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Ultra-Compact LADAR Systems for Next Generation Space Missions

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ABSTRACT

Bridger Photonics and Montana State University have pioneered the active stabilization and control of highly-power efficient, extremely broadband swept laser sources for novel laser radar (LADAR) systems. By using a stretched processing technique similar to that of microwave radar, an FMCW LADAR system has numerous advantages that can help break the insertion barrier for LADAR-based sensors on small satellites (small-sats). These advantages include: (a) their extreme sensitivity allowing very low return light levels, (b) their capability to deliver extremely high down-range resolution using low-bandwidth receiver electronics, (c) their high electrical power efficiencies, (d) their compact, robust packaging and (e) their flexibility to perform a variety of advanced missions. The team has recently demonstrated the highest resolution LADAR measurements in the world (sub-50 microns) with range precisions on the nanometer scale. Examples of 3D imagery are also shown and a discussion of the future opportunities for sensors enabled by these novel sources and the FMCW approach is provided.

INTRODUCTION

To address the needs of tomorrow's space missions, future space systems will capitalize on fleets of smaller, more efficient, and more cost-effective satellites. These satellites will provide more orbiting sensors, with more flexibility and redundancy, as well as the agility to fly in formation and cooperatively gather intelligence, identify and classify space objects, and work together to protect vital space infrastructure. These small space systems are much less vulnerable to attack compared to larger space assets and are less expensive to launch.[1] Many systems in development today are based upon formation flying concepts with small satellites.[2] CubeSats and other very small satellite bus architectures are also becoming a routine way to provide access to space with much lower costs and the ability to provide a useful platform for a variety of missions ranging from imaging earth-based objects and the atmosphere to examining space debris.[3]

For example, space situational awareness (SSA) has become ever more critical, as other countries continue to show their expanding space-based capabilities. The Jan. 11, 2007 Chinese anti-satellite (ASAT) demonstration against their Fengyun-1C spacecraft highlighted the need for a more concerted effort to identify and characterize space objects, to understand their military significance, and to assess their potential capabilities and posture.[4] In addition, the demonstration also highlighted the need to identify and avoid space debris for orbiting assets, as the collision contributed an estimated 150,000 pieces of orbital debris larger than 1 cm.

There have been a wide range of programs to address the fundamental needs for smaller space-based assets, such as communications, power, attitude and control.[5] However, it is apparent that as the space platform size shrinks, so must the deployable mission payloads. Sensors that require either high sustained power or large physical sizes are especially vulnerable to the tight platform constraints associated with these smaller architectures. For example, to achieve two meter resolution imagery from 500 km, fairly large and costly satellites, with total masses of ~3000 kg and large conventional imaging apertures (≥30 cm) are required.[6] Because aperture size must be reduced in proportion with the satellite's size, conventional imagers are relegated to support only wide field-of-view (FOV) missions on small-sat platforms from even low earth orbit (LEO).[7,8] If imaging of an unknown space object is required, conventional optical imaging approaches require that the probe satellite get very close to the object, which raises international concerns and attention.[9] In addition, boosting an orbit to more closely interrogate an unidentified object requires the expenditure of propellant, and the finite amount available on small-sats severely limits the number of interrogations.

Active LADAR systems have the potential to bring multiple benefits for space based missions and space based LADAR and LIDAR are not new.[10] LIDAR systems (defined here as a laser radar system that probe soft targets such as gases) are typically used to examine gas concentrations and speeds in the upper atmosphere. LADAR systems (defined here as a laser radar system that probe hard targets) can be multifunctional and used at a variety of ranges. Short-range applications include using a laser ranger for autonomous docking between two spacecraft, for inspection of a spacecraft's outer surface for damage, and for proximity warning. Medium-range applications include metrology systems for precision formation flying and scanned 3D imaging of other spacecraft and space debris. Longer-range applications can include precision ranging for orbit determination, target identification by using vibrometry, and advanced high-resolution missions for terrestrial or space object imaging and identification via synthetic aperture and distributed aperture imaging.[11, 12]

Unfortunately, the use of traditional LADAR systems in space, especially on smaller space platforms, has been extremely limited because of their high electrical power demands, their limited sensitivity, their poor cross-range resolutions due to their reliance upon conventional imaging approaches, and their huge data storage and communication needs.

Bridger Photonics and Montana State University have pioneered the active stabilization and control of highly-power efficient, extremely broadband swept laser sources for novel LADAR systems. By using a stretched processing technique similar to that of microwave radar, Bridger Photonics LADAR systems have numerous advantages that can help break the insertion barrier for LADAR-based sensors on small-sats. These advantages include: (a) their extreme sensitivity allowing low return light levels, (b) their capability to deliver extremely high down-range resolution using low-bandwidth receiver electronics, (c) their high electrical power efficiencies, (d) their compact, robust packaging and (e) their flexibility to perform a variety of advanced missions.

The team has recently demonstrated the highest resolution LADAR measurements in the world (sub-50 microns) with range precisions on the nanometer scale. Such a LADAR system can be used to break the fringe ambiguity of laser interferometers providing absolute distance measurements that are critical for formation flying satellite architectures and distributed metrology of large deployable space structures such as space telescopes. In addition, we have demonstrated

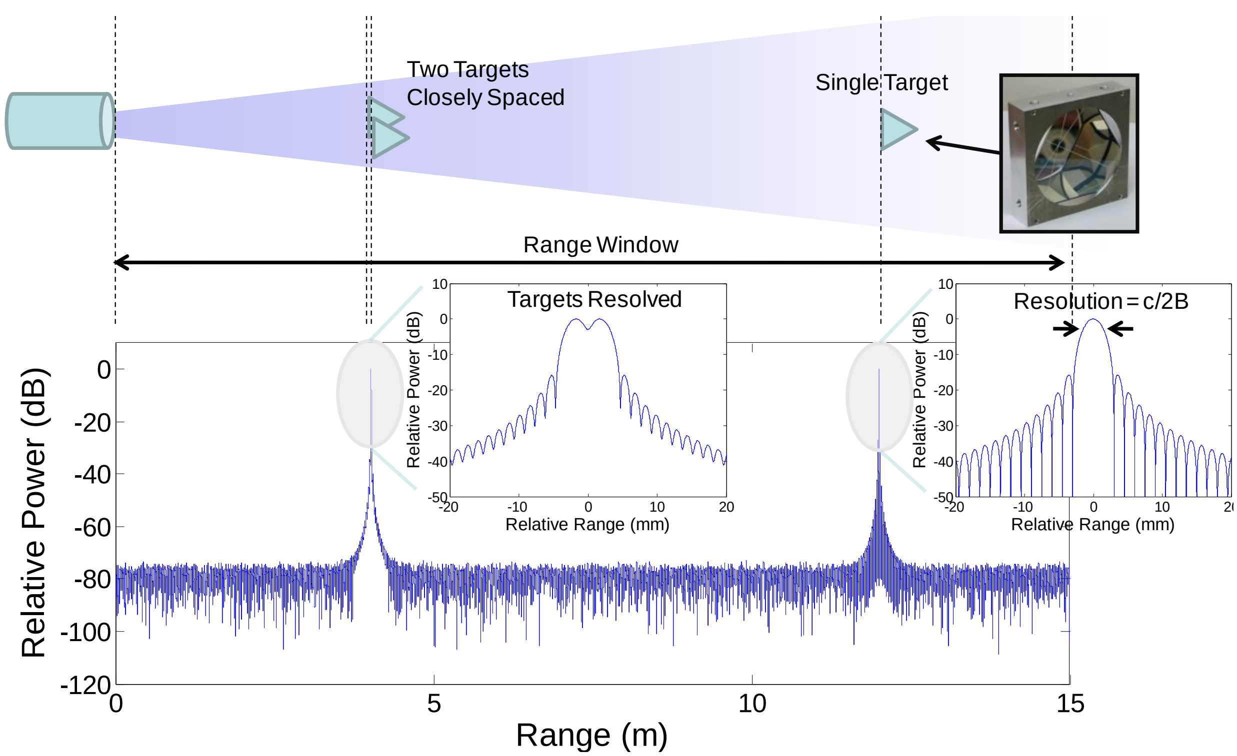

Figure 1: A laser ranging system depicting system resolution and range window.

advanced 3D imaging architectures that can work at medium range that have no-moving parts, are capable of compressive imaging resulting in reduced data loads, and that can provide rapid target identification.[13] Finally, recent link budgets have shown that our systems may be capable of providing advanced, high-resolution synthetic aperture images from distances beyond 100 km.

In this paper, we highlight the mission benefits of LADAR systems in space, the barriers to their insertion, and how our advanced laser sources may help overcome these barriers. We describe our most recent measurements and show some of our high resolution imagery.

LADAR BACKGROUND AND TRADESPACE

Some Definitions

The range resolution of a LADAR system is a typical performance metric and is useful for comparing various LADAR approaches. The range resolution is defined in analog to the Rayleigh spatial resolution criteria, which is the distance at which two targets being measured simultaneously can be resolved at their half power points.[14] This is shown in Figure 1 for a pulsed time-of-flight ranging system. In such a system it is easy to envision that shorter pulses will lead to enhanced measurement resolution. As is well known, by shortening the temporal duration of the pulse, the signal (or information) bandwidth, B, of the signal is increased. It can be shown that the range resolution, ΔR is given as $\Delta R = c/2B$, where c is the speed of light. Thus, in order to achieve better resolution, one desires signals with larger optical bandwidths. The resolution is a useful parameter for comparing ranging systems because it does not depend on any characteristics of the return light (target reflectivity, collection optics, etc.). An estimate of a target's position can be determined better than the resolution, and is given by the range precision (i.e. uncertainty in position or Cramer-Rao lower bound) as $\sigma_R \approx \Delta R/\sqrt{SNR}$, where SNR is the signal-to-noise ratio.[15] For two systems with equal resolution, the system with the highest SNR will achieve the best measurement precision.

Pulsed LADAR Systems

Conventional LADAR systems based on direct detection and time-of-flight measurements of laser pulses seek to both increase the pulse power (for improved signal fidelity and maximum range) and decrease the pulse duration (that is to increase bandwidth for improved range resolution). However, it is difficult to achieve these two features simultaneously because both lead to increased peak power. The high peak powers can damage optical components, which limits power scalability. The inability to scale the power of existing pulsed systems presents a barrier to improved LADAR performance in terms of both range and signal fidelity. Traditional solid state laser rangers that can operate over large distances typically have very poor power efficiencies of approximately 3% (10% conversion optically times 30% for pump). This can be a significant problem for power constrained platforms.

In addition to this limitation, improved range resolution in pulsed laser LADAR systems requires large receiver bandwidths. For example, to achieve a 1 cm down-range resolution, a 15 GHz system bandwidth is required. While 15 GHz photodetectors are available, both thermal and shot noise sources scale as the square root of the receiver bandwidth, leading to a decrease in the *SNR*. Additionally, commercially available analog to digital converters (ADCs) that operate at such bandwidths are not available and it is well established that ADCs suffer from significant performance limitations with increased bandwidth.[16] While smaller and more efficient monolithic pulsed laser rangers could be used from space, such systems will still suffer from the receiver and range resolution problems described above.[17] Finally, pulsed laser based LADAR systems are typically used with direct detection and are thus unsuitable for advanced coherent sensing applications such as vibrometery, range-Doppler imaging, and distributed or synthetic aperture LADAR. All of these deficiencies combined with poor power efficiency make pulsed laser source LADAR systems very unattractive for use in space.

FMCW Chirped Heterodyne LADAR

An attractive alternative to utilizing pulsed lasers for LADAR is the use of frequency swept or chirped optical waveforms along with coherent detection. The technique, known as frequency modulated continuous wave (FMCW) chirped heterodyne LADAR has several advantages that make it an ideal candidate for use on constrained platforms.[18] The technique is shown in Figure 2. The frequency chirped laser light passes through a splitter, with the transmit portion passing first through an optical circulator and then towards a distant target object. Light that returns from the target is time delayed by $\tau_D = 2R/c$, where R is the distance to the object and c is the speed of light. This time-delayed light is collected, passes out of the circulator to be recombined with the portion of the original chirped light that is not time delayed called the reference or local oscillator. When the recombined light is detected, a constant frequency offset exists between the two chirps as a result of the time delay. This appears as a heterodyne or "beat note" which has a frequency $f_{beat} = \kappa\tau_D = 2\kappa R/c$, where κ is the chirp rate in Hz/s. The distance to the object, R, can therefore be determined by measuring the beat note frequency. As before, the range resolution ΔR of this LADAR technique is given by ΔR = c/2B, where B is the bandwidth of the optical chirp. Typically, FMCW chirped LADARs have much better range resolution because the optical bandwidths that they can cover are much larger. The maximum range window or beat note that can be measured is often limited by the bandwidth of the digitizer used and can reach large distances >1km. Note by delaying the reference path, the range window can be shifted, so that a 1 km wide debris field could be examined several tens of kilometers away.

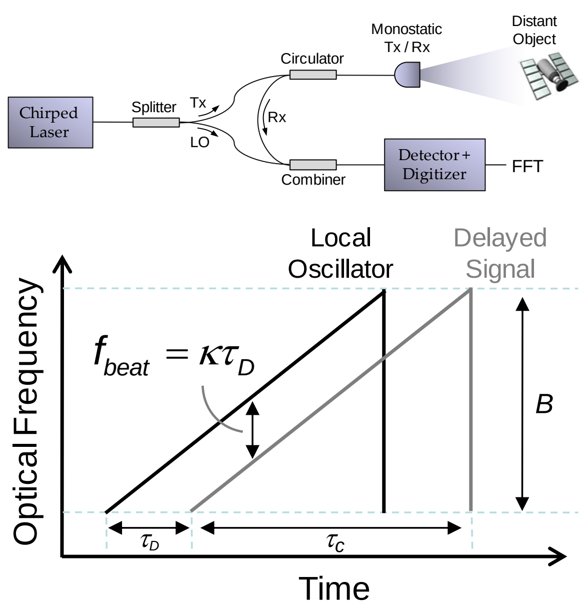

Figure 2: (Top) The setup for an FMCW chirped heterodyne LADAR system. (Bottom) The optical frequency versus the sweep time for the local oscillator and delayed return signal.

Optical chirped FMCW LADAR offers a number of benefits over pulsed direct detection techniques including enhanced detection sensitivities which translates to lower optical power requirements to cover the same range extent, the potential for much higher range resolutions while simultaneously using lower bandwidth, higher dynamic range receiver electronics, and the potential for fiber delivery allowing use of extensive telecom components.[14] In addition, the technique lends itself nicely to a variety of imaging techniques, which will be discussed below, and can provide target vibrometry. FMCW LADAR is not a new technique and was derived from analogous methods used in the radio-frequency (RF) domain (chirped radar).[19] FMCW systems have been proposed in the past to sense both absolute and relative lengths on the micro- to nanometer range to control satellites flying in formation.[15] Previous demonstrations employing this technique when paired with CW interferometers have even shown nanometer accuracies.[20] Unfortunately, due to poor linearity and source coherence, the unambiguous range windows when using extremely large optical bandwidths have been limited to the sub-centimeter scale.[20] In fact, chirp linearity and repeatability has been singled out as a significant impediment to successful implementation of high-resolution synthetic aperture imaging LADAR (SAL).[11]

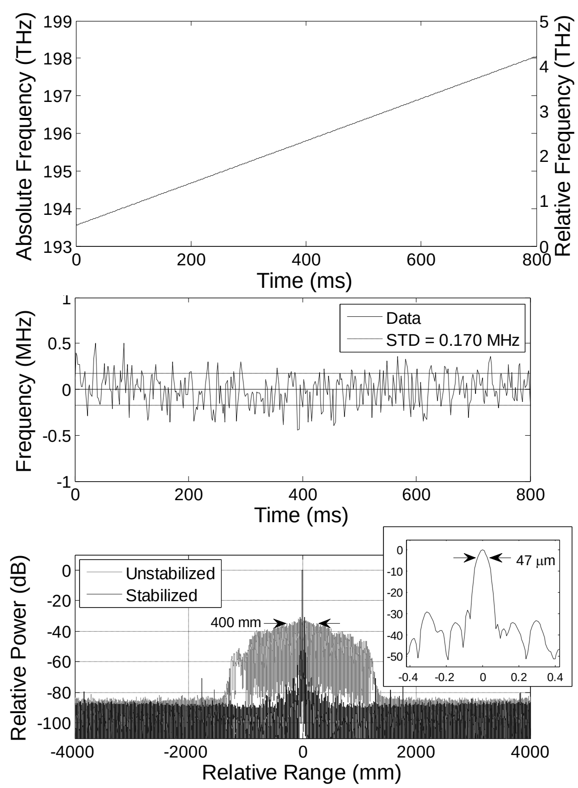

Figure 3: (Top) A frequency sweep from the SLM-H laser system shown covering more than 4 THz of optical bandwidth. (Middle) The residual sweep errors from linearity showing a 170 kHz standard deviation. (Bottom) Two range profiles for (grey) an unstabilized sweep with 400 mm FWHM and (black) a stabilized sweep with 47 μm FWHM.

During the past two years, Bridger Photonics has developed chirped laser sources with an unprecedented combination of bandwidth, linearity and coherence. Bridger Photonics' innovation provides active laser stabilization during the frequency sweep dramatically reducing sweep nonlinearities and substantially increasing the swept source coherence length.[21] This has enabled four orders of magnitude improvement in the range window over previous chirped laser radar demonstrations along with world class resolutions and precisions better than 1 part in 10^7.[22,23] For example, Figure 3 (top) shows the measured optical frequency versus time from Bridger Photonics SLM-H laser source. The total optical bandwidth exceeds 4 THz. Figure 3 (middle) shows the measured residual sweep error from the source. This error has a standard deviation of ~170 kHz or about 2 parts in 10^7 when compared to the total sweep bandwidth. Figure 3 (bottom) shows the range profiles for the sweep when the laser is unstabilized (gray) or stabilized (black). The stabilization approach leads to transform limited range profiles, which for this optical bandwidth provides a peak resolution of 47 μm.

Bridger Photonics has been employing active stabilization to three different types of swept laser sources. Two of these sources, found in the SLM-H and the SLM-M series of lasers, are external cavity diode lasers, while the SLM-L series of lasers is based on distributed feedback (DFB) diode lasers. Diode lasers are generally known for their high wall-plug efficiency, which can easily exceed 30%. This makes them an attractive candidate for space based applications. In addition, the actual laser source itself is contained in a small 2 cm x 2 cm x 0.5 cm butterfly package, again making it attractive as compared to the size of typical pulsed laser sources. Finally, if larger optical powers are required, these sources are in the telecom band allowing efficient amplification.

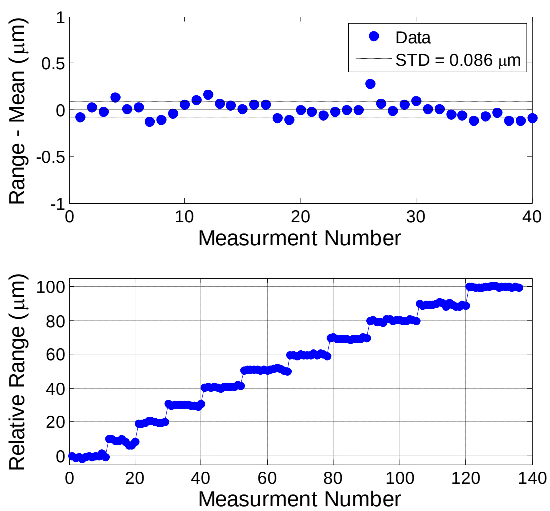

Figure 4: (Top) Thirty independent range measurements of the length of a 1-meter fiber, giving a repeatability or precision of 86 nm. (Bottom) Measured ranges of a target on a stage manually stepped in increments of 10 microns.

RECENT RANGING AND 3D IMAGING

Nanometer Scale Ranging

Bridger Photonics' SLM-H and SLM-M systems are capable of achieving range precisions below 100 nm. This is a combination of both the system's inherent resolution and excellent signal-to-noise ratio.

Figure 4 (top) shows a series of maximum-likelihood range estimates for the length of an 1-meter optical fiber. The range precision is given as the standard deviation of the range estimates and is shown to be 86 nm. This represents 1 part in 10^7 relative to the length of the fiber and was performed without an length or temperature stabilization. Figure 4 (bottom) measures the range to a free-space target. The target range was manually altered using a micrometer-driven stage in 10 μm increments. These steps are easily resolved, showing the system is capable observing these distances for real targets.

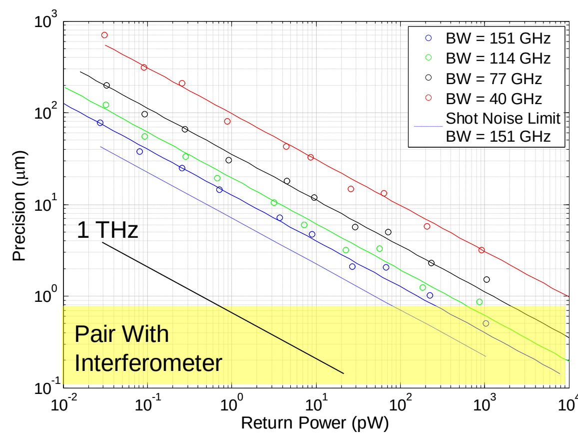

Figure 5: A plot showing the measured range precision versus return power for various optical sweep bandwidths. The yellow shaded section indicates the precision required to break the fringe ambiguity of a λ = 1.55 micron CW interferometer.

Figure 5 shows the range precision versus return power for various chirp bandwidths. For these data, the measurement time was 2 ms. The yellow rectangle represents the region in which the precision will be less than λ/2 for λ = 1.55 μm. For 1 THz bandwidth, less than 1 pW of return power is required to achieve λ/2 range precision, whereas approximately 2 nW of return power is required to achieve the same precision with a bandwidth of 77 GHz. Overall, Figure 5 shows that the system is capable of breaking the fringe ambiguity of a conventional CW interferometer with very little return power. By pairing the system with a CW interferometer, absolute ranging could then be performed with extremely high range precision.

Doppler Compensation

While there are numerous advantages to a coherent heterodyne range measurement, sensitivity to Doppler and vibrations is a potential drawback. The presence of Doppler can lead to both shifts in the measured range (range-Doppler coupling) and reduced precision (Doppler broadening). By pairing the LADAR system with a CW interferometer, many of the Doppler effects can be cancelled, as shown by Beck and Buell. [11]

Figure 6 shows experimental data from Bridger Photonics' implementation of this technique. Both range shifts due to range-Doppler coupling and Doppler broadening are compensated. The residual error on the linear fit (red) of the compensated data (black) is below 5 µm.

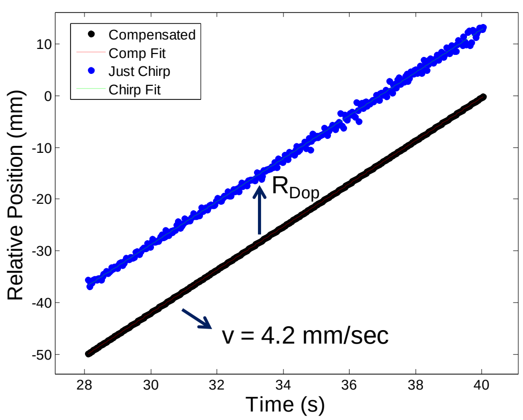

Figure 6: (Blue) A direct range measurement on a target moving with a fairly constant velocity. The black line shows a compensated measurement taken with both a chirp and a CW interferometer.

Ranging Tests at 1 km and 14 km Distances

Bridger Photonics' long range demonstrations show the system's applicability to space-based missions. Figure 7 (top) shows a schematic of the experimental setup. These experiments were performed using a 2" optic on the transceiver and 100 mW transmit power. Figure 7 (bottom) highlights the SLM-H performance at ~1 km standoff distance for a scene consisting of three retroreflectors spaced by ~100 mm and ~250 mm with respect to the first retroreflector. The measured range profile is shown with the three targets easily resolved with the 3dB resolution of 100 µm. In practice, the results are limited by atmospheric turbulence. For space-based systems, turbulence is expected to be limited.

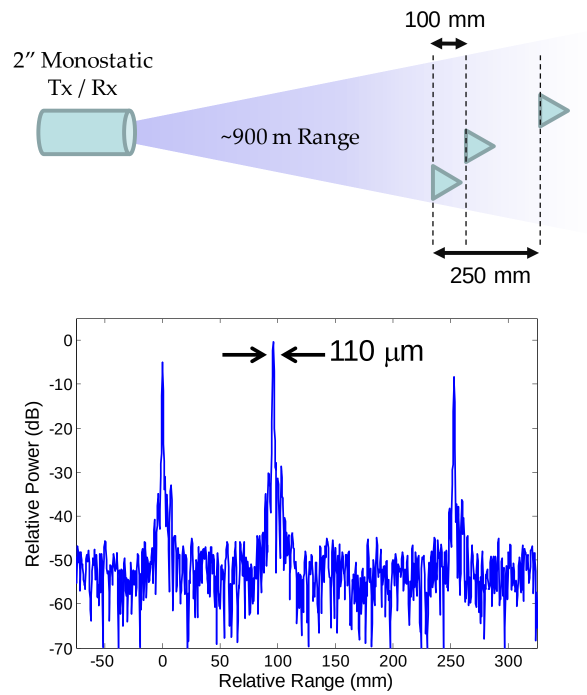

Figure 7: (Top) A schematic of the ~1 km test. The target consisted of three retroreflectors spaced at ~100 mm and ~250 mm in down-range are shown. (Bottom)The range profile showing that the three targets are easily resolved. The FWHM measured ~110 µm for each peak.

The team performed additional demonstrations at a range of 14 km. For these experiments, an 8-inch transceiver was used with only 3 mW of transmit power. Figure 8 shows the retroreflector array (inset) and the position of the array relative to the transceiver. The retroreflector array was positioned at a location with substantial elevation gain to ensure line of sight.

Figure 9 shows the ranging results for the 14 km demonstrations. The average SNR was 31.4 dB and the range precision was 1.32 mm. The data were taken near dawn to minimize atmospheric effects but are nevertheless atmospherically limited. These data again represent a precision of 1 part in 10^7 relative to the total distance.

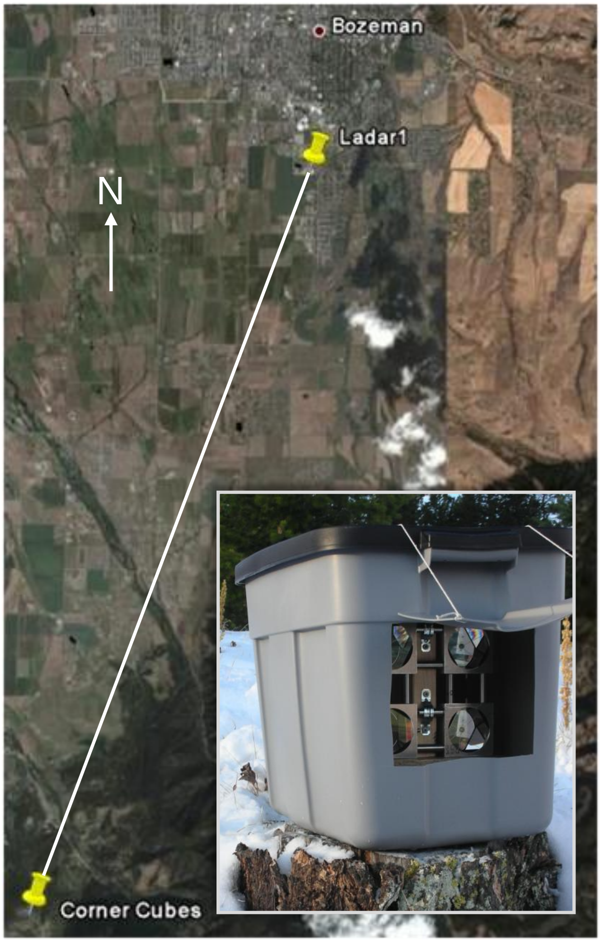

Figure 8: A map showing the retroreflector target position for the ~14 km tests. (Inset) A picture showing the four 2" retroreflectors in their housing.

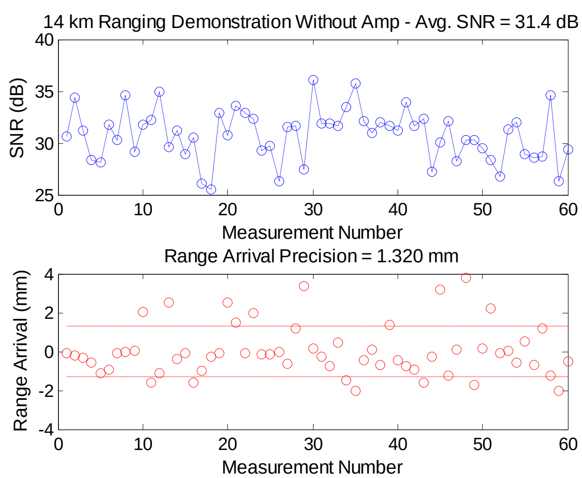

Figure 9: (Top) The measured SNR for 50 measurements from the target. (Bottom) The corresponding range measurement minus the mean range measurement showing an atmospherically limited standard deviation of 1.32 mm.

3D Imaging

Another use for actively stabilized laser sources is in the creation of advanced 2D and 3D imaging. Conventional LADAR imaging systems follow two different design types each of which typically uses pulsed lasers as the source. First, there are scanned systems which rely upon a mechanical spatial beam scanner synchronized with a pulsed laser system and a single fast photodetector. Recent advances in micro-electro-mechanical systems (MEMS) technology have made fast, compact and rugged beam scanners available and potentially space qualifiable.[24] Because these systems scan the beam spatially, the receive detector and the electronics for time of flight measurement only needs to be replicated once. The second approach relies upon spreading the pulsed laser energy across the full FOV and placing fast detector arrays at the focal plane, so called fast focal plane arrays (FPAs) or flash LADAR. The advantage for FPA systems is that the FPA is used to collect both the cross range and down range content during a single pulse of the laser system. Unfortunately, the use of pulsed laser sources in both these systems makes them unattractive for space based systems. In addition, for higher resolution systems, FPAs become very cost prohibitive. Hybrid systems, which incorporate both scanning and focal plane arrays are getting increased attention. This is because the ability to scan some of the field-of-view can be traded against the cost and development of the FPA. Combining the hybrid concept with an FMCW LADAR ranging approach is even more attractive because the bandwidth and digitizer requirements on the FPA are further reduced.

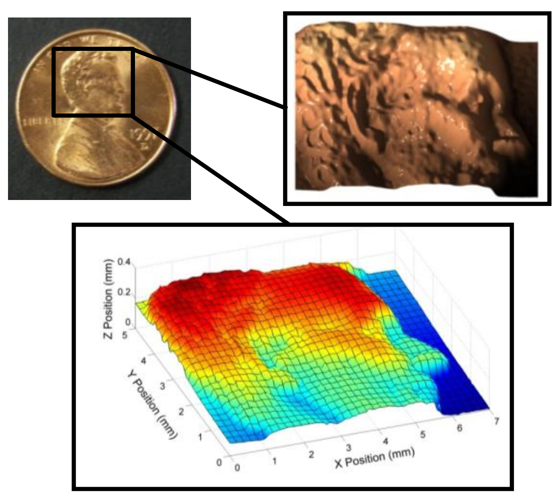

Figure 10: (Top Left) The approximate location of the scanned section for a U.S. Penny. (Top Right and Bottom) Renderings of the three dimensional imagery acquired with the swept source.

To demonstrate the capability of the SLM-H laser source to create 3D imagery, a U.S. penny was set up on a 2D translation stage. An effective delay of 1 m was created to the target and a single down-range capture was made per scan point. The range to the surface of the penny was then estimated from the rang profile and stored in matrix form with the x and y coordinate from the stage serving as an index into the matrix. Figure 10 shows the results for 3D renderings of the measured data. The upper left conventional image shows the approximate location of the scan. The image in the upper right was a 3D shadowed rendering of the data showing that very fine surface structure is apparent. The lower 3D plot shows the surface height as a function of color and provides a scale. From this plot, the features on Lincoln's face are measured to be a few hundred microns in height. This proof-of-concept demonstration showed that the actively stabilized laser source could be utilized for 3D imaging.

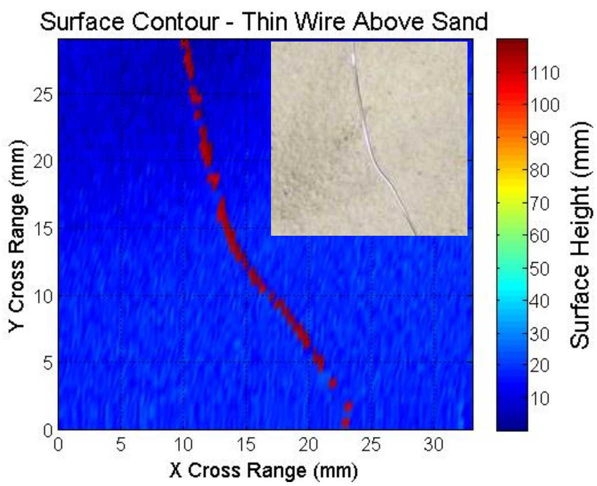

Figure 11: A three dimensional image of a sub-1 mm diameter wire suspended about 100 mm above a sandy surface. (Inset) A conventional image of the scene showing the sand and wire.

The next demonstration utilized the hybrid scan plus FPA approach. In this case, the laser was made to scan across the scene, which consisted of a sandy surface with a sub-mm diameter wire suspended ~110 mm above the surface. Approximately 100 GHz of sweep bandwidth was used in each cross range cell to give a lower resolution image than the U.S. penny shown above. Figure 11 shows the 3D image result as a color map, where x and y represent the cross range location on the ground and the z-dimension (colormap) represents the height above the ground. The wire is distinguished by the red line. Some points are missing and are a result of highly specular reflections that sent most of return light away from the receiver. The blue background shows the sandy surface and shows the pits and depressions made in the surface. The image is a very accurate rendering of the actual scene, which is shown in the inset.

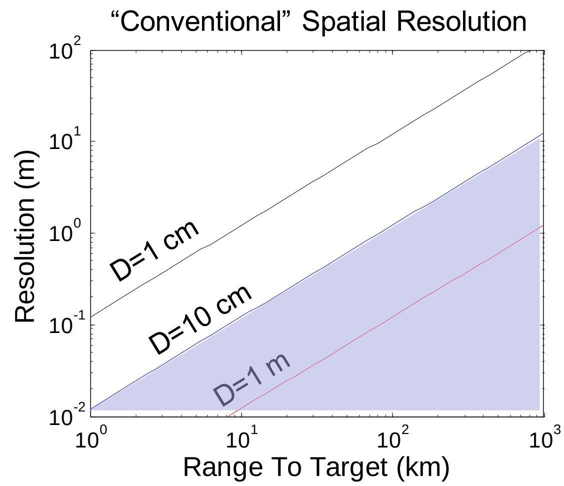

Figure 12: The spatial resolution as a function of the range to the target for an ideal imaging system for various aperture diameters.

FUTURE OPPORTUNITIES FOR SPACE BASED LADAR SYSTEMS

One of the challenges to achieving high resolution imagery with any small-sat platform is the limited space for conventional optics. This limitation is depicted in Figure 12. The ideal spatial resolution that can be obtained as a function of range from the target is shown for various aperture diameters. For small-sats, an ~10 cm diameter aperture can be obtained. For this diameter, only meter-class resolution can be expected on targets that are further than a hundred kilometers from the imager. Because of the large lengths to targets from space based platforms, methods for overcoming this hurdle are needed to form either 2D or 3D images of targets.

There are three main approaches to overcoming this aperture limitation: 1) deployable space structures, 2) coherent distributed apertures and 3) synthetic apertures.

NASA is considering several missions that will require spacecraft to unfold apertures that are larger than the spacecraft sent into orbit.[25] These so-called deployable space structures will require portions of the aperture to unfold and lock into position allowing the spacecraft to image with an aperture that is substantially larger than the original spacecraft sent into orbit. It is anticipated such deployable structures will possibly require real-time monitoring of the absolute length of booms and mirror locations to ensure that the space telescope operates without imaging artifacts. This will require metrology systems that can be easily distributed throughout the deployable space structure. FMCW LADAR would be a promising candidate for this approach as it can be easily distributed through a fiber network or via free space with gimbaled mirrors. Other candidates for these types of distributed metrology systems include multi-color interferometers.

Distributed aperture systems usually refer to multiple distinct telescopes or apertures that are coherently combined to form a larger aperture.[26] In space, such systems would require multiple smaller satellites to cooperatively image the same target and to feed their light into a central beam combiner. Because the spacecraft would not be attached to one another, very tight attitude control and formation flying is required. This presents unique challenges to the individual spacecraft as they try to maintain pointing on the targets of interest while flying in their prescribed orbits. Such a problem will require numerous levels of metrology, for coarse, medium and fine range control of individual satellites in a formation. Again, with the capability to provide large range windows and the capability to break the fringe ambiguity of CW interferometers, the FMCW LADAR approach should be a promising candidate metrology system for distributed aperture approaches in space.

Finally, the synthetic aperture approach for image formation has been very successful at forming images in the microwave radar band, so called synthetic aperture radar (SAR). To form a synthetic aperture, a single real aperture is translated through a larger distance, known as the synthetic aperture, as shown in Figure 13. At each location along the track, a coherent waveform is transmitted and received from the target. By coherently combining the received signals, the synthetic aperture system can form a 2D image with the resolution of the synthesized aperture, which is much better than that of the real aperture used to transmit and receive the waveform. SAR systems are routinely and successfully used in space for a variety of missions. There are drawbacks to using microwaves as the carrier frequency for the synthetic system. For example, the bandwidth of the waveform is typically limited to less than 1 GHz, giving a lower limit of 15 cm for the image resolution. Second, the scattering characteristics of the microwave carrier are dramatically different than those of optical carriers, which leads to images that are not easily interpreted or visually appealing to observers used to visible wavelength imagery.

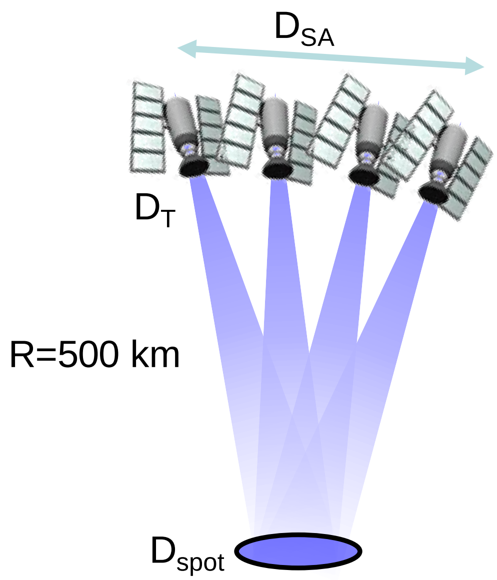

Figure 13: A schematic showing the synthetic aperture LADAR concept.

Synthetic aperture LADAR (SAL) has been proposed to overcome the SAR limitations.[11] By using an optical carrier, the imagery produced is much more visually appealing and the bandwidth limitations are removed. Millimeter class imagery could be obtained even from very long ranges assuming suitable transmit power were used. Back of the envelope calculations for a SAL system indicate that high-resolution imagery of terrestrial objects from low-earth orbit may be possible with kilowatt class lasers. Again due to the numerous advantages of the FMCW approach, it will be a promising candidate as the source for such a system. If SAL is shown to be feasible in space, it may provide a suitable method for finding and mapping large scale debris fields of even very small objects.

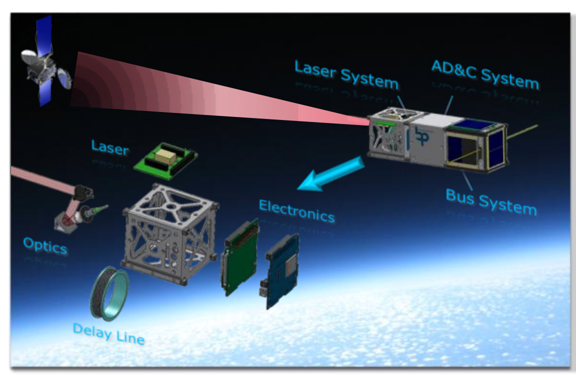

Figure 14: A schematic showing some of the basic components required for a scanned 3D imager in a CubeSat architecture.

CONCLUSIONS

Overall, the size, weight and power constraints on small-sat platforms are very demanding. This will limit a variety of potential LADAR systems from operating on such platforms. Because of its numerous advantages, the FMCW LADAR system is a promising candidate approach for use on a small-sat. An initial exploded design diagram for a CubeSat deployed FMCW LADAR imaging system is shown in Figure 14. In this configuration, a hybrid mode 3D imager could provide 3D images of targets possibly beyond 1 km. Such a system would be useful for imaging the structure of unknown or outdated satellites that may need to be captured and de-orbited.

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