a small contributory factor to the overall ~1300kg mass estimate.

6.2 SWAP Optimization Options

While the HALAS-space variant is estimated to be above the 500kg mass recommended by NOAA, there are ways to minimize the SWAP. For a winds-only measurement, as requested in the BAA, some of the “Science Equipment” will not be required, specifically the filter box, spectrograph, and transient recorder. Removing these instruments reduces the HALAS-space mass by ~30kg, approximately 10% of the total mass. This is a significant SWAP savings, but the resulting HALAS-space variant will not have the capability to measure temperature, density, or humidity which is a distinguishing benefit of the HALAS technology.

Another potential area for SWAP optimization, among the “Science Equipment”, is to change the detector used in the interferometer. If the photomultiplier tube (PMT) array is used instead of the current camera system, about 40% of the volume could be removed and a similar reduction in mass could be achieved, reducing interferometer mass from ~35kg to ~21kg. Switching to a PMT detector is also described below in Section 7.1, as a potential solution to overcome the technological challenge of a high instrument background (see discussion in Section 4.4).

Weight reduction of materials is an important area where mass minimization can be achieved. Although ALADIN had a telescope with a cross-sectional area almost 18× that of the HALAS-Airborne's 14-inch telescope, the mass of the telescope is just 1.8× larger than the ~10kg for the transmit/receive subsystem on the HALAS-Airborne system. Such efficient mass-to-volume ratio was achieved by using lightweight ceramic materials. Given that both are Cassegrain telescopes, similar materials and efficiencies should be achieved with the appropriate space optics design. Another material solution for minimizing telescope mass is to use a ferromagnetic ionic liquid (i.e., liquid-metal) mirror telescope. Honeywell has developed a liquid-metal mirror for ground-based astronomical telescopes, but the goal is a space-based telescope mirror product. A liquid-metal mirror could provide a lower SWAP telescope (~15kg for 24-in telescope), self-healing capability if damaged, and can be self-assembled in orbit, reducing the need for the space launch transport survivability of a fragile HALAS component, the telescope mirror. While the technology is at a lower Technology Readiness Level (TRL) than HALAS currently, it could feasibly fit into the schedule for a future satellite mission and benefit the overall HALAS SWAP minimization and ruggedization efforts.

7. Technological Challenges

While the airborne and ground HALAS systems have been developed and demonstrated beyond TRL6, the satellite-based HALAS system is at a relatively low concept maturity level. Multiple technological gaps need to be solved to develop this concept into a technology ready for a space mission. Many of the technological development needs have been mentioned in the prior sections; in this section all major technological challenges will be described in more detail along with possible mitigations and solutions with an assessed risk level.

7.1 Instrument Background

The level of instrument background on the HALAS camera is currently a limiting factor for the performance, as discussed in previous sections. Eliminating the background can substantially improve performance to meet key performance targets as highlighted in Figure 5, and a satellite-based design should address this technological challenge. There are a couple options for overcoming the limitation.

One option is to use an alternate detector technology, such as a photomultiplier tube (PMT) array. A PMT array has the advantages of a lower level of instrument background (meaning less random uncertainty) and higher vertical resolution (meeting maximum vertical resolution requirements in Table 1). There are some disadvantages to using a PMT array. The lower number of pixels would lead to a less accurate fit of the fringes and higher systematic errors. Its smaller linear dynamic range may limit the full vertical extent of the wind measurement and prevent meeting the maximum requirements in Table 1. Whereas EMCCD technology has been reliably used for over a decade, PMT technology has only recently been experimentally tested for HALAS wind measurements in 2024. There is ongoing work to prove successful wind measurements using a PMT array, and the technology requires more development.

Another option is to use an alternate charge-couple device (CCD) for the detector. Teledyne Space Imaging has a pedigree in space-based imaging solutions and supplied the detector for ALADIN (Lux et al. 2024). Their CCD detectors may provide a better solution for a space-based HALAS system. They sacrifice number of pixels and vertical resolution to achieve better quantum efficiency. Furthermore, the Teledyne CCD has been ruggedized for space, unlike the current EMCCD or PMT array options described above. The Honeywell team may pursue technical discussions with Teledyne to assess their detectors' suitability for use on a future HALAS-space system.

Finally, rather than explore a new CCD detector with Teledyne, changes to the configuration of the current EMCCD camera can be explored to optimize measurements for a space-based mission and minimize the detector noise.

7.2 Solar Background

Solar background on the detectors can impact measured signals by increasing the overall random and systematic errors. Currently for HALAS-ground, the scanner avoids pointing the telescope at or near the sun, which has a significant impact on the solar background and the ability to measure at higher altitudes. Overall, the solar background is ranked a lower risk compared to instrument background for a HALAS-space 3D winds measurement.

There is limited data on the impact of solar background to performance for a downward-looking telescope in low Earth orbit (LEO). Aeolus provides relevant information and mitigation techniques. Aeolus used the furthest range gate (#25) to measure the solar background signal and corrects the atmospheric signal at other range gates using this information (Lux et al. 2024). This is similar to a technique that HALAS-ground employs for removing solar background from signals being processed for the solar-sensitive data products (i.e., temperature, humidity, and density).

HALAS could use a similar analysis technique to measure solar background and remove it before calculating the winds measurements to minimize errors.

Besides analysis techniques, hardware changes could help minimize the impacts of solar background. A filter for solar wavelengths could be added in the path of the returned light.

Finally, satellite orbit selection and/or pointing direction can reduce the severity of solar background. Aeolus used a dawn-dusk, sun-synchronous polar orbit, and the ALADIN telescope pointed to the dark side of the terminator. HALAS could use a similar technique to avoid solar background. However, to reach the mid-point or maximum requirements for update rate (which exceed Aeolus), either additional satellites or a non-sun-synchronous orbit would be needed, and solar background would need to be dealt with using data analysis or hardware techniques described above.

7.3 Measurement Bias

The HALAS system must achieve consistently low bias, or systematic errors. Not all methods of error reduction used on ground and airborne systems will apply in space, and Aeolus demonstrated there can be bias sources that are unique to a space version of the instrument (Lux et al. 2024). There are improvements to the core sensor and algorithms to reduce the bias of the system that have been proposed and modeled, and they should be tested before a HALAS-space system is deployed. An interferometer using a hybrid approach consisting of a camera and a PMT array (see section 7.1) was built in 2023 to enable some of these bias reduction strategies, as well as demonstrate the high gain, low noise detector scheme. Testing of this interferometer began in 2024 and additional testing and integration into a HALAS system are planned in 2025 which would aide bias reduction efforts. These and other bias reduction and performance improvements are being funded internally by Honeywell, independent of any future satellite programs.

7.4 Hard Target Return

Hard target return of the laser off the ground is a potential technological challenge that does not affect existing HALAS systems, which are upward looking. Hard target return off the ground could saturate the detector, limiting the system’s ability to measure low altitude (i.e., surface) winds and achieve mid-point vertical extent requirement in Table 1. Several hardware upgrades to core sensors (such as a mechanical shutter or electrical gate) are available to eliminate or mitigate this issue, and while this has not been implemented on current HALAS systems, this problem has been solved by other lidars and, therefore, this challenge is rated as low risk.

7.5 Calibration

Calibration is an important consideration for achieving peak performance of HALAS systems. For the HALAS winds measurements, calibration is not required, but the HALAS team is considering calibrating certain parameters within the wind solution algorithm to remove bias or systematic error. Therefore, these efforts at wind calibration fall under the measurement bias reduction technological challenge described above.

For HALAS-ground and HALAS-Airborne systems, calibrations of temperature and humidity are usually performed using radiosondes. Radiosondes could be used for a HALAS-space system when both measurement regions are coincident in time and space. Another possible method for calibration is to use passive satellite remote sensing systems. These remotely measured atmospheric datasets may increase the match between the altitudes and vertical resolutions of a HALAS-space system. Better understanding of the satellite resources available now and in the future, as well as the development of calibration algorithms, are required to enable calibration of the non-wind data products for a HALAS-space system. Calibration is deemed achievable and assessed as low risk.

7.6 Ruggedization for Space

Ruggedization of all HALAS subcomponents beyond current levels are required to survive the harsh environmental conditions presented by an energetic space launch and multiple years in LEO. The current HALAS-Airborne system's subcomponents have been ruggedized to work in a pressurized, climate-controlled compartment of a UAV and achieved some but certainly not all requirements for a space-based HALAS system. Lessons learned from previous and ongoing ruggedization efforts include the need for vibration isolation of sensitive systems. Key areas of focus include hardening of electronics to withstand harsh radiation environments of space, space launch survivability, outgassing of materials, and thermal management.

While ruggedization requires significant non-recurring engineering (NRE), most of the general categories for subcomponents of the HALAS systems such as laser, optical devices, and computers have been successfully deployed in past spacecraft missions. Therefore, the risk of not being able to achieve the necessary ruggedization is low, but it will require NRE and SWAP tradeoffs. Honeywell and its suppliers for the laser, optics, and other components have significant experience in ruggedizing instruments for space, which can be leveraged for these efforts. The optical detector devices (e.g., interferometer/PMTs, spectrometer, filter boxes) require the most engineering and development for ruggedization, but Aeolus and other missions have demonstrated that space deployments are achievable for these categories of devices.

8. Cost and Time of Development

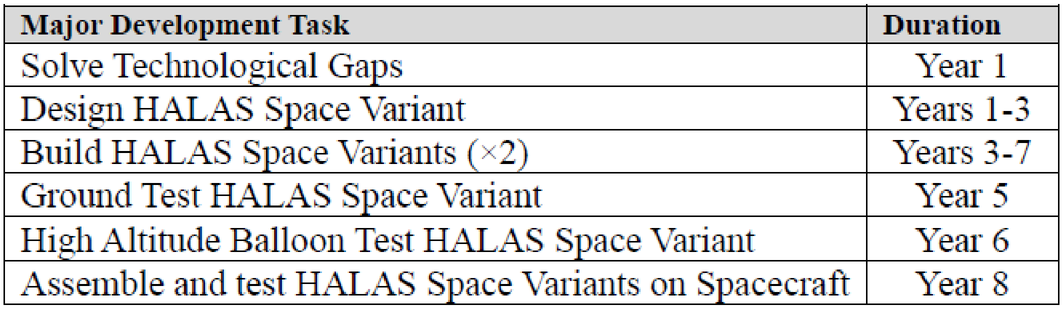
A Rough Order Magnitude (ROM) estimate was requested by NOAA for the cost and time of development of the space variant of HALAS technology described in this report. Therefore, Honeywell has developed and here provides a ROM proposal for the development of a HALAS space variant. The ROM request did not precisely define the scope of development of HALAS space variant so the assumed activities within this scope and other assumptions will be defined in the next paragraph.

Honeywell is proposing to design, build, test, and integrate two HALAS space variant systems up to the point of being ready for launch and subsequent operations in space. The HALAS system that is proposed for development would have instrument parameters as described in Section 4.5 and would accomplish 3D Winds measurements by employing the multiple satellite strategy described in Section 5.1. Importantly, this ROM proposal calls for the development of two (2) HALAS space variants. The key activities include a) solving key technological challenges (see Section 7.0), b) designing a HALAS space variant, c) building two HALAS space variants and an engineering qualification model, d) laboratory, ground, and high-altitude balloon testing of the engineering qualification model, e) assembly and testing of the HALAS space variants onboard two separate spacecraft, and f) planning CONOPS of the space mission. Activities that are not covered by this proposal include but are not limited to: spacecraft design and build, space launch execution, and post-launch operations/support. The HALAS space variant systems delivered would be built to a level to meet operational product assurance requirements (e.g., fully redundant electronics) for a period of ~5 years.

Overall, the ROM price of all these activities is estimated to be $120M ($120,000,000). Regarding estimated timeline for the full scope of the HALAS space variant development proposed, eight (8) years are estimated to be required to complete the enumerated activities. Table 8 outlines a hypothetical schedule to complete all major development activities included in this proposal. For the purposes of estimation program start date of January 1, 2026 was assumed.

This ROM proposal is subject to final agreement by the parties, is not intended to be, and shall not constitute in any way a binding offer or legal agreement or impose any legal obligation or duty on either Honeywell or the recipient.

Table 8: Proposed Schedule for the HALAS Space Variant Development Program



Major Development Task	Duration
Solve Technological Gaps	Year 1
Design HALAS Space Variant	Years 1-3
Build HALAS Space Variants (×2)	Years 3-7
Ground Test HALAS Space Variant	Year 5
High Altitude Balloon Test HALAS Space Variant	Year 6
Assemble and test HALAS Space Variants on Spacecraft	Year 8

9. Optimal Approach Summary and Future Work

During the Aeolus-I missions, ALADIN demonstrated that 355nm direct-detection Doppler lidar can be an effective and impactful space-based 3D Wind Measurement technology. While the HALAS technology has distinct features, some proprietary, to differentiate from ALADIN, the general theory and benefits of the approach are shared. HALAS technology currently exists in ground-based and airborne-based variants (HALAS-ground and HALAS-Airborne), and HAWCS developed the initial concept for what a space-based HALAS system may look like and what performance is achievable. In the BAA for HAWCS, NOAA defined the trade space for desired performance capabilities of a 3D wind measurement satellite, and the HALAS modeling framework demonstrated reaching this trade space requires some technological alterations to the current HALAS-Airborne system, ultimately meeting the desired minimum performance requirements as shown in Table 9. First, the telescope size was increased to match the diameter of the HALAS-ground system at 24 inches, which was important for achieving desired measurement uncertainty given the SNR scales linearly with diameter. Secondly, the HALAS interferometer's EMCDD detector, a significant source of background noise, was replaced by a detector with significantly lower (0.2%) background noise. Honeywell is actively working candidate technology with demonstrated low background noise. With these important modifications and other model parameters set to at least minimum requirements (4 km vertical resolution, ~400 km horizontal resolution) the modeled HALAS-space system comfortably achieves <10m/s uncertainty in Figure 7. Note that having some margin is important for achieving wind speed and direction uncertainties with multiple LOS wind speed measurements.

Three strategies for achieving the multiple LOS wind retrievals as required to measure 2D wind vectors were proposed: multiple satellites, multiple telescopes, and one moving telescope. Each strategy had advantages and disadvantages with multiple satellites being recommended overall for its highest likelihood of achieving minimum performance requirements or better (especially wind uncertainty and horizontal resolution) and minimal SWAP per satellite.

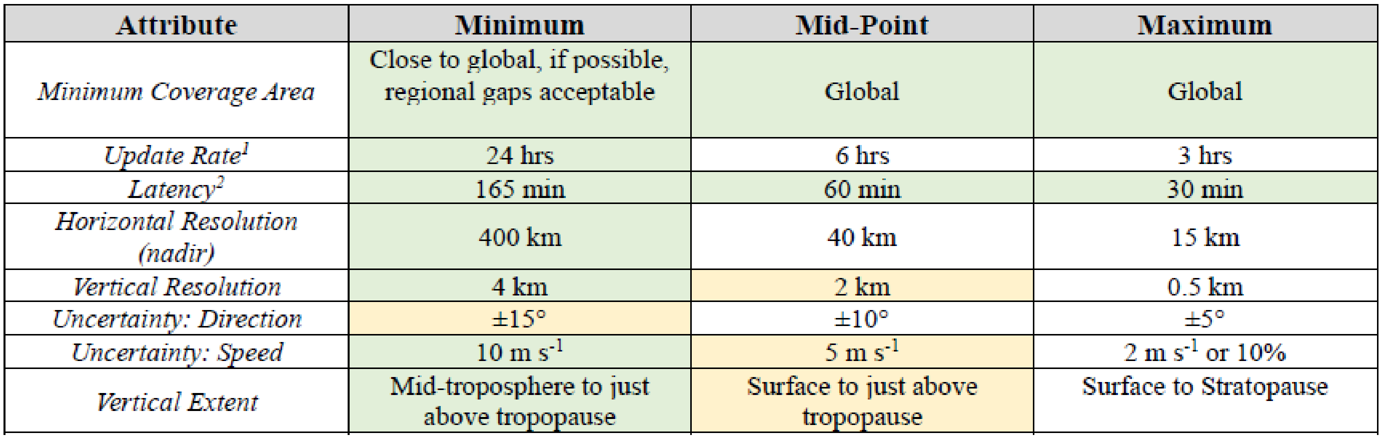
The SWAP for the HALAS-space system was estimated based on current HALAS-Airborne components. The weight/mass was identified as most out-of-scope for a "smallsat" (desired mass

≤500kg) when using conservative factors added to each component which account for the potential added engineering and materials' mass for space ruggedization. The mass was conservatively estimated for the scientific payload (e.g., HALAS as successor to ALADIN) to be 441 lbs with overall spacecraft weight of ~1300 lbs, just under the Aeolus total wet weight. On the other hand, the volume was estimated to be reduced compared to Aeolus due to the smaller telescope. With an estimated ~0.7 m^2 cross-sectional area (~20%), the size of HALAS-space would be in range of a typical 'smallsat'. The volumetric efficiency may allow for mass efficiencies not captured in the conservative mass estimate and additional mass optimization options are possible as described in Section 6.2.

The development of the proposed HALAS-space system requires addressing multiple technological challenges to meet performance requirements in BAA-NOAA-3DWinds-2022, particularly for winds uncertainty. First, a lower background detector technology is being developed and tested, and additional detector solutions should be investigated. Once a solution is fully demonstrated, the risk of a HALAS-space system will not meet BAA-NOAA-3DWinds-2022 requirements, will be reduced. The second major technological challenge is the measurement bias. With current measurement bias levels, HALAS typically requires ≥ 3 LOS to achieve 2D altitude-resolved wind vectors as requested by BAA-NOAA-3DWinds-2022. Ongoing efforts by Honeywell are addressing this issue, and a solution would reduce the required LOS to 2 from 3, benefiting the HALAS-space system in the areas of overall cost, SWAP, and wind uncertainty performance.

Taken together Honeywell suggests a satellite-based HALAS system capable of meeting the NOAA BAA requirements highlighted in green in Table 9. The global requirements with an update rate of 24 hours naturally arise from the satellite nature of the measurement, with faster update rates requiring additional satellites. The latency estimates can easily be met with HALAS-ground systems regularly reaching <15-min latency. The horizontal resolution, vertical resolution, uncertainty, and vertical extent are all related with gains in one area affecting the capabilities of another. The designed system is targeted at meeting the minimum requirements for all these characteristics, with a 400 km resolution limited by the 1-min collection time of the system for sufficient signal integration. Likewise, the 4 km vertical resolution integrates more signal to appropriately deliver the <10 m/s wind speed uncertainty from the surface to the tropopause (~20 km in altitude). Note that wind direction uncertainty is dependent on background wind speed so may not be achievable at lowest wind speeds. Importantly, the wind speed uncertainty performance is achieved with some margin (Figure 7) allowing for a robust measurement to be made and potential for measurement parameter modification to achieve higher performance in a particular measurement attribute. In Table 9, requirements that are partially met or fully achievable with minor system modifications or trade-offs are highlighted in yellow. Overall, HALAS has the capability to meet all minimum requirements and multiple mid-point requirements, and following discussions and continued development the proposed HALAS-space system may be adapted in future iterations to achieve additional performance requirements of highest priority to NOAA and the scientific community.

Table 9: Recommended HALAS System Performance Compared to the BAA requirements. Requirements that have been met are shown highlighted in green.



Attribute	Minimum	Mid-Point	Maximum
Minimum Coverage Area	Close to global, if possible, regional gaps acceptable	Global	Global
Update Rate[1]	24 hrs	6 hrs	3 hrs
Latency[2]	165 min	60 min	30 min
Horizontal Resolution (nadir)	400 km	40 km	15 km
Vertical Resolution	4 km	2 km	0.5 km
Uncertainty: Direction	±15°	±10°	±5°
Uncertainty: Speed	10 m s^{-1}	5 m s^{-1}	2 m s^{-1} or 10%
Vertical Extent	Mid-troposphere to just above tropopause	Surface to just above tropopause	Surface to Stratopause

[1] Update rate is the time interval between successive collections of data from the same geographical point on, or above, the surface of the earth.

[2] Data Latency is defined as the period from the time of observation of all requisite data by the satellite until the data product produced from those date is available to the user at the distribution system

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11. Acronyms

Acronym	Description
AB	Airborne
ALADIN	Atmospheric Laser Doppler Instrument
BAA	Broad Agency Announcement
CCD	Charge-Coupled Device
EMCCD	Electron Multiplying Charge-Coupled Device
ESA	European Space Agency
LEO	Low Earth Orbit
LOS	Line of Sight
NRE	Non-Recurring Engineering
PMT	Photomultiplier Tube
ROM	Rough Order of Magnitude
SNR	Signal-to-Noise Ratio
SWAP	Size, Weight, and Power
TRL	Technology Readiness Level
UV	Ultraviolet

Acronym	Description
2D	Two-Dimensional
3D	Three-Dimensional