Mobile 4D Imaging Technologies for Construction & Life-cycle BIM model dimensional information management

Advanced Methods of Manufacturing Workshop
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DOE 2015.2, Topic 32F (DE-SC0013835; Jun 8, 2015 – Mar 7, 2016)

About Voxtel Companies

- Founded 1999
- 50 employees (30% PhD, 80% Advanced Degree)

VoxtelOpto (Beaverton, OR)

Eye-safe 3D Imaging Technologies

- Avalanche Photodiode (APD) and PIN Detectors and Arrays
- Eye-safe Pulsed Laser Transmitters
- Rangefinders, 3D Imaging, LADAR, and Electro-Optic Systems
- Readout Integrated Circuits (ROICs)
- Active & Act./Passive Focal Plane Array (FPA)

Voxtel Nano (Eugene, Oregon)

Nanocrystal Printed Imagers and Threat Reporting Sensors

- Nanotechnology Technologies Group
- Nanocrystal VIS-SWIR-Thermal IP Imaging Products
- Analytical Facilities (HRTEM, SIMS, XRD, UPS/XPS)

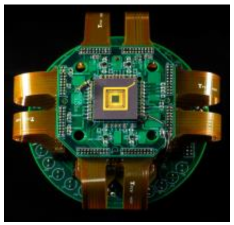
Vadient Optics (Corvallis, Oregon)

3D Freeform GRIN Optics

- Spun out in 2013; Inkjet-printed Solid-Freeform Fabrication of GRIN Optics

Vertically-integrated 3D Imaging

LADAR FPAs & Receivers


LIDAR FPAs


LADAR Receivers

Eye-safe Laser Rangefinders


LRF OEM Module


Eyesafe Rangefinders

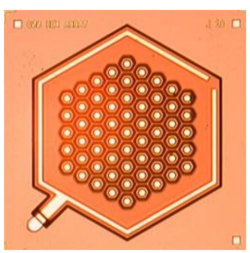
SWIR & MWIR Active/Passive Imaging (See Spot / Time Spot)

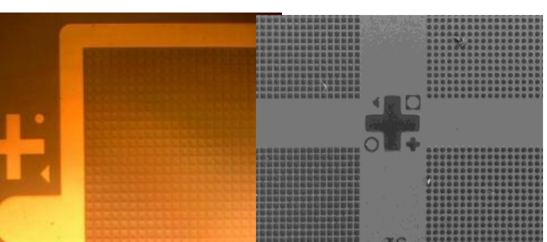

See-spot & Time-spot with Asynchronous Laser TOF and PRF


Transient MWIR Detection & MWIR Passive

Avalanche Photodiodes & APD Detector Arrays


High-gain, Low-noise APDs


InGaAs Photodiode and APD Arrays

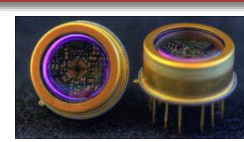

Back-illuminated Mesa Arrays

Eye-safe Lasers


100 µJ 1 mJ 50 kHz, 10 µJ

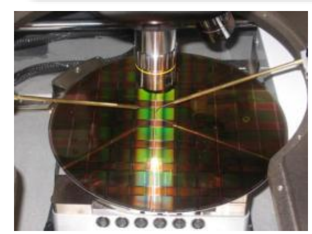
APD Photoreceivers

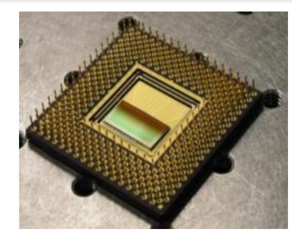

Low-noise MHz-GHz SWIR Receivers

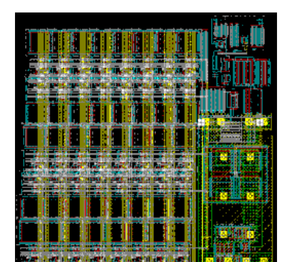

LRF rRceivers

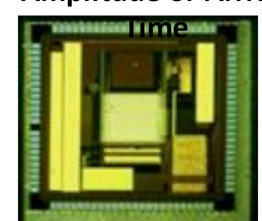

APD Receiver Modules

Readout Integrated Circuits & Monolithic Imagers


3D Wafer Stacked Imagers


Sparsified, Event-driven Amplitude or Arrival Time


Waveform Sampling (1 ns time slices)


Asynchronous Event-driven Photon Counter with Time Stamping

Mobile LADAR 3D Tool for Civil, Construction, and Building Management

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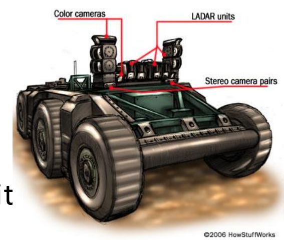
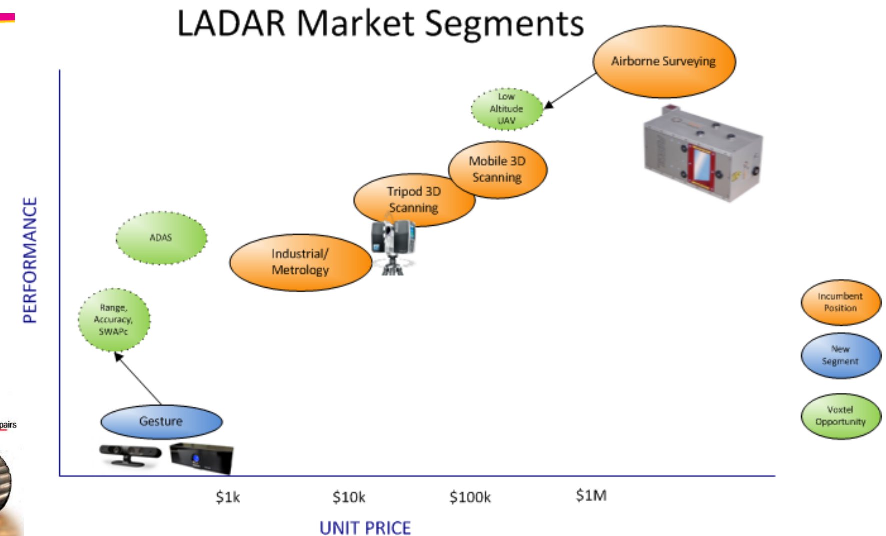
Problem

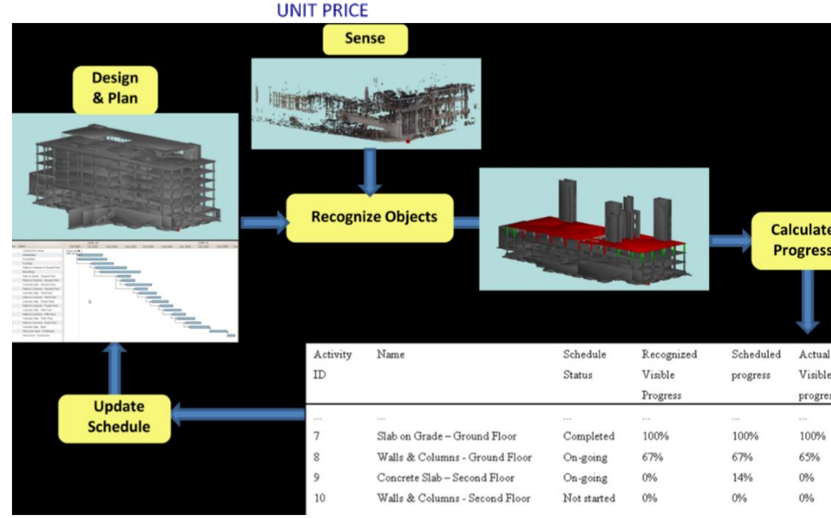
- $100M construction job, between $0.5M and $1M spent on track of tens thousands of things on site
- Approximately 2% costs devoted to manually intensive quality control and inventory management
- One of the challenging tracking tasks is the determination of geometry changes
- The tracking of amorphous data is important: excavation, spoil pipes, concrete placement, etc
- Also need to capture as-built conditions and clarify complex operations
- Mechanical, Electrical and Plumbing (MEP) monit is resource intensive
- low resolution scanning equipment do not support sufficient imaging of small details, (e.g., anchor bolts)
- Design-construct-BIM integration not established
- Automation and robotic need to be established



Solution

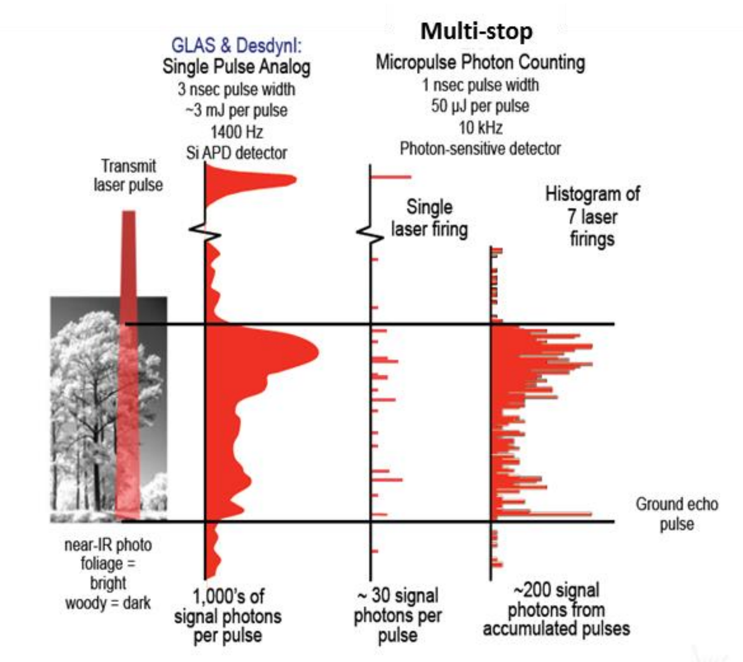
- A low cost, compact mobile laser 3D imaging system that can image a construction area in "real-time".
- wirelessly transfer range data from the field to a remote office.
- Link the rangefinder to GPS position and attitude measurement systems so that the range data can be registered to a known reference frame.
- Develop a user interface to: (a) automatically operate the scanner. (b) display the 3-D data. (c) determine cut/fill requirements

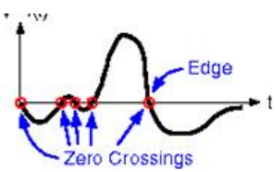


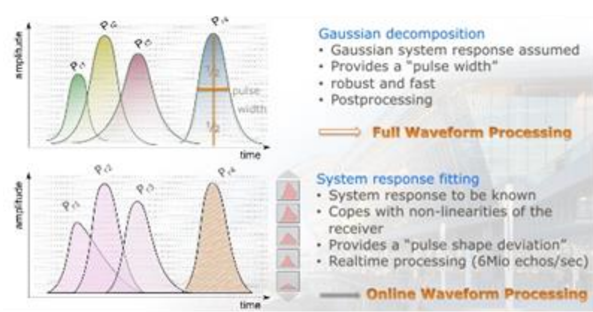


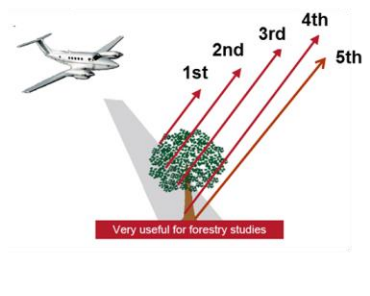
Activity ID	Name	Schedule Status	Recognized Visible Progress	Scheduled progress	Actual Visible progress
...	...	...	...	...	...
7	Slab on Grade – Ground Floor	Completed	100%	100%	100%
8	Walls & Columns - Ground Floor	On-going	67%	67%	65%
9	Concrete Slab – Second Floor	On-going	0%	14%	0%
10	Walls & Columns - Second Floor	Not started	0%	0%	0%

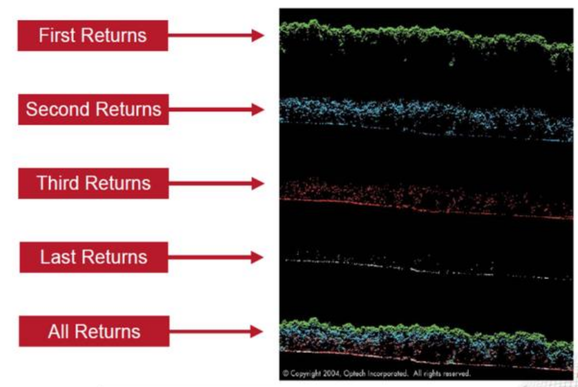
Analog Full-waveform, Sampled, and Photon Counting Time of Flight (tof) LADAR Operating Modes

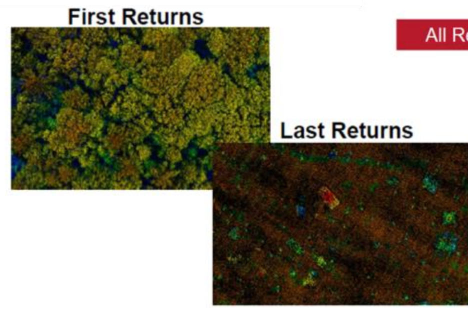


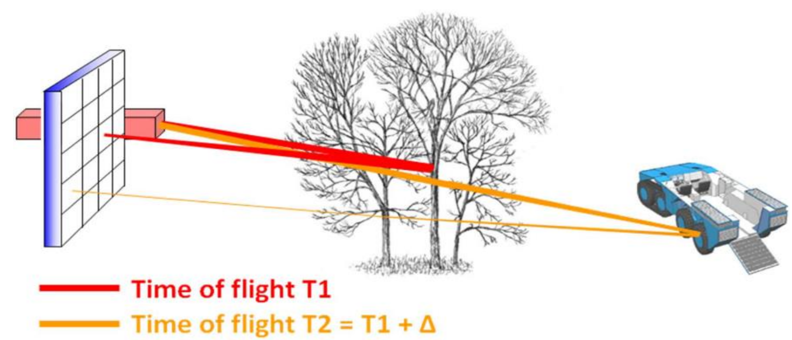












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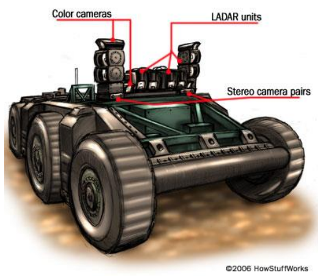
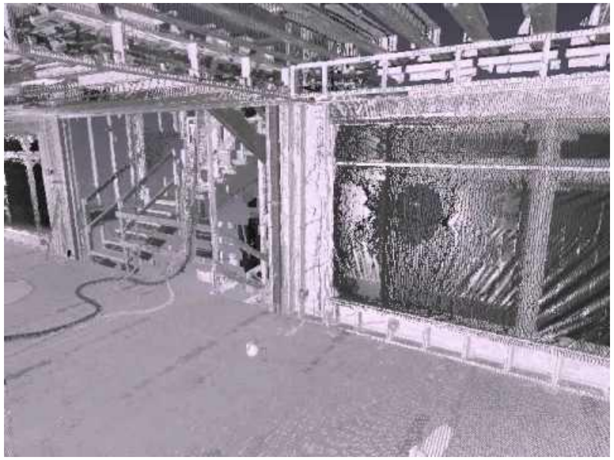
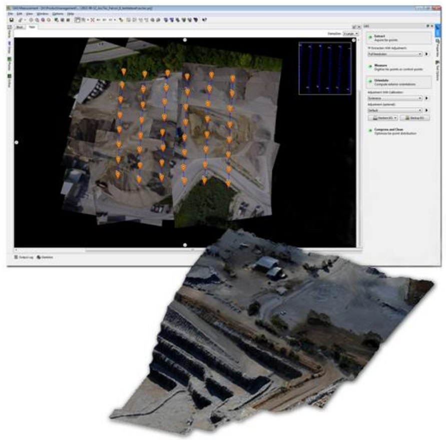
UV-Based LADAR 3/4D Imaging for Building and Construction Management

LIDAR	
Scanning principle	Vertically rotating mirror w/MEMS scanner
Range principle	Ultra-high speed time-of-flight
Scanning Speed	1 million pts/sec
Maximum range	450 m
Range noise	<1 – 2 mm
Range measurement	
Laser class	1, eye safe in accordance with IEC EN60825-1
Laser wavelength	1.535 µm, invisible
Laser beam diameter.	6–10–34 mm @ 10–30–100m
Minimum range	1 km m on reflectivity, 300 m on very low reflectivity (5%)
Range noise. . ,	<(1) 2 mm from 2 m- 120 m on 18–90% reflectivity
Range systematic error..	<2 mm
Scanning	
Field of view..	30°x 7°
Angular accuracy.	.80 µrad
Environmental	
Temperature	
Operating	–20 °C to +50 °C (–4 °F to +122 °F)
Storage	.–40 °C to +70 °C (–40 °F to +158 °F)
Operating humidity .	100% condensing
Dust and water protection.	. . .IP54
Shock:Non-operating drop test.	.Survive 2 m (6.6 ft)
Visible Camera	
Lens type. . .	.f-theta
Angle per pixel.	0.39 mrad/Pix (1.33 arcmin/Pix)
Focal length	3.63 mm (0.14 in)
Depth of field.	0.1 to ∞ m
Calibration of Camera.	better than 1 Pix







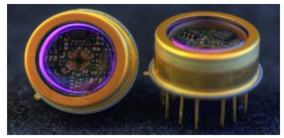
ROX™ Miniature Laser Rangefinder
w/ 9-axis IMU for Georeferenced Range Vectors & Ballistics Computing

Eye-safe APD LRF Features

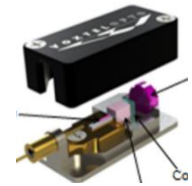
- Smallest fully integrated COTS micro-laser rangefinder available
- 15 mm optic
  - 8x (4 mm) expander for 0.5 mrad divergence
- Temperature-stabilized APD photoreceiver
  - no thermoelectric cooling required
- Eye-safe pulsed laser
  - Diffraction-limited beam delivers photons to target
  - 10 Hz – 200 KHz @ 100 μJ – 10 uJ
- Simple USB interface with Bluetooth option
- Visible (640 nm) boresight laser
- Rechargeable LIPO battery
- Multi-pulse (10) accumulation
- Waterproof IP65

Eyesafe APD Performance

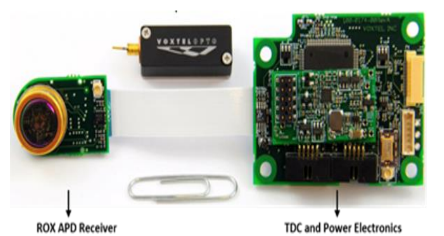
- 0.6 nW NEP / 3 nW Sensitivity
- 3 km range performance (15 mm option) / 8 km (25 mm optic)
- < 100 mm range precision
- < 0.75 mrad beam divergence (5x beam expander)
- 1 M shot lifetime
- 45 gram weight
- 1.7 W / 80 mW power
- 200K shots per battery charge



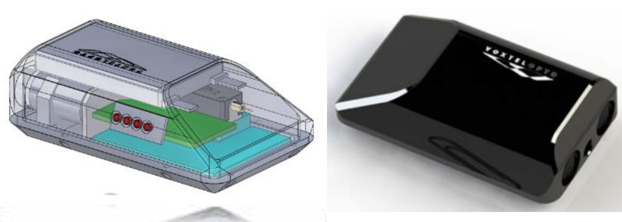
APD Receiver



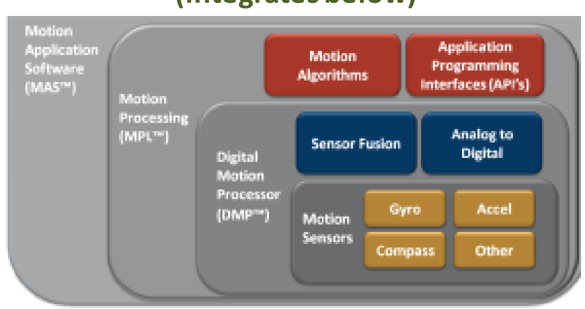
Er:glass Laser



OEM Module



ROX™ Laser Rangefinder (integrates below)



9-axis IMU

Avalanche Photodiode Receiver (Rx)

- Low-noise ASIC
- Low-noise APD with 10x better sensitivity than PIN detector
  - Enables 10x lower laser power and commensurate SWAP-C reduction
- No thermoelectric cooler → temp-compensated gain
- Integrated microcontroller provides flexible control and biasing
- Factory calibration over -45°C to +80°C operation stored in each receiver

Micro-miniature Passive Q-switch Er-doped Transmitter (Tx)

- 100 – 300 μJ pulse energy achieves 10 km ranging
- 10 Hz to 20 kHz pulse rates for multi-pulse and stabilized pointing
- Excellent beam quality ($M^2 = 1.1$) extends range operation
- Enhanced reliability over mJ-class lasers
- Highly reliable passive Q-switch, self-aligned design is low cost

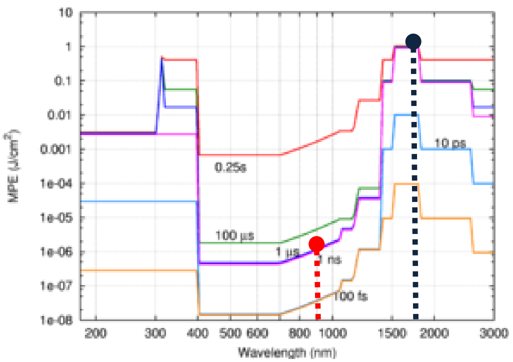
Laser Rangefinder (LRF) OEM Module

- Integrated laser driver, temperature compensation, multi-pulse accumulation, and range-walk (time-over-threshold, TOT) calibration
- Serial I/O
- Onboard storage of operating modes
- On-board 12-bit digitizer
- Designed for integration with rifle scopes and portable electronics

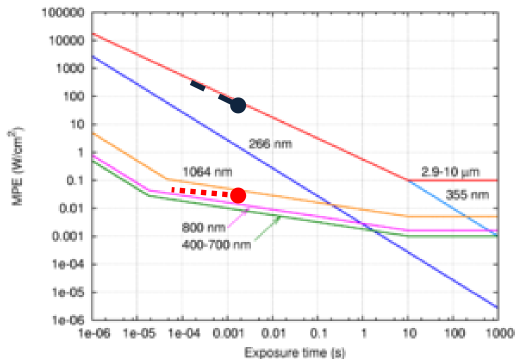
Integrated Commercial LRFs

- Up to 7 km range operation with 25 mm (and smaller) optics
- Less than 100 mm resolution with range walk (TOT)
- Multi-pulse processing for extended range with small apertures

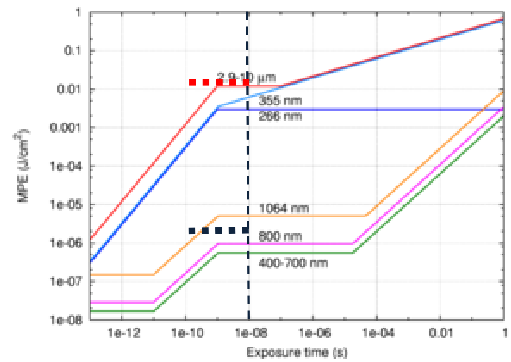
Laser Safety



Maximum permissible exposure (MPE) as power density versus exposure time for various wavelengths



MPE as energy density versus wavelength for various exposure times (pulse durations).

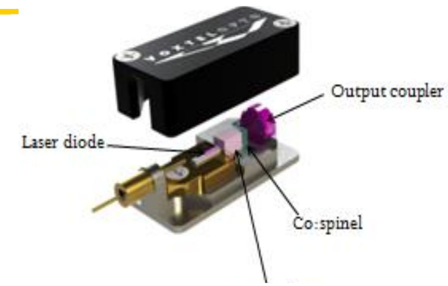


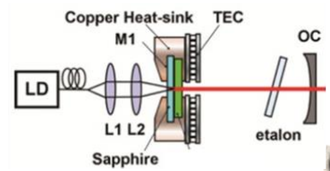
MPE as energy density versus exposure time for various wavelengths.

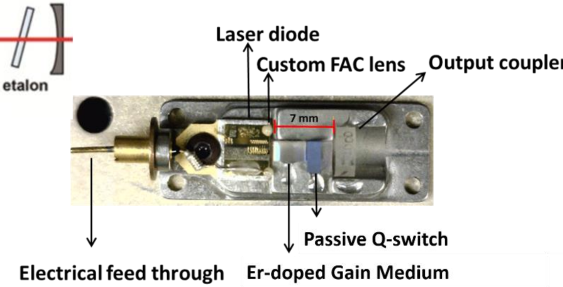
- **Class 1 laser maximum permissible exposure (MPE) per pulse (10 ns) is ~6,000 greater for 1550 nm:**
  - 905 nm: $1.37*10^{11}$ photons/mm^2
  - 1550 nm: $7.8*10^{14}$ photons/mm^2
- **allowing eyesafe lasers to be used with:**
  - smaller sized collimating and collection optic
  - arrays
  - full waveform returns
- **Range is roughly proportional to R^2 so 1550 nm eyesafe operation can**
  - range 77x times further, and
  - scatters less in aerosols and rain

ROX Tx: Ultra-miniature Er-doped Solid-state Laser

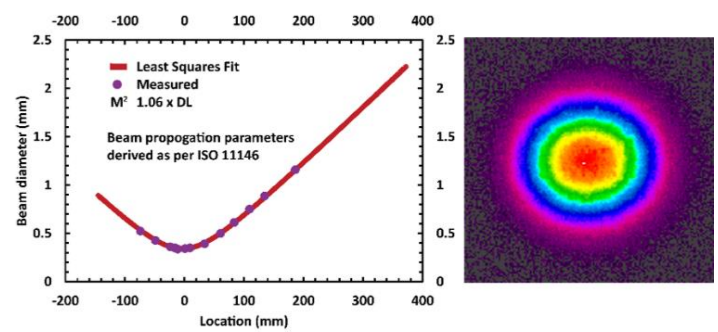
Eye-safe	Class 1 (1535 nm)
Laser pulse energy	10 – 200 µJ
Short pulses	3.8 ns FWHM
Low beam divergence (0.25 mrad with	4 mrad 12x expander)
Beam quality	1.06 x DL
Pulse averaging	1 – 50 KHz
Manufacturable, low-cost solid-state	
Domestic component sources	







10-200 µJ (1 mJ) Er:Ceramic Laser



Measured M^2 = 1.06*DL Data

Replaces expensive, large size, weight, power, and lower peak power fiber lasers (3 uJ, < 6 kW pp) – & – 100 nJ laser diodes

Ultra-compact, high rate micro-chip laser

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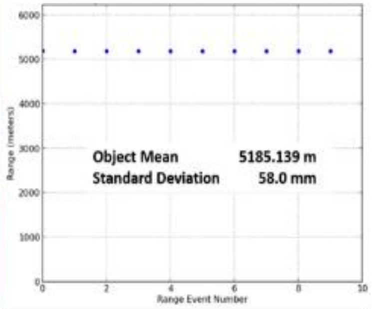
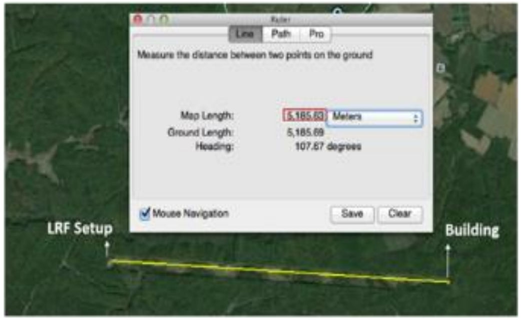
ROX^{TM} LRF Range Performance

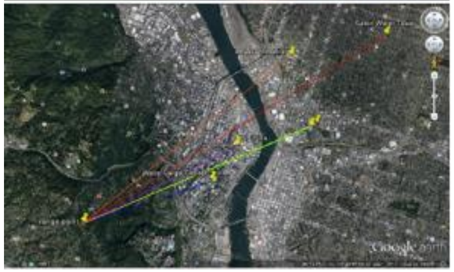
	WF Ctr	Big Pink	Lloyd Bldg. 1	Lloyd Bldg. 2	Legacy Bldg.	Sabin WT
LRF Dist (m)	2802	3625	5287	5413	5891	7901
Std Dev (m)	0.07	0.10	0.22	0.14	0.14	0.21
Rtrn Rt (%)	100	100	100	90	100	50
Thrsld (V)	0.53	0.53	0.52	0.52	0.519	0.518
Ggle Erth Dist (km)	2.81	3.62	5.28	5.41	5.88	7.89

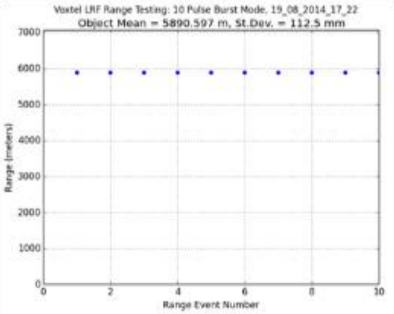
Ranges out to 8 km with 25 mm optic



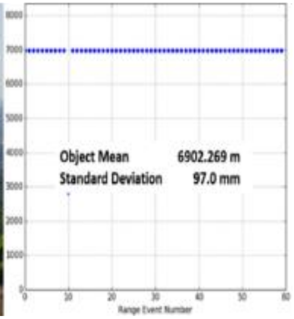


Ranging back toward building at AP Hill at 5185 meters (σ = 58.0 mm)



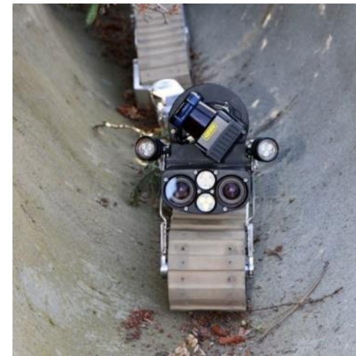


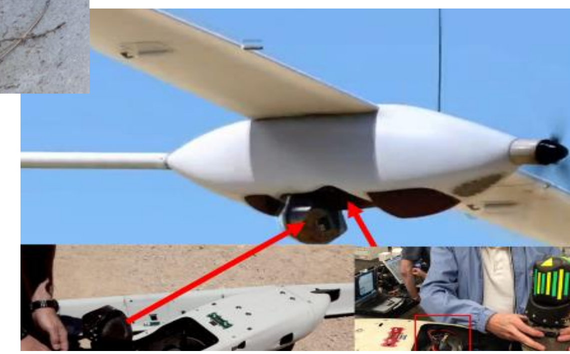
Ranging from Portland, Oregon, West Hills, at targets of opportunity (rooftops) in the North Willamette Valley, at almost 7 km range.

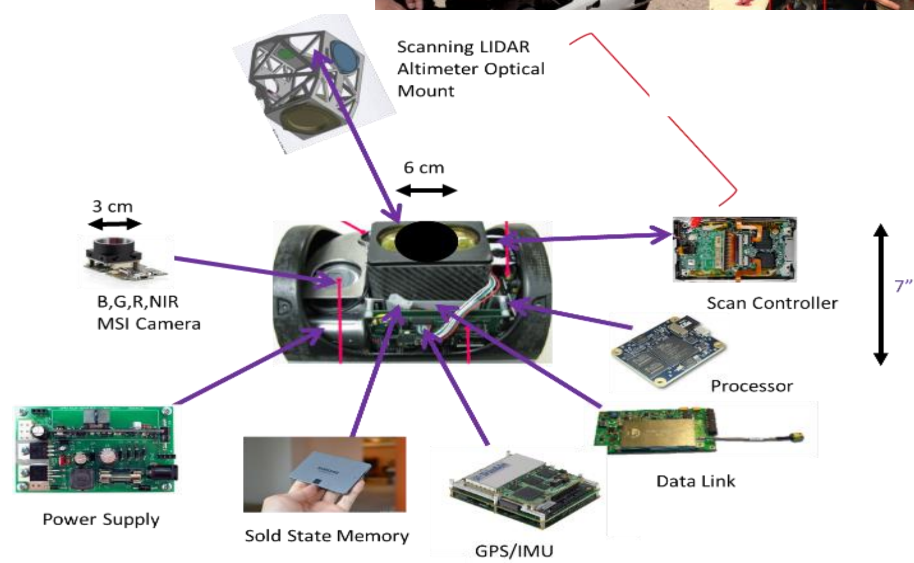


UAV/UGV 3D Imaging LADAR System

- Ultra-miniature custom-designed, dual-wavelength (1550 nm) diode-pumped solid-state microchip laser
- Compact afocal achromatic optical system
- achromatic holographic optical element (HOE) scanner
- High-gain, low-excess-noise APD array for each channel
- 1.6 GHz full-waveform digitization with leading edge time-to-digital (TDC) conversion
- Real-time waveform processing using a Xilinx Zynq-based processing system
- Real-time geo-registration and uncertainly modeling using GPS/INU data with 9-axis IMI
- Boresighted stereo cameras with depth processing
- Over 1 TB of local solid-state memory
- RF communications link
- Robust, modular design,







Fusion of Multiple Sensor Modalities

Photogrammetry (3D imagery) alone is not enough…

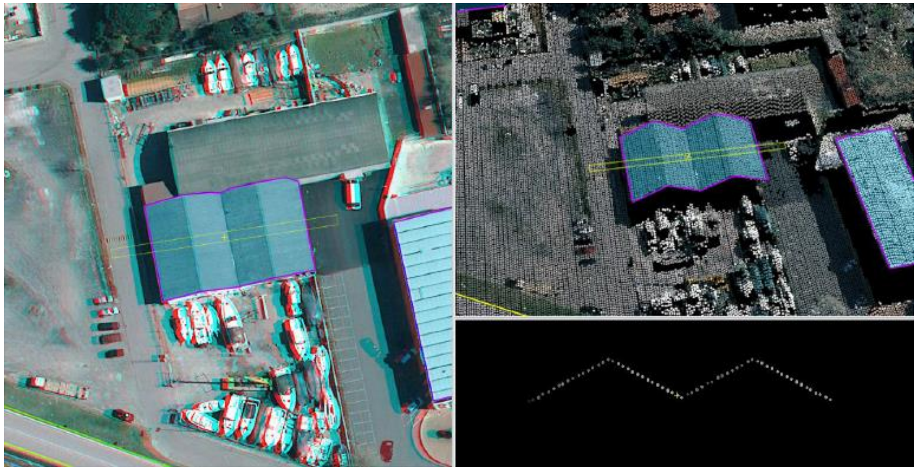
- Optimal photointerpretation (image data is continuous)
  - Use of RGB, CIR images with 8+ bit per channel
  - Already experienced operators, well known procedures and system
- New digital cameras have bad B/H ratio so Z quality is poor (respect to the LiDAR data at the same flight height)
- Data quality is not geometrically constant (Z in particular) because depends on the operator (stereoscopic perception)
- Image correlation often have problems exactly where we need (for ex. roof edges)

LiDAR alone is not enough…

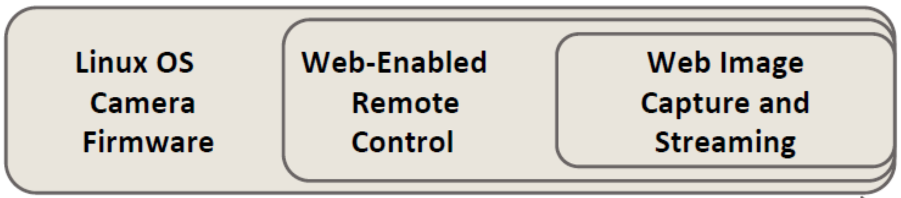
- Optimal precision (especially Z) respect to the photogrammetry at the same flight height
- Possibility to classify the points cloud
- Data quality is geometrically constant (Z in particular) because does not depend on the operator (snap)
- Data have low costs and short acquisition times
- Interpretation is very poor because the data is discrete
- **Point density impacts a lot on cost**
- The points don't have directly the color of the objects
- XY precision is poorer than Z

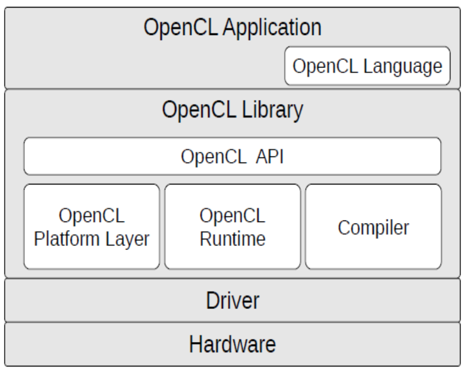
Combine stereo images and LiDAR point clouds to obtain the best accuracy and efficiency

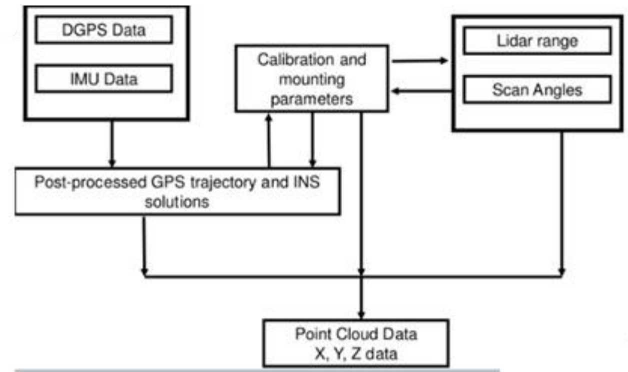
- Stereo imagery are used for XY and photointerpretation
- LiDAR point clouds are used for updating collimation mark height (Z)
- use camera image sequences (video) to quickly navigate…
- Use the point cloud for the 3D precise measure task
- Use the images to recognize objects

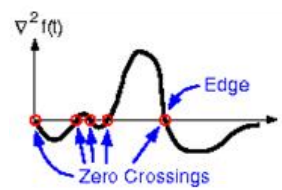


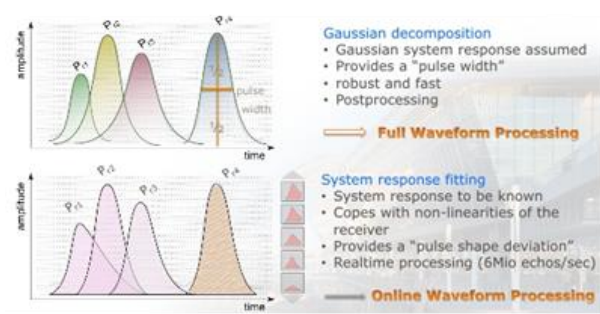
Voxtel LADAR Local Processing Environment

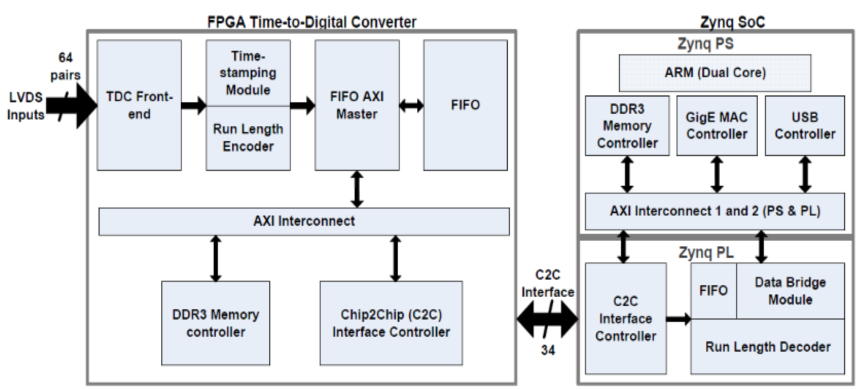


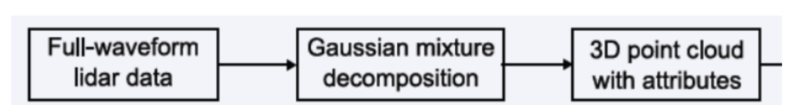










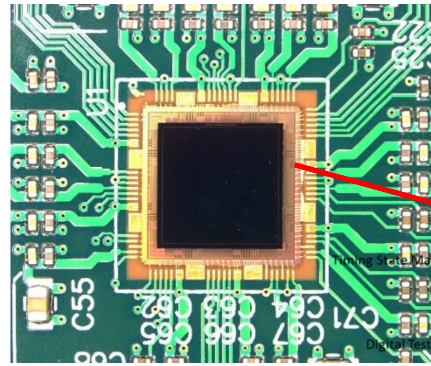


2D Full-waveform Sampling 3D LIDAR

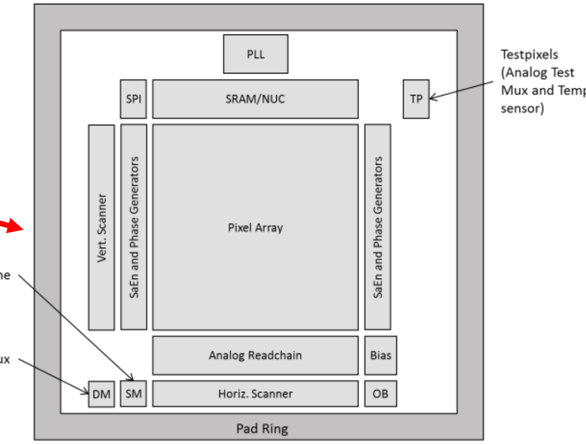
VOXTELOPTO

Parameter	Specification
Pixel pitch (µm)	50
Resolution (X by Y pixels)	128 x 128
Windowing resolution (pixels)	16 x 16
Return samples (per pixel)	24 (circular)
Program sample time (ns)	2 – 16
Sample jitter (ps RMS)	< 100
Receiver bandwidth (MHz)	100
Frame rate (Hz)	94
Output data rate (MHz)	20
Analog output ports	2
Input noise (nA RMS)	6.0
Linear dynamic range (bits)	8.1
Compressed DR (bits)	9.3
Saturated dynamic range (bits)	> 16.0
Detector bias range (V)	0.6 @ 6 bits
AFE peak transimpedance (kΩ)	501
ROIC area (mm)	15.2 x 16.4
Operating temperature (K)	230
Power consumption (mW)	< 250
Instantaneous current (A)	< 30.0

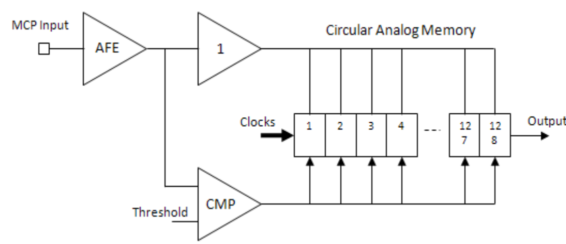
Specification



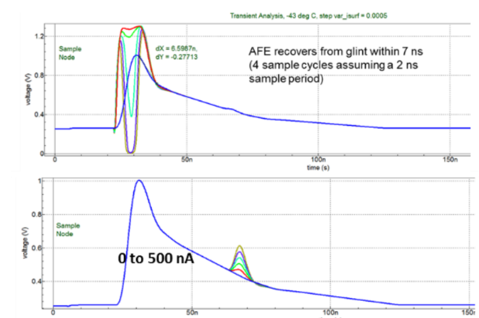
8.91 x 8.91 mm FPA



FPA Architecture



Pixel Schematic

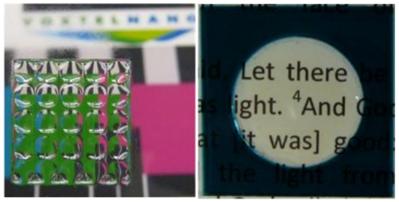


Simulation Surface Targets

- **Accommodates large surface glints**
  - Recovers within < 6 ns from large signals
- **High sensitivity to submerged targets**
  - Detects target shadows
- **Exceeds current capabilities of streak tubes**
- **All solid-state, domestically fabricated**

VIRGO 3D Freeform GRIN Optics

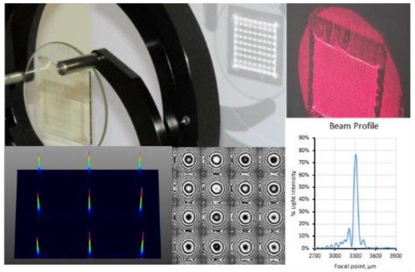
- Nanocomposite inks engineered with desired refractive index and chromatic dispersion properties:
- Drop-on-demand inkjet print (IJP) fabrication with sub-micron alignment used to fabricate 3d freeform gradient index (GRIN) lenses
- Cured optics implement complex 3D freeform optical functions, which “sculpt” light waves
  - Corrects for geometric aberrations
  - Corrects for chromatic aberrations
- Surface shaping provides additional power and degree of freedom
- Numeric Optics Solver used to accommodate 3D freeform optimization of multi-objective lens designs



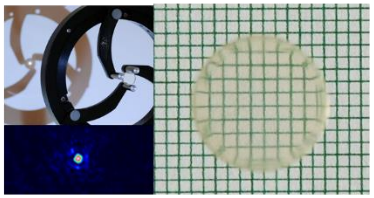
Flat Lenses including baffles and stops

LA1301 lens: without compensation (left); with phase corrector plate (center); and with phase corrector plate and 1.5 mm offset (right).

4” phase corrector plate on an optic flat



Planar 57 x 57 385 µm (top) and 9 x 9 3 mm (bottom) lenslet arrays w/diffraction limited optic performance



13 mm φ x 2.4 mm lens, 50 µm focal point, 126 mm fL, f10

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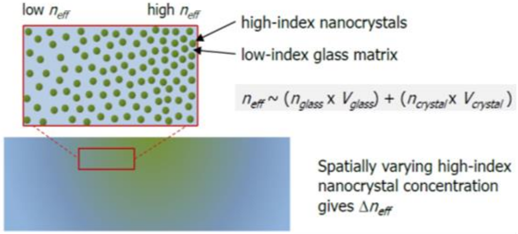
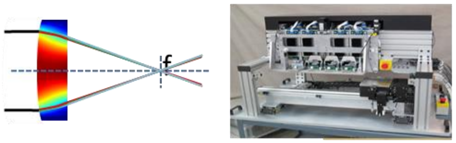
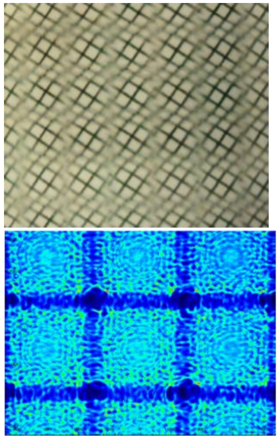
Low-cost Inkjet Print Fabrication



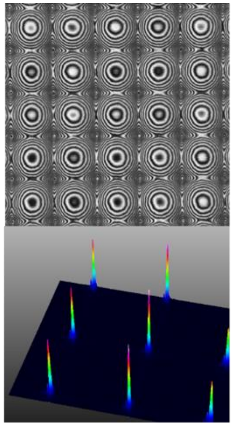
Non-scattering, well-dispersed nanofiller concentrations create index gradients



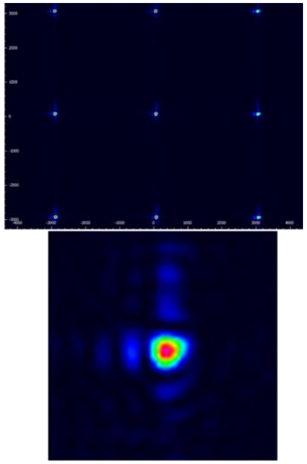
3D GRIN profiles fabricated using inkjet printing



Top: Image through Wood lenslet array BOTTOM: near field image of LED light through lens



TOP: Inteferogram of flat lenslet array showing nanofiller concentration (optical index) gradients; BOTTOM: point spread function map



Point Spread Functions measured on lenslet array

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VIRGO Offers Diffraction-limited Performance