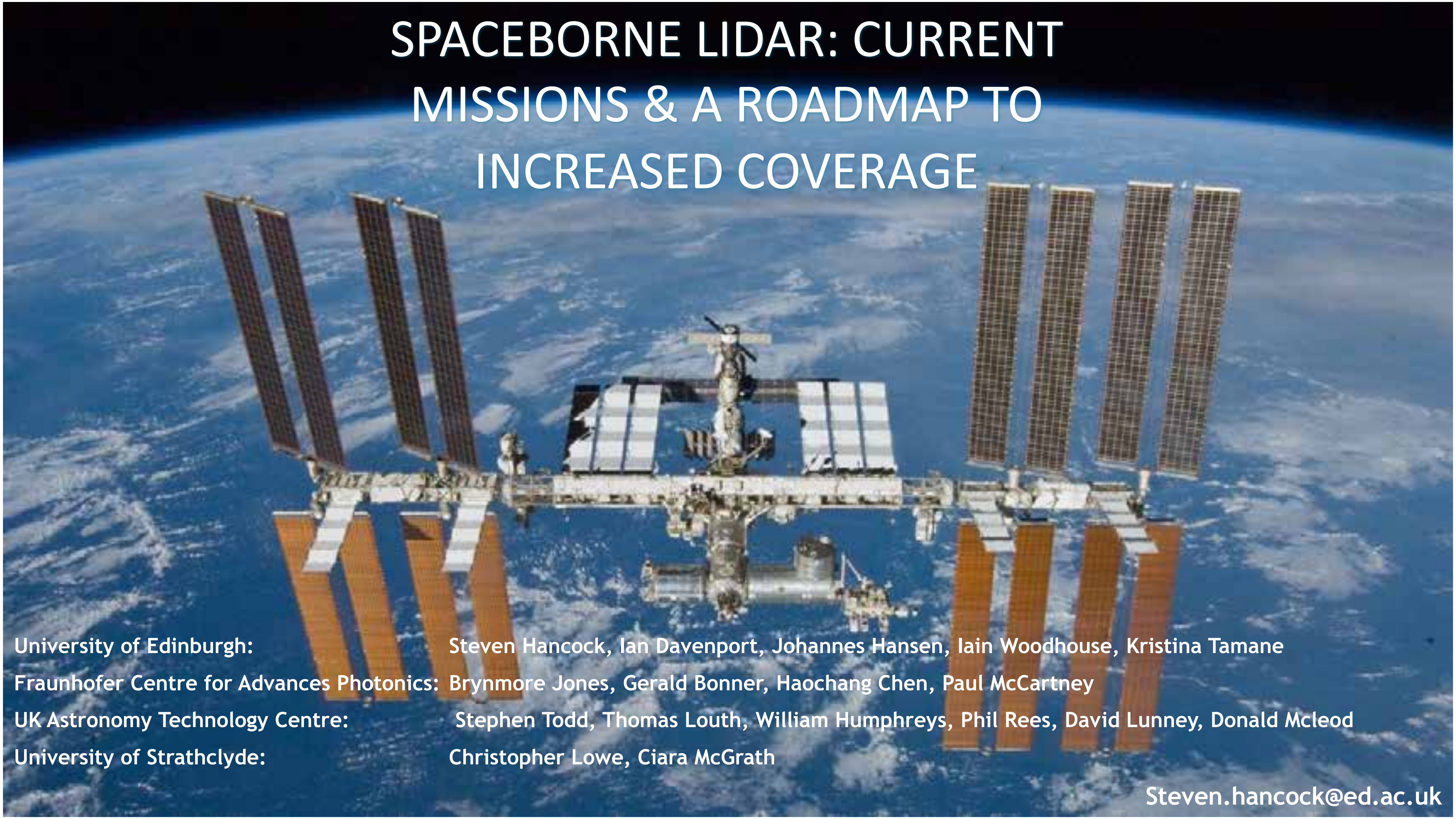

SPACEBORNE LIDAR: CURRENT MISSIONS & A ROADMAP TO INCREASED COVERAGE

University of Edinburgh: Steven Hancock, Ian Davenport, Johannes Hansen, Iain Woodhouse, Kristina Tamane

Fraunhofer Centre for Advances Photonics: Brynmore Jones, Gerald Bonner, Haochang Chen, Paul McCartney

UK Astronomy Technology Centre: Stephen Todd, Thomas Louth, William Humphreys, Phil Rees, David Lunney, Donald Mcleod

University of Strathclyde: Christopher Lowe, Ciara McGrath

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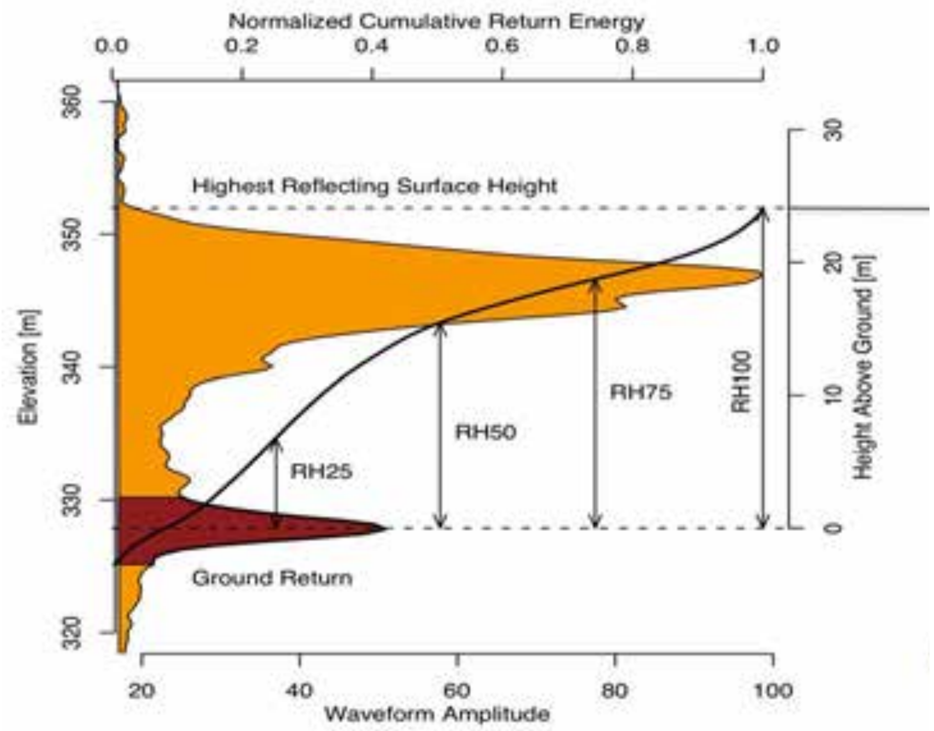
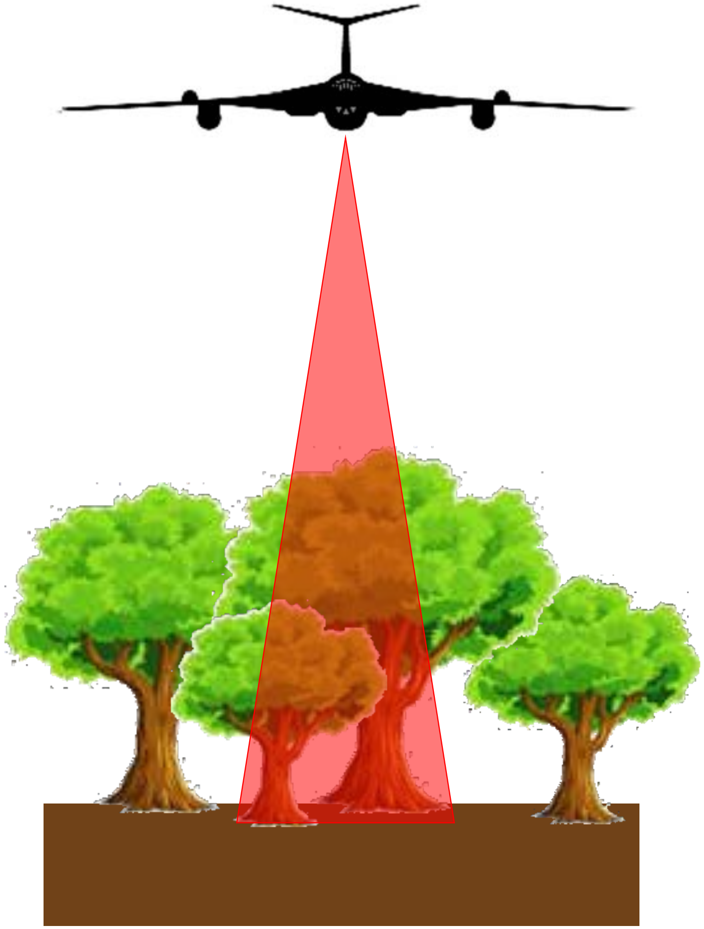
The need for lidar data

Why lidar?

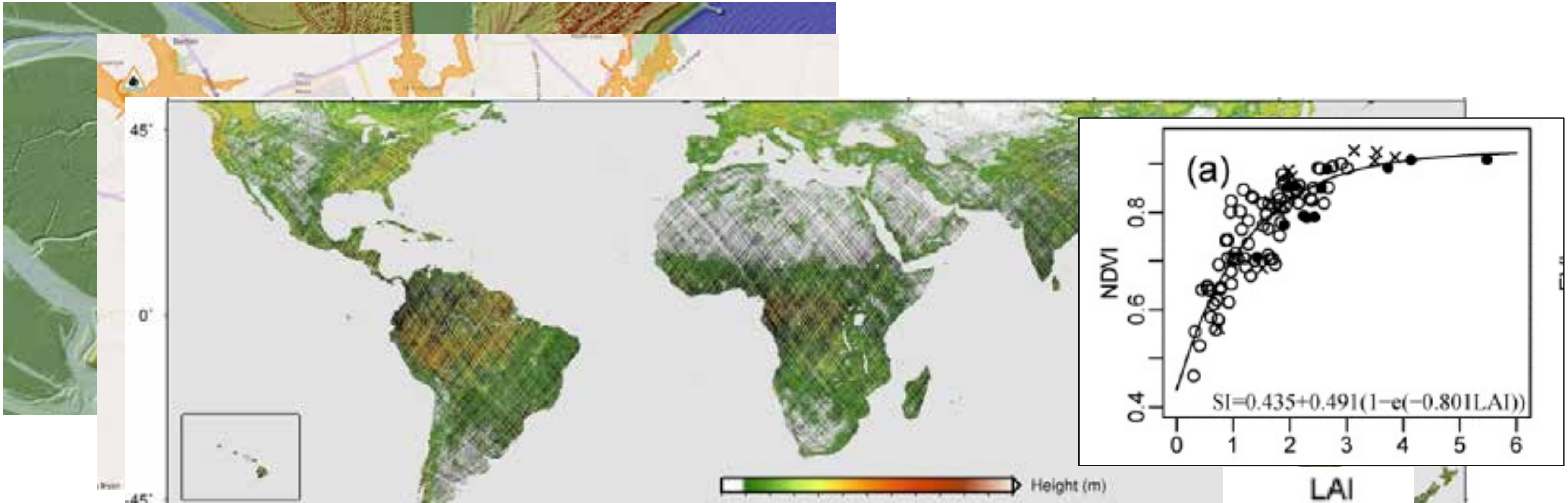

Normalized Cumulative Return Energy
0.0
0.2
0.4
0.6
0.8
1.0
360
350
340
330
320
Elevation [m]
Highest Reflecting Surface Height
RH25
RH50
RH75
RH100
Ground Return
30
20
10
0
Height Above Ground [m]
20
40
60
80
100
Waveform Amplitude



Lidar data products

Allows unbiased, non-saturating measurements of:

- Bare-Earth topography (even in complex environments)
- Tree height, vegetation density and biomass



Tanaka, S., Kawamura, K., Maki, M., Muramoto, Y., Yoshida, K. and Akiyama, T., 2015. Spectral index for quantifying leaf area index of winter wheat by field hyperspectral measurements: a case study in gifu prefecture, central Japan. *Remote Sensing*, *7*(5), pp.5329-5346.

Spaceborne lidar missions

NASA LITE: 1994

- Technology demonstrator

NASA ICESat/GLAS: 2003-2009

- Ice elevation and volume

NASA Calipso/CALIOP: 2006-2019+

- Cloud profiles

NASA CATS: 2015-2017

- Cloud profiles

ESA Aeolus/ALADIN: 2018-2021+

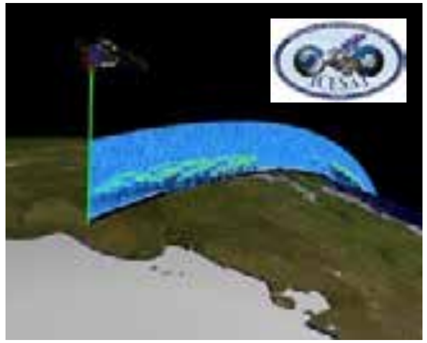
- 3D wind speed

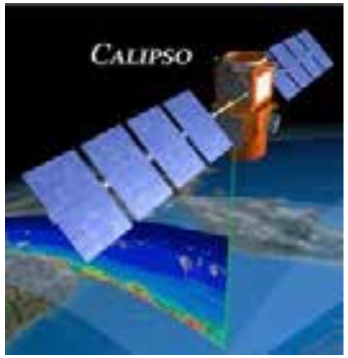
NASA ICESat-2/ATLAS: 2018-2021+

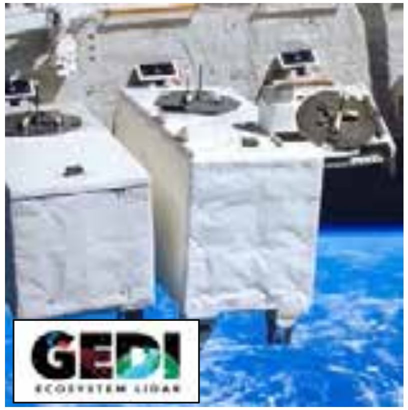
- Ice elevation and volume

NASA GEDI: 2018-2021+

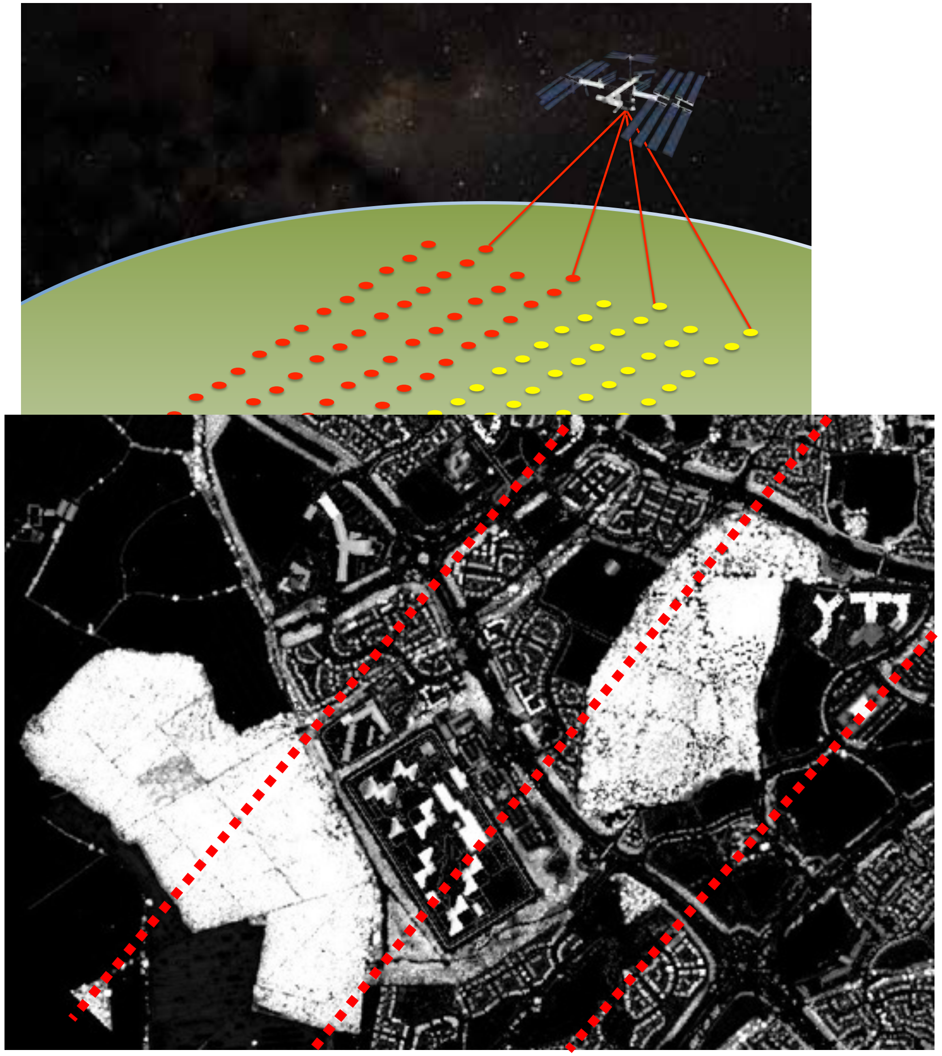
- Forest biomass and structure







Lidar coverage



Sparse coverage limits applications

- Coarse resolution inference (forests, ice mass)

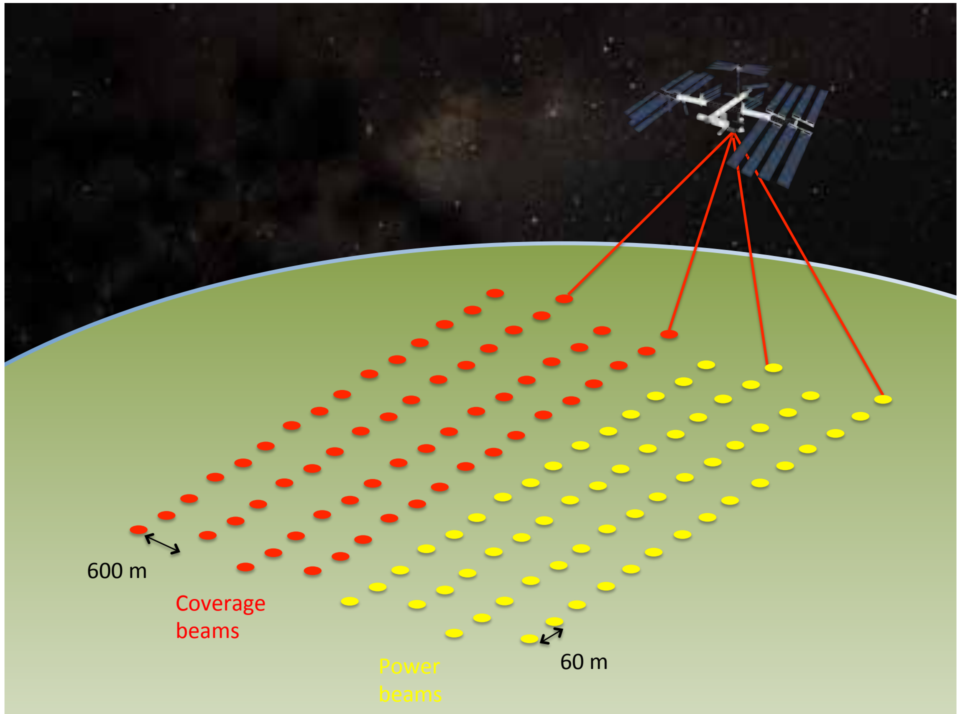
Too coarse to allow

- Continuous mapping
- Flood modelling
- Anything in urban areas
- Train line monitoring
- Commercial forestry

Sparse sampling leads to uncertainty

- Complicates robust change detection

Maximising coverage

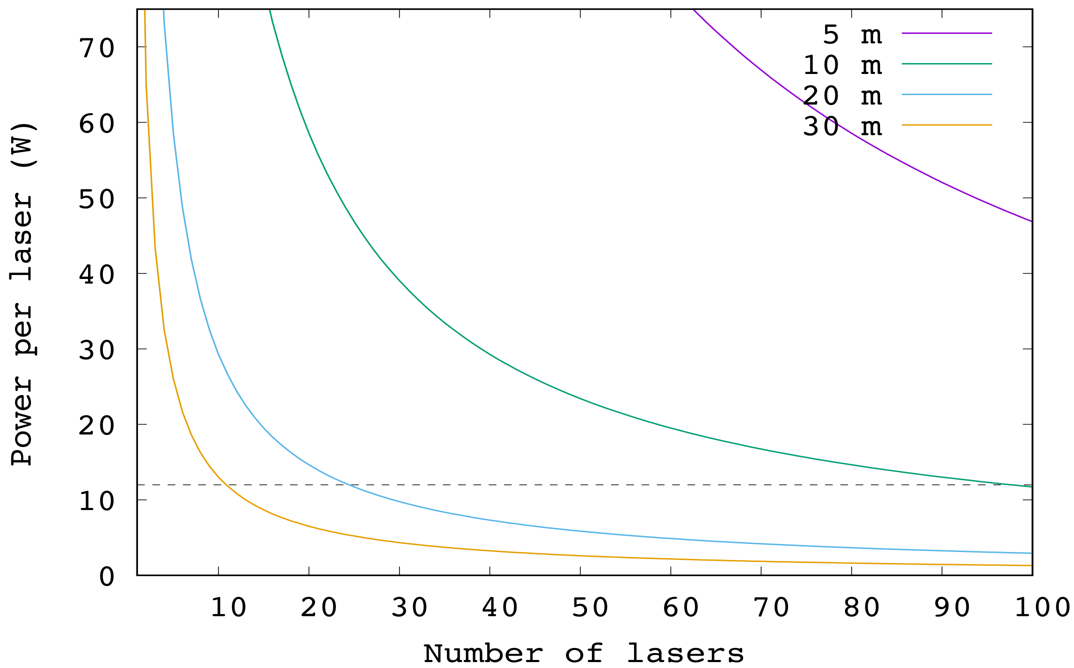


Increasing lidar coverage

$$s = \frac{P_{pay} L_e}{E_{det}} \frac{A}{2\pi h^2} Q \rho \tau^2 \frac{r^2 (R+h)^{\frac{3}{2}}}{R\sqrt{GM}}$$

Where

- s - swath width (m)
- **E_{det}** - minimum detected energy per pulse
- **P_{pay}** - payload power (W)
- **L_e** - laser efficiency
- **A** - telescope area (m^2)
- **h** - orbital altitude (m)
- **r** - spatial resolution (m)
- Q - detector efficiency
- ρ - surface reflectance
- τ - atmospheric transmittance



Coverage once per 5 years

Increasing lidar coverage

$$s = \frac{P_{pay} L_e}{E_{det}} \frac{A}{2\pi h^2} Q \rho \tau^2 \frac{r^2 (R+h)^{\frac{3}{2}}}{R\sqrt{GM}}$$

Which parts could we adjust to maximise coverage per unit cost?

- **Instrument:** Laser and detector efficiencies improved with new photonics?
- **Platform**: Maximise payload power and telescope area per unit cost?
- **Processing**: Reduce energy requirements with signal processing?

UK SPACE AGENCY

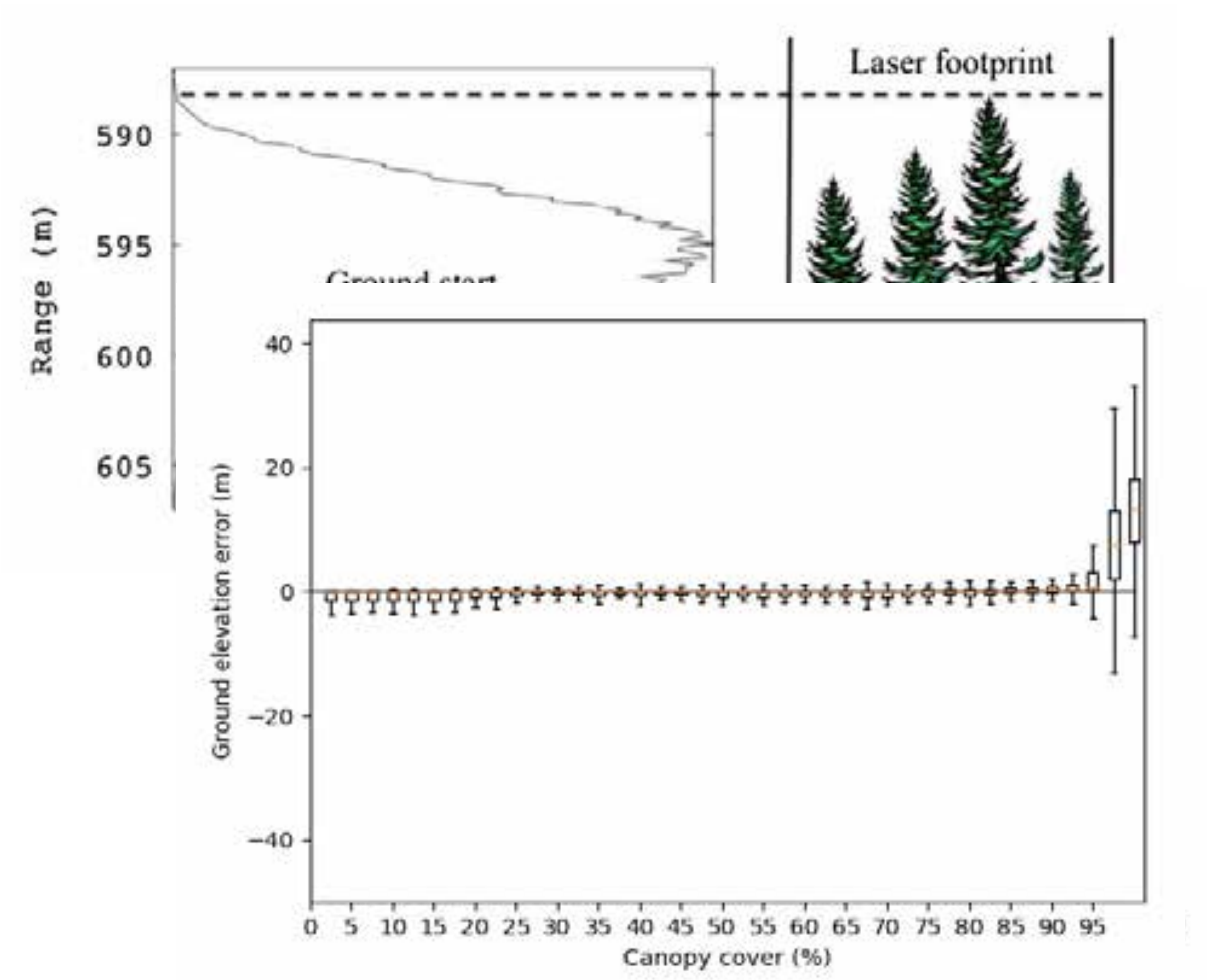
Measurement requirements

Spatial and temporal resolution

- 5-30 m spatial
- Anything better than 10 years temporal

Signal to noise ratio

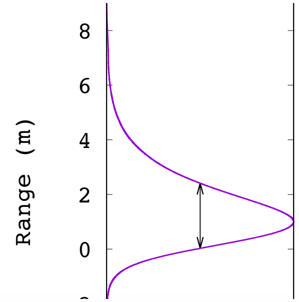
- See the ground through a dense canopy
- >=95% “beam sensitivity”



Instrument: Laser

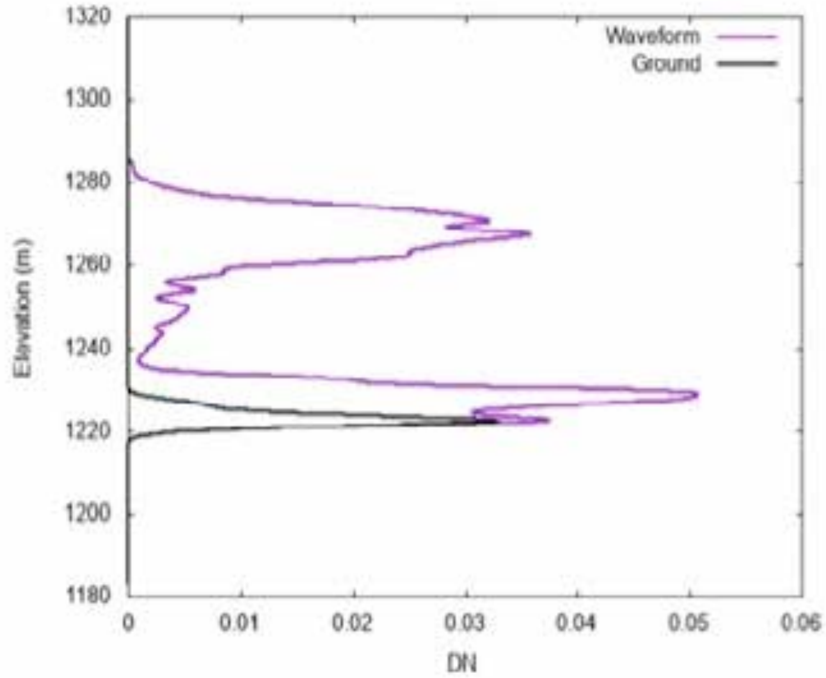
All past spaceborne lidars use Q-switched solid state lasers

- <= 15 ns long pulse
- >= 10 mJ per pulse
  - **66 kW peak instantaneous power**
- 3-8 % efficient

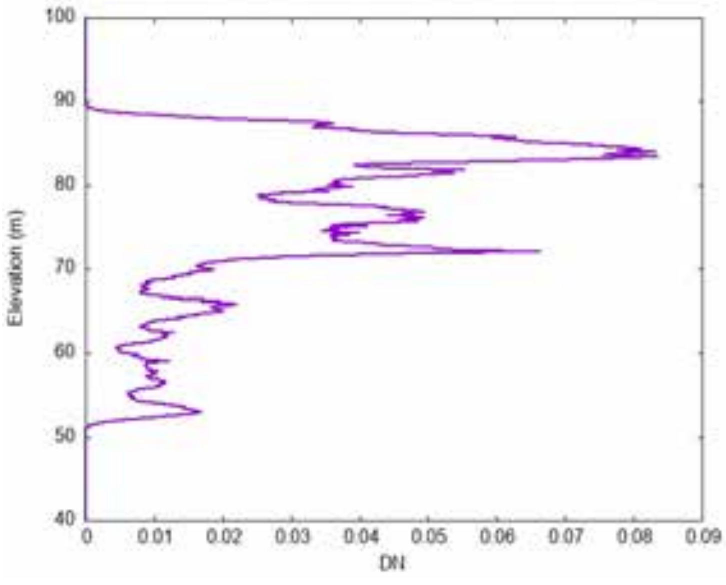


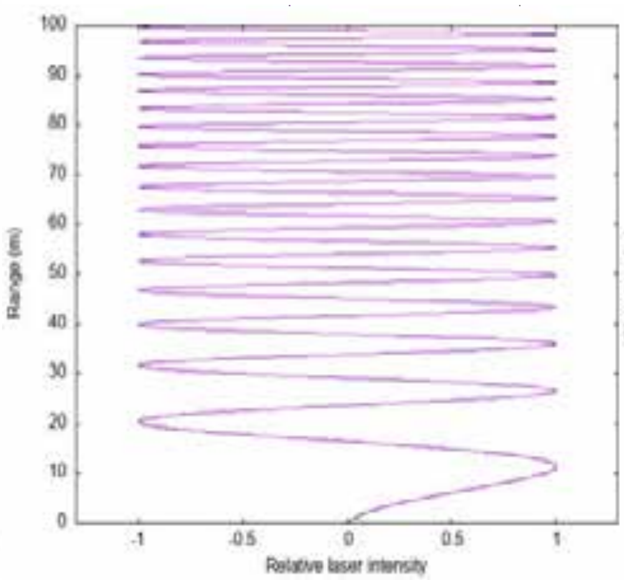
Tapered diode lasers?

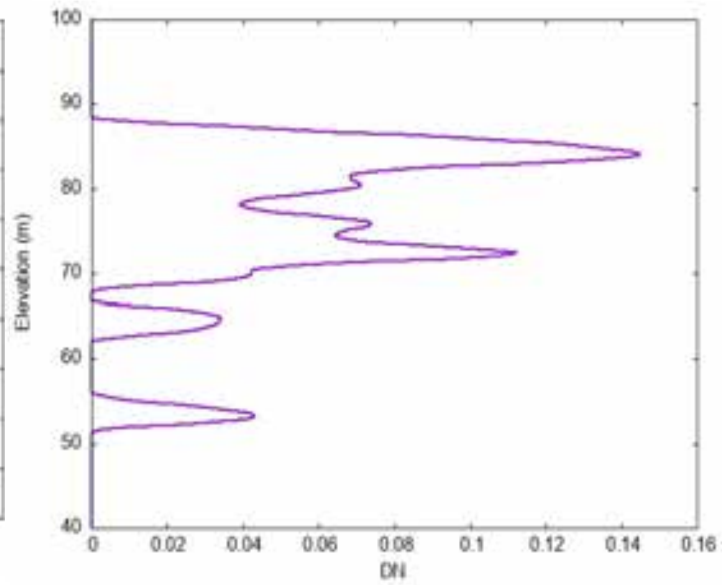
- 25% efficient
- 5W instantaneous power limit for good beam quality
  - **Cannot fit sufficient energy in to a short pulse**
  - **Need to use Pulse Compressed Lidar**
- Combine with photon-counting detectors



Pulse compressed lidar



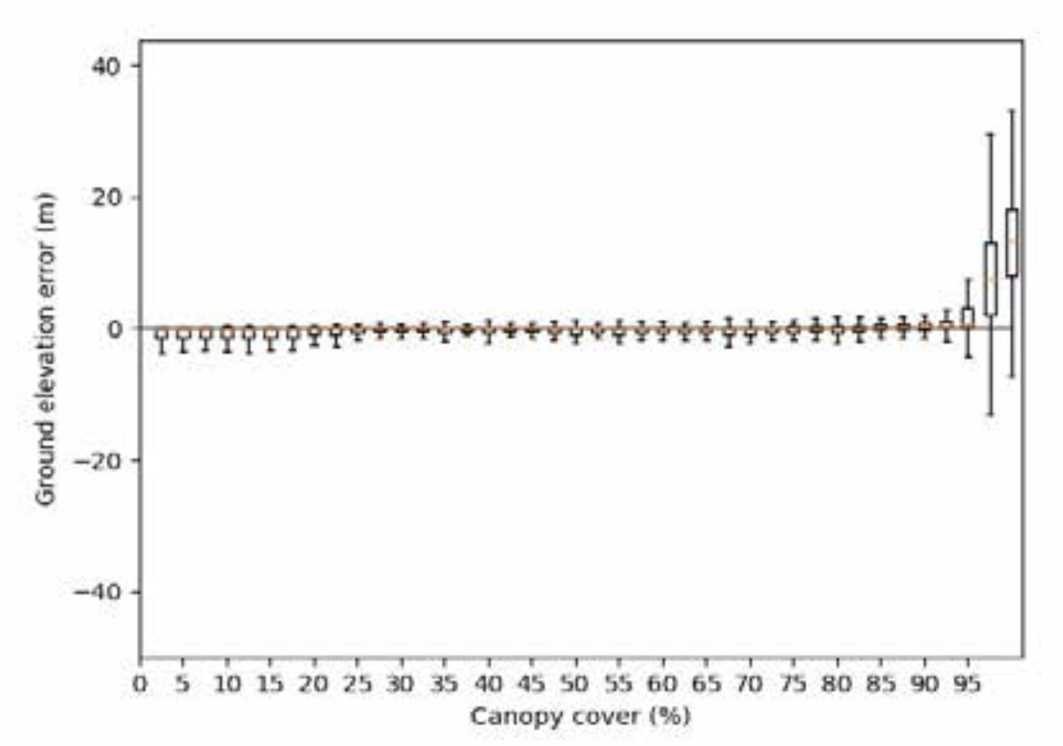




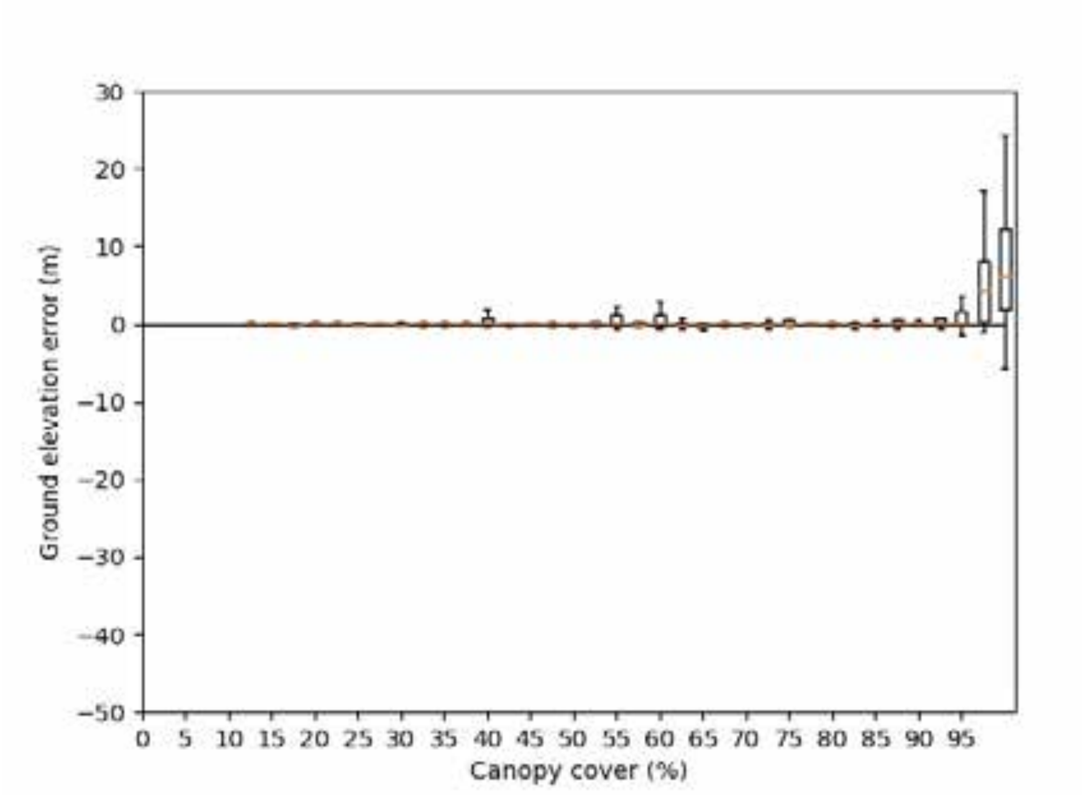
Pulse compressed lidar

Is PCL suitable for satellite remote sensing?

- Use a spaceborne lidar simulator



Solid state simulation

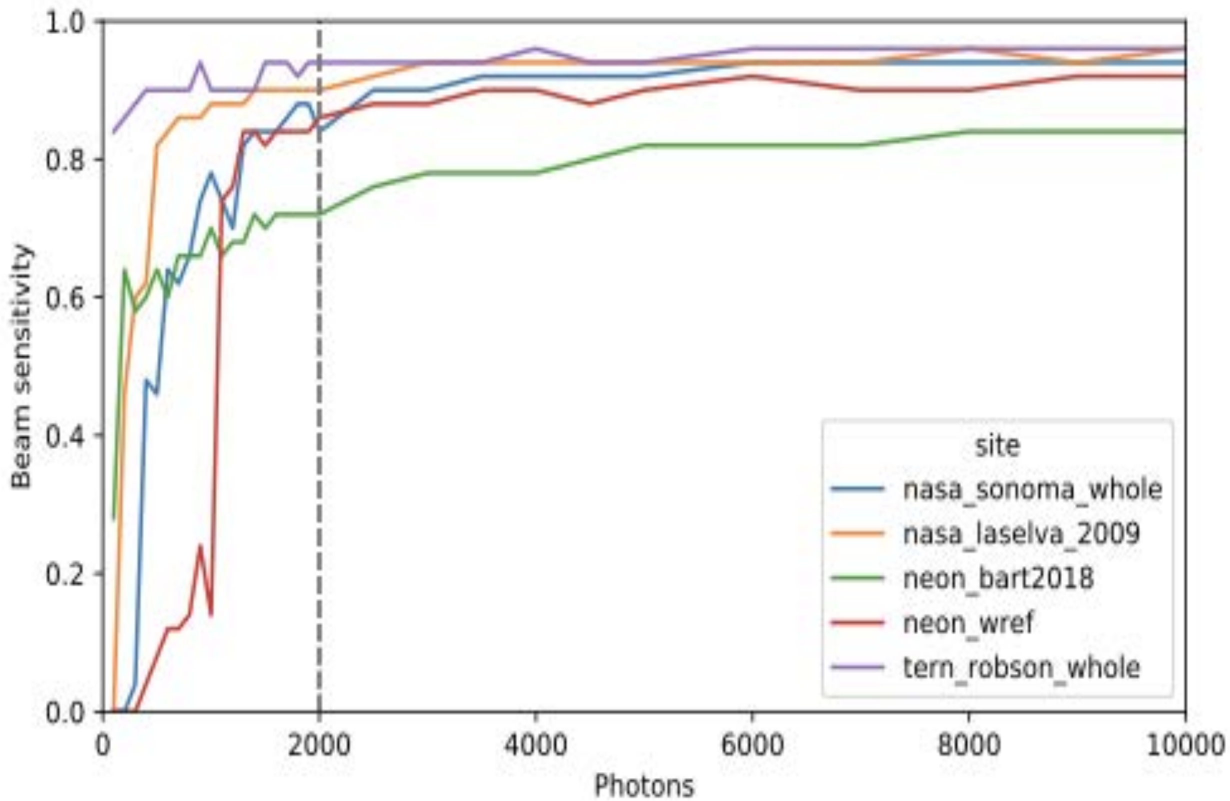


PCL simulation

Pulse compressed lidar

How many signal photons do we need?

- 2,000 photons, Edet=0.467 fJ at 850 nm (slightly less than GEDI's 0.562 fJ)



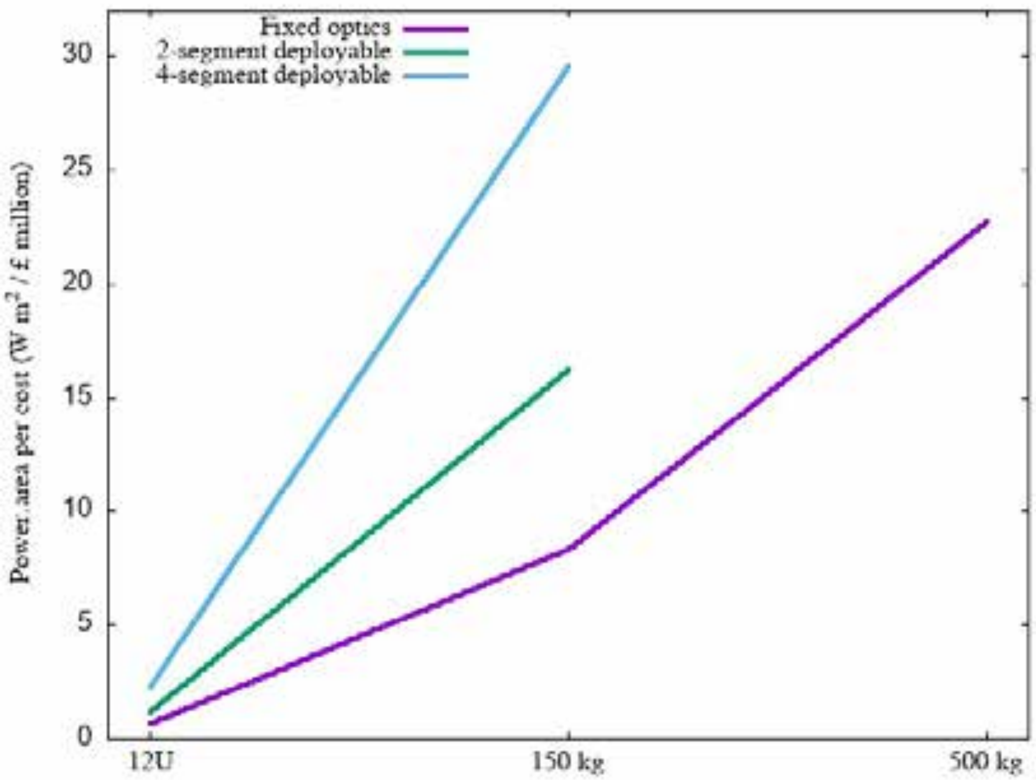
Platforms

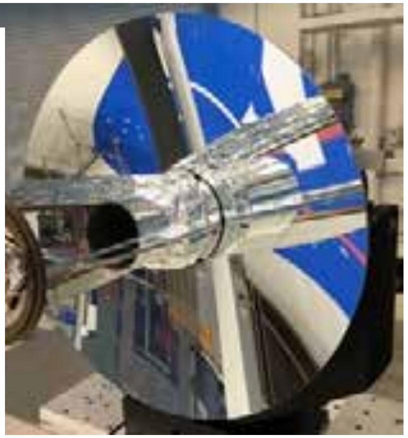
Most cost effective way to build up coverage?

- A few large platforms?
- Constellation of small-sats?

Manufacturer	12U	150 kg	500 kg	Comment
Payload volume (m^3)	0.008 (8U)	0.2	0.8	Volume should be assumed cube-like, although options exist on different platforms
Payload (aperture) area (m^2)	0.04 (2U x 2U)	0.4 (~0.6m ø)	1 (~1m ø)	Assuming square surface area, such that a circular aperture would have diameter ≈ side length
Payload mass (kg)	14	75	250	
Peak power (W)	115	250	500	Peak power available for use by the payload
Orbit average power (W)	40	160	300	Long-term average power available to the payload, assuming eclipse and platform demand
Pointing accuracy (deg)	0.002	0.002	0.002	Pointing accuracy highly variable between platforms and not considering *stability*
Downlink data rate (Mbps)	100	250	400	Downlink likely something that could be upgraded if deemed necessary
Delta-V (m/s)	200	300	300	Direct impact on lifetime, in particular for 12U platform due to greater impact from drag
Cost per platform (M$)	1	3	5	Multi-platform discounts likely, see section 5.4.1 in the platform architecture report

Platform coverage per cost

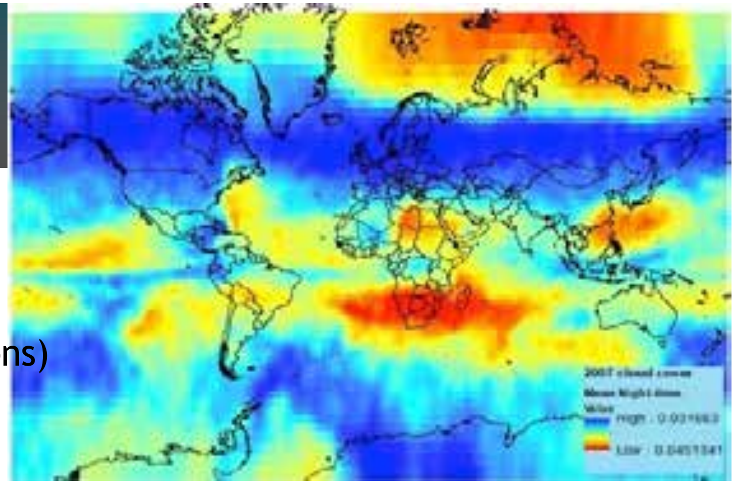




	12U	150kg	500kg
Deployable aperture area - 2 segments (m^2)	0.058	0.50	--
Deployable aperture area – 4 segments (m^2)	0.115	1.00	--
Payload available power (before laser efficiency conversion) (W)	40	160	300
Cost per platform (M$)	1	3	5
Cost per launch (M$)	0.595	1.35	2.2

$$s = \frac{P_{pay} L_e}{E_{det}} \frac{A}{2\pi h^2} Q \rho \tau^2 \frac{r^2 (R+h)^{\frac{3}{2}}}{R\sqrt{GM}}$$

Orbital simulations



Estimates of the cost for global coverage within 1 year

- 400 km orbit. Cloud cover taken from CALIPSO
- Platform + launch + optics in million £ (all other costs are the same for constellations)

		Solid-state				Photon-PCL			
Platform	**Optics**	**5 m**	**10 m**	**20 m**	**30 m**	**5 m**	**10 m**	**20 m**	**30 m**
12U	Fixed								
12U	2-Segment								
12U	4-Segment								
150 kg	Fixed			2995	615			520	191
150 kg	2-Segment			718	251		1563	219	92
150 kg	4-Segment		3209	338	134		592	120	51
500 kg	Fixed		3208	396	163	24381	691	144	63

12U options could not collect sufficient energy, even with 4-segment deployable optics

- Unless output power can be increased by 10%

GLAMIS conclusions

Continuous coverage lidar could be achieved from space

- Would allow new applications

Photon-PCL is suitable for spaceborne lidar

- Increased laser efficiency
- Greater coverage than solid-state lasers (?)

Larger platforms more cost-effective than smaller

- Worth investigating an Aeolus class satellite?

Deployable optics more cost-effective than fixed

- Costs too uncertain to decide on 4-segment 150 kg or 500 kg fixed
- Focussing requirements much less than for optical imager

12U not quite feasible to see the ground with a diode laser at 30 m resolution

- Could provide singe track at 30 m spacing with 4-petal optics if laser output power increased by 10%

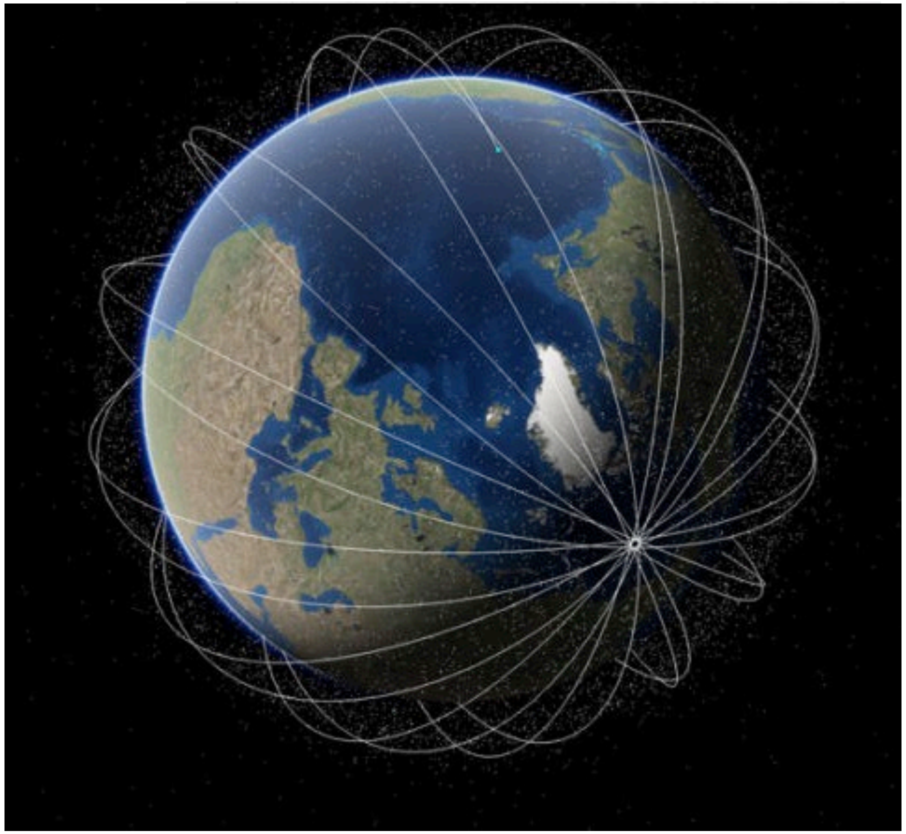
Spaceborne instrument design

Instrument	Pulse rate	Energy per pulse	N Lasers firing	Total laser power	N backup lasers	Wavelength	Detector type	Telescope diameter	Operated
ICESat	40 Hz	100 mJ	1	4 W	3	1064 nm/532 nm	Full-waveform	80 cm	2003 - 2009
CALIPSO	20 Hz	110 mJ	1	2.2 W	3	1064 nm/532 nm	Full-waveform	1 m	2006 -
CATS	5 kHz	1-2 mJ	2	15 W	0	1064 nm/532 nm/ 355 nm	Photon-counting	60 cm	2015 - 2017
Aeolus	51 Hz	110 mJ	1	5.6 W	3	355 nm	Full-waveform	1.5 m	2018 -
ICESat-2	10 kHz	1.2 mJ	1	12 W	3	532 nm	Photon-counting	80 cm	2018 -
GEDI	242 Hz	10 mJ	3	7.3 W	0	1064 nm	Full-waveform	80 cm	2018 -

Why measure from space?

Why not use ALS everywhere?

- ALS data is expensive (~£100's per km^2)
  - Coverage has been limited
  - Eg. ~£2-3 million to cover Wales. This scales to:
    - £25 million for all Great Britain
    - £62 billion for all Earth's land
- Satellites are global
  - Cover the whole world for a few hundred million dollars.
  - Globally consistent dataset



http://richiecarmichael.github.io/sat/index.html

Comparing Lidar and Radar satellites

ICEsat-2 and Sentinel-1 are roughly similar sized instruments

- Sentinel is a bit bigger and heavier and has four and a half times the power

	ICESat-2	Sentinel-1
Dimensions	2.5 × 1.9 × 3.8 m	3.9 m × 2.6 m × 2.5 m
Total mass	1,514 kg	2,300 kg
Total power	1.3 kW	5.9 kW
Altitude	500 km	693 km
Pulse rate	10 kHz	1-3 kHz
Wavelength	532 nm	~ 6 cm
Swath	6 x 14 m footprints	80-400 km (depending on mode)

- Sentinel 1, with 4.5 times the power, gets 1000-5000 times the coverage
  - ICESat-2 requires around 11,000 times more energy per photon than Sentinel-1