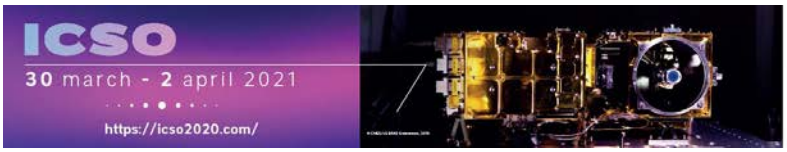
International Conference on Space Optics—ICSO 2020

Virtual Conference

30 March–2 April 2021

Edited by Bruno Cugny, Zoran Sodnik, and Nikos Karafolas



ICSO 2020
INTERNATIONAL CONFERENCE
ON SPACE OPTICS
VIRTUAL

Imaging Lidar systems

esa icso proceedings cnes

International Conference on Space Optics — ICSO 2020, edited by Bruno Cugny, Zoran Sodnik,
Nikos Karafolas, Proc. of SPIE Vol. 11852, 118526C · © 2021 ESA and CNES
CCC code: 0277-786X/21/$21 · doi: 10.1117/12.2600286

Imaging Lidar SYSTEMS

Rees; David; The Paradigm Factor Ltd.

Laser Altimeters have been used in space and ground-based / aircraft applications for many years. This presentation concentrates on recent technology developments and the possibility of exploiting the laser ranging technique in a multitude of relatively new areas:

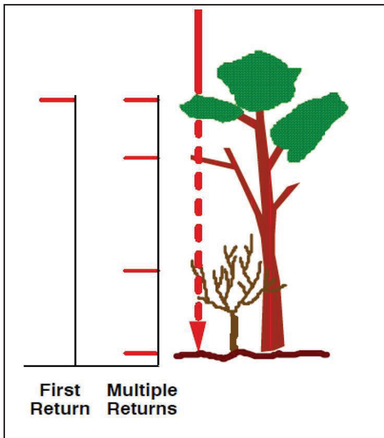
- Bathymetry (measurement of the sea depth in shallow water zones);

- Canopy (distribution of the scattering elements from the top of canopy down to the ground);

- Snow depth mapping and ice thickness mapping;

- Global 3-D imaging.

These applications can all exploit high rep-rate multi-beam laser systems with multi-element photon-counting detector arrays with appropriate high-precision timing and image reconstruction to provide high-resolution 3-D images of the sub-orbital path. The ability of Imaging Lidar to penetrate cloud and other obscurations can also be exploited.



The "traditional" Laser Altimeter operates as on the left, the return signal from a low re-rate, high power laser, with analogue signal detection picks up only the 1st return – whether from ice, snow, vegetation or the ground / sea-surface.

The development of multi-element photon-counting detectors allows major improvements in spatial and range resolution:

- Not only can the Forest Canopy be detected, but the distribution of all structural (scattering) elements from the top of the canopy down to ground-level can be sensed.

Figure 1: - These abilities can be extended to the bathymetry of surface water over land areas and the study of sub-surface regions to depths of order 50 – 100 metres in the Continental Margins.

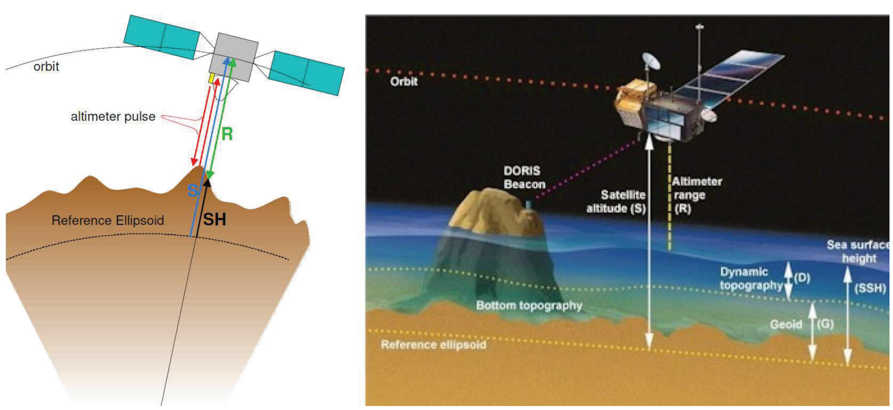
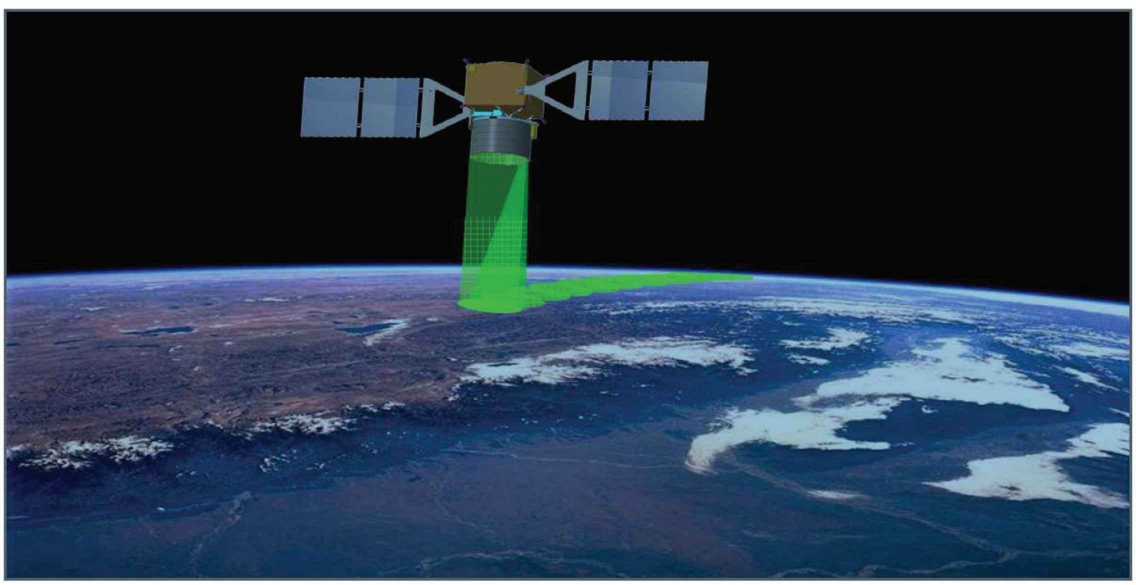


Figure 2:

Table 1: Some Previous Space Missions Exploiting Laser Altimeters

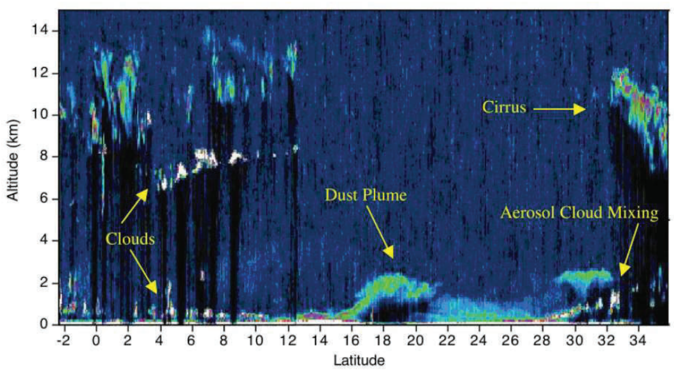
Mission	Clementine (NASA)	NEAR (NASA)	Mars Global Surveyor (NASA)	ICESat (NASA)	MESSENGER (NASA)	BepiColombo (ESA)
Launch year	1994	1996	1996	2003	2004	2014 (planned)
Destination	Moon	433 Eros	Mars	Earth	Mercury	Mercury
Laser Altimeter	Laser ranging system	NLR	MOLA	GLAS	MLA	BELA
Application	Moon topography	Asteroid topography	Mars topography	Ice-sheet topography	Topography, Gravimetry	Topography, Gravimetry
Altimeter wavelength	1064 nm	1064 nm	1064 nm	1064 nm	1064 nm	1064 nm
Pulse energy	171 mJ	15.3 mJ	42 mJ	75 mJ	20 mJ	50 mJ
Repetition frequency	0.6 Hz	1 Hz	10 Hz	40 Hz	8 Hz	10 Hz
Telescope aperture ∅	130 mm	90 mm	500 mm	1000 mm	106 mm (4 apertures)	250 mm

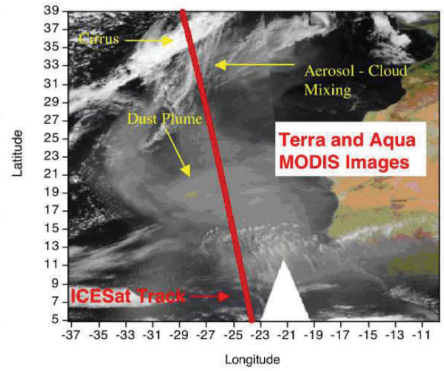
Illustration of the historical « analogue » laser altimeter systems



Using a relatively large « spot size » and low repetition rate, the ground resolution of analogue laser altimeter systems is limited to a few hundred metres

Clouds/aerosol characterization from ICESat data

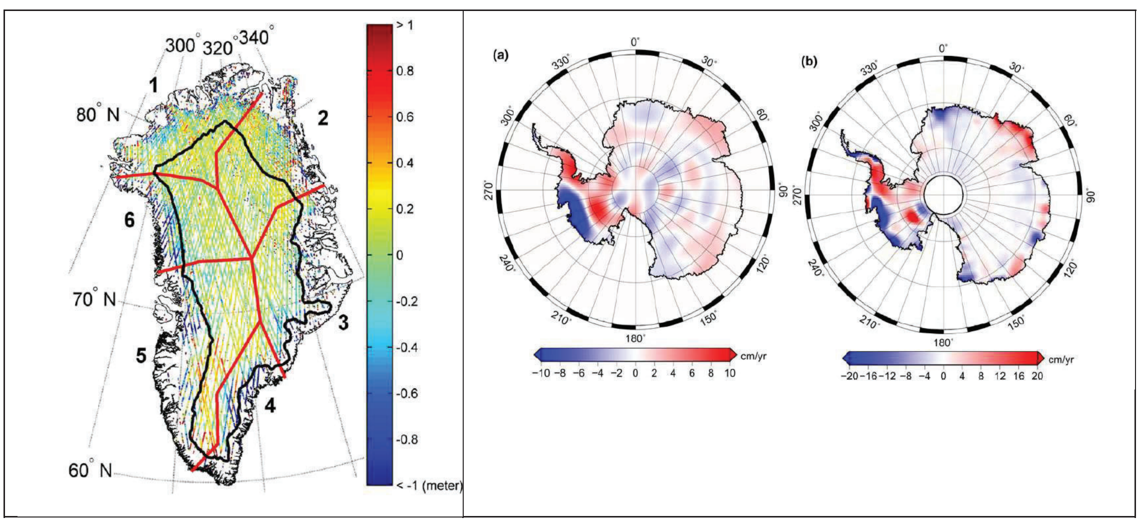




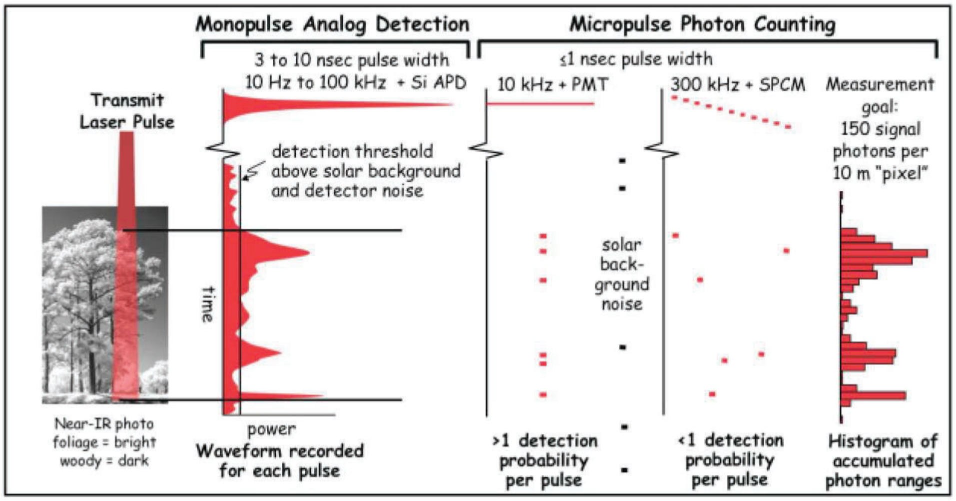
The image at left illustrates the sophisticated range of atmospheric measurements obtainable from an altimeter system such as ICESAT.

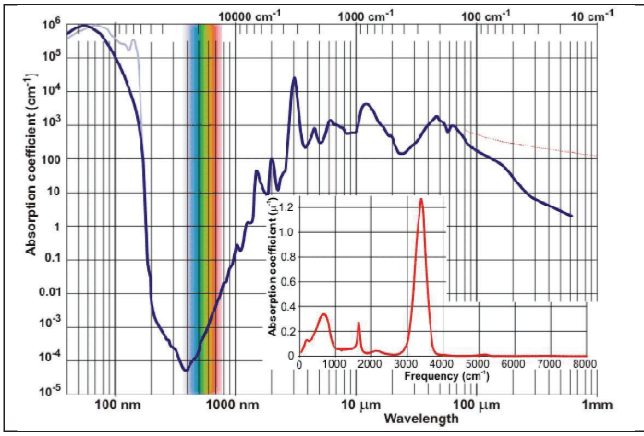
The image at right is combined from MODIS data covering the track.

Greenland Height change map (ICESat) **Mass Change (GRACE).**



Conceptual illustration of laser ranging approaches



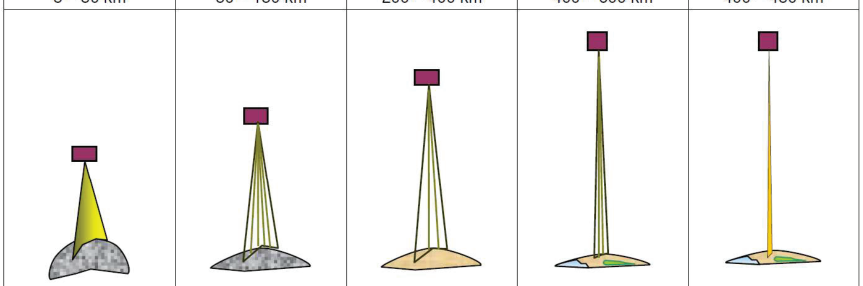


The spectral transmission of water has a peak near 400 nm.
Using a laser at or near 355 nm provides the best capability for investigating surface inventories of water, rivers, estuaries and the continental margin to a depth of order 100 metres.

Operational Requirements – footprint / beam divergence

Application	Footprint [m]			Beam divergence [μrad]		
	Threshold	Breakthrough	Objective	Threshold	Breakthrough	Objective
Altimetry - Land topography	100	50	1	250	125	2.5
Altimetry - Global ocean topography	100 km	50 km	1 km	250 mrad	125 mrad	2.5 mrad
Altimetry - Ocean bathymetry	25 km	10 km	1 km	62.5 mrad	25 mrad	2.5 mrad
Altimetry - River/lake height	500	200	10	1.25 mrad	500	25
Shallow Water Bathymetry	25	2.5	1	62.5	6.25	2.5
Vegetation canopy	50	25	5	125	62.5	12.5
Ice/snow thickness mapping	50	50	5	125	125	12.5
Fluorescent measurements	50	25	5	125	62.5	12.5
3D imaging	100	30	10	250	75	25

Misson Requirements for Advanced Altimeters for Terrestrial, lunar and Planetary Missions

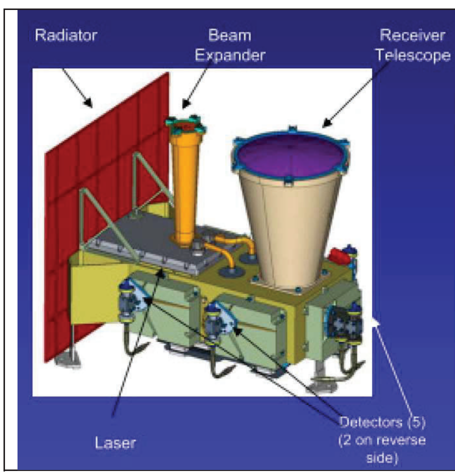
Mission				
Asteroids	Moons	Mars, Mercury	Earth topography	Vegetation canopy
5 – 50 km	50 – 150 km	200 – 400 km	400 – 600 km	400 – 450 km
				
3D imaging (multi kHz, multi beam)	Multi kHz, swath 10 – 30 beams	Multi kHz 4 – 10 beams	Multi kHz 4 – 10 beams multi wavelength	Waveform recording multi wavelength
PRN, scanning	PRN, scanning	PRN	Waveform recording	-
Power – Aperture product, mW.m^2				

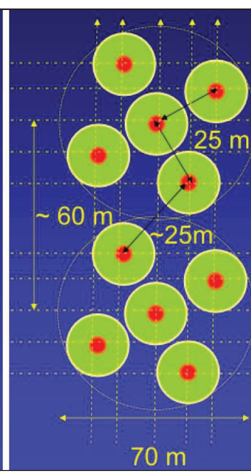
Multi-beam laser altimeter systems have crucial roles to play in many cutting-edge fields of space research.

CryoSat-2 (top) and IceSat-2 (bottom)

CryoSat-2 and IceSat-2 and will hopefully operate until mid-decade, flying to 88 degrees North and South from the equator. They see the entire Arctic and Antarctic regions, bar a small circle about 430km in diameter at the poles. This is essential to cover the great swathe of the central Arctic Ocean and its frozen ice-floes.
CryoSat-2 is already we;; beyond its design life. Launched in 2010 with an expected 3.5 years life. IceSat-2 was launched in 2018 with a design life of three years and fuel until 2025. Without a new Mission, there will be a gap of between two and five years in our polar satellite altimetry capability. This gap will introduce a decisive break in the long-term records of ice sheet and sea-ice thickness change and polar oceanography. This will degrade our capacity to assess and improve climate model projections."

LOLA – Lunar Orbiter Laser Altimeter





LOLA will exploit a multi-beam laser altimeter systems to meet its objectives in studying the lunar surface in unparalleled detail

What can an Imaging Lidar System provide?

Given a clear atmospheric conditions or cloudy / foggy conditions:

- Full 3-D instantaneous structure of everything within the field of view of the Imaging Lidar:-
- Range for every identifiable object;
- Velocity (speed + direction) for every object;

Detection, and Identification are subject to the normal rules of optical resolution / distance and signal to noise ratio etc.

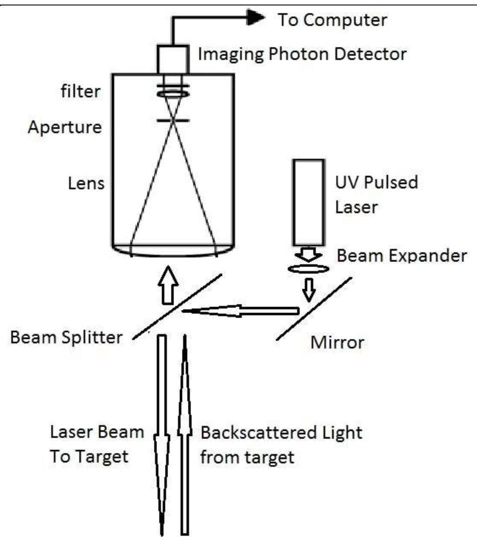
Fog and cloud causes blurring and diffusion in normal vision.

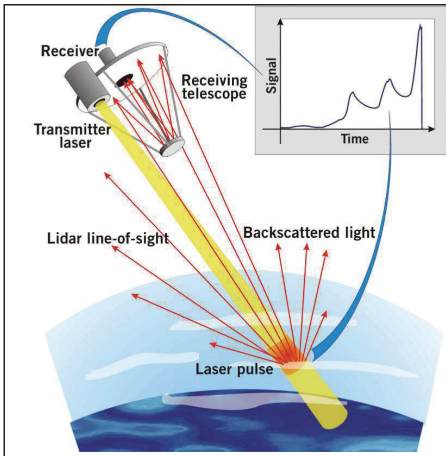
How does the Imaging Lidar avoid this?

The negative effects of a foggy or cloudy atmosphere on normal vision and imaging are familiar:-

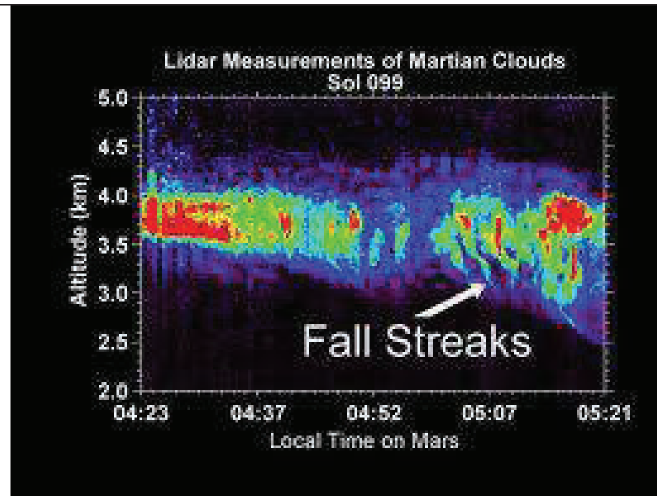
- The outlines of objects quickly become blurred;
- Identification becomes difficult / impossible;
- Beyond ~3 optical thicknesses even the outlines disappear into the fog or cloud.

The Imaging Lidar circumvents the blurring and diffusion caused by fog and cloud by the combining of temporal and spectral filtering with image deconvolution.

	The Target is illuminated by a pulsed UV laser A polarising beam-splitter and ¼ wave plate are used to ensure high efficiency of transmission and reception of the Lidar Signals. The back-scattered signal from the Target region is gathered by a lens or Cassegrain / Schmidt used as the receiver and passed to the Imaging Photon Detector. A narrow-band filter transmits a very narrow wavelength range about that of the laser, allowing (if necessary) for Doppler Shifts due to target movement / Earth rotation. The laser pulse (~100 pico-sec duration) synchronises the "data acquisition chain" to process the data acquisition chain and to time-tag detected photons with a resolution appropriate for the target. The time-tagged data from the detector is then sent to the computer for deconvolution into full 3-D images.

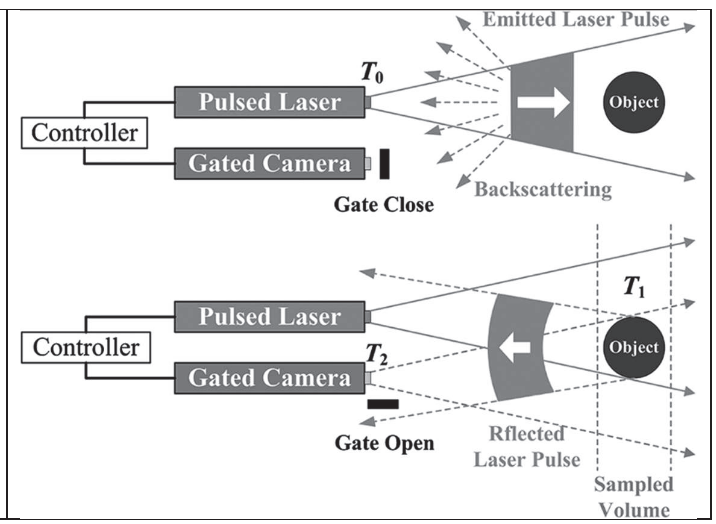


The delay time depends on the distance of the target and the time it takes the laser beam to travel there and back.

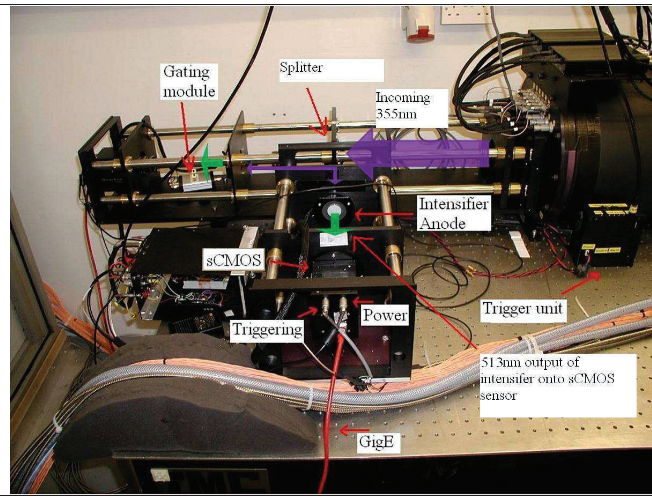


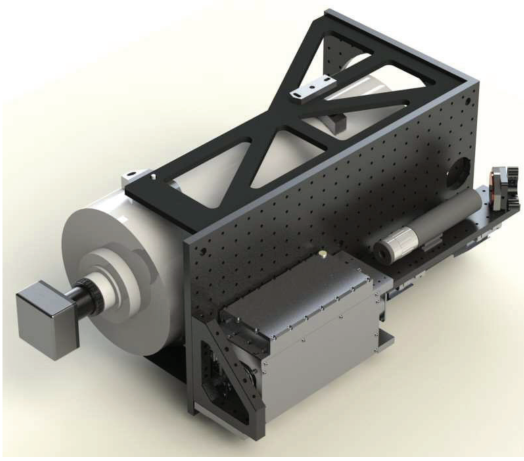
Lidar data from Martian clouds using Photek Imaging Photon detector on Mars Orbiter.

The Laser fires a pulse towards target.
The backscattered light from fog / cloud is ignored by detector while gate closed.
The Reflected pulse is imaged by detector. Gate (shutter) opened to just allow light from range of interest to be collected.



The Imaging Doppler Lidar System as used for EU Framework Project “Greenwake” was based on the use of an iCCD camera detector.

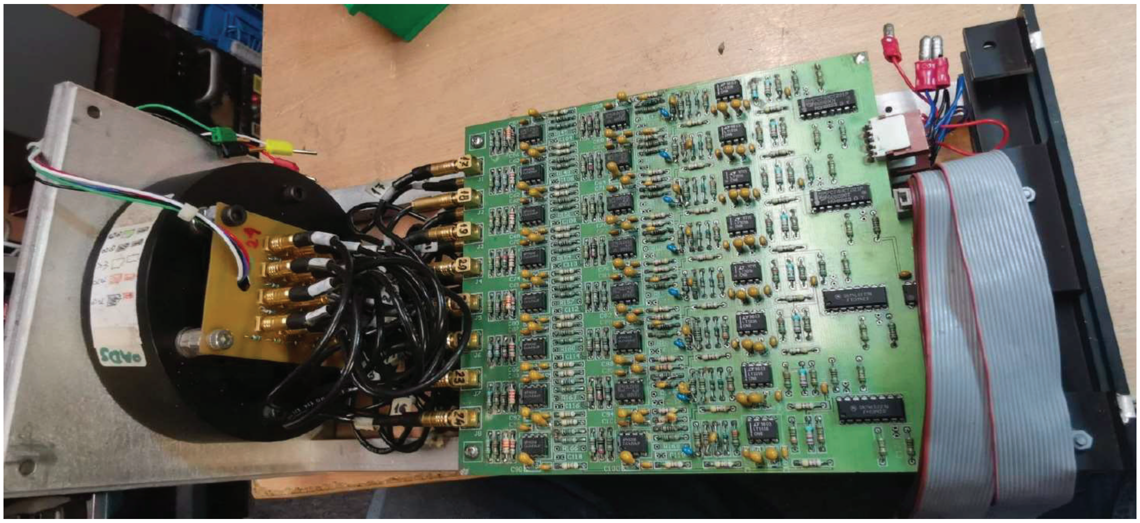


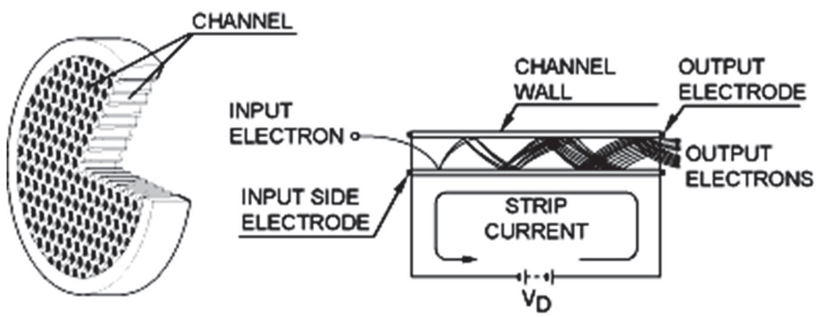


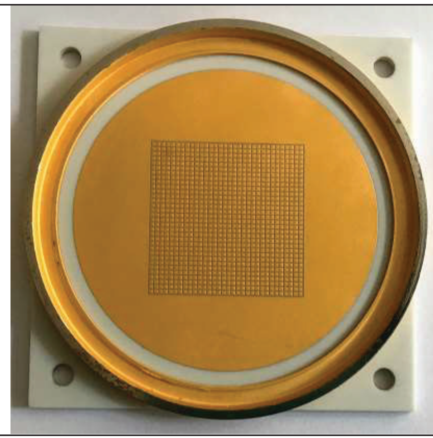
The compact Imaging Lidar system has been demonstrated to be capable of target detection and identification far beyond the limits of normal capabilities of eye and/or camera capabilities under conditions where visibility is highly challenged by Fog or Cloud.

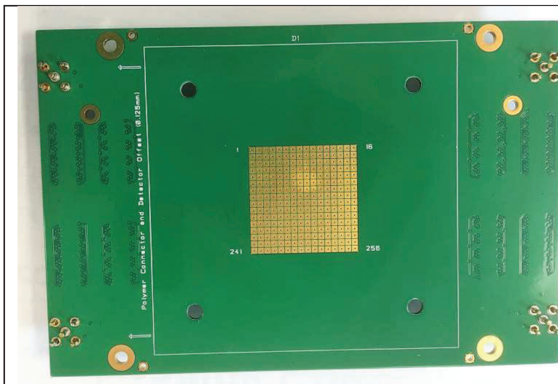
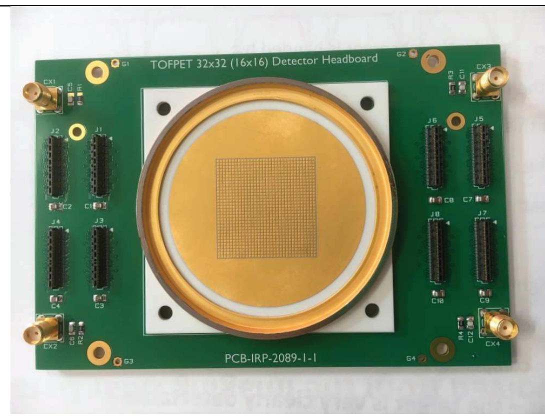
The Lidar employs a near-UV Laser (355 nm) with a short-duration pulse as the source.

The near-UV system has major advantages due to the combination of eye safety and the maturity of laser and imaging photon detector technologies.

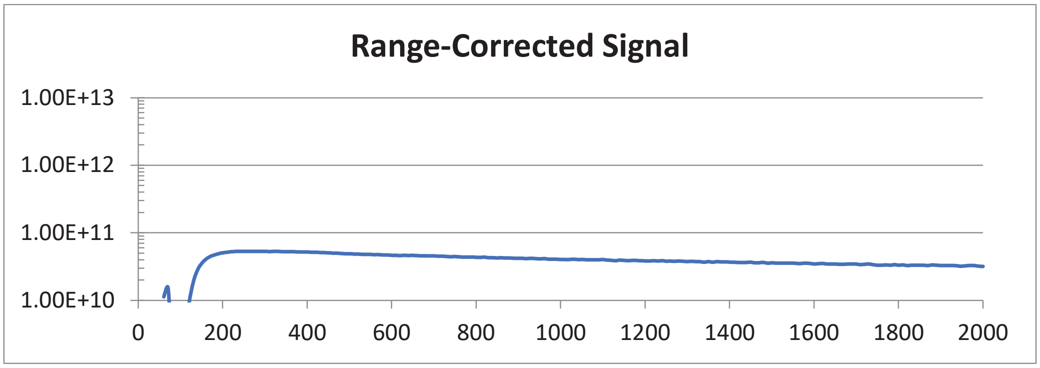


The UV-sensitive photocathode detects single photons (individual light particles), converting them into photo-electrons. Gating (or electronic shuttering) at a few nanoseconds duration of the photocathode controls the effective viewing-range of the system. (Rule of thumb: Light travels 1 m in about 3.3 nsec – one way – or 6.7 nsec for the round-trip exploited by Lidar)	High gain microchannel plates allow individual photo-electron bursts to be amplified by multiplication. 

The electron cloud hits the position-sensitive anode which splits the signal into 1024 blocks in a 32 x 32 grid.	

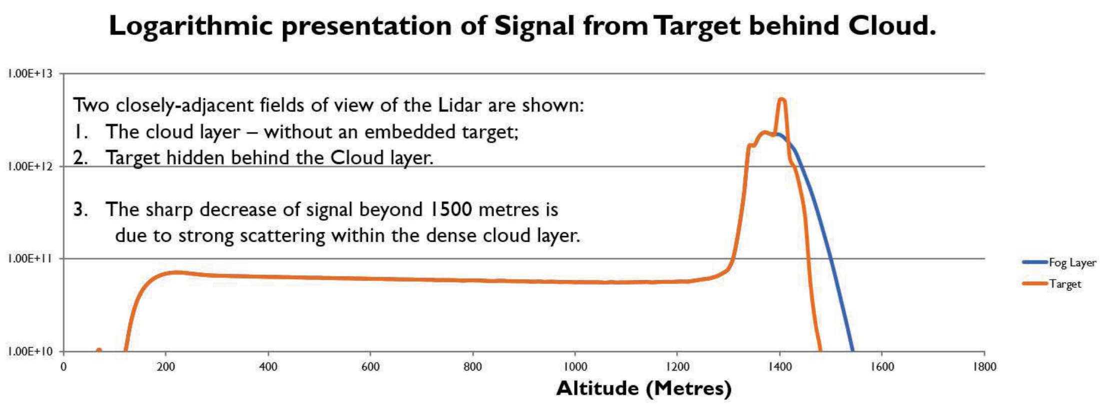
	
Readout PCB	Readout PCB with detector anode plate mounted. The position of each photon event is recorded and time tagged. These data are then logged in software for image reconstruction.

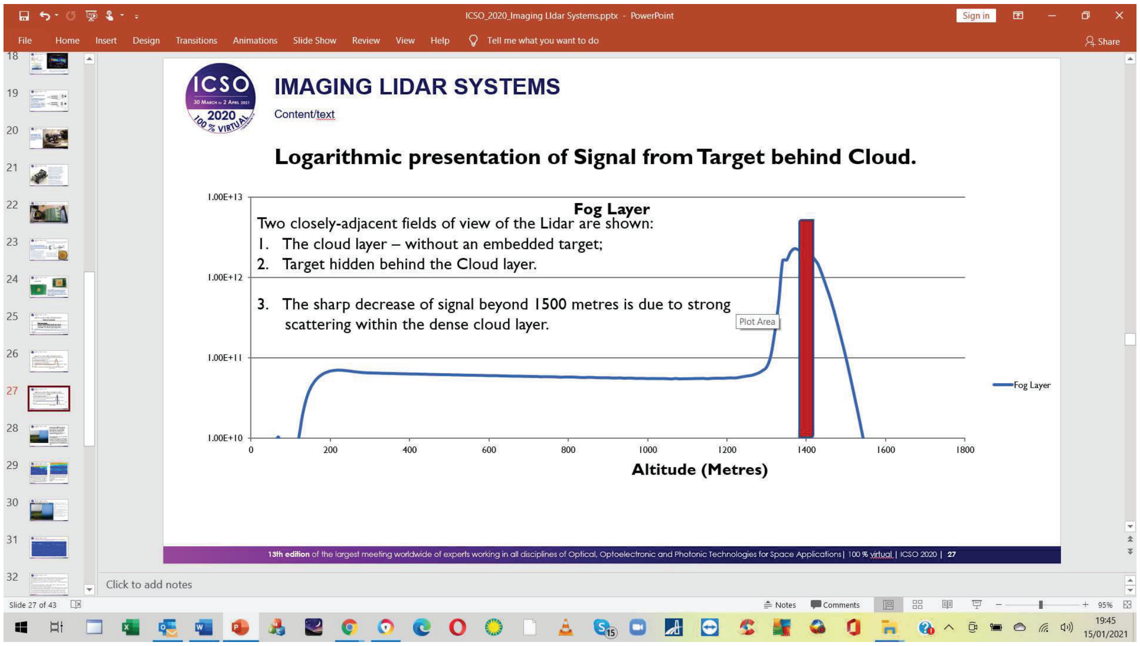
Logarithmic presentation of Signal from Target behind Cloud.



Clear Atmosphere:

The signal, range-corrected, drops off slowly due to attenuation and the decrease of atmospheric density with altitude. The "clear sky" signal is slightly lower than when a cloud layer is present.



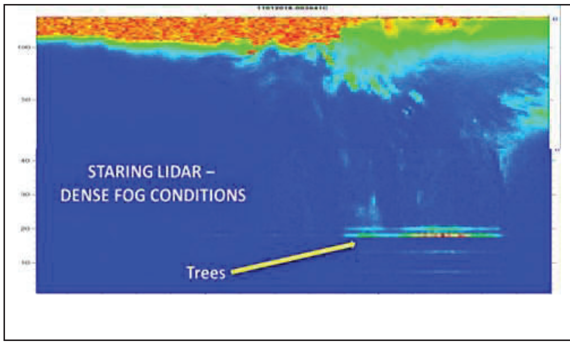


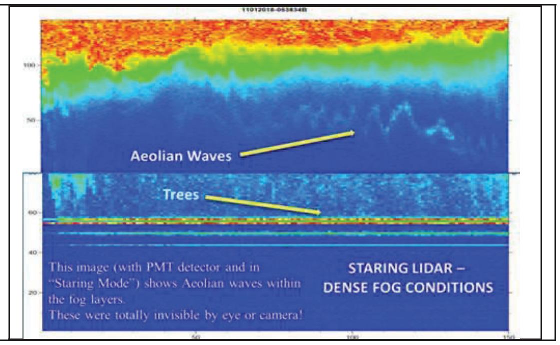
In addition to producing 3-D images of the distant field, the imaging Lidar – when using a 2-D imaging photon detector with 100 psec time-tagging has a remarkable capability for detecting and imaging targets through cloud and fog, well beyond the visibility offered by eye or normal camera.

A standard Nikon Camera shows the comparative views under clear and foggy conditions.

A best estimate of normal “visibility” in the fog (right) is between 30 – 50 metres.

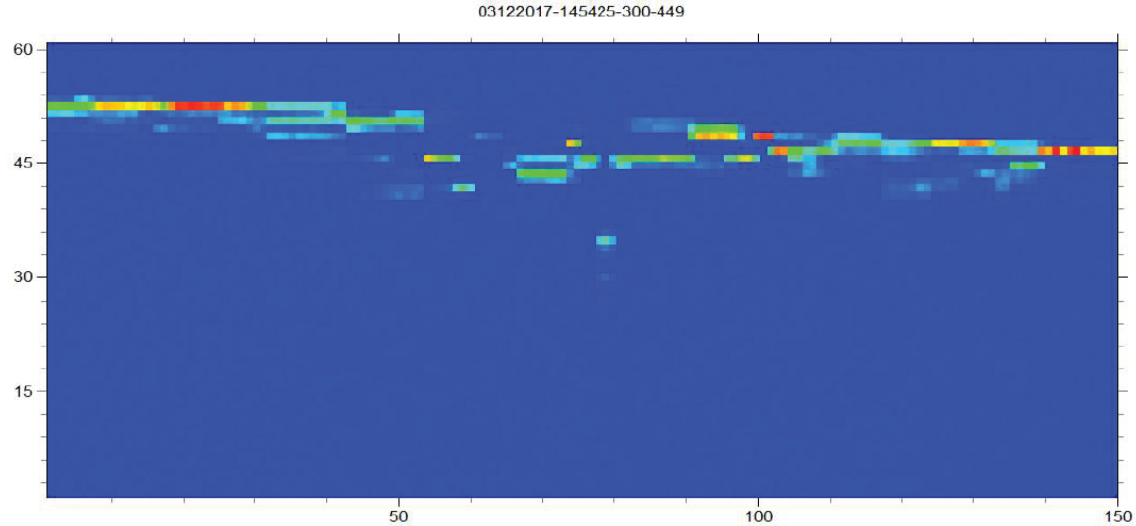
The following images demonstrate the capability of the Imaging Lidar to not only image the far field in 3-D, but also to provide essentially the same information when the visibility is severely compromised by heavy fog. The red spot covers trees at a distance of 600 metres. This is some 12 times the “visibility” as indicated by the camera images!



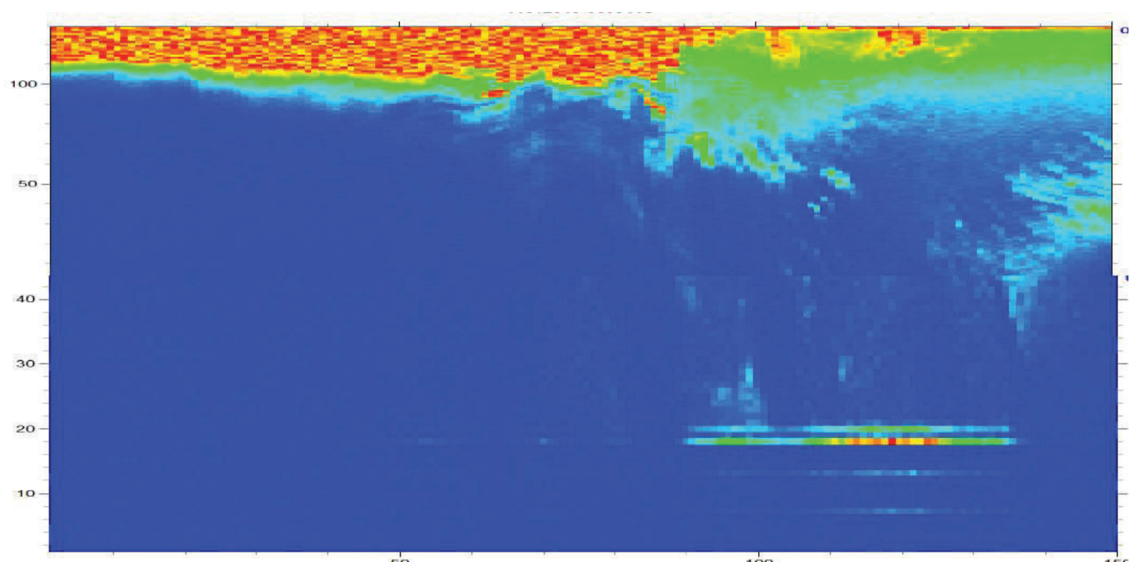


This image shows the back-scattered signal from the lidar when used with a conventional PMT detector and operated in “Staring” Mode. Time is running from left to right – the 1 km distant trees appear through heavy mist – having been obscured, even to the Lidar, earlier	The Imaging Lidar shows Aeolian Waves well-hidden (by eye / camera) within the fog layer. The “visibility conditions” were those of the earlier image. (< 50 metres “visibility” by either eye or camera).

The image on the left shows the “normal” appearance of this field of view.
At right is the contrasting “foggy” image
A red circle indicates the centre of the fov of the Imaging Lidar System and the approximate region illuminated by the beam-expander of the UV laser (355 nm).
The region illuminated is centred on the foliage of a large Oak tree.

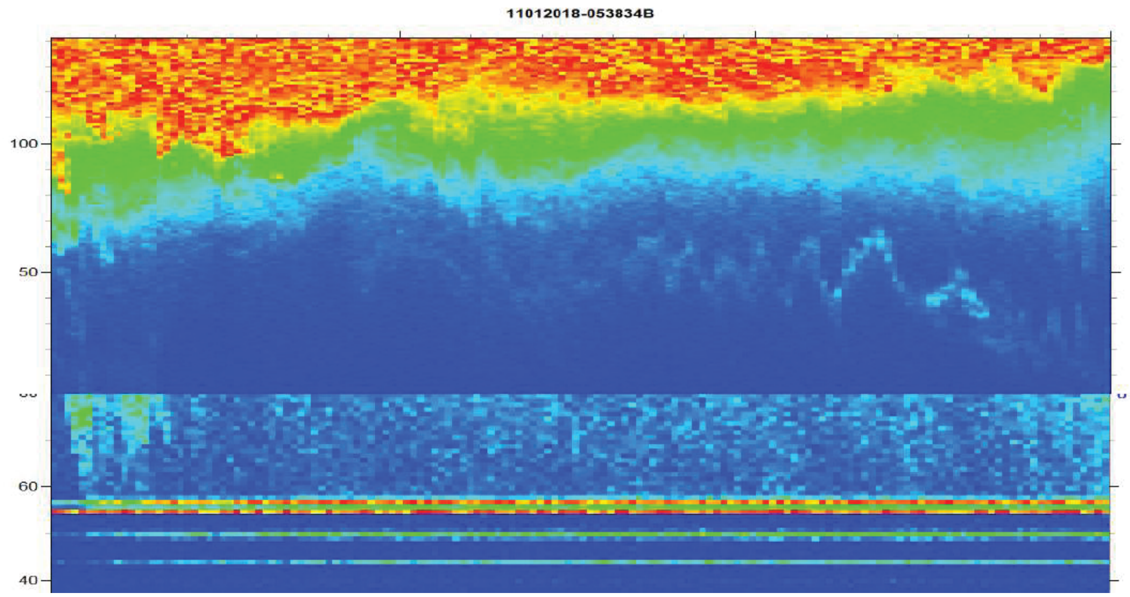


Scanning Lidar System with PMT detector – observing trees etc at ~800 – 1000 metres.



This image shows the back-scattered signal from the lidar used with a conventional PMT detector and operated in a 2-D "Scanning Mode". Horizontal distance (perpendicular to the line-of-sight) is now running from left to right.

The structures are trees and fence-posts at distances of 800 – 1000 metres from the lidar.



This image PMT detector and in "Staring Mode" shows Aeolian waves within the fog. All totally invisible by eye or camera!!

« Staring » lidar observing trees / fences at 800 metres through dense mist / fog.

The image shows the propagation of Aeolian waves along the valley, within the fog layer.

These features were totally invisible by eye or to a normal camera.

Zero Range is at top!

This image shows the back-scattered signal from the lidar used with a conventional

PMT detector and operated in "Staring Mode". Time is running from left to right.

The zero range for the atmospheric signal at short range is at the top, showing dense fog at the start, clearing slightly in the period to the right. A range of tree / fence structures are then visible (near bottom), despite the continuous but slightly less dense fog.

Signal versus range. Image – the white spot is a tree at 600 metres

There is a weak “clear sky” atmospheric signal at short range.

There is a strong signal return from the tree at 4 msec (to left).

The “atmospheric” signal is also present.

Signal versus range. Image – the white spot is a tree at 600 metres

The “clear sky” atmospheric signal at short range is totally dominated by the return from a tree.

This is the very strong signal return at 4 msec (to right) from the tree

Signal versus range. Image – the white spot (37) is a tree at 600 metres.

This image shows the back-scattered signal return from pixel 37.

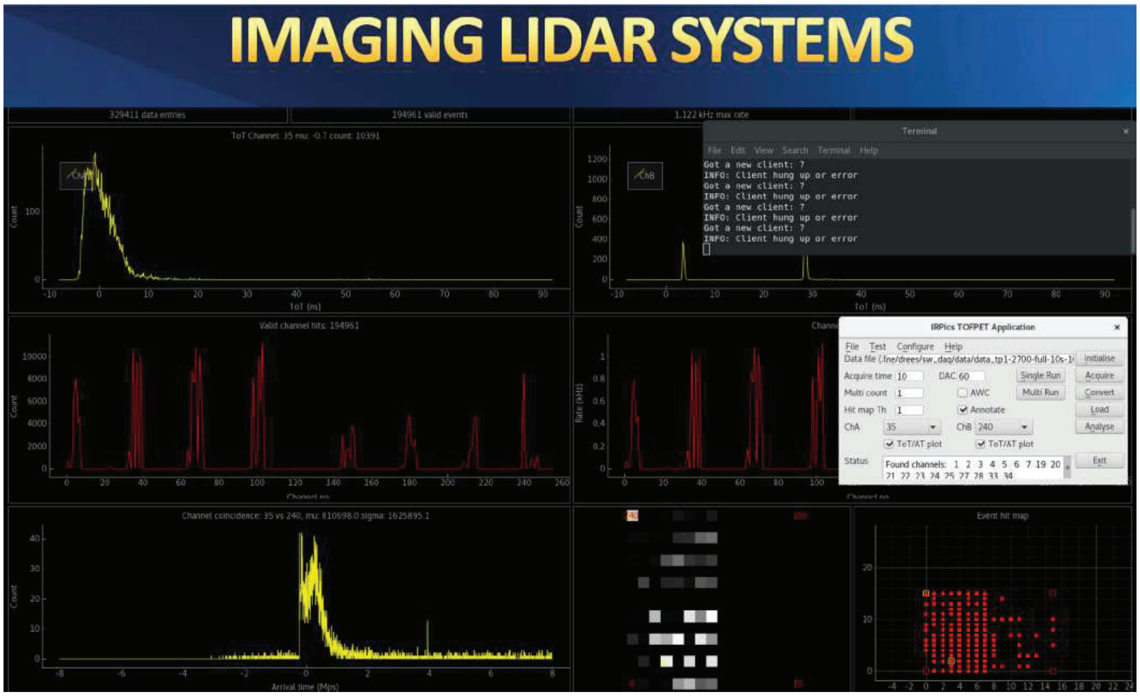
The atmospheric signal at short range is strong (enhanced by the mist / fog).

There is a weak but easily measured signal return at ~4 msec (to right) from the tree.

Signal versus range. Image – the white spot (37) is a tree at 600 metres.

The atmospheric signal at short range is strongly enhanced by the mist / fog.

There is a weak but easily measured signal return at ~4 msec (arrow to right) from the tree.



Signal versus range. Image – the white spot (35) is a tree at 600 metres.

This image, at 22:42 UT, shows the back-scattered signal return from pixel 35.

The atmospheric signal at short range is strong (enhanced by the mist / fog).

There is a weak but easily measured signal return at 4 msec (to right) from the tree

Current and Future Developments:

A 64 * 64 element version of the current photo-detector has already been built.

However, the development of the sophisticated processing electronics currently lags the development of the photo-tube by a significant factor!!

Image Resolution:

The 32 * 32 image may be deconvolved to provide 128 * 128 element resolution;

The future generation of 64 * 64 element detector we believe will be capable of providing 512 * 512 element resolution via deconvolution.

SUMMARY

This presentation is intended to demonstrate the state of art of Imaging Lidar Systems appropriate for future ground-based / airborne and Space-based Missions.

The technologies required in terms of space-qualifiable lasers, detectors and signal processing electronics have matured dramatically during the last decade.

These are the enabling steps required for the future productive exploitation of these Imaging Lidar Systems.

A number of examples of data from space and ground-based systems have been used to demonstrate that these are now practical and affordable possibilities.