Using Unmanned Air Systems to Monitor Methane in the Atmosphere

CMPE 185 Final

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INTRODUCTION

GLOBAL warming likely caused by human activity is a recent phenomenon. The amount of methane in the atmosphere has significantly increased and this has become an increasing threat to the delicate heat balance of Earth. Our understanding of the contribution of atmospheric methane to climate change is limited and it is crucial that we learn more about the sources of methane so that we can better formulate a way to stabilize or end the increasing release of methane. With increased knowledge, there can be increased general awareness of the issue, which in turn, will cause a greater focus on the issue of methane gas in the atmosphere. The amount of methane trapped in permafrost that is being released every year due to climate change induced thaws is unclear, but we do know the amount trapped in the ice is far larger than our atmosphere can absorb without significant effects on global average temperature.

Permafrost is defined as perennially frozen ground that remains at or below zero degree Celsius for two or more years [1]. It generally forms in regions where the mean annual temperature is colder than zero degree Celsius and underlies approximately twenty two percent of the earth?s land surface [2]. Assessing methane emissions are difficult due to the lack of reliable estimates and data collected in the arctic regions. The amount of methane hydrates in the permafrost is estimated to range from 7.5 to 400 billion tons of carbon-equivalent [3]. This large range illustrates the uncertainty that surrounds methane in the permafrost. The origin of the methane, however, is well understood. Methane hydrates are a type of clathrate compound, a polymeric lattice structure that traps or contains another molecule– in this case, methane [4]. Methane clathrate, or methane hydrates, are composed of methane gas frozen into ice, formed at cold temperatures and under high pressure, conditions that are found in the permafrost and under the ocean floor [3]. As the the earth’s temperature rises, melting occurs, releasing the trapped methane [4]. This process can, however, be inhibited by the presence of ice in the permafrost region above the destabilized clathrate as long as the permafrost is not completely melted [4]. The area and zones where the permafrost is melting is currently the area most critical for this study, and as such, we have focused on the Mackenzie River Delta.

The concept for this campaign is to make detailed measurements of methane concentrations over an extended period of several months using remote sensors mounted on an UAV. The Mackenzie Delta, including offshore undersea regions, is overlain by a thick layer of permafrost trapping known deposits of gaseous hydrates that contain very large quantities of methane. This region is the target of much exploratory drilling for the purpose of commercial extraction of natural gas. Drilling activities plus natural seepage eventually leads to significant emissions of methane that need to be accurately quantified. Since the seepage can be from point sources, an intensive search pattern needs to be flown to pinpoint releases. This region is chosen to illustrate the concept of operations, but any similar region of interest can be targeted using a sampling strategy described in this report.

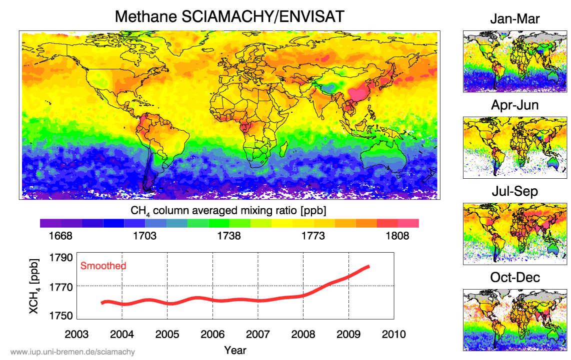

Fig. 1. Methane gas retrieved by near-infrared nadir spectra of reflected and backscattered solar radiation measured [8]

0.1 The Importance of Methane

Methane, CH_4, is one of the most potent greenhouse gases, meaning it traps infrared radiation (heat) emitted from the earths surface and increases the surface temperature. Without greenhouse gases, however, life on Earth as we know it would not be possible; the earth would be too cold to support human life. The issue is though, as a result of human activity, the concentration of gases in the atmosphere have increased to levels that are having an effect on global average temperature sufficient that global warming has become a concern.

Currently, CH_4 concentrations are 2.5 times greater than that of the pre-industrial atmosphere [5]. In 2013, methane "accounted for about 10% of all U.S. greenhouse gas emissions from human activities" [6]. Globally, over 60% of all methane emissions are caused by humans [6].Other sources of methane include, but are not limited to: wildfires, wild animals, vegetation, and wetlands [7]. Methane, unlike carbon dioxide, only spends about 12 years in the atmosphere. During that time, however, it causes the damage of 28-36 years of carbon dioxide equivalent [6]. The relative impact of CH_4 on global warming is 25 times greater than CO_2 over a 100-year period [6]. Additionally, the oxidation of methane by hydroxyl in the troposphere leads to the formation of formaldehyde, carbon monoxide, and ozone [5]. These chemicals also affect the concentration of water vapor and ozone in the stratosphere which too have an effect on the Earth's climate system [5]. The listed effects emphasize that methane is far more effective than other greenhouse gases in absorbing the Earth's emitted heat and thus causing a temperature increase. The process of releasing methane hydrates becomes a positive feedback loop increasing the rate of melting making it possible that a runaway release of methane may occur.

0.2 Why UAS Observations?

This methane mission is designed to collect spatially and temporally detailed observations that cannot be provided by the current set of satellites that provide methane data. UAS are also able to fly more frequently and are able to make continuous observations, therefore, making it possible to track the thaw of the methane hydrates. Although satellite sensors are able to provide a wide, global coverage, they have long repeat cycles. With UAS, we can have monthly and annual observations and we can better observe biogenic signals at fine spatial scales. Passive sensors on satellites can provide swath coverage but have limited sensitivity in the lower troposphere and at high latitudes, especially around where the Mackenzie Delta is located. Passive sensor data is highly susceptible to bias from aerosol and cloud contamination. In contrast, an active sensor can be placed on a UAS for high accuracy data at night or during the day, in all seasons and at any latitude. UAS missions comprising of active and passive sensors allow for long duration intensive observations of key trace gases in targeted areas. UAS missions could provide diurnal, monthly, and annual measurements of methane in regions with both natural and anthropogenic emissions. This also allows us to link satellite and surface observations due to increased sensitivity in lower troposphere. With this proposed mission, we can use the UAS methane data to help calibrate and validate other satellites instruments. Having both active and passive sensors allows for high accuracy and precision methane measurements along with observations of other key trace gases: CO_2, CO, and H_2O that aid in the classification of emission sources.

0.2.1 Current and Future Observations

Currently, NASA does not have an active methane monitoring satellite. GOSAT (Greenhouse Gases Observing Satellite), or Ibuki, is one of the satellites making methane observations since its launch in January of 2009 [9]. It has produced a large number of high-resolution spectroscopic observations using reflected sunlight [9]. As described previously, SCHIAMACHY was a satellite with a spectrometer that provided data from 2002 to 2012. Another satellite launched into orbit in 2002, the Atmospheric Infrared Sounder, AIRS, is an infrared spectrometer on the Aqua satellite that can detect a number of gas species, including CO_2 and CH_4 [5], [10]. Infrared Atmospheric Sounding Interferometer (IASI) and TES (Technology Experiment Satellite) are other satellites with similar qualities to AIRS [11], [10]. IASI was carried by the European Operational Meteorology platform, launched around 2002 and TES was part of the Earth Observing System (EOS-Chem1) that would provide long-term data sets for Earth system Science [11]. Both instruments recorded atmospheric spectra using Earth's thermal emissions [11]. TES was dedicated to chemistry and climate research while AIRS and IASI were the next generation for weather forecasts [11], [10].Future satellites that may enhance methane measurement data include GOSAT-2, CarbonSAT (Carbon Satellite), TROPOMI (Tropospheric monitoring instrument) on the Sentinel-5 Precursor mission, and MERLIN (Methane Remote Sensing Lidar)

Future observations include GOSAT-2, CarbonSAT (Carbon Satellite), TROPOMI (Tropospheric monitoring instrument) on the Sentinel-5 Precursor mission, and MERLIN (Methane Remote Sensing Lidar). These Satellites represent a future

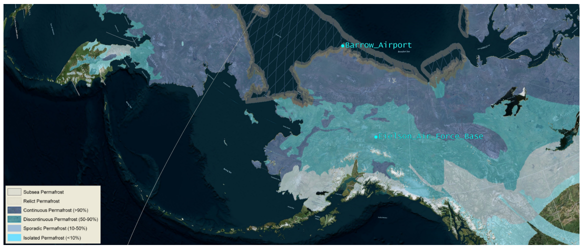

Fig. 2. A map of permafrost data from the National Snow and Ice Data Center generated using the Satellite Tool Kit software [12].

of methane observations. Satellite observations, however, often do not reach the arctic regions in the winter and there are long time periods between each passover which does not allow detailed observations, which is why we are seeking for an alternative system like UAS.

0.3 Mackenzie Delta

The map in Figure 2 shows the two important landmarks for UAV use in the Alaskan arctic region and western Canadian territory. Both the Yukon River delta and the Mackenzie River delta are within reasonable reach of the Eielson Air Force Base (Eielson AFB), one of the bases that these missions could be flown from. For this mission, the Mackenzie Delta will be the primary focus for the following reasons: 1) the Mackenzie Delta is hypothesized to contain large amounts of methane stored in inland permafrost regions, and even more methane hydrates stored in offshore shelves; 2) there is increased activity in oil and gas production in that area (the primary source for the keystone pipeline in the United States); and 3) the Mackenzie Delta has a longer growing season due to the presence of the Arctic Ocean, relatively warm river water, and low elevaion which can locally enhance thawing and emissions. The thawing is indicated by the small patch of lighter blue near the border of Alaska and Canada.

1 Campaign Requirements & Objectives

1) The proposed campaign is focused on the growing/thawing season during the late spring into early fall: May to October. It would consist of monthly flights, each making use of the maximum UAVs endurance. As the temperatures begin to warm seasonally and the days become longer, the snow and permafrost begin to melt. In the longer term, as the ocean temperature increases, it causes sub-sea hydrates to thaw.
2) NASA manned aircraft and UAVs suitable for this campaign are based at Edwards Air Force Base/Armstrong Flight Research Center in Edwards, California. This makes Edwards one of the main places to consider as a base. Eielson Air Force Base near Fairbanks, Alaska is another base of interest. Although Eielson Air Force Base is much closer to the site of interest, a long term mission such as the one proposed would require a six month relocation of all ground-crew that are required to be present, including a subset of the science PIs for all instruments, and the ground operations station for take-off and landing.
3) The sample region of interest should be flown over at a constant altitude above 20 kft, using a grid pattern with a desired spacing of about 6nmi. This sample region should contain land of the Mackenzie Delta, as well as some

over the ocean flight paths to measure the ocean methane hydrates emissions.

4) Two sensors would be preferred. The primary sensor of this mission is a LIDAR and the sec- ondary sensor is a passive spectrometer. The spectrometer requires daylight and a ground view unobstructed by clouds in order to take measurements.
5) Fly on clear days or days with minimal cloud during daylight by preference, but continue through the night when UAV endurance permits (LIDAR can measure at night, spectrometer requires reflected sunlight).
6) The UAV is controlled and monitored via Iridium satellite links that have 100% coverage in all regions, including the poles.
7) The sensors can be sent commands (if necessary) and monitored via Iridium at low data rates (a few kb/s).
8) All data from the sensors must be recorded onboard the UAV for later retrieval. Minimal data may be sent over the Iridium link to confirm all instruments are working throughout the duration of the mission. Data can also be sent over a KU-band satellite link at up to 25 mb/s but the link is less reliable at high latitudes and is unusable above 70 degrees latitude.

2 Sensors

The sensors consist of a LIDAR and passive infrared spectrometer using reflected sunlight. At this time, no in-situ sampling from the UAV is envisaged. Ground level samples could be taken or sampling from a manned aircraft to complement and confirm the remote sensing measurements. In addition some fights could be timed to coincide with an overpass of a satellite with methane measurement capability for comparison. Measurements are to be made over an extended time period between May and October on a monthly basis. This favors basing the UAV at Edwards or Wallops for logistics and cost reasons. The penalty is a 4200 nmi round trip to the region of interest that substantially reduces time and distance on station. Eielson air force base is an option for basing the UAV closer to the region of interest, but is more suited to a shorter duration campaign rather than a campaign that extends over many months. This is because a mobile ground station and operations crew would need to be located at Eielson for the duration of the campaign.

3 Mission Planning

Measurements are to be made over an extended time period between May and October on a monthly basis. This favors basing the UAV at Edwards or Wallops for logistics and cost reasons. The penalty is a 4178 nmi round trip to the region of interest that substantially reduces time and distance on station. If the UAV is stationed at Wallops, there would be a penalty of 5316 nmi, putting it outside the range of most UAVs. Eielson air force base is an option for basing the UAV closer to the region of interest, but is more suited to a shorter duration campaign rather than a campaign that extends over many months. This is because a mobile ground station and operations crew would need to be located at Eielson for the duration of the campaign.

3.1 Baseline Concept

1) Base UAV at Edwards or Wallops. (At least two potential UAV types will be evaluated for consideration.)
2) Campaign consists of 6 flights, spaced at monthly intervals starting in May, ending in October.
3) Sample region of interest flying at constant altitude above 20kft, using a grid pattern with a maximum spacing of 6nm, finer if UAV endurance permits. (Use maximum vehicle endurance.)
4) Fly on clear days or days with minimal cloud during daylight by preference, but continue through the night when UAV endurance permits (LIDAR can measure at night, infrared spectrometer requires reflected sunlight).
5) The UAV is controlled and monitored via Iridium satellite links that have 100% coverage.
6) The sensors can be sent commands (if necessary) and monitored via Iridium at low data rates (a few kb/s).
7) Data can be sent over a KU band satellite link at up to 25 mb/s but the link is less reliable at high latitudes and is unusable above 70 degrees latitude.
8) Data also needs to be recorded on board the UAV for later retrieval.

4 VEHICLES

UAS, as per its namesake, are aircraft systems with no human pilot present. UAS differ from Unmanned Aerial Vehicles (UAV) because the aircraft is only a part of the Unmanned System. There is also a remote ground station that monitors and controls the aircraft in case of an emergency or abnormality. In our missions, there will also be scientists monitoring the live feed from the craft, and may choose to deviate from the path in order to investigate a specific anomally or take manual control in case of an emergency. During take off and landing, there is always a ground-crew that takes remote control to ensure a safe and successful landing.

4.1 Advantages and Disadvantages of UAS

The biggest advantages of UAS is that they have long endurances with useful payloads. In the case of the NASA Global Hawk, it has about 31 hours worth of endurance and the Aurora Flight Sciences' Orion has a five day endurance, longer than most manned airplanes with the same payload. UAS can also operate autonomously once the flight path has been planned. Furthermore, Aurora Flight Sciences claims that the Orion can use its onboard intelligence to adjust the flight trajectory to avoid hazardous weather, which is useful because there can be many uncertainties with planning weather five days in advance. The NASA Global Hawk has a slightly less advanced system that allows it to detect and avoid obstacles through human interaction and control. Most UAS, if not all, are able to take off, land, and do en-route operations autonomously and do not require piloting skills. This also allows for a smaller crew to operate. Aurora Flight Sciences claims that the Orion will be operable by a minimum of two pilots at all times and those pilots can be stationed anywhere. That means that there is also no flight crew risk or risk of fatigue. There are also no hour limiters besides the fuel capacity. Because of the long endurance of these UAS, there are also no safety problems associated with flying at night.

In contrast, the greatest disadvantages of UAS is the smaller payload than large manned aircraft and UAS generally fly much slower than manned aircraft. Although the Global Hawk has a reasonable cruise speed of 310 knots, the Aurora Flight Sciences' Orion has a significantly slower cruise speed of 70 knots. This means that the Orion cannot be stationed in high winds. Due to the larger wingspans, UAS tend to be less robust to turbulence and other hazardous conditions and cannot take off with a crosswind greater than 15 knots. Lastly, FAA restrictions on flying in controlled air space require a certificate of authorization (CoA).

4.2 Vehicle Comparison

The aircrafts that we examine to use, in particular, will be Medium Altitiude, Long Endurance (MALE) or High Altitude, Long Endurance (HALE) crafts. MALE aircrafts are UAS that fly up to 30,000 feet, whereas HALE UAS fly over 30,000 feet. In the study for MALE UAS, we examine the use of the "Ikhana" Predator and for HALE type UAS, we examine the use of a NASA Global Hawk. In regards to future missions, we examine the use of a Aurora Flight Sciences' Orion (Aurora Orion), the current record holder for the longest unmanned flight. In comparison, we will study the use of a manned vehicle for the same mission. In this scenario, a DC-8 was considered for its long endurance and flexibility.

In figure **??**, the superior range of the NASA Global Hawk becomes distinctive. We use the NASA as the baseline for all comparisons. The time spent on station by the Aurora Flight Sciences Orion, however, is also greatly emphasized with twice the amount of time of the Global Hawk. The DC-8 is significantly inferior to both the

Fig. 3. Aurora Flight Sciences' Orion

UAVs in terms of time or distance on station.

4.3 NASA Global Hawk

Currently, NASA owns six Global Hawks. Only two of these are configured for NASA use, and of these two, there is only one that is currently operational The operational Global Hawk is currently the sixth Global Hawk built and given to NASA by the U.S. Air Force. The Global Hawk has the ability to carry large payloads for an extended period of time. Its thirty-one hour endurance coupled with its 1500 lb payload at max endurance makes it the favored choice on paper, but the reality is that the NASA Global Hawk struggles to fly at max endurance with more than 850 lbs of payload, about the weight of one single instrument. Additionally, due to the payload capacity of the Global Hawk, both instruments were designed for the same compartment and would require reconfiguration before implementing the mission. The NASA Global Hawk has a nominal cruise speed of 310 knots and a max speed of 350 knots. Its nominal cruise altitude is 55,000 feet. It burns about 470 pounds of fuel per hour, which is reasonable for a UAV and far less than a DC-8. A disadvantage of the NASA Global Hawk is that requires a large team to operate. What the NASA Global Hawk saves in fuel is largely spent in the cost of supporting the UAS.

4.4 Aurora Flight Sciences' Orion

Aurora Flight Sciences Orion is a MALE UAS that is near production. It is advertised with a 8,400 nmi flying range at a low speed of 70 knots, ideal for observations, but a disadvantage for long transits to the site. The LIDAR and the infrared spectrometer will be able to get far accurate readings with the slower speed because the sensors the measurements can be integrated (averaged) over a long time period. Additionally, Aurora Flight Sciences advertises the Orion as being designed to have low operating costs and an open architecture improving accessibility of the aircraft. Although the aircraft is still in the prototype phase, it is not considered to be a future aircraft due to its near-term availability. Aurora Flight Sciences advertises its fuel burn at an extraordinary low 42 pounds per hour, verified by flight test, a fraction of any other vehicle of this size.

Aurora Flight Sciences also claims that the vehicle can be operated by one pilot from the ground station, although two would be used for redundancy, and the operator does not need to be a qualified pilot.. In contrast to Global Hawk, Orion does not require a large crew the aircraft. The Aurora Orion should be able to hold both of the sensors in its payload but its endurance will be greatly impacted if it is carrying both sensors due to the large weight. If there is only one sensor onboard, the Aurora Flight Sciences Orion has the potential to fly for the full 120 hours that it is advertised for.

4.5 Alternative Vehicles: DC-8

An alternative concept of operation for comparison with the UAS is to use a suitable manned aircraft, based at NASA Armstrong/Edwards. The chosen craft is a DC-8: with the range of upwards of 5,700 nmi, it has the capacity to fly to the Mackenzie area and spend around900 nmi flying on station before having to return. With a cruise speed of 450 knots, the plane is able to reach the delta in around 5 hours and spend around 2 hours on site. This craft typically has eight crew members to operate and consumes far more fuel than any competing UAV. It is, however, large and is able to hold both sensors with ease and also carry a whole science team to analyze the data on-board. As a manned aircraft, it has the advantage of being able to operate in Federal Air Space with few restrictions.

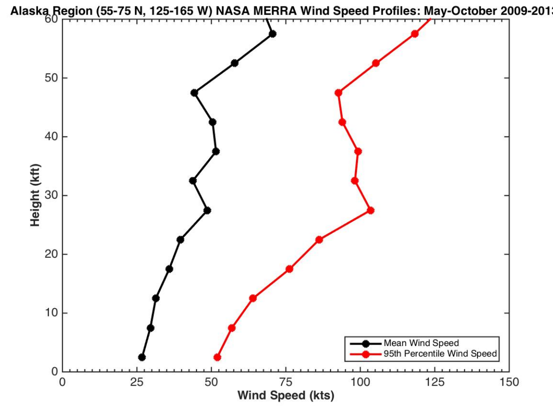

Fig. 4. This map was generated using wind data from 2009 to 2013 in the targeted months.

4.6 Wind and other Issues

One of issues to flying a UAV is weather and wind restrictions.

A restriction of one of high spectral imager is that it requires the use of reflected sunlight in order to map out the region. This is, however, in effective if there is no reflected sunlight such as at night or when it is cloudy. Although the Global Hawk can fly above most of the weather and is generally unaffected by it, the LIDAR and high spectral imager cannot "see" through most clouds so the team would need to plan for a few clear days in a row. In the case of the Orion, the UAV flies under most of the weather and, if it is cloudy, it would not be

Fig. 5. Boeing's Phantom Eye

able to detect much reflected sunlight due to the light being blocked and therefore the results would be just as unclear. Due to the slow cruise speed of the Orion, the team must prepare for and predict four or five days of sunny days which may be hard to achieve.

On the contrary, due to the high latitude, there are many hours of sunlight during the summer which is conducive to making measurements with the high spectral imager if there are more than two clear days to fly per month.

5 Future Vehicles

As this mission is a model for future missions, we looked towards the future to see what other crafts would be suited to the proposed mission. The ideal vehicle would be able to fly in lower and higher altitudes, have a large payload of 2000 lbs, and have a fast cruise speed to go to its target location quickly before slowing down and making detailed observations with its sensors. Furthermore, it would be well suited for the mission if it had a multi-day endurance due to the long-legs of the mission.

5.1 Boeing Phantom Eye

The Boeing Phantom Eye is a hydrogen fueled, HALE aircraft designed for surveillance, much like the Aurora Flight Sciences' Orion. It was designed to fly at higher than 60,000 feet and have a 7-10 day endurance with a 2,000+ payload and a decent cruise speed of 150 knots. The Boeing Phantom Eye would be about twenty five years in the future and currently Boeing needs about 150 million USD in order to proceed with the project and build another demonstrator aircraft.

5.2 General Atomics Aeronautical Systems' Predator B ER

The General Atomics' Predator B ER is advertised as a MALE aircraft at a lower altitude of 45,000 feet and a 42 hour endurance. It has a meager payload of 450 lbs and a cruise speed of 155 knots. The General Atomics' B ER would be ideal for a single sensor mission but it would be better suited to flying out of Eielson Air Force Base due to its shorter endurance.

5.2.1 NASA "Ikhana" Predator

The NASA MQ-9 Predator B "Ikhana" was a acquired by NASA late 2006 to support Earth science missions [13] and was an original candidate for the mission. Unfortunately, the Ikhana cannot reach the Mackenzie Delta from Edwards Air Force Base/Armstrong.

6 Conclusion

The atmosphere is currently a fragile system on the verge of collapse. With these proposed further studies into methane, its release, and sources, we are able to better understand how methane can be stopped from being released into the atmosphere. Additionally, we may be able to further our calculations for the amount of methane hydrates trapped within the permafrost and better estimate the future damage that global warming will cause and how we might be able to prevent the damage. The proposed mission would be to use the Global Hawk from Edwards and in the future, we propose that we would use the Aurora Flight Sciences' Orion out of Eielson despite the long-term mission. The Orion, however, can be operated remotely and is ultimately better for making in depth measurements and taking more accurate data samples.

The proposed methane monitoring mission consists of six intensive observation campaigns in the northern high latitudes to quantify permafrost methane emission during the summer growing season. Mackenzie Delta was identified as a potential sampling area where natural permafrost thaw signals are large and oil and gas exploration is actively growing. Monthly sampling strategy sufficient to capture seasonal variability. Long endurance UAV allow for observation of diurnal variability within sampling area. Basing a team at a remote base near the site is not an efficient use of the UAV or personnel unless the methane measurement campaign can be combined with a campaign that does require frequent measurements, such as a cloud study. Flying out of Edwards is preferable, but requires a long transit to the site. DC-8 does not have much endurance from Edwards, both Global Hawk and Aurora Orion have the required endurance to transit and remain on site for an extended period. Global Hawk has a much higher cruise speed that is advantageous for the transit, but for the actual measurements the slow speed of Orion would allow longer integration times leading to better accuracy. NASA experience with Global Hawk is that it is a very effective platform when long endurance/ distance is required, but it is very costly and does not have a good record of reliability of starting the mission. Once in flight it is very reliable. The use of the Global Hawk requires development of a radome over zone 25 and active cooling system to allow for implementation of the methane LIDAR system. The aircraft modifications would account for a large fraction of the total mission cost and would take 1-2 years to implement. Both sensors will likely require the use of zone 25 for operation on Global Hawk, thus making this platform not ideal for an active+passive mission concept. Aurora Orion may be considerably cheaper to operate and more reliable, has an open architecture and may be easier and cheaper to modify. The option to buy time on Orion using the Aurora Owned and Operated business model may be attractive. If the stated cost of the Orion of $15m is a reality, then this does not seem expensive for the capability. Limitations of Orion are slow cruise speed and lower altitude limit than Global Hawk, future versions with turbocharged engines may be able to reach 50 kft or more but with less endurance. Orion has the best endurance of any operational UAV and is ideally suited for campaigns where fast cruise speeds and high altitudes are not required.

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