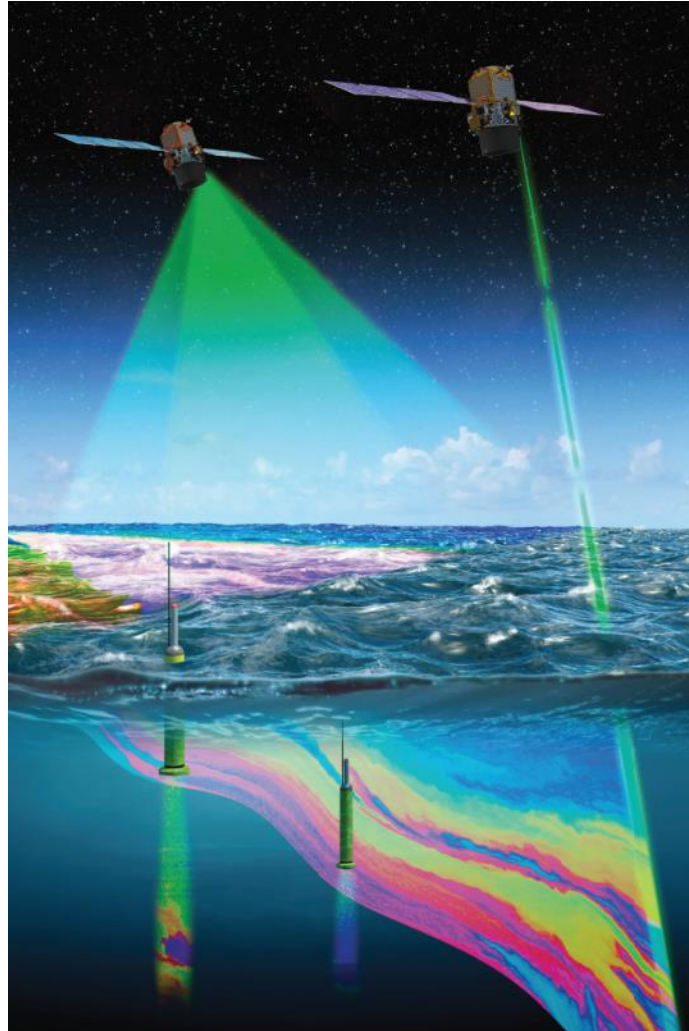
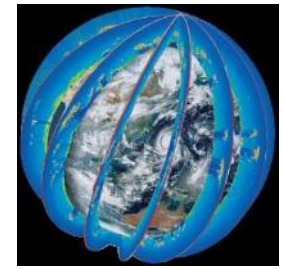




Reimagine Lidar to Address NASA Earth Science Objectives

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NASA Langley Research Center (LaRC)

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Outline



- LaRC airborne and spaceborne heritage
- Decadal Survey objectives, where MESCAL fits in
- Backscatter lidar technique
- Our “vision” for the ideal detector for Earth Science lidar
- What we’re driving toward
- Mission timeline

LaRC airborne lidar instrumentation



UV DIAL/HSRL
Ozone, Aerosols
1983 - Present



LASE
Water Vapor, Aerosols
1994 - Present



HALO
Methane, Water Vapor, Aerosols
2018 - Present



HSRL-1
Aerosols, Clouds, Ocean
2004 - Present



HSRL-2
Ozone, Aerosols, Clouds, Ocean
2012 - Present



ACES
Carbon Dioxide
2014 - Present

LaRC spaceborne lidar instrumentation

LITE (1994)

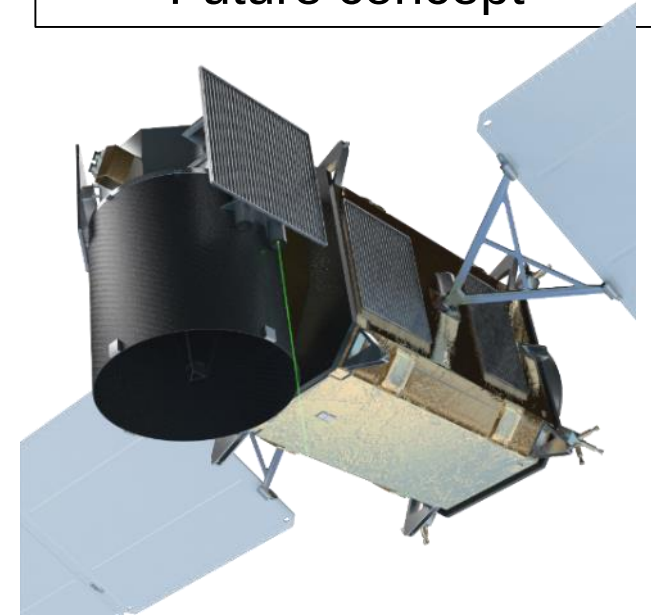
First civilian lidar in space



CALIPSO (2006 - Present)
Longest-operating lidar in space



MESCAL (ca. 2028)
Future concept



NASA Langley Research Center has designed, built and operated some of the world's most successful spaceborne aerosol-cloud-ocean lidars, and is looking to continue this legacy with the MESCAL mission

Decadal Survey outlines NASA's Earth Science priorities



TABLE S.2 Observing System Priorities

Targeted Observable	Science/Applications Summary	Candidate Measurement Approach	Designated Explorer	Incubation
Aerosols	Aerosol properties, aerosol vertical profiles, and cloud properties to understand their effects on climate and air quality	Backscatter <u>lidar</u> and multi-channel/multi-angle/polarization imaging radiometer flown together on the same platform	X	
Clouds, Convection, and Precipitation	Coupled cloud-precipitation state and dynamics for monitoring global hydrological cycle and understanding contributing processes including cloud feedback	Radar(s), with multi-frequency passive microwave and sub-mm radiometer	X	
Mass Change	Large-scale Earth dynamics measured by the changing mass distribution within and between the Earth's atmosphere, oceans, ground water, and ice sheets	Spacecraft ranging measurement of gravity anomaly	X	
Surface Biology and Geology	Earth surface geology and biology , ground/water temperature, snow reflectivity, active geologic processes, vegetation traits and algal biomass	Hyperspectral imagery in the visible and shortwave infrared, multi- or hyperspectral imagery in the thermal IR	X	
Surface Deformation and Change	Earth surface dynamics from earthquakes and landslides to ice sheets and permafrost	Interferometric Synthetic Aperture Radar (InSAR) with ionospheric correction	X	
Greenhouse Gases	CO₂ and methane fluxes and trends , global and regional with quantification of point sources and identification of sources and sinks	Multispectral short wave IR and thermal IR sounders; or <u>lidar**</u>	X	
Ice Elevation	Global ice characterization including elevation change of land ice to assess sea level contributions and freeboard height of sea ice to assess sea ice/ocean/atmosphere interaction	<u>Lidar**</u>		X
Ocean Surface Winds and Currents	Coincident high-accuracy currents and vector winds to assess air-sea momentum exchange and to infer upwelling, upper ocean mixing, and sea-ice drift	Doppler scatterometer	X	
Ozone and Trace Gases	Vertical profiles of ozone and trace gases (including water vapor, CO, NO ₂ , methane, and N ₂ O) globally and with high spatial resolution	UV/Vis/IR microwave limb/nadir sounding and UV/Vis/IR solar/stellar occultation	X	
Snow Depth and Snow Water Equivalent	Snow depth and snow water equivalent including high spatial resolution in mountain areas	Radar (Ka/Ku band) altimeter; or <u>lidar**</u>		X
Terrestrial Ecosystem Structure	3D structure of terrestrial ecosystem including forest canopy and above ground biomass and changes in above ground carbon stock from processes such as deforestation and forest degradation	<u>Lidar**</u>		X
Atmospheric Winds	3D winds in troposphere/PBL for transport of pollutants/carbon/aerosol and	Active sensing (<u>lidar</u> , radar, scatterometer); or passive imagery	X	X

MESCAL→

	water vapor, wind energy, cloud dynamics and convection, and large-scale circulation	or radiometry-based atmos. motion vectors (AMVs) tracking; or <u>lidar**</u>			
Planetary Boundary Layer	Diurnal 3D PBL thermodynamic properties and 2D PBL structure to understand the impact of PBL processes on weather and AQ through high vertical and temporal profiling of PBL: temperature, moisture and heights	Microwave, hyperspectral IR sounder(s) (e.g., in geo or small sat constellation), GPS radio occultation for diurnal PBL: temperature and humidity and heights; water vapor profiling DIAL: lidar; and <u>lidar**</u> for PBL: height			X
Surface Topography and Vegetation	High-resolution global topography including bare surface land topography ice topography, vegetation structure, and shallow water bathymetry	Radar; or <u>lidar**</u>			X
** Could potentially be addressed by a multi-function lidar designed to address two or more of the Targeted Observables					
Other ESAS 2017 Targeted Observables, not Allocated to a Flight Program Element					
<u>Aquatic Biogeochemistry</u>		Radiance Intercalibration			
<u>Magnetic Field Changes</u>		Sea Surface Salinity			
<u>Ocean Ecosystem Structure</u>		Soil Moisture			

With appropriate readout modalities, a photon counting/timing detector array sensitive to $\lambda=532$ nm would have the potential to address at least 8 targeted observables:

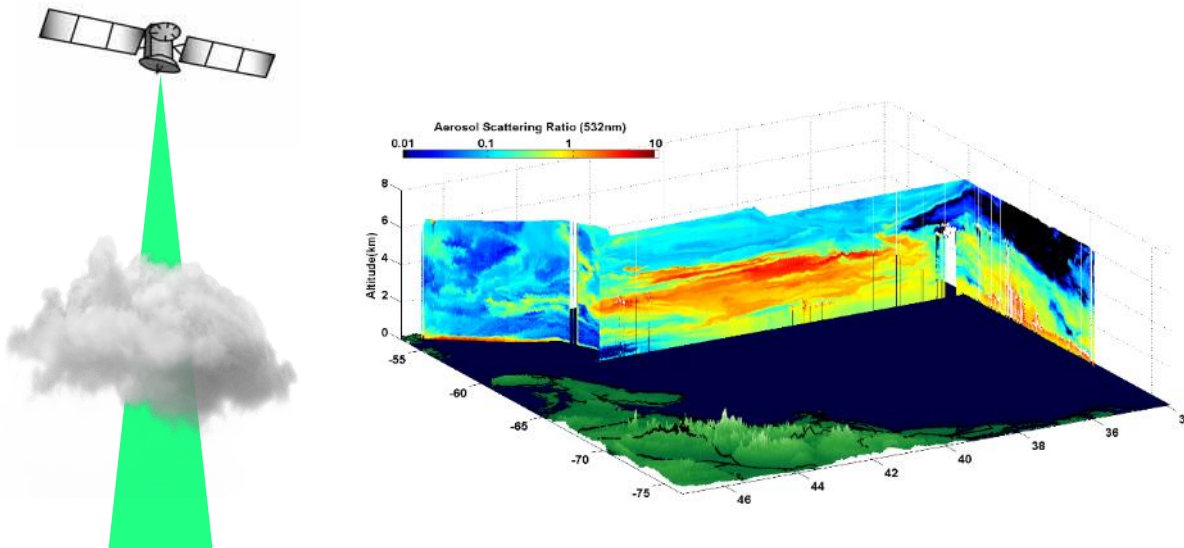
1. Aerosols
2. Ice Elevation
3. Snow Depth and Snow Water Equivalent
4. Terrestrial Ecosystem Structure
5. Atmospheric Winds
6. Planetary Boundary Layer
7. Surface Topography and Vegetation
8. Ocean Ecosystem Structure/Aquatic Biogeochemistry

Two lidar categories address all DS objectives



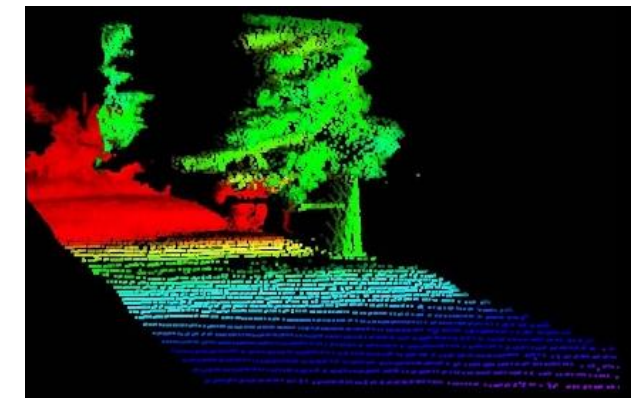
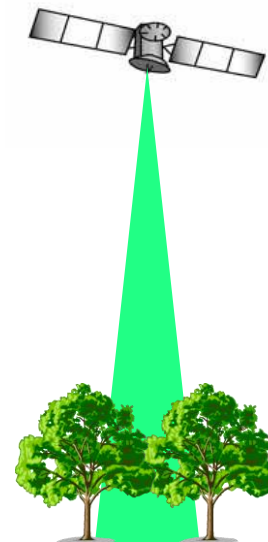
“Backscatter” Lidar

- Aerosols
- Atmospheric Winds
- Planetary Boundary Layer
- Ocean Ecosystem Structure



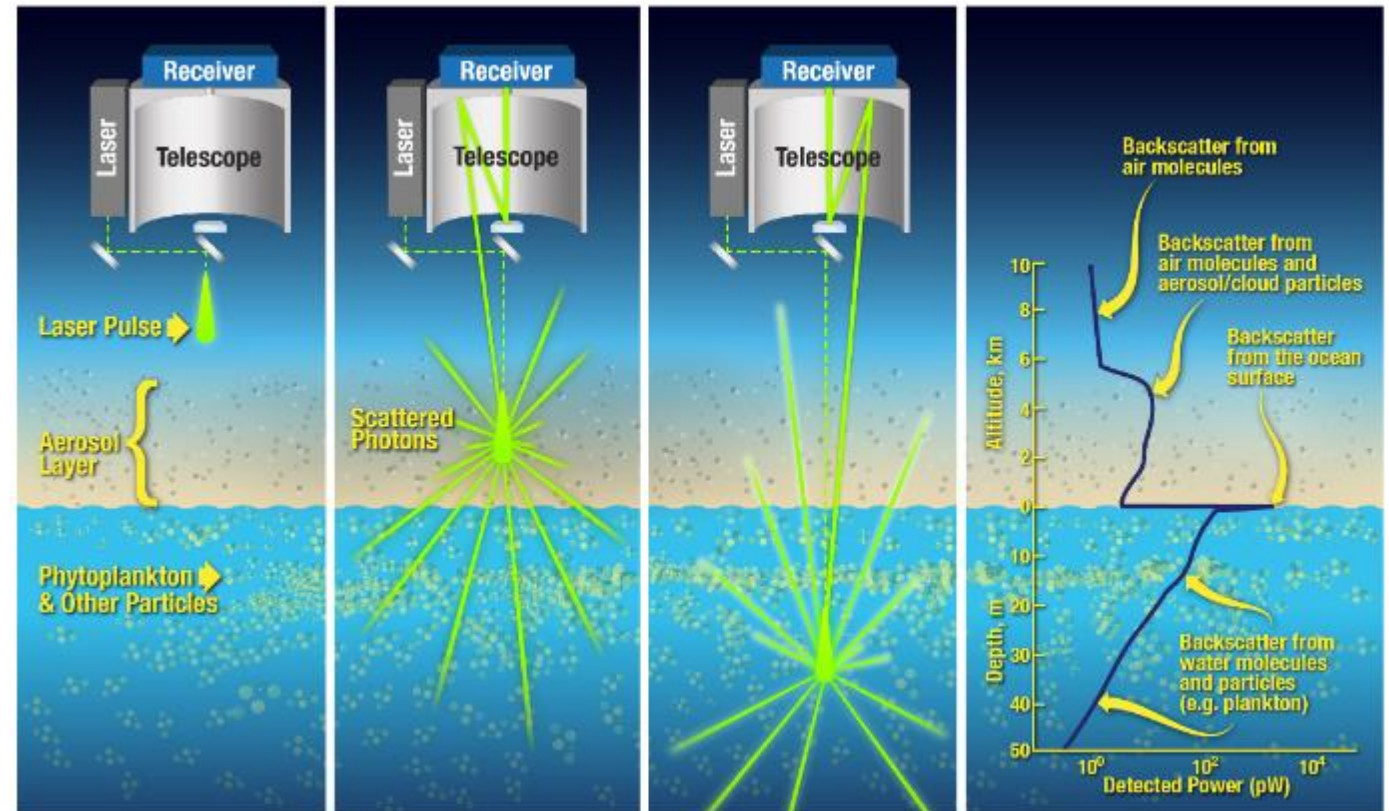
Flash Lidar

- Ice Elevation
- Snow Depth and Snow Water Equivalent
- Terrestrial Ecosystem Structure
- Surface Topography and Vegetation



Backscatter lidar technique

- Laser emits pulse
- Detector records backscatter waveform; time correlates with range to scatterer and intensity relates to scatterer type, density, and the intermediate extinction
- Scatterers can be molecules, aerosols, clouds, plankton, etc.
- Intermediate extinction contains information on concentration of particles and/or gases of interest
- Scatterer type/shape is retrieved from measuring spectrum, polarization, and wavelength ratio of the backscatter



Hostetler, C. A., Behrenfeld, M. J., Hu, Y., Hair, J. W., & Schullien, J. A. (2018). Spaceborne lidar in the study of marine systems. *Annual review of marine science*, 10, 121-147.



Our vision for the “perfect” backscatter lidar detector

1. A large-format array detector (versus a “single pixel” detector)
2. Fast reset Geiger mode array elements with a low dark count rate
3. High detection efficiency at $\lambda=532$ nm



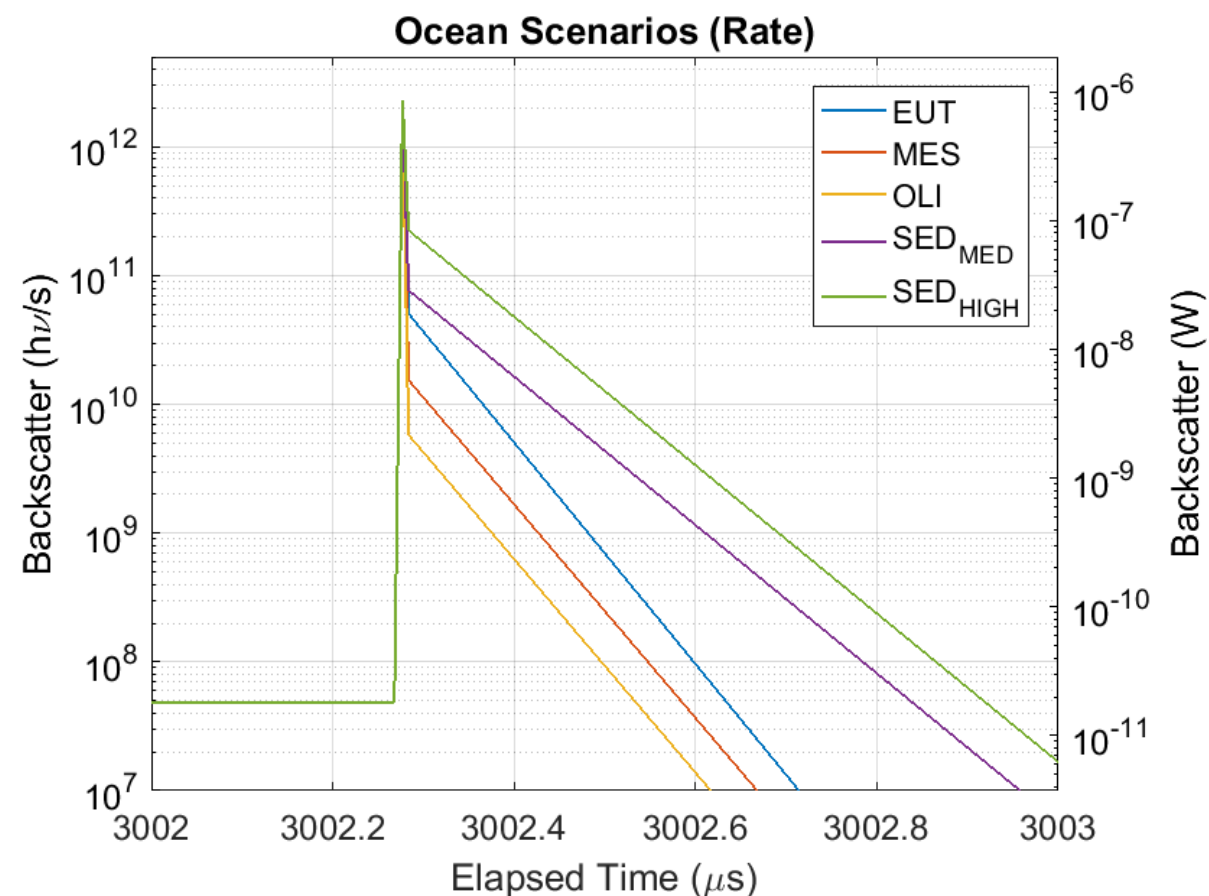
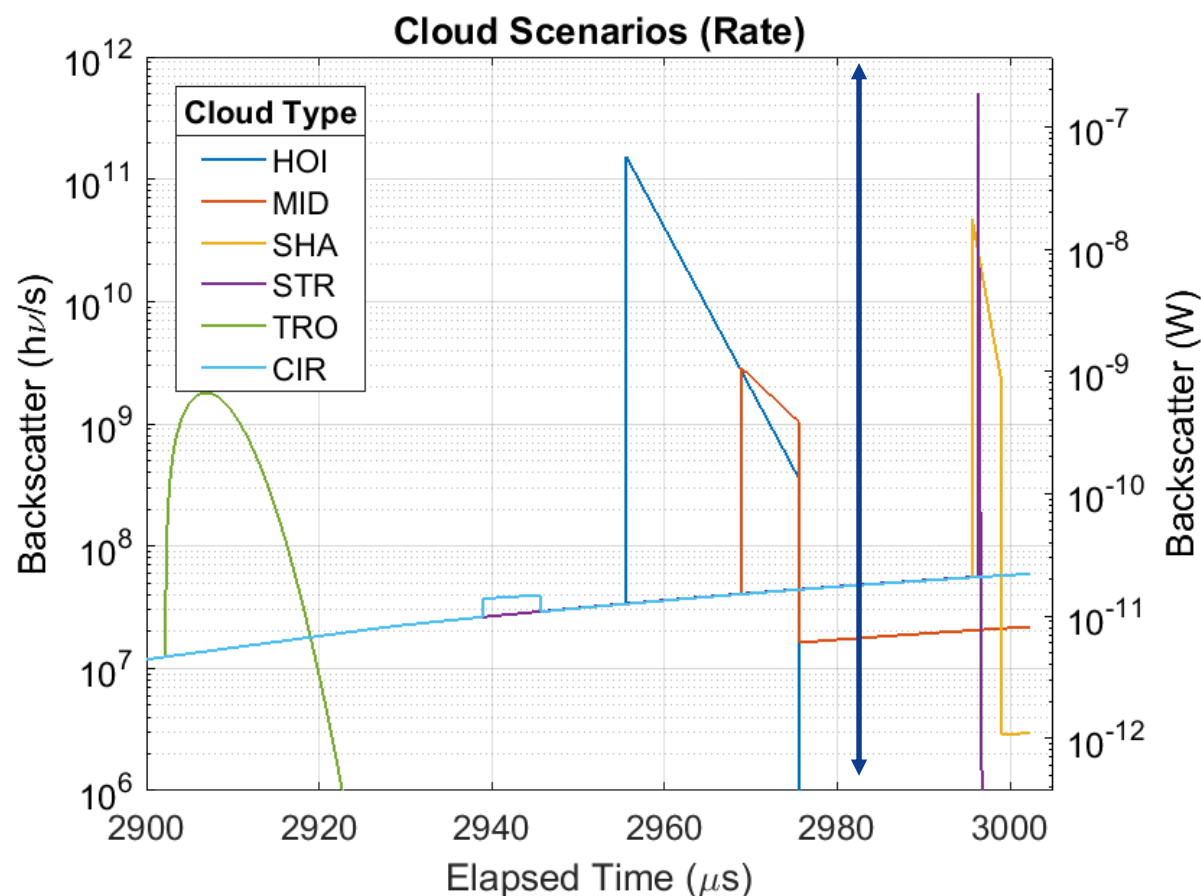
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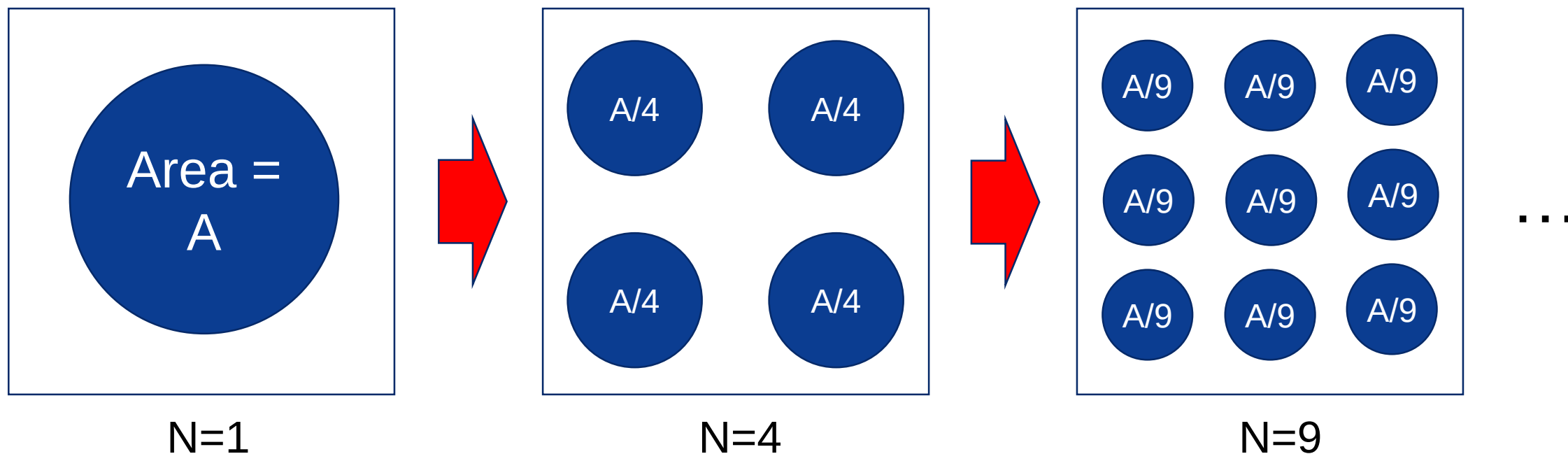
Simulations illustrate stressing dynamic range requirement

50+ dB dynamic range required



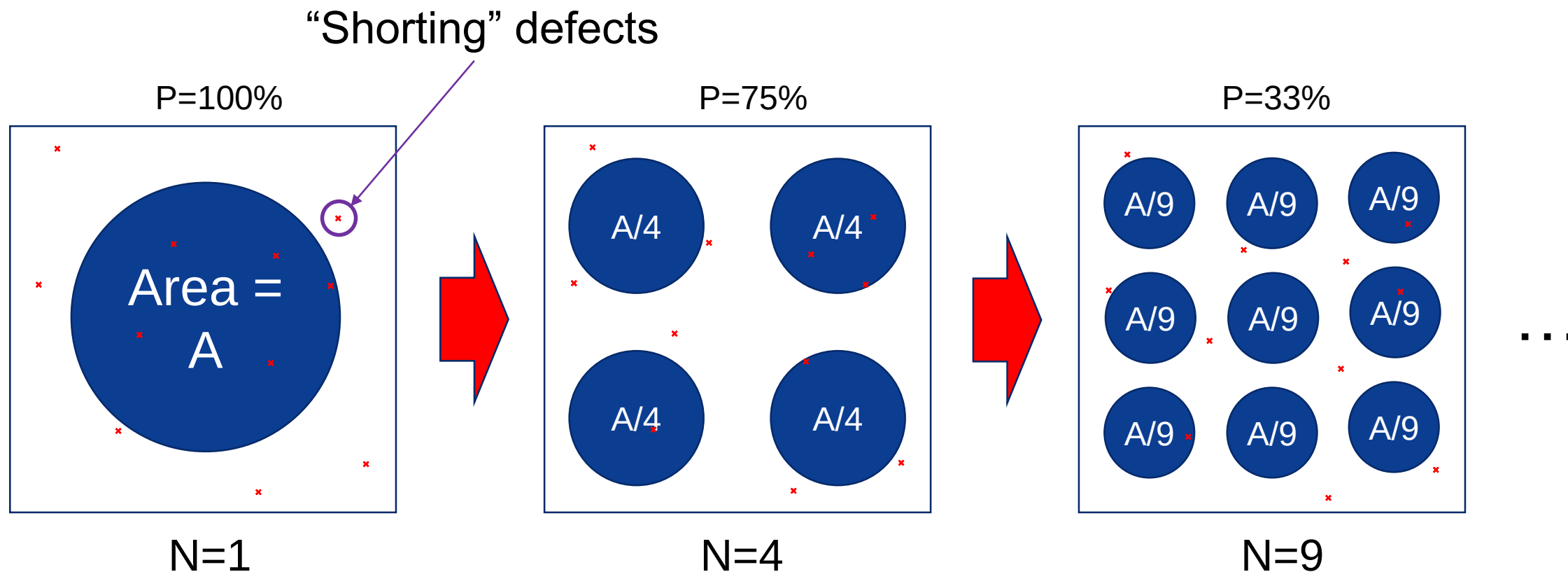
Dynamic range is multiplied by using an array

Dark count rate $\propto$ Area



The low end of the dynamic range remains the same, but the high end increases in proportion to the number of elements (N)

Defects are isolated to a limited subset of the elements



The proportion (P) of the array that contains shorting defects decreases as the element area decreases



Smaller elements have more radiation tolerance

Table 3

Proton irradiation results at $-15\text{ }^{\circ}\text{C}$ at PSI.

Fluence (proton/cm ²)	DC (Hz) 50 μm	DC (Hz) 50 μm	DC (Hz) 350 μm	DC (Hz) 500 μm	DC (Hz) 500 μm
0	69	48	11,500	9200	8400
1.5×10^7	74	55	9900	39,600	4400
3.0×10^7	39	30	10,200	40,400	1.0×10^5
4.5×10^7	39	26	9540	42800	1.1×10^5
2.0×10^8	50	20	34,800	5.7×10^5	2.6×10^5
5.0×10^8	73	24	2.8×10^5		3.7×10^5
1.0×10^9	88	58			
3.0×10^9	8×10^5	203			

F. Moscatelli et al, "Radiation tests of single photon avalanche diode for space applications," *Nuclear Instr. and Methods in Phys. Res. A*, 2013.

If on-orbit con-ops is to disable elements that experience a significant enhancement in their dark count rate:

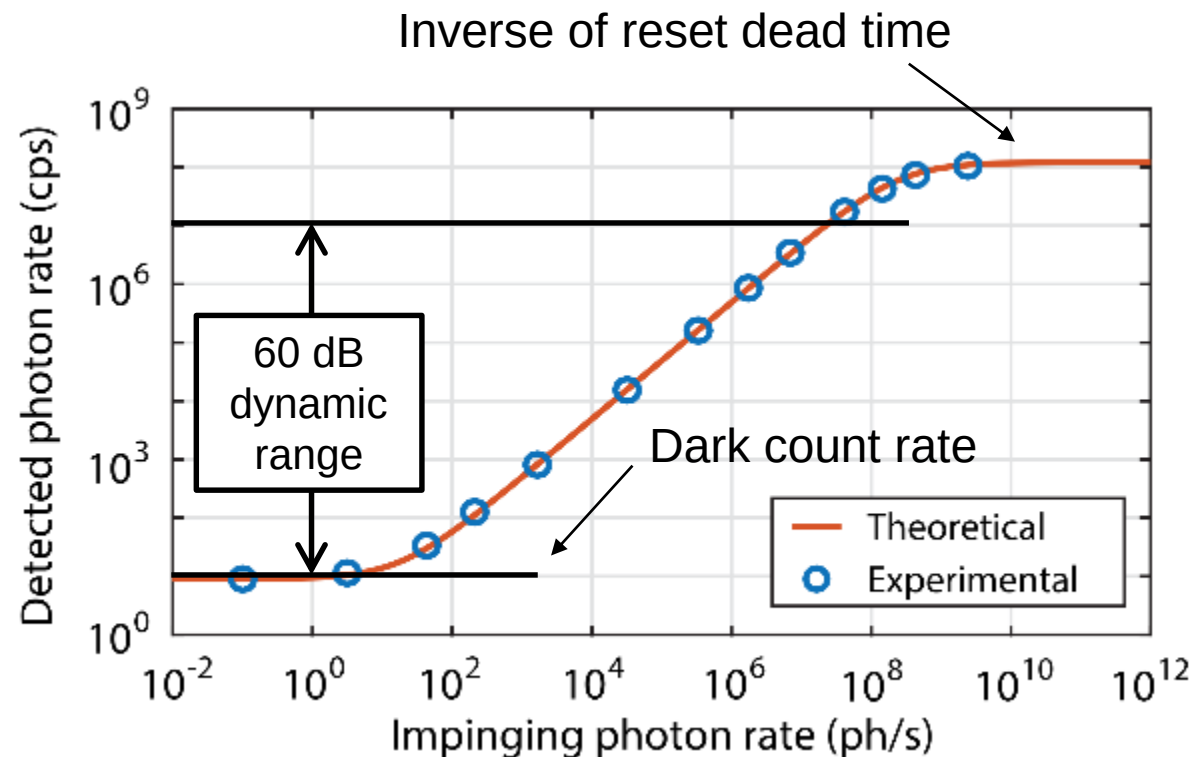
Element diameter	Fraction of elements remaining after 3×10^9 protons/cm ² fluence
500 μm	$\approx 0\%$
350 μm	$\approx 0\%$
50 μm	31%
25 μm	75%
10 μm	95%
5 μm	99%



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Advantage of Geiger mode SPAD devices



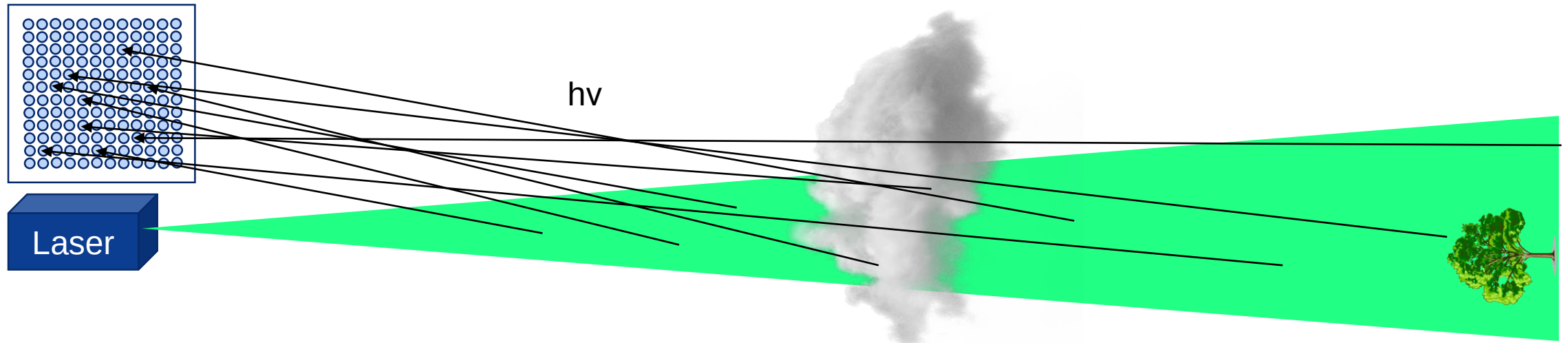
- Photon counting produces a digital representation of a signal that is inherently digital
- Noise statistics follow a distribution entirely parameterized by the measured signal mean

F. Ceccarelli et al, "152-dB Dynamic Range With a Large-Area Custom-Technology Single-Photon Avalanche Diode," *IEEE Phot. Tech. Lett.*, 30 (4), 2018.

What if $N \gg$ number of photons to detect?



If $N \approx 1$ Megapixel, then probability of 2 or more photons detected per pixel is small



- The backscatter is “randomly spatially multiplexed” across the array
- As with typical flash lidar, each pixel records a single time-of-arrival
- Time tags are readout and histogrammed between laser pulses to generate a backscatter waveform



Our vision for the “perfect” backscatter lidar detector

1. A large-format array detector (versus a “single pixel” detector)
2. Fast reset Geiger mode array elements with a low dark count rate
3. **High detection efficiency at $\lambda=532$ nm**

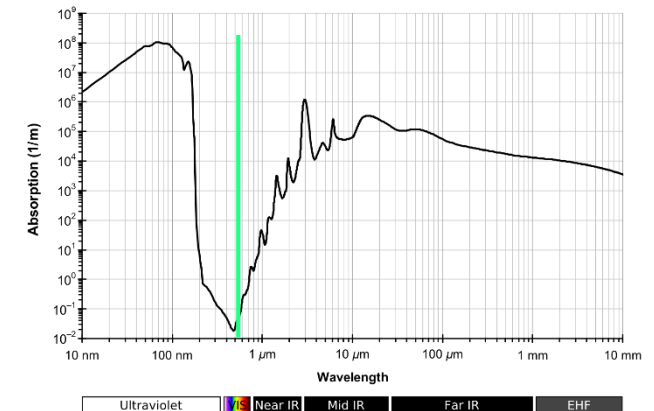
Why $\lambda=532$ nm?



- Lasers with space heritage (Nd:YVO₄, Nd:YAG) emit 1064 nm, but detector options are less noisy at the second harmonic
- The peak of the solar spectrum is 550 nm, so measurements at 532 nm are more complementary to those from passive instruments, like imagers and radiometers
- Blue-green spectrum has excellent water penetration
- The backscatter cross-section for aerosols and gas molecules is larger at shorter wavelengths (by more than a factor of $1/\lambda$). More backscattered photons = better statistics.
- Detectors with larger bandgaps and thinner depletion regions should generally exhibit better radiation tolerance, which is important for noise sensitive space missions



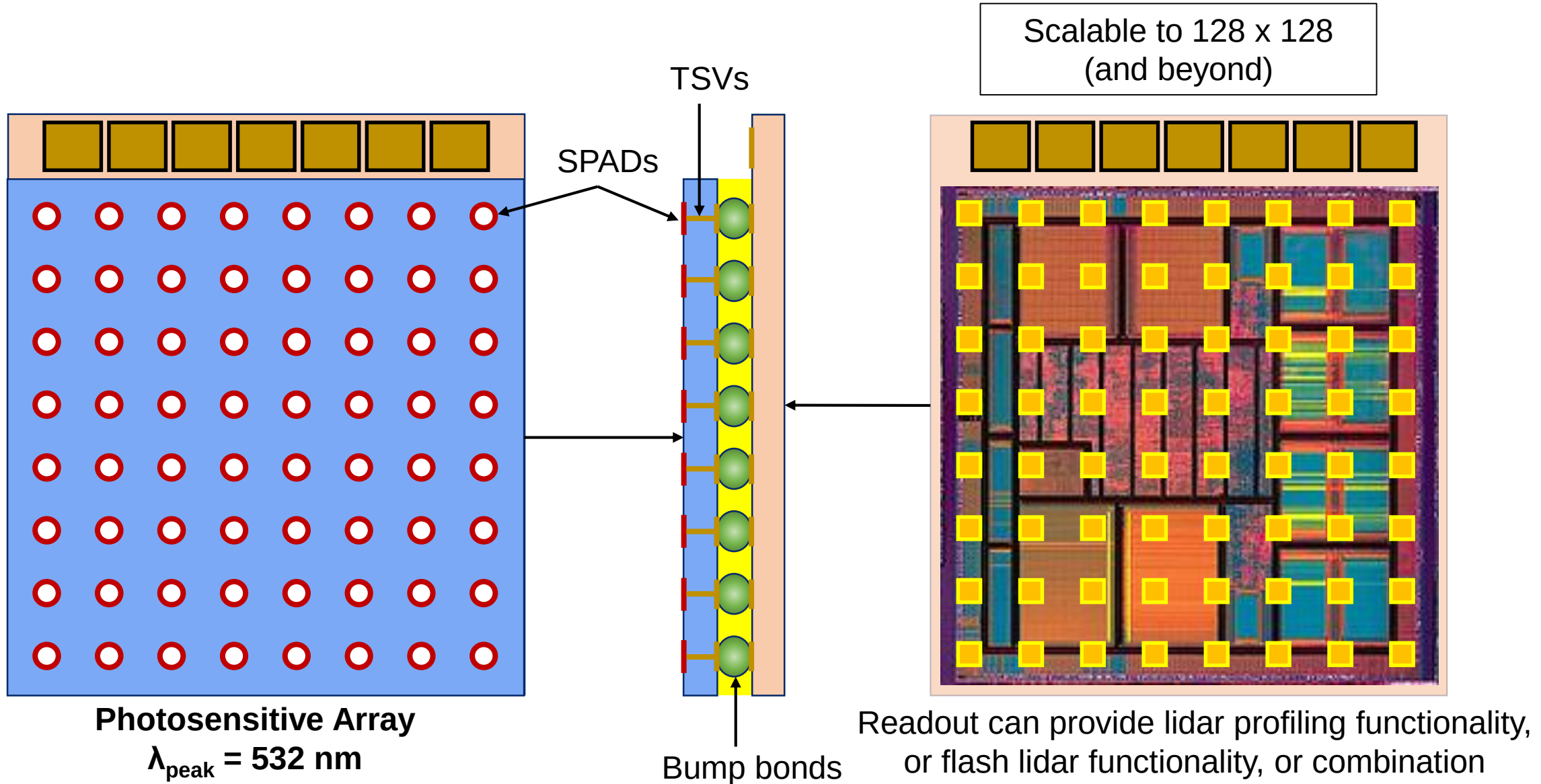
<http://fibertek.com/what-we-do/our-programs/>



Water Absorption

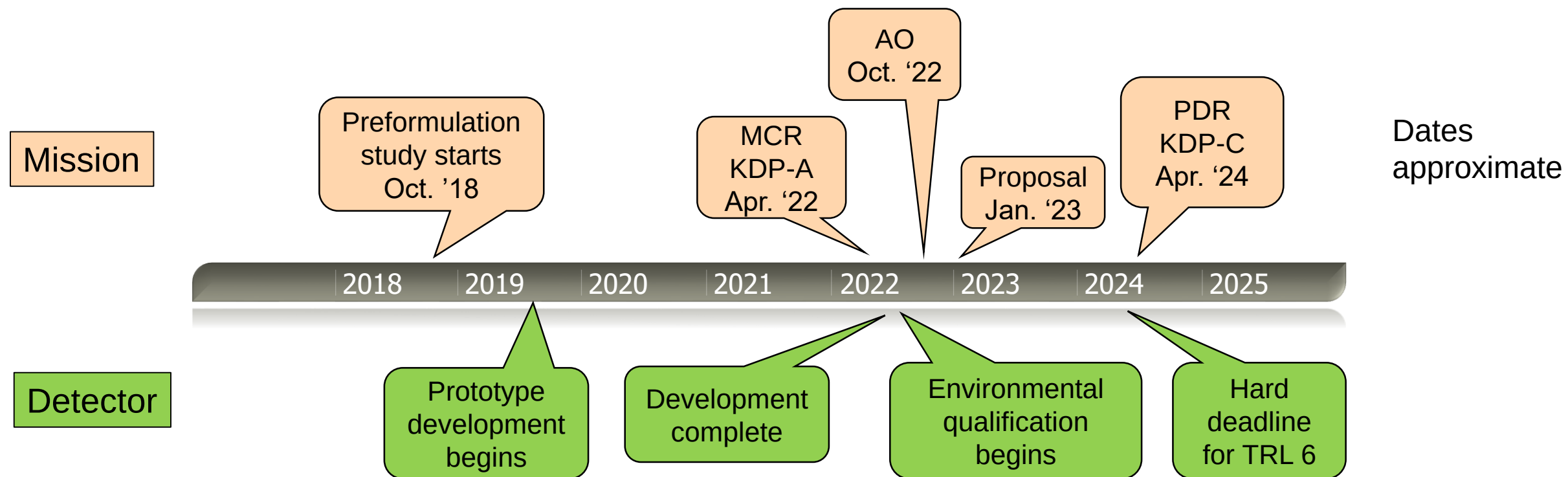
By Kebes at English Wikipedia, CC BY-SA 3.0,
<https://commons.wikimedia.org/w/index.php?curid=23793083>

What we've been driving towards



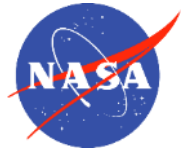


Timeline for detector development



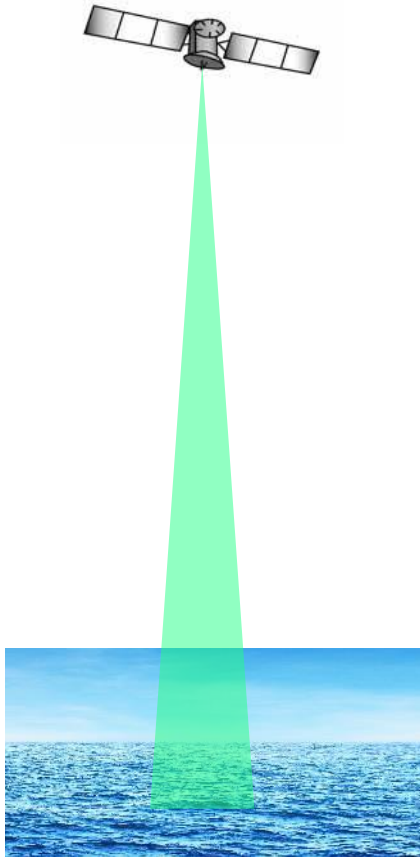
- About 3 years to develop prototype to TRL 4
- 1 year needed for environmental qualification to TRL 5-6
- TRL 6 by AO preferred, by PDR required

Software-defined readout opens up possibility of far more advanced readout schemes and modalities

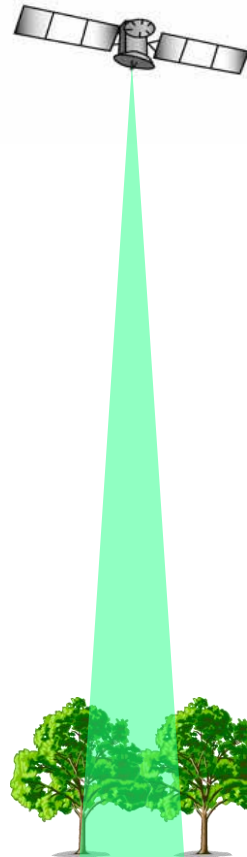


Mode:

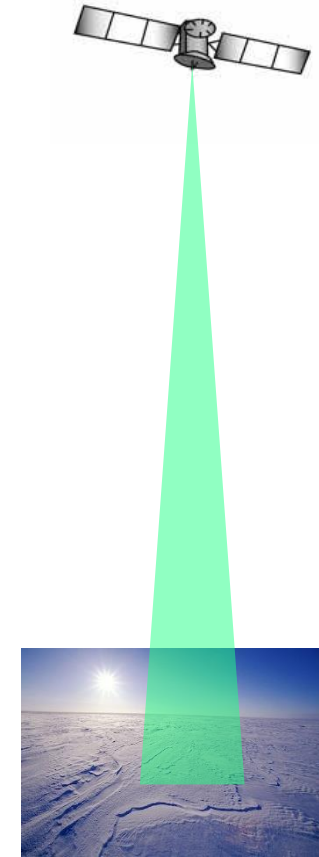
“Ocean”



“Canopy”



“Topography”



Detector identifies the scene below and configures its readout appropriately, in real time
Future, steerable lasers could be directed towards a scene of interest

Conclusions



- There is a lot more information content in our backscatter than our current SOA lidar sensors are capable of resolving and/or downlinking
- More advanced detectors are needed in order to enhance the Information:Data ratio for remote/spaceborne platforms
- Reconfigurable readout would mitigate significant risk areas in our current array detector development paths
- Single photon sensitive array detectors optimized for ≈ 532 nm with reconfigurable readout would be capable of addressing a huge number of NASA's priorities in the next decade (and beyond)