Evaluation of Current and Upcoming LIDAR Systems

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Lee Hathcock, Mississippi State University, Geosystems Research Institute

Explanation of LIDAR

LIDAR is short for LIght Detection And Ranging. The purpose of LIDAR is to detect elevation changes by sending out pulses of light and measuring the time it takes for the pulse to return to the sensor. The return pulse's time indicates the distance to the target.

Most current LIDAR sensors primarily use a rotating mirror setup. The entire device spins at a set rate, and emits laser pulses as well as detects them while spinning. This spin rate can generally be set by the user. Typically, the faster the spin rate, the shorter the range at which objects can be detected. This means that to increase range, the point cloud density is decreased, and vice versa.

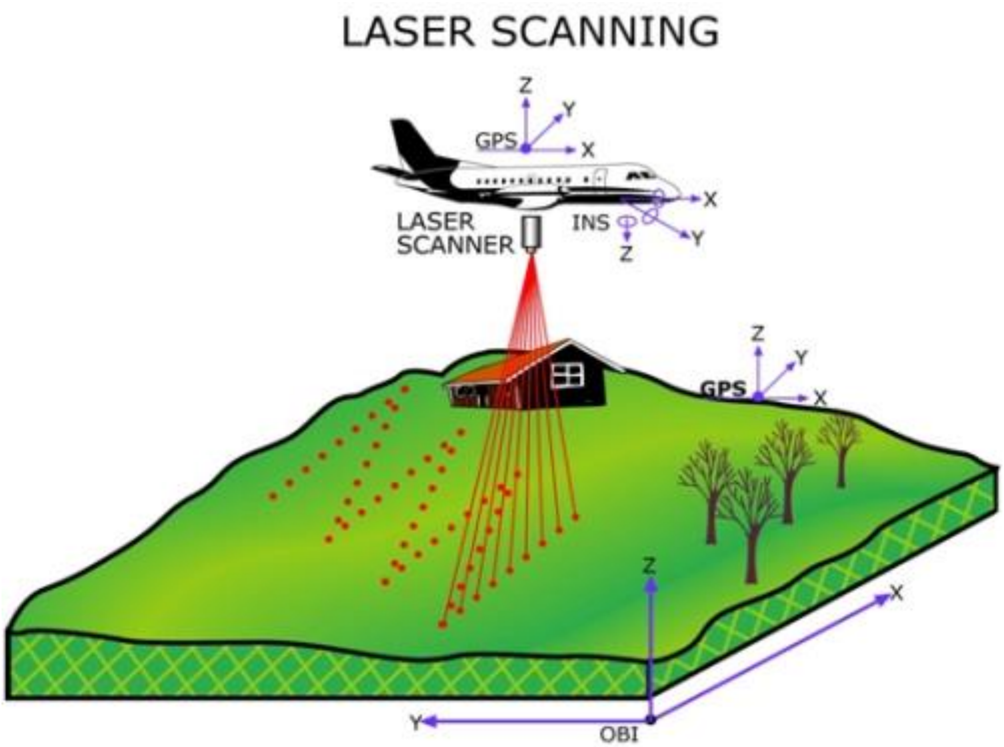


Figure 1: Laser Scanning with LIDAR

http://www.xp-detectors.co.uk/wp-content/uploads/2015/10/lidar-1.jpg

LIDAR generates what is known as a "point cloud", a collection of individual returns that collectively give elevation data over an area. These point clouds typically need robust filtering, either from the sensor itself, or through post-processing, to remove erroneous data points.

In LIDAR, pulses can often generate more than one return per pulse. Depending on the LIDAR system in use, these can be utilized or ignored. Being able to process multiple returns can be very useful, however. When measuring in an area with trees, for example, the first return may reflect off the canopy, whereas some of the return may travel further down, potentially all the way to the ground. This is extremely useful in cases where bare-earth measurements are desired. It should also be noted that there are generally enough gaps in tree cover that the laser pulses can slip through cracks to the ground and return. Many small UAS LIDAR are at least dual-return; the strongest (generally the first return) and the last (generally the weakest, or the one that traveled the furthest). This would fit with the example above of reflecting off the canopy, and then penetrating to the earth below.

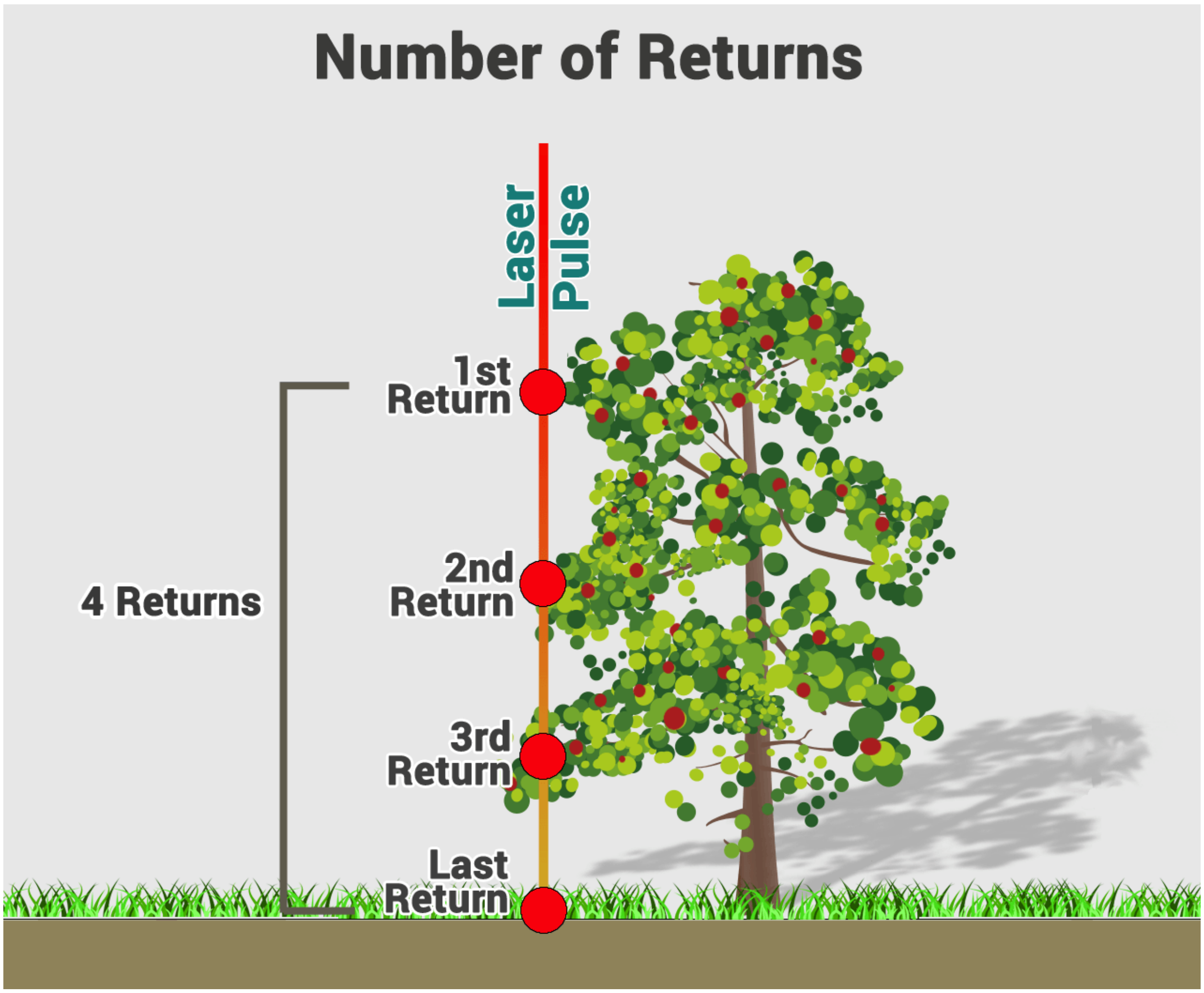


Figure 2: Multiple LIDAR Returns

http://i0.wp.com/gisgeography.com/wp-content/uploads/2015/08/Number-Returns.png

One source of error that can arise are multi-path errors. In this case, light takes an indirect path back to the sensor, as opposed to a direct reflection. This can be difficult to differentiate from multiple returns.

In the image below, the blue circle is the sensor point. The solid red lines are the emitted laser pulse and return, both of which are correct. These will generate a point at the green oval on the object. However, there is also a portion of the signal that is reflected from the object that hits the ground, and then returns to the sensor, as denoted by the dashed red line. Since it took longer for the pulse to return along this path, an additional, incorrect point will be produced at the orange oval indicated, parallel to the original pulse emitted. Various algorithms and statistical methods can be applied to reduce the effects of this phenomenon.

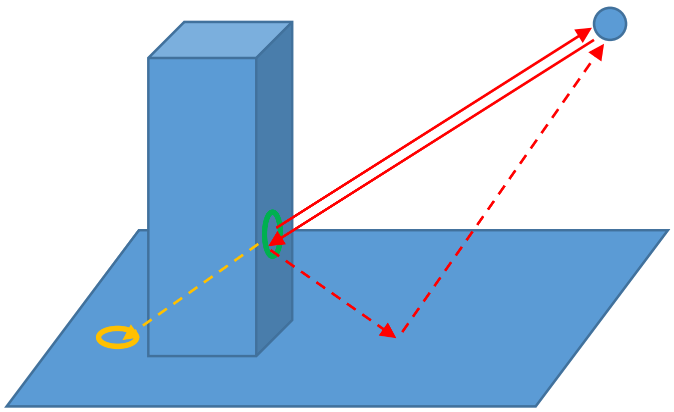


Figure 3: Example of Multipath Returns

Sloped surfaces may also increase error, and changes in the type of terrain cover can also impact the accuracy of LIDAR systems.

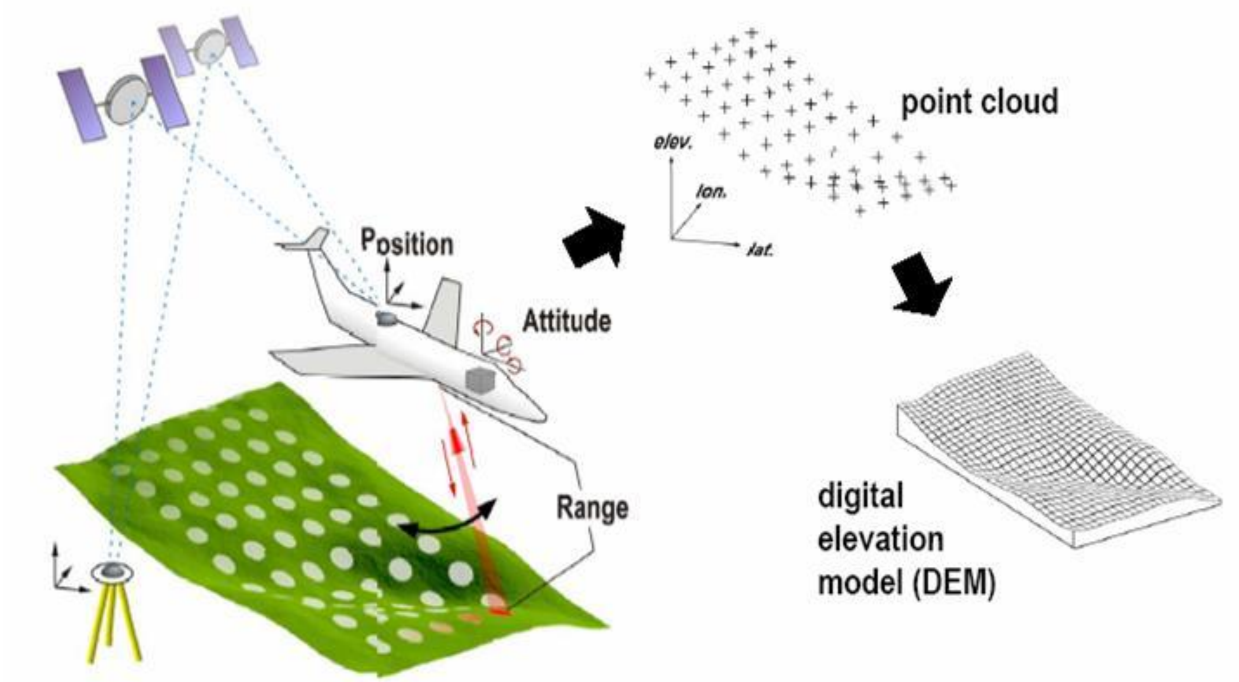


Figure 4: LIDAR Point Clouds to DEM

https://historicmappingcongress.files.wordpress.com/2012/06/lidar.jpg

Once the point filtering has been performed, a digital elevation model (DEM) can be produced from the point cloud. The point cloud is typically irregular in nature, so this step effectively puts the points on a regular grid, and may involve interpolation between data points, depending on the specified data granularity. These products are generally distributed in raster formats.

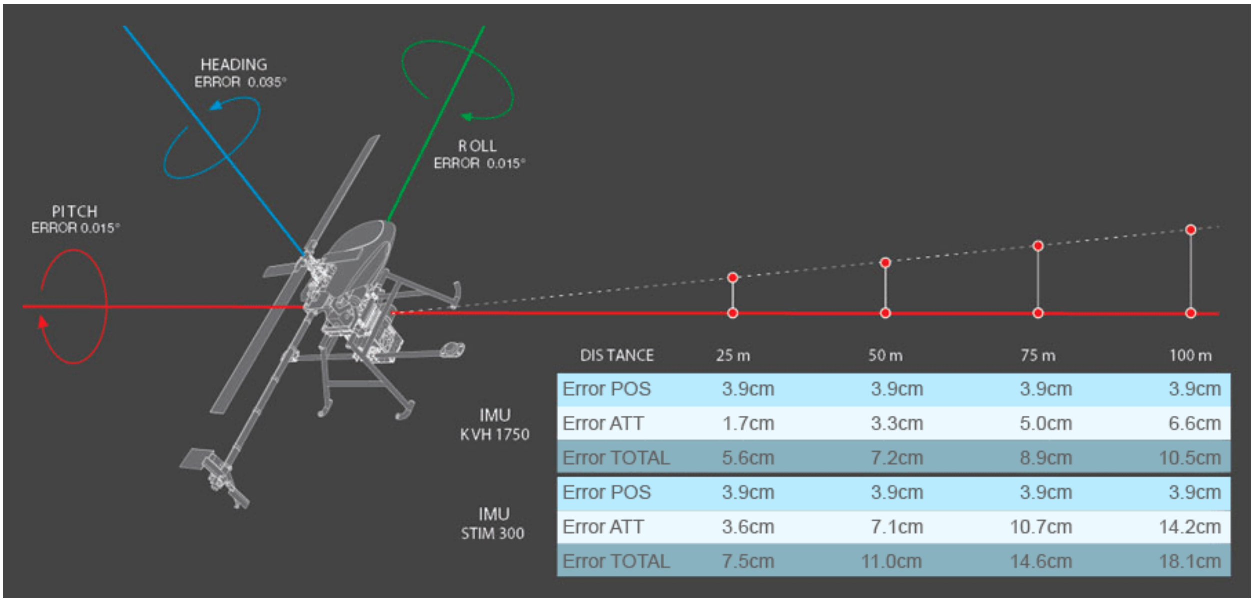
Some LIDAR systems have both a horizontal and vertical field-of-view (FOV). The horizontal FOV is defined as the field-of-view for a single rotation of a rotating-mirror. For example, if the specified horizontal FOV is 330 degrees, then points in 330 degrees of a full circle on a single plane will be returned. Relative to an aircraft, this would be a line of received points perpendicular to the flight path. Vertical FOV is typically achieved by adding more laser/detector pairs. This gives more lines or planes of measurement, each emitting and detecting along the horizontal FOV.

Many of the LIDAR systems surveyed use laser wavelengths around 900 nm, which is in the near-infrared region. Depending on your application, this may not be a good choice for wavelength. Other systems like RIEGL's VUX-1 sensors use 1550 nm, which is in the infrared region. If using LIDAR for coastal applications where water penetration is desired, these wavelengths will be insufficient, as water absorbs a significant portion of signals in this region. Typically, maximum penetration of water is achieved around the green band, so something closer to 550 nm will be more appropriate. Still, even with this adjustment, bathymetry is very challenging with LIDAR, depending very much on the turbidity and clarity of the water. In less than ideal conditions, one could expect to only get 1-2 feet of penetration.

GPS/IMU Solutions

While point clouds can be collected without the use of a GPS or inertial measurement unit (IMU), in UAV applications, georeferenced point clouds are preferred. The accuracy of these points will directly correlate not only to the accuracy of the LIDAR unit itself, but also the accuracy of the GPS and IMU units. If a unit is purchased that does not include a GPS/IMU, work will need to be done to integrate that solution with the sensor. Most LIDAR manufacturers supply complete solutions that include GPS/IMU, and many third-party sellers of integrated systems exist as well.

Note that there are two kinds of accuracy: absolute and relative accuracy. Absolute accuracy is primarily dependent on the accuracy of the GPS solution, and manifests as a shift of the entire point cloud. This is relatively simple to correct, and not as important to evaluate as the relative accuracy. The relative accuracy reflects how accurate each point in the point cloud is relative to each other. Manufacturers' accuracy statement usually reflects relative accuracy, although some like RIEGL also give absolute accuracy (they use the terms "accuracy" and "precision"). [1]



IMU	DISTANCE	25 m	50 m	75 m	100 m
IMU KVH 1750	Error POS	3.9cm	3.9cm	3.9cm	3.9cm
	Error ATT	1.7cm	3.3cm	5.0cm	6.6cm
	Error TOTAL	5.6cm	7.2cm	8.9cm	10.5cm
IMU STIM 300	Error POS	3.9cm	3.9cm	3.9cm	3.9cm
	Error ATT	3.6cm	7.1cm	10.7cm	14.2cm
	Error TOTAL	7.5cm	11.0cm	14.6cm	18.1cm

Figure 5: GPS/IMU Accuracy Error

http://www.phoenix-aerial.com/files/9914/4503/6846/accuracy.gif

In this example from Phoenix Aerial, the error is shown in their IMUs as well as the entire system (LIDAR error). As can be observed, the error very quickly comes from the IMU unit, and increases as range increases.

There is also the issue of optimal GPS/IMU setup in a LIDAR system. There are several different ways to achieve the issue of orientation:

- Use three GNSS antennas. Very complex and heavy.
- Use a medium-grade IMU with a single GNSS antenna. Must use motion to obtain heading. Sensitive to vibration and flight lines must be very straight.
- Use a high-grade IMU and keep the system static when initializing. This isn't always an option depending on operating environment.
- Use an IMU coupled with two GNSS antennas. Allows solid reading of heading from the two antennas, and is more robust.

Phoenix Aerial Systems recommends the last option for reliability. The other options can be cheaper, however, and may be sufficient depending on the accuracy required. [2]

Much like any other system, as the capability and accuracy of the system increases, so too does the cost of the system. IMUs, in particular, need to be very accurate for LIDAR surveying.

Along with this, there are typically two different options for IMUs available: micro electro-mechanical systems (MEMS) and fiber-optic gyroscope (FOG). The former is lighter and uses less energy, but comes at a cost of accuracy. The latter is very accurate, but is also heavy and consumes much more power than a MEMS system. This is an important choice depending on the UAV platform and accuracy requirements.

Currently Available Sensors

The most popular sensors on the market now for small UAS purposes are manufactured by RIEGL and Velodyne. In particular, Velodyne has some of the lightest LIDAR currently on the market. There are other options, however, and they will be covered briefly. Note that both RIEGL and Velodyne have more capable LIDAR systems available, but they are significantly heavier and consume more power, making them unusable for small UAS (less than 55 lbs.) purposes.

Note that there are other LIDAR systems available, but typically have not been integrated with a GPS/IMU. These would still be usable for UAV work provided the setup provides the required range, accuracy, weight, and power requirements. One example is the solid-state LIDAR system from Leddar like the LeddarVu or Leddar16 sensors.

Velodyne LIDAR Systems

Velodyne has two major core systems on the market for the small UAS market: The HDL-32E and the VLP-16, which has three variants of its own. While their HDL-64E could technically be carried aboard a large UAV (like RIEGL's RiCOPTER), it is heavy enough (13 kg) to not warrant serious consideration based on size and capability compared to RIEGL's options. It is more built for autonomous ground vehicles than aerial platforms.

Velodyne HDL-32E

The Velodyne HDL-32E is the larger of the two Velodyne small UAS sensors. It doubles the number of returns of its smaller brother, the VLP-16, having 32 laser/detector pairs. It also has slightly better accuracy, at the expense of a bit more weight and energy consumption. [3]

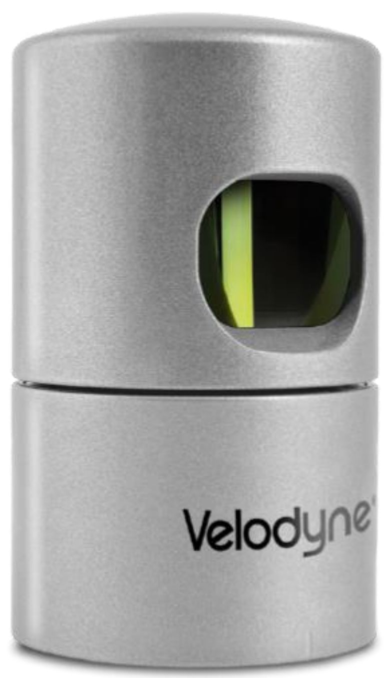


Figure 6: Velodyne HDL-32E

http://velodynelidar.com/images/products/hdl-32e/HDL32_TopImage.png

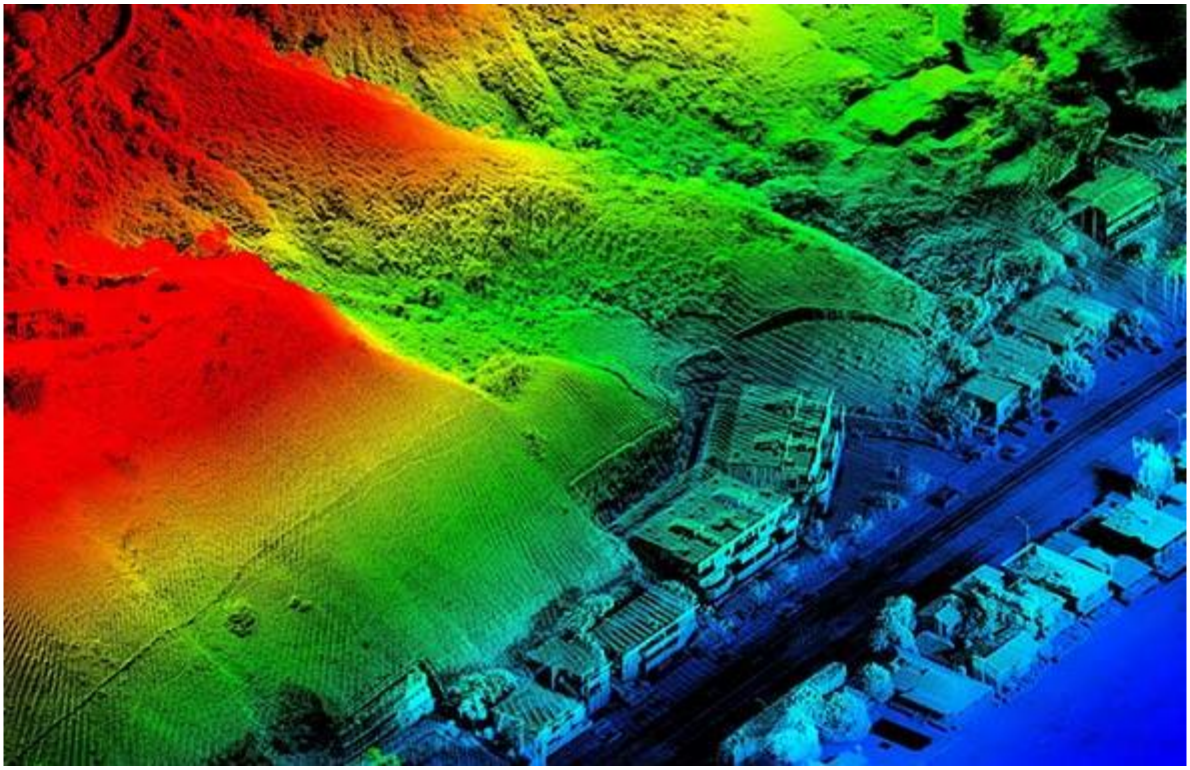


Figure 7: Sample Velodyne LIDAR Data

http://www.phoenix-aerial.com/files/4714/2783/8079/homepage_banner2.jpg

Velodyne Puck

There are three different variants of the Puck sensor (or VLP-16). The original Puck, the Lite, and the Hi-Res. The difference between each model is weight (the Lite) and the vertical FOV (Hi-Res) versus the original model. All else is unchanged. Pricing as of 9/28/16 is $7999.

The primary difference between this model and the HDL-32E is less laser/detector pairs (16 vs. 32), 50% less accuracy (+/- 3 cm vs. +/- 2 cm), but less weight (nearly half for the Puck Lite) and less power consumption (8W vs 12W). [4]

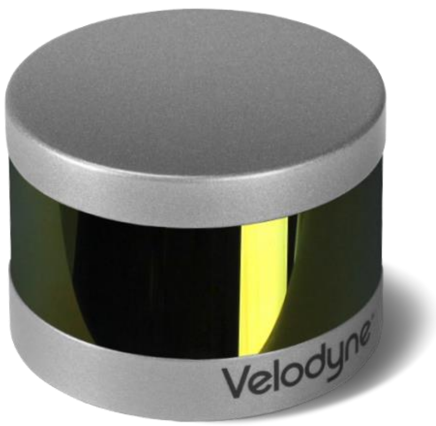


Figure 8: Velodyne VLP-16 Puck

http://velodynelidar.com/images/products/vlp-16/puck.png

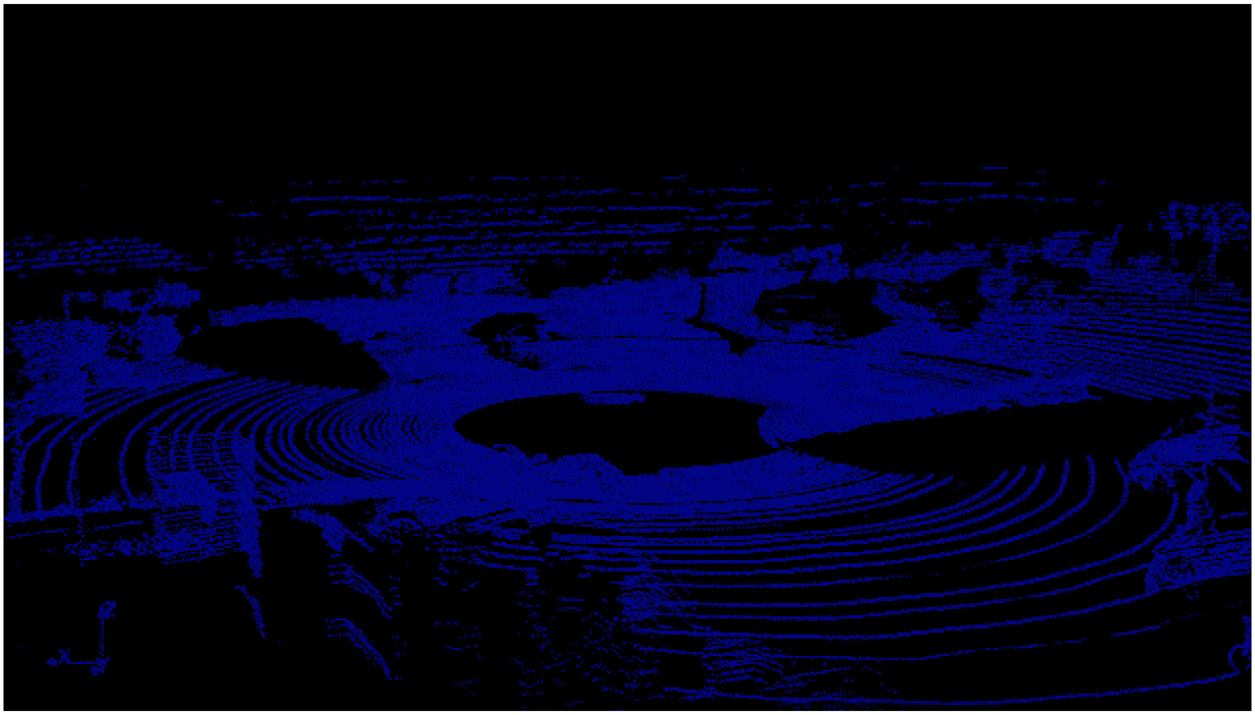


Figure 9: Sample VLP-16 Point Cloud

http://velodynelidar.com/images/products/vlp-16/data.gif

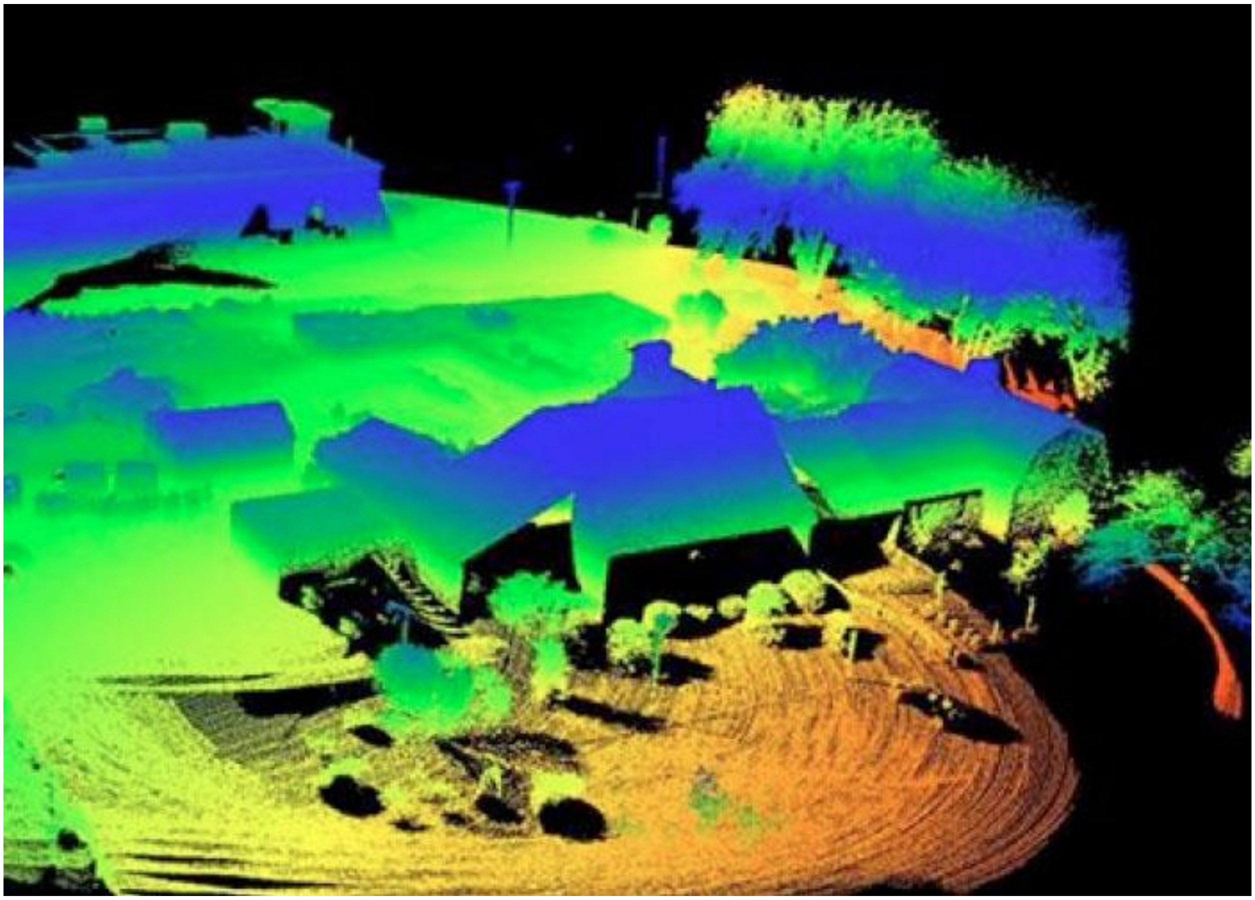


Figure 10: Sample Velodyne User Data (XactSense)

http://velodynelidar.com/images/products/vlp-16/UserData_XactSense_Large.jpg

Velodyne Puck Lite

Functionally, this is identical to the Puck. The weight is the only difference, being lightened to 590g from 830g. [5]

Velodyne Puck Hi-Res

Functionally, this is identical to the Puck in all but vertical FOV. It has been reduced from 30-degrees to 20-degrees. This increases the vertical resolution in returns. [6]

RIEGL LIDAR Systems

RIEGL VUX-1 Series

RIEGL produces the VUX-1 LIDAR system, a significantly lighter sensor than RIEGL's VQ-480-U, but still very heavy compared to the other sensors surveyed. It weighs in at 3.5kg without the cooling fan, and 3.75kg with. This cooling fan is necessary if air convection around the sensor does not exceed 5 m/s in temperatures above 15-degrees Celsius.

The maximum range listed for this sensor varies with the sampling rate. The lower the sampling rate, the longer the range, but this also decreases the point cloud density. At the lowest sampling frequency (50,000 samples/second), in "average" weather conditions, with perpendicular angle-of-incidence, a flat target, and atmospheric visibility of 23km, the maximum range to a target with 60% reflectivity is 920m. This number is lowered in bright sunlight, as opposed to overcast conditions. The amount of irradiance for these conditions is not listed.

According to the curves plotted in the datasheet, objects with greater than 80% reflectivity can be detected under the same conditions at a range of approximately 1050m. This would be something like limestone or white plaster work. [7]

An interesting feature of the RIEGL sensor is that the FOV is adjustable. The maximum is 330 degrees, but can be reduced to decrease angular distance between measurements. VUX-1 uses a single laser, so it has no vertical field-of-view.

The VUX-1 supports up to four returns, which gives a more accurate assessment of topography. For small UAS work, if accuracy is the number one goal, the VUX-1 is the best choice for small UAS LIDAR surveying.

Since the LIDAR consists of a spinning part, one issue is that the sensor can emit a laser pulse, and make another complete revolution and emit another pulse before receiving a return associated with the first laser pulse. RIEGL uses a modulation system to sort out which pulses are associated with which revolution of the sensor.

VUX-1 comes in three variants: 1UAV, HA, and LR. The HA is the high-accuracy model, with shorter range, but higher accuracy. The 1UAV is the middle option, with medium accuracy and range compared to the other two. The LR is long-range, sacrificing accuracy (15mm) for range (~1400m). [7] [8] [9]

Figure 11: RIEGL VUX-1 Series LIDAR

http://www.riegl.com/uploads/pics/VUX-1_2016-06-07.jpg

RIEGL VQ-480-U

The largest sensor outlined in this report, the VQ-480-U is a very long range LIDAR system, but also weighs in at 7.5 kg (sensor only), which means that only the largest small UAV platforms will be able to carry the system effectively. The VUX-1 series should be able to accomplish similar tasks while halving the weight. [10]

Figure 12: RIEGL VQ-480-U

http://www.riegl.com/uploads/pics/RIEGL_airborne_laser_scanner_VQ-480-U_01.jpg

Quanergy LIDAR Systems

Quanergy M8-1

The Quanergy M8-1 is a sensor that is somewhat similar to the Velodyne Puck Lite. It has a measurement range of 200m @ 80% reflectivity, eight laser/detector pairs, a 360-degree horizontal and 20-degree vertical field-of-view, and weighs 900g (~2 lbs). Current pricing as of 9/28/16 is $6,100.

The primary tradeoffs here are that the M8 is cheaper than the VLP-16, but consumes more power (18W). In exchange, though, the range is greater (200m vs. 120m to detect an object with 80% reflectance), and the angular resolution is greater than that of the VLP-16. It has less lasers, though, which leads to less vertical resolution. [11]

Figure 13: Quanergy M8-1 LIDAR

http://www.quanergy.com/wp-content/uploads/2014/04/m8-image.jpg

ibeo Automotive LIDAR Systems

ibeo LUX series

The LUX series from ibeo Automotive Systems is a fairly light, but relatively low-accuracy LIDAR compared to the Velodyne system. Phoenix Aerial Systems uses these sensors as part of their setups, however, and they may have a decreased cost associated with them. They do support three returns as opposed to the comparable HDL-32E's two, but the maximum number of point samples the system can handle was not listed in the datasheet. [12]

There are two models of this sensor, both with the same form factor: The LUX-4 and LUX-8. The LUX-8 doubles the field-of-view by doubling the number of lasers, from four to eight.

Figure 14: ibeo Automotive LUX-series LIDAR

http://www.phoenix-aerial.com/files/3414/3164/7979/lidar_ibeo_lux.png

Integrated LIDAR/GPS/IMU Systems

There are also a number of complete systems that can be purchased from various retailers. These include the LIDAR system along with the UAV platform. Some options for these are listed below. Most of the typical options either include a RIEGL or Velodyne LIDAR for the sensor.

RIEGL

RIEGL VUX-SYS

Couples a VUX-1 LIDAR paired with an Applanix AP20 IMU. Available on a complete system with the RIEGL RiCOPTER as detailed later. [13]

XactSense

XactSense SSP-360-16E

A Velodyne VLP-16-based solution, with gimbal, camera, batteries, laptop. Currently $52,449.99 at base price.

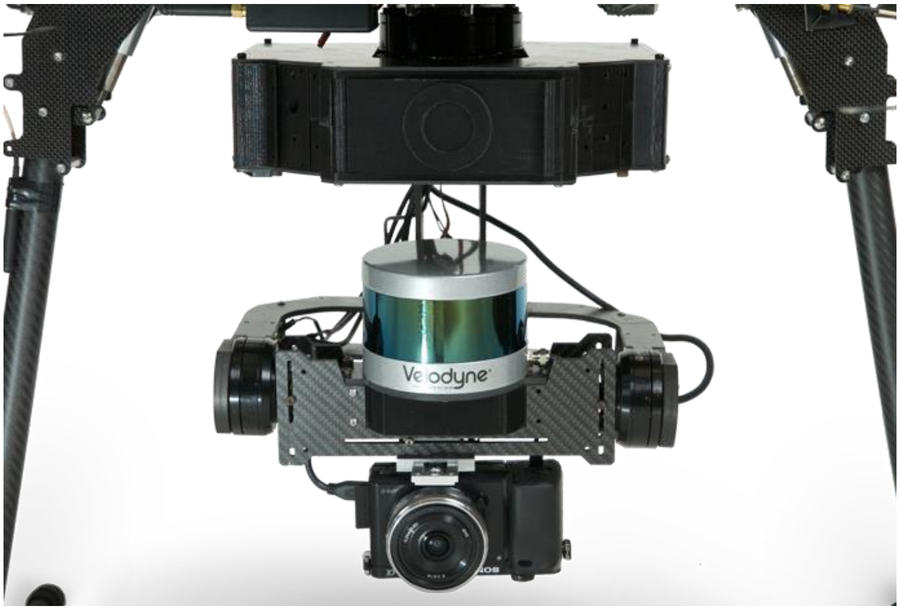


Figure 15: XactSense SSP-360-16E

https://dqzrr9k4bjpzk.cloudfront.net/images/5816035/380835564.jpg

XactSense SSP-360-32E

Similar to the above, but based around the HDL-32E instead. $75,499.99 base price.

Figure 16: XactSense SSP-360-32E

https://dqzrr9k4bjpzk.cloudfront.net/images/5816035/380835568.jpg

YellowScan

YellowScan is a company based out of France. They assemble integrated LIDAR and GPS/IMU solutions.

YellowScan Mapper

While not listed, this integrates an IMU and LIDAR system, at a weight of around 2 kg. Given the choice of a VLP-16 in the Surveyor, the system likely uses a Velodyne HDL-32E for the core.

Figure 17: YellowScan Mapper

http://www.yellowscan.fr/wp-content/uploads/yellowscan-mapper-sensor.png

YellowScan Surveyor

An integrated Applanix APX15 IMU with a VLP-16 core. Total weight is around 1.5 kg.

Figure 18: YellowScan Surveyor

http://www.yellowscan.fr/wp-content/uploads/yellowscan-surveyor-scanner-drone.png

Phoenix Aerial Systems

According to Phoenix Aerial Systems, their systems cost from $85,000 to $250,000, depending on configuration options chosen. They have many options available, which will be briefly mentioned here. [14]

Phoenix Aerial Systems Ranger Series

Uses the RIEGL VUX-1 series LIDAR coupled with a Fiber Optic Gyro (FOG) IMU. The high-grade IMU is necessary given the ranges this LIDAR is capable of.

Figure 19: Phoenix Aerial Systems Ranger Package

http://www.phoenix-aerial.com/files/4714/2784/1972/11_1-icon_compressed.png

AL3-16

Weight-optimized version of the AL2. Couples the Velodyne VLP-16 Puck LITE with the KVH Fiber Optic Gyro IMU.

Figure 20: Phoenix Aerial Systems AL3-16 Package

http://www.phoenix-aerial.com/files/8114/3819/7437/vlp-16_stim2.png

AL3-32

Identical to the AL3-16, except built around the Velodyne HDL-32E LIDAR.

Figure 21: Phoenix Aerial Systems AL3-32 Package

http://www.phoenix-aerial.com/files/8914/2784/1493/55-icon_compressed.png

Scout Series

Also used the Velodyne VLP-16 Puck LITE, but uses two different options for IMUs: the Sensonor STIM300 or the ADIS 16488. Both of these are MEMS-based IMUs, which are less accurate than the fiber-optic gyro (FOG) options. The STIM-300 is the more accurate of the two, with slightly more weight and energy consumption. Both are under 2W, however.

Figure 22: Phoenix Aerial Systems Scout Package

http://www.phoenix-aerial.com/files/7214/4052/7757/9_1.png

Complete Systems

There are several manufacturers of complete, turn-key solutions. These include not only the integrated LIDAR/GPS/IMU solution, but the UAV platform as well.

RIEGL Complete Systems

RIEGL RiCOPTER

A very large octocopter that integrates the VUX-SYS LIDAR/GPS/IMU. It can carry a maximum payload of 16 kg. This puts the weight of the system at 25 kg, or right at the 55-pound small UAV limit. Maximum flight endurance with an 8 kg payload is 30 minutes.

Figure 23: RIEGL RiCOPTER

http://www.riegl.com/uploads/pics/ricopter-2016-06-22-2.jpg

Phoenix Aerial Systems Complete Systems

TerraHawk-V T-16

The TerraHawk-V T-16 is a vertical-takeoff-and-landing (VTOL) platform. It operates as a fixed-wing aircraft when not taking off or landing, leading to greater flight times. It uses electric motors for VTOL operation and a gas engine for fixed-wing flight. It can stay airborne roughly 4-6 hours. It integrates the VLP-16 LIDAR. Maximum payload is 1.75 kg.

Figure 24: Phoenix Aerial Systems TerraHawk-V T-16

http://www.phoenix-aerial.com/files/8614/6411/2383/COWCROP.png

TerraHawk T-32

The T-32 is based around the HDL-32E LIDAR and the Sensonor STIM IMU. It uses electric propulsion, and is based around UASUSA's Tempest UAV platform. Flight times are approximately one hour, and it can carry a maximum of 2.5 kg.

Figure 25: Phoenix Aerial Systems TerraHawk T-32 LIDAR/UAV Scale

http://www.phoenix-aerial.com/files/8214/3863/5064/Render_HDL_32_copy.JPG

Figure 26: Phoenix Aerial Systems TerraHawk T-32 Photo

http://www.phoenix-aerial.com/files/6114/1801/6040/Tempest_Colors.jpg

M600 UAV

Can mount Ranger, AL3, or Scout GPS/IMU-integrated systems.

Figure 27: Phoenix Aerial Systems M600

http://www.phoenix-aerial.com/files/9914/7147/7155/m600_resize.jpg

Phoenix Aerial Systems also has several other ready-to-fly rotorcraft options for mounting their Ranger, AL3, or Scout platforms, depending on the size. The Alta 8 octocopter supports all their payloads, the S1000+ octocopter and ALTA 6 hexacopter support the AL3 and Scout, and the Scout S900 supports the Scout only.

Pulse Aerospace Vapor 55

The Pulse Aerospace Vapor 55 is a single-rotor system which carries the Ranger LIDAR system. It can carry heavier payloads, however, up to around 11 kg (24 pounds).

Figure 28: Pulse Aerospace Vapor 55

http://www.phoenix-aerial.com/files/6614/4469/1977/vapor55.png

Upcoming Sensors

There are several companies working on sensors that are looking to release in 2017.

Quanergy Upcoming LIDAR Sensors

Quanergy is working on two different solid-state LIDAR systems. Solid-state means that the systems do not employ a traditional rotating mirror. Instead, an optical phased array is used as a transmitter, which allows for steering pulses of light by shifting the pulse's phase as it is projected through the array. This can be a boon in difficult operating environments, and will likely lead to a more robust sensor in general. It remains to be seen if Quanergy will reach their specified operational targets, however. [15]

Quanergy S3-Qi

This is a lighter-weight version of the S3, a solid-state LIDAR sensor. It is a single-laser system, and is very light, but also has a rather short range and angular resolution. Depending on the application, this might not be an issue. Target pricing for this sensor in full production is $1,200 as of 9/28/16. Sample kits are currently available at around $50,000. [16]

Quanergy S3

Data is somewhat sparse on this sensor. Unlike the S3-Qi, the S3 has a vertical field-of-view. If it is employing multiple lasers, it is unknown from the datasheets available. These are slated to begin production in 2017. It has a horizontal FOV of 120 degrees, like the S3-Qi. While the angular resolution is not listed, it is likely the same as the S3-Qi, variable from 0.1-0.5 degrees. [17]

Figure 29: Quanergy S3 Solid-State LIDAR

http://www.quanergy.com/wp-content/uploads/2014/04/s3-image.jpg

Scanse LIDAR Systems

Scanse Sweep

This is a very low-cost LIDAR system that is likely more suited to applications that do not require significant accuracy. Target pricing for this sensor is $255. It returns significantly less samples and point density, but as is evidenced by the price, it will likely open the door for hobbyists to get involved in LIDAR systems. [18]

Figure 30: Scanse Sweep LIDAR

http://scanse.io/sites/default/files/product/image/FRONT.JPG

Applications

LIDAR has a multitude of uses, many of which enable safer operations in high-risk environments. Some of the applications include:

- Coastal applications - If the wavelength of the laser is chosen correctly, it can penetrate, at least to some depth, water. The penetration depth will depend on the strength of the laser, the wavelength, and the turbidity and/or clarity of the water. If the water is not very clear or still, the laser may only be able to reflect a few feet deep. Nonetheless, this can help produce both coastal topography and shallow-water bathymetry. In particular, bare-earth DSMs and shallow-water bathymetry can help improve flood extent modeling and mapping, helping to assess areas of flood risk.
- Precision Agriculture – While many current applications focus on photogrammetric solutions and various vegetative indices, LIDAR could be very helpful for mapping topography in agricultural applications, particularly to model runoff or get more accurate measures of plant heights.
- Surveying – One of the more obvious uses of LIDAR, this can be used to obtain topography for many types of terrain mapping, from mining to canyons to urban environments.
- Corridor mapping – Many applications require close monitoring of various resources along a corridor, such as power lines, railways, and pipelines. A LIDAR system can provide very detailed data and potentially detect problems before a human would via visual inspection.

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[1] Phoenix Aerial Systems, "Phoenix Aerial Systems :: Home," September 2016. [Online]. Available: http://www.phoenix-aerial.com/information/accuracy-explained/.

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Appendix A – Table of various LIDAR systems

Most data here was obtained from the various datasheets listed in the references. Other data not listed came from Phoenix Aerial Systems’ table on their offered products. [19]

Sensor	Accuracy	samples	Distance	FOV (h/v)	Lasers	wavelength	angular res	returns	Size	Weight	Energy
VQ-480-U	2.5cm	275,000	1500m (60%)	60	1	1550nm	0.002 - 0.36	N/A	347mm d x 183mm	7500g	55W
VUX-1UAV	1cm	500,000 (max)	920m (60%)	330	1	1550nm	0.006 - 1.5	4	227x180x125mm	3500g/3750g	60W
VUX-1HA	0.5cm	1,000,000 (max)	420m (80%)	360	1	1550nm	0.0036 - 0.3	4	227x180x125mm	3500g/3750g	65W
VUX-1LR	1.5cm	750,000 (max)	1350m (60%)	330	1	1550nm	0.004 - 1.5	4	227x180x125mm	3500g/3750g	65W
LUX4	10cm	N/A	200m (90%)	110/3.2	4	905nm	0.125h/0.8v	3	165x94x88mm	1100g	8W
LUX8	10cm	N/A	200m (90%)	110/6.4	8	905nm	0.25h/0.8v	3	165x94x88mm	1100g	8W
HDL-32E	+/- 2cm	1,390,000 (dual)	~100m	360/41.33	32	903nm	0.1-0.4h/1.33v	2	85.34mm d x 144.24mm h	1000g	12W
Puck	+/- 3cm	600,000 (dual)	~100m	360/30	16	903nm	0.1-0.4h/2v	2	103mm d x 72mm h	830g	8W
Puck Hi-Res	+/- 3cm	600,000 (dual)	~100m	360/20	16	903nm	0.1-0.4h/1.33v	2	103mm d x 72mm h	830g	8W
Puck Lite	+/- 3cm	600,000 (dual)	~100m	360/30	16	903nm	0.1-0.4h/2v	2	103mm d x 72mm h	590g	8W
M8	< 3 cm	> 400,000	200m (80%)	360/20	8	905nm	0.03-0.2/2.86v	N/A	102 mm diam x 86m h	900g	18W
S3	N/A	~480,000	150m (80%)	120/10	1	905nm	N/A	N/A	90x60x60mm	300g	10W
S3-Qi	N/A	N/A	100m (80%)	120/NA	1	905nm	N/A	3	40x30x50mm	150g	6W
Sweep	1% of dist (4-40m)	500	40m	360	1	905nm	1.4-7.2	1	65mm d x 52.9mm h	120g	3W