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Mission Design of the Global Lidar Altimetry Mission (GLAMIS)

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Abstract The Global Lidar Altimetry Mission (GLAMIS) proposes a distributed network of novel spaceborne lidar to provide a regularly updated global lidar map that could be employed by governments and businesses for applications such as flood modelling, urban planning and commercial forestry. The very narrow swath of a lidar instrument makes achieving global coverage a significant challenge. Unlike with most Earth observation technologies, the swath width of a lidar system increases as the orbit altitude decreases, due to the reduction in energy per shot needed to get a measurable return for each pulse. Because of this, Very Low Earth Orbits (VLEOs) offer the possibility to significantly decrease the number of spacecraft required for GLAMIS to achieve global coverage in a given time. This paper presents the analysis of a range of mission architectures, showing that the performance improvement at VLEO altitudes is significant. Assuming a desired imaging probability of >80% (when accounting for cloud cover), 14 500 kg spacecraft at a 200 km altitude would provide the desired coverage at 20m resolution to 95% of the Earth's land in one year. Using a 400 km altitude orbit, 63 spacecraft would be required to provide the same coverage. As such, the use of a VLEO 200 km altitude orbit could provide a reduction in mission cost of approximately 70%, from $355M to $96M. If a propulsion system that could maintain the VLEO altitude could be integrated for less than this cost difference, then GLAMIS could see significant cost savings.

Keywords Lidar · Satellite Constellation · Very Low Earth Orbit

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1 Introduction

Lidar (Light Detection and Ranging) is a remote sensing method used to examine the surface of the Earth. Using a pulsed laser, lidar uses ranging measurements of the Earth to generate very precise topographical information, such as bare Earth elevation and the structure of vegetation [1,2]. Airborne lidar has been used by governments and businesses to make maps for use in flood modelling, carbon content mapping, and investigation of archaeological sites, among others [3–5]. However, airborne lidar requires the dedicated flight of a lidar equipped aircraft over the region of interest. As such, it has a high cost per unit area and is impractical for global mapping.

Spaceborne lidar has the potential to provide global lidar mapping through continuous observation from orbit. However, this remains challenging to achieve in practice as spaceborne lidar must provide sufficient power for the lidar payload. This power requirement results in spaceborne lidars sampling very small areas. GEDI [2] has the widest swath of existing spaceborne lidar and is hosted on the International Space Station (ISS). Even so, during its two year mission, GEDI's sparse sampling will result in only around 2-4% of the Earth's land surface being directly imaged.

The Global Lidar Altimetry Mission (GLAMIS) proposes using multiple spacecraft hosting spaceborne lidar instruments to provide a regularly updated global lidar map. The very narrow swath of a lidar instrument makes achieving global coverage a significant challenge. However, in contrast to optical and radar instruments, the swath width of a lidar system increases as the orbit altitude decreases. This is due to the reduction in energy needed per pulse at lower altitudes, allowing the same laser power to be spread over a wider swath [6]. Because of this, Very Low Earth Orbits (VLEOs) offer the possibility to significantly decrease the number of spacecraft required to achieve global lidar coverage in a given time [7]. However, this would require the use of active propulsion to maintain the altitude of the orbit as well as accurate pointing for the duration of the mission.

2 Method

2.1 Lidar coverage estimation

The swath width of a spaceborne lidar can be defined as a function of output laser power, detected power, altitude, resolution, telescope area, laser efficiency, detector efficiency, surface reflectance and atmospheric transmissivity [6], as

$$s = \frac{P_{laser}}{E_{det}} \frac{D^2}{8h^2} Q\rho\tau^2 \frac{r^2 \left(R+h\right)^{3/2}}{R\sqrt{\mu}} \tag{1}$$

where s is the swath width, P_{laser} is the power emitted by the laser calculated as $P_{payload} \times P_{eff}$, E_{det} is the energy detected at the receiver, D is the telescope diameter, h is the orbit altitude, τ is the atmospheric transmittance, Q is the detector quantum efficiency, ρ is the surface reflectance, R is the mean Earth radius, r is the desired spatial resolution of the instrument, and μ is the standard gravitational parameter of Earth.

In order to estimate the number of spacecraft required to provide the desired coverage in a given time, the circumference of largest band of the Earth to be covered should be calculated. For GLAMIS, which requires global coverage, this will be the equator, with a known circumference c_{eq} of 40,075 km. The number of orbit revolutions required to provide full coverage of the equator can then be estimated as

$$N_{rev} = \frac{c_{eq}}{2W} \tag{2}$$

where W is the width of the portion of the equator covered by a single pass of the spacecraft, and noting that a single revolution will provide two passes of the equator: an ascending and a descending pass. The width of the portion of the equator covered by a spacecraft in a single pass is calculated as

$$W = \frac{s}{\sin i} \tag{3}$$

where i is the orbit inclination. It should be noted that as the orbit inclination, i, approaches 0 deg, the width W will tend to infinity. As such, the above approximation is not valid at inclinations close to 0. However, as the expectation is that GLAMIS will require quasi-polar orbits to achieve global land coverage, the use of equation (3) is considered suitable.

Assuming that full coverage of the equator will ensure full coverage of all latitudes, the number of spacecraft required to provide global coverage in a given time can be calculated as

$$N_{sats} = \left\lceil \frac{N_{rev}}{(1 - f_{cloud})} \frac{T}{t} \right\rceil \tag{4}$$

where f_{cloud} is the assumed global mean cloud fraction, such that $0 \leq f_{cloud} \leq 1$, and t is the total time to desired coverage in seconds. T is the satellite orbit period, calculated for circular orbits as

$$T = 2\pi \sqrt{\frac{(h + R)^3}{\mu}}. \tag{5}$$

It should be noted that the above calculations assume no overlap between adjacent orbit passes, and also use an average global cloud fraction. These factors will impact the overall number of spacecraft required and will be considered in the detailed results provided in section 4.

3 Sensitivity analysis: Constellation size as a function of orbit altitude

In this section, the variation in size of the lidar instrument swath and, consequently, the possible reduction in number of spacecraft required for global coverage will be investigated as a function of orbit altitude. Constants that will be used throughout the analysis are given in Table 1 and the values outlined in Table 2 will be used.

The expected swath of a lidar instrument with the parameters given in Table 2 is calculated considering a range of altitudes from 200 km - 800 km in 5 km increments. To do this, the expected swath width, s, is calculated as a function of altitude using equation (1) for a desired spatial resolution of 5 m, 10 m, 20 m, and 30 m. The results of this are shown in Figure 1.

The number of total spacecraft required to provide coverage in a given time of oneyear is then calculated by combining equations (2) – (5) to give

$$N_{sats} = \left\lceil h^2 \frac{\sin i}{tr^2} \frac{E_{det}}{P_{laser} D^2 Q \rho \tau^2} \frac{8\pi c_{eq} R}{(1 - f_{cloud})} \right\rceil \tag{6}$$

noting here that the number of spacecraft required would be proportional to the altitude squared, if all other variables remained constant. The results of this analysis are shown in Figure 2. As expected, the number of spacecraft required decreases as the altitude of the satellites decreases.

Table 1 Analysis Constants.

Parameter	Symbol	Value	Unit
Circumference of Earth at equator	c_{eq}	40075	km
Mean Earth radius	R	6371	km
Gravitational parameter of Earth	μ	3.986004418 $\times 10^{14}$	$m^3 s^{-2}$
Earth flattening factor	f	3.3528 $\times 10^{-3}$	-

Table 2 Sensitivity analysis parameters

Parameter	Symbol	Value	Unit
Surface reflectance	ρ	0.4	-
Atmospheric transmittance	τ	80	%
Cloud cover fraction	f_{cloud}	50	%
Inclination	i	97	deg
Energy detected at receiver	E_{det}	0.562	fJ
% quantum efficiency	Q	45	%
Laser Power	P_{laser}	12	W
Optics diameter	D	0.8	m

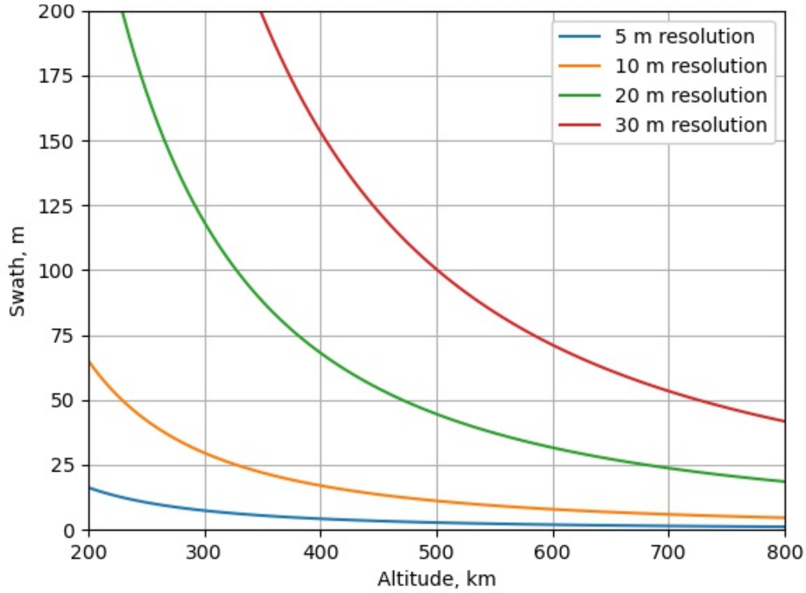

Fig. 1 Altitude sensitivity analysis results: swath width as a function of orbit altitude and lidar resolution.

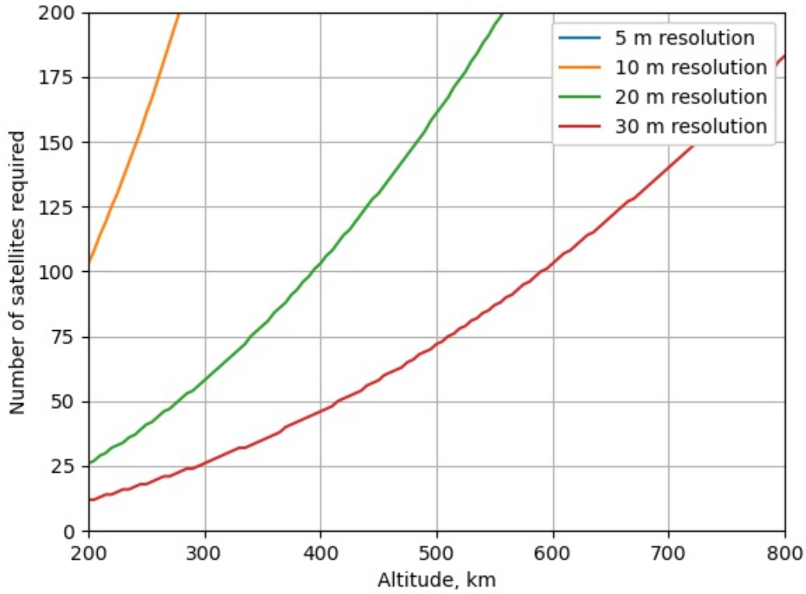

Fig. 2 Altitude sensitivity analysis results: number of spacecraft reqired for global coverage in one year as a function of orbit altitude and lidar resolution.

4 GLAMIS System Design

4.1 Spacecraft Platform

Having established the benefits of a VLEO orbit for a global lidar constellation, a preliminary mission design for the GLAMIS system is presented. A state-of-the-art full-waveform lidar instrument is taken as the assumed payload, with the parameters given in Table 3.

Table 3 Parameters for a full waveform 1064 nm laser.

Parameter	Symbol	Value	Unit
Surface reflectance	ρ	0.42	-
Atmospheric transmittance	τ	85	%
Energy detected at receiver	E_{det}	0.562	fJ
% quantum efficiency	Q	45	%
% Laser Power conversion efficiency	P_{eff}	8	%

The decision as to what satellite platform will best meet the needs of the Global Lidar Altimetry Mission (GLAMIS) depends on the capabilities of the platform in supporting the lidar payload, as well as how those platforms will perform at the mission level. To address the first of these aspects, an investigation of current capabilities of a range of spacecraft platforms was carried out to provide estimated capabilities for 12U CubeSat, 150kg and 500kg class satellites. Information was gathered in a top-down manner from satellite platform providers, collated and used to generate best-fit relationships for certain attributes, supported by good engineering judgement where necessary. Table 4 captures the attributes that are of most importance. From this, analysis of the mission performance and overall cost can be carried out, resulting in a mission architecture recommendation. The costs of each bus are estimated based on limited information available from vendors. Additionally, it is expected that a discount per unit would be applied when scaling to larger numbers of platforms. To offer a conservative but consistent approach, a discounted relationship is proposed for platform cost as a function of the total number manufactured N, with a baseline cost c_b of \$1M for a 12U platform, \$3M for 150kg class and \$5M for 500kg class. This relationship is defined as

$$c_{bus} = c_b \left(1 - \frac{N-1}{2n_{50\%}}\right) \tag{7}$$

where $n_{50\%}$ is the number of additional platforms at which a 50% discount is reached. For the purposes of this work, $n_{50\%} = 99$, such that 100 platforms would result in a 50% discount per platform, and it is assumed that a 50% discount on the baseline cost is the minimum unit cost achievable.

Launch costs are estimated for the platforms selected based on costs publicly available from a rideshare launch provider [8], and extrapolated where necessary to provide an estimate. This information then feeds into the results in Section 4.4.

Table 4 Payload and platform attributes for key platform classes.

Platform	12U	150kg	500kg
Payload volume (m^3)	0.008 (8U)	0.2	0.8
Payload (aperture) area (m^2)	0.04 (2U x 2U)	0.4 (∼0.6m ø)	1 (∼1m ø)
Payload mass (kg)	14	75	250
Peak power (W)	115	250	500
Orbit average power (W)	40	160	300
Pointing accuracy (deg)	0.002	0.002	0.002
Downlink data rate (Mbps)	100	250	400
Delta-V (m/s)	200	300	300
Baseline cost per platform (M$)	1	3	5
Launch cost per platform (M$)	0.595	1.35	2.2

4.2 Orbit Maintenance

In order to maintain the spacecraft altitudes, propulsion will be required to counteract the effects of atmospheric drag. A reasonable approximation for atmospheric drag force (F_D) experienced by a spacecraft can be made as

$$F_D = \frac{1}{2}\rho V^2 A C_D \tag{8}$$

where ρ is the atmospheric density, V is the orbital velocity, A is the cross sectional area perpendicular to the velocity direction and C_D is the drag coefficient, which is typically assumed to be between 2.1 and 2.4 for blunt bodies.

Assuming that the spacecraft surface area, drag coefficient and velocity remain constant over the mission lifetime (t_L), the drag force, and therefore required thrust force to overcome it, will also remain constant. This, along with the thruster specific impulse (I_{sp}), can be used to obtain the propellant mass (M_p) required for the mission. The mass flow rate ($\dot{m}$) can be equated to

$$\dot{m} = \frac{M_p}{t_L} = \frac{F_D}{g_0 I_{sp}}, \tag{9}$$

where g_0 is the accelleration of gravity on Earth (9.81m/s). From this, propellant mass M_p required to maintain a specific orbit for a lifetime duration of t_L is calculated as

$$M_p = \frac{t_L F_D}{g_0 I_{sp}}. \tag{10}$$

Table 5 Drag compensation and propulsion parameters for selected spacecraft platforms

Platform	12U	150kg	500kg
Platform mass (kg)	20	150	500
Ram-direction area (m^2)	0.06	0.4	1
Propulsion system	TILE 3 [11]	Micro R3 [12]	Micro R3 [12]
Specific impulse (s)	1650	4000	4000
Thrust (mN)	0.45	0.2	0.7
Total impulse (Ns)	755	50,000	50,000
Power required (W)	20	40	80

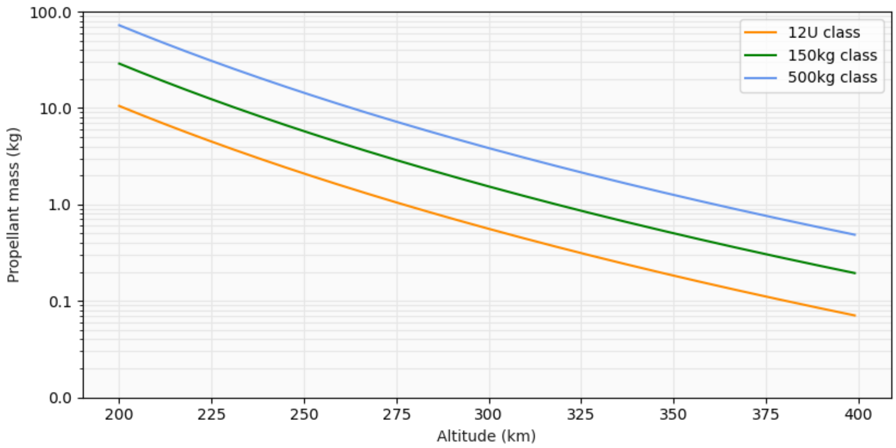

Fig. 3 Propellant mass required for each platform class at altitudes between 200km and 400km.

Using equations (8) - (10), and using the values of mass and surface area for the platform classes as specified in Table 4, propulsion systems can be specified for each platform class (Table 5) and drag compensation analysis carried out. In this case, a TILE3 system by Accion [11], with a specific impulse of 1650s, is evaluated for the 12U class, and variants of the Micro R3 system by Enpulsion [12] (specific impulse of 4000s) are evaluated for the 150kg and 500kg classes. The results of this analysis are shown for propellant mass (Figure 3) and number of thrusters (Figure 4) required to maintain altitudes between 200km and 400km. It should be noted that the use of propulsion systems specifically designed for operation in VLEO, such as air-breathing systems [7,9], and/or the use of aerodynamic coatings and materials [10] could significantly reduce the volume of propellant required for orbit maintenance, particularly at altitudes below 300km.

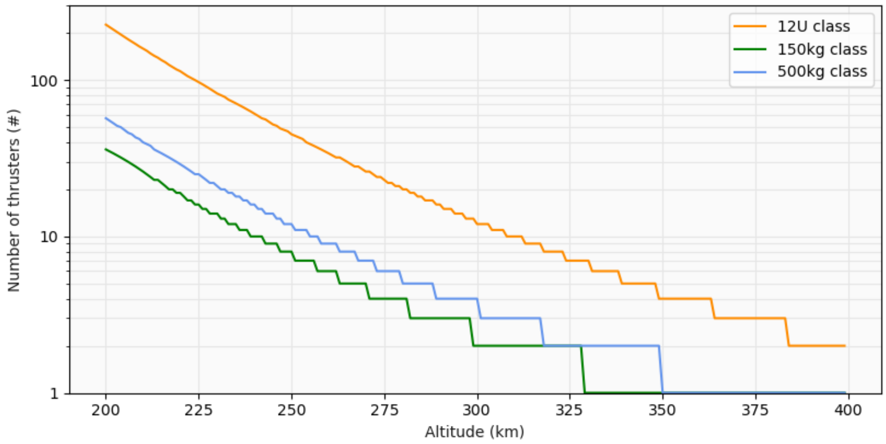

Fig. 4 Number of thrusters required for each platform class at altitudes between 200km and 400km.

4.3 Constellation Sizing

Having defined suitable platform classes, the number of spacecraft that would be required to meet the GLAMIS mission requirements for varying platform sizes, spatial resolutions and orbit altitudes are then calculated. The parameters of the platforms to be examined are given in Table 4 and the laser parameters are given in Table 3. Based on the preliminary investigation in section 3, a resolution of 20m is selected as suitable and the number of spacecraft required to provide coverage of the Earth in one year at this resolution is investigated considering constellation altitudes of 200km, 300km, and 400km.

To estimate the number of each spacecraft platform required to provide the desired coverage, an approach similar to that outlined in section 2 is used with adaptations to consider the coverage as a function of latitude, the necessary overlap between adjacent swaths and using a 2 deg $\times$ 2 deg grid of global average cloud cover. The cloud cover data used is the 2007 night time data from the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) Cloud-Aerosol LIdar with Orthogonal Polarization (CALIOP) instrument, a 1064nm LiDAR1 [13]. This data provides the mean cloud cover probability at night for all longitudes between -80.55 deg and +76.57 deg latitude.

The probability of obtaining a cloud-free pass of each grid point is calculated using a geometric cumulative distribution function and the number of spacecraft required to provide an 80% likelihood of a cloud free image over 95% of the Earth's land is calculated.

Additionally, given the non-linear relationship between swath width and resolution, it is possible that a crossing point exists at which the swath width becomes narrower than the resolution. In this case, the platform would not be capable of providing sufficient energy to maintain continuous along-track observations and the results would be considered invalid.

4.4 Results

The swath widths calculated for each scenario analysed are given in Table 6. Those solutions which are infeasible due to the swath being smaller than the desired resolution are shaded red.

The number of spacecraft needed for each scenario to provide 80% confidence of obtaining a cloud free image over 95% of land between -80.55 deg and +76.57 deg latitude in one year is also given in Table 6. Using the cost estimates given in Table 4, and using the cost discount function described in section 4.1, the estimated cost of each mission is calculated and also presented.

The results of the analysis show that 14 500 kg spacecraft in a 200km altitude orbit would provide the desired land coverage at 20m resolution in less than one year. This system would have an estimated cost of $96M but would require >50 thrusters and 72 kg of propellant to maintain this orbit altitude for five years. The top image in Figure 5 shows the expected coverage from this system. The middle image in Figure 5 shows the expected coverage in one year from the same system in a 300km altitude orbit, which would require four Micro R3 thrusters and only 3.8 kg of propellant. The lower image in Figure 5 shows the coverage that would be expected were the system placed at 400km altitude. This would require require one Micro R3 thruster and approximately 0.5 kg of propellant. These results clearly illustrate the significant improvement in performance, or reduction in system cost, that could be achieved if operating the system at VLEO altitudes using efficient and appropriate propulsion systems.

Table 6 Results for a lidar constellation providing 20m resolution data with an 80% likelihood of obtaining a cloud free image over 95% of the Earth's land from a variety of VLEO altitudes. Red shading indicates scenarios in which the swath is less than the possible minimum.

	Altitude	**Swath**	**No. s/c**	**Cost**
12U Cubesat	200 km	4.92m		
	300 km	2.24m		
	400 km	1.29m		
150 kg	200 km	157.32m	70	$231M
	300 km	71.52m	201	$573M
	400 km	41.14m	784	$2234M
500 kg	200 km	737.42m	14	$96M
	300 km	335.25m	33	$211M
	400 km	192.84m	63	$355M

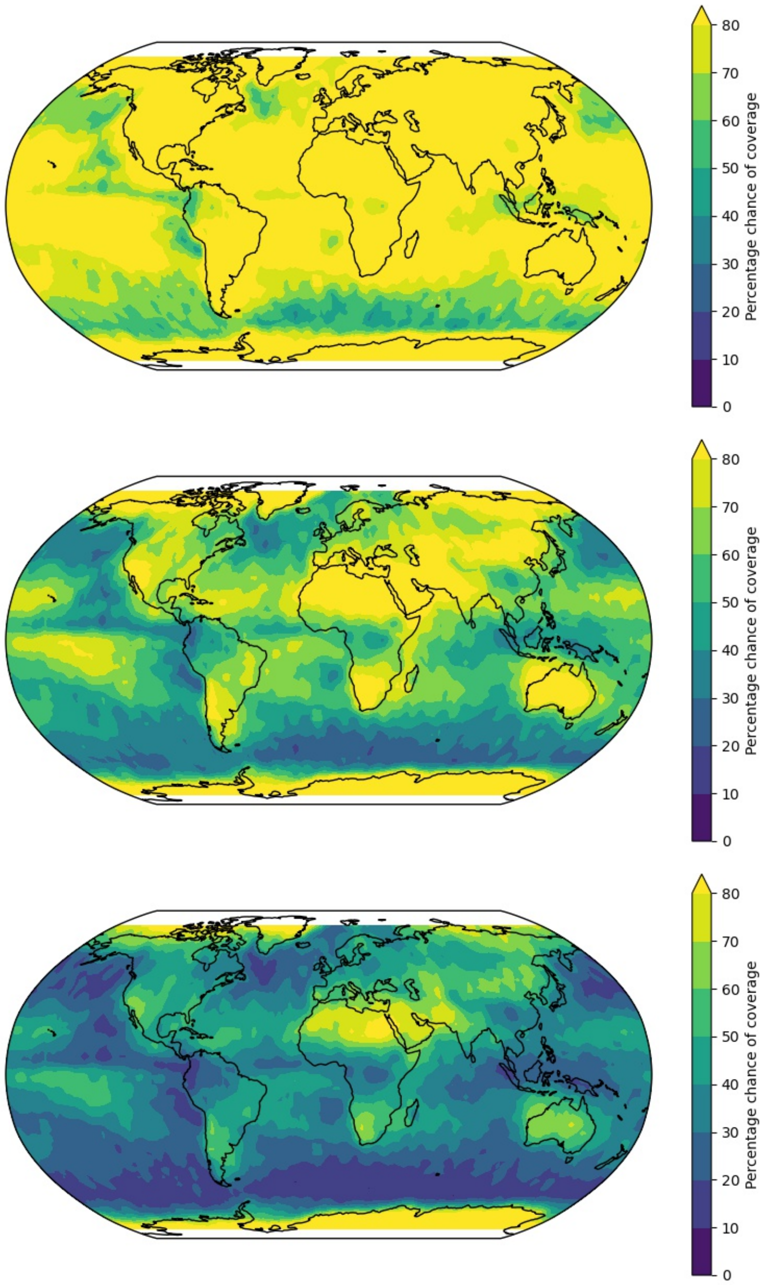

Fig. 5 Coverage expected after one year from 14 500 kg platforms from (top) a 200km altitude orbit, (middle) a 300km altitude orbit, and (bottom) a 400km altitude orbit.

5 Conclusion

The use of lower altitude orbits reduces the number of spacecraft required to provide global lidar coverage, but these will require a higher volume of propellant to maintain the orbit altitude. A 12U CubeSat constellation cannot provide a swath of a sufficient size to produce a feasible solution. For a given data resolution and altitude, a 500 kg spacecraft platform is the lowest cost solution, but requires a propellant mass of over 70 kg per platform. While this is perhaps feasible, it could likely be reduced using more appropriate VLEO propulsion systems. A system comprising 14 500 kg spacecraft in a 200 km altitude very low Earth orbit (VLEO) could provide 80% confidence of achieving a 20 m resolution cloud free lidar image over 95% of the Earth's land in one year. Such a system is estimated to cost $95M for build and launch and would require >50 thrusters and 72 kg of propellant to maintain its VLEO altitude for 5 years. A system comprising 33 500 kg spacecraft in a 300 km altitude very low Earth orbit (VLEO) could provide the same coverage for an estimated cost of $211M for build and launch and would require four thrusters and 3.8 kg of propellant to maintain its VLEO altitude for 5 years. Operating at a 200 km VLEO altitude provides an estimated 50% system cost reduction compared to a 300 km altitude, and an estimated 70% cost reduction compared to a 400 km altitude. As such, if an efficient VLEO propulsion system could be integrated for less than this cost saving, GLAMIS could benefit from a performance in improvement for the same system cost.

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