POPULAR SUMMARY

The Multiple Altimeter Beam Experimental Lidar (MABEL), an airborne simulator for the ICESat-2 mission

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The Ice, Cloud, and land Elevation Satellite-2 (ICESat-2) mission is currently under development by NASA. The primary mission of ICESat-2 will be to measure elevation changes of the Greenland and Antarctic ice sheets, document changes in sea ice thickness distribution, and derive important information about the current state of the global ice coverage. To make this important measurement, NASA is implementing a new type of satellite-based surface altimetry based on sensing of laser pulses transmitted to, and reflected from, the surface. Because the ICESat-2 measurement approach is different from that used for previous altimeter missions, a high-fidelity aircraft instrument, the Multiple Altimeter Beam Experimental Lidar (MABEL), was developed to demonstrate the measurement concept and provide verification of the ICESat-2 methodology. The MABEL instrument will serve as a prototype for the ICESat-2 mission and also provides a science tool for studies of land surface topography. This paper outlines the science objectives for the ICESat-2 mission, the current measurement concept for ICESat-2, and the instrument concept and preliminary data from MABEL.

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Abstract: This paper presents the motivation for, and initial results from, the Multiple Altimeter Beam Experimental Lidar (MABEL) instrument. The MABEL instrument provides a new capability for airborne altimetry measurements and serves as a prototype for an upcoming NASA satellite mission. Designed to be highly flexible in measurement capability, MABEL serves as both a demonstration of measurement capability and a science tool for cryospheric and biospheric remote sensing. It is important to document the instrument specifications and essential background information to provide a suitable reference for the detailed MABEL results and science investigation publications that will be forthcoming.

1. Introduction

Quantifying ongoing ice sheet and sea level changes remains an Earth Science priority. The Ice, Cloud, and land Elevation Satellite-2 (ICESat-2) mission is the second-generation laser altimeter designed for cryospheric science to continue measuring elevation changes of the Greenland and Antarctic ice sheets, document changes in sea ice thickness distribution, and derive important information about the mass and energy balance between ice sheets, sea ice, and climate system.

Following recommendations from the National Research Council for an ICESat follow-on mission [NRC, 2007], NASA initiated the ICESat-2 mission, which is now under development for launch in 2016. The primary goals of the ICESat-2 mission are to continue measurements of sea ice thickness change and ice sheet elevation changes at scales from outlet glaciers (~100 km^2) to the entire ice sheet (~10^6 km^2).[Abdalati *et al*., 2010] Unlike the original ICESat, which used a laser operating at 40 Hz and an analog detection system to record reflected laser energy in the infrared as a waveform [Abshire *et al*., 2005; Schutz *et al*., 2005], ICESat-2 will employ a photon-counting approach. The current concept uses a high repetition rate (10 kHz), low pulse energy laser in conjunction with single-photon sensitive detectors to measure range to the Earth's surface using 532 nm light. The ICESat-2 concept also makes use of multiple beams to allow unambiguous separation of ice sheet slope and elevation change [Zwally *et al*., 2011], while the higher repetition rate generates dense along track sampling. Combining ICESat-2 data with existing and forthcoming altimetry data will yield a 15+ year record of elevation change.

Given the substantially different design of ICESat-2 compared with ICESat, the ICESat-2 project elected to develop an airborne ICESat-2 simulator to verify ICESat-2 instrument models, simulate ICESat-2 data over the cryospheric targets that are the focus of ICESat-2, and generate ICESat-2-like data for algorithm development. Consequently, the Multiple Altimeter Beam Experimental Lidar (MABEL) was developed to meet the project needs. This paper outlines the science objectives for the ICESat-2 mission, the current measurement concept for ICESat-2, and the instrument concept and preliminary data from MABEL. Subsequent papers detailing MABEL science results and ICESat-2 comparisons will be able to reference this paper as background on the MABEL instrument.

2. ICESat-2 science objectives

The primary goals of the ICESat-2 mission are consistent with the direction outlined by the National Research Council [NRC, 2007]: to deploy a spaceborne sensor designed to collect altimetry measurements of the Earth's surface, optimized to measure ice sheet elevation change, sea ice thickness, and global vegetation biomass. The ICESat-2 ad-hoc science team developed science objectives in each of these measurement areas:

- Quantify polar ice-sheet contributions to current and recent sea-level change and the linkages to climate conditions;
- Quantify regional signatures of ice-sheet changes to assess the mechanisms driving those changes and improve predictive ice sheet models; this includes quantifying the regional evolution of ice sheet change, such as how changes at outlet glacier termini propagate inward;
- Estimate sea-ice thickness from freeboard measurements to examine ice/ocean/atmosphere exchanges of energy, mass and moisture;

- Measure vegetation canopy height as a basis for estimating large-scale biomass and biomass change.

In particular, ICESat-2 has a requirement to produce an ice surface elevation product that enables determination of whole ice-sheet elevation changes to 0.4 cm/yr accuracy on an annual basis. This is a demanding requirement that drives pointing knowledge, measurement signal-to-noise ratio, and orbital considerations.

3. ICESat-2 measurement concept

The measurement approach selected for ICESat-2 is a photon-counting system with a high repetition-rate, low pulse energy laser and single-photon sensitive detectors. The outgoing laser beam is split into six transmitted beams to enable measurement of cross-track surface slope.

The ICESat-2 instrument is designed for operation at 532 nm. Arguments for science benefits of 1064 nm versus 532 nm are manifold, with pros and cons for each wavelength. However, the reality is that spaceflight qualifiable single-photon sensitive detectors at 532 nm are readily obtainable, whereas none are currently available in the 1-micron wavelength region.

The concept of photon-counting lidar is not new, having been employed for many years in atmospheric (e.g., cloud and aerosol) profiling.[McGill *et al*., 2002] The photon-counting concept is, however, a relatively new concept for altimetry. Traditionally, altimeters have used analog detection with fast digitization of the return signal. The photon-counting concept permits use of less powerful lasers, which lessens thermal and power requirements for a satellite-based instrument. However, to avoid being overwhelmed by solar background at 532 nm requires small instrument field of view to limit solar signal. In the case of ICESat-2, the diameter of each laser footprint on the surface is ~10 m (from a nominal 500 km orbit) with a receiver field of view of ~40 m diameter. For ICESat-2, the plan is to use 6 transmit beams in three pairs, in a rectangular configuration. A yaw angle from the satellite track then sets the specific spacing of the footprints.

Once a decision was made to pursue the photon-counting approach for ICESat-2, the need for an airborne demonstrator instrument became apparent. Although not required to be an exact scaled-down duplicate of the ICESat-2 instrument, the demonstrator instrument would have to be configured to permit evaluation of science and engineering trade spaces. The primary flexibilities required in the instrument design were:

- ability to vary the laser repetition rate. This is necessary to permit evaluation of multiple-pulse ambiguity. From the nominal 500 km orbit, ICESat-2 will have ~35 pulses in flight at any one time. At the 10 kHz repetition rate of ICESat-2, signal photons from the surface as well as clouds at 15 km height arrive at ICESat-2 at the same time, leading to a range ambiguity of 15 km. The MABEL laser is capable of operation in discrete steps from 5 kHz (no ambiguity from 20 km flight altitude) up to 25 kHz.
- ability to time-tag every photon event. This is the very heart of the ICESat-2 concept, so demonstration is critical.
- ability to oversample the expected spaceborne resolution. Demonstration and validation measurements should always be obtained at higher resolution that the instrument being validated, and the inherent difference in satellite and aircraft speeds satisfies this objective. Oversampling is also a critical component of developing ICESat-2-like data from MABEL data.
- ability to vary the viewing geometry/footprint pattern. This flexibility permits determination of optimal geometry and validation of the spaceborne instrument design. This also allows great flexibility for future validation of the spaceborne measurements.
- ability to operate at both 532 and 1064 nm. Although ICESat-2 is single wavelength (532 nm), initially there was a desire to use either 1064 nm or both wavelengths. Even so, operating the airborne instrument at both wavelengths permits better validation measurements and allows quantification of differences in reflectivity and water or snow penetration, for example. Dual-wavelength data will also aid in relating ICESat data (at 1064 nm) to ICESat-2 data (at 532 nm).
- ability to vary the energy level for each footprint. This capability is needed to explore the dynamic range trade space and inform the design of the satellite instrument and to verify the link model for the satellite instrument.

- ability to capture data for use in algorithm development and testing. This means acquiring data with clouds and other environmental effects that will be encountered by the satellite-based instrument. Of all the instrument design goals, acquiring data for algorithm development is perhaps the most important contribution MABEL has made to the ICESat-2 development process.

Designing one instrument capable of exploring the multiple trade spaces was challenging. Based on previous experience and desiring to mimic the satellite observation as closely as possible led to selection of the NASA ER-2 aircraft as the target platform. The ER-2 flies at ~65,000 ft (~20 km) as thus is above ~95% of the Earth's atmosphere. More importantly, flying at high altitude allows data collection over a variety of cloud types, and allows examination of the range ambiguity that results from having multiple pulses simultaneously propagating through the atmosphere. These are important considerations for the ICESat-2 mission and cannot be adequately addressed by flying instruments at low altitudes. Developing an instrument for the ER-2 platform also permits an easier transition to the unmanned Global Hawk, or most any other platform, for future science and validation applications.

MABEL is not intended as, and need not be, an exact duplicate of the ICESat-2 instrument. The primary purpose of MABEL is to verify the measurement concept and provide data for algorithm development, rather than attempting to achieve the best possible range precision to the surface. Consequently, the aircraft instrument does not need to have the same level of geolocation, pointing accuracy, or range precision as the spaceborne instrument. MABEL is meant to obtain data similar to ICESat-2 but with flexibility to explore science and engineering trade spaces.

4. MABEL instrument design

The MABEL instrument uses a high repetition-rate pulsed laser fabricated by Fibertek, Inc. The laser repetition rate is variable from 5 kHz to 25 kHz, although typical operations will use 10 kHz to mimic the on-orbit behavior of

ICESat-2. The laser pulse length is 2 ns. If the laser is operated in 10 kHz mode, then a pulse is emitted every 2 cm along track given nominal 200 m/s speed of the ER-2.

The laser generates both 1064 and 532 nm output. However, because only one laser is used, a means to divide the output energy into multiple transmit paths is required. To accomplish this feat, the transmitter fiber splitter box was developed. Refer to Figure 1 for an overall optical layout of MABEL, and Table 1 for a compilation of the primary instrument parameters. Essentially a series of cascading beam splitters, the transmitter fiber splitter box separates the laser output into the two wavelengths then divides the output pulse energy down to the 5-7 nJ level. The output of the transmitter fiber splitter box is a series of eight 1064 nm output beams and sixteen 532 nm output beams. Each output is focused into a 50 μm diameter fiber. In addition, just prior to coupling into the fibers, each beam path can accommodate a small neutral density filter to be used to vary the energy level for each footprint.

The real heart of the MABEL design, and the aspect that permits great flexibility in selecting and changing the instrument viewing geometry, is the transmitter fiber select box and the corresponding transmitter fiber array. Basically, an array of 215 fibers (107 fibers for each wavelength, plus one center fiber) defines the instrument transmit/receive geometry. The fiber arrays were custom fabricated by Fiberguide, Inc. The instrument geometry as defined by the fiber arrays is illustrated in Figure 2. At any given time, sixteen of the 107 532 nm fibers can be coupled to the 532 nm transmitter fibers and eight of the 107 1064 nm fibers can be coupled to the 1064 nm transmitter fibers. Selection of a set of transmitter fibers thus defines the instrument viewing geometry. Because each wavelength has a separate set of transmitter fibers, it is possible to have both wavelengths interrogate the same surface area (e.g., the footprints for each wavelength can overlap). While not changeable during flight, the geometry can be changed between flights to permit evaluation of instrument geometry or to optimize validation capability.

The transmitter fiber array is positioned at the focus of a 5-inch diameter telescope. The telescope is f/4.17, resulting in a 100 μrad field of view for the transmitter. From nominal 20 km operating altitude this corresponds to a laser footprint on the ground of 2 m diameter. Two matched telescopes, both custom fabricated by Special Optics, Inc., are used in the system. The maximum view angle for the system is +/- 3 degrees, or about +/- 1.05 km cross-track.

The receiver is similar, except the fibers are 105 μm diameter resulting in a 210 μrad receiver field of view. The receiver fiber array, positioned at the focus of the matched receiver telescope, is precisely aligned to the transmitter array. The same fiber positions illuminated on the transmitter fiber select box are selected on the receiver fiber select box. The sixteen 532 nm receiver fibers are routed to a 16-channel Hamamatsu model H7260 photomultiplier tube (PMT) detector. The eight 1064 nm receiver fibers are routed to eight individual Excelitas single photon counting modules (SPCMs). The detector dead time on the SPCMs is not ideal for precision ranging, but choices of photon-counting detectors able to operate in the near-IR region are limited.

The signals collected by the detectors are time-tagged by custom electronics developed by Sigma Space Corporation. As prototype for the ICESat-2 mission, demonstrating the electronics was an important step. The time-tagging electronics have a measured resolution of 83 ps (about 12 mm), which is smaller than the ICESat-2 requirement of 150 ps. The data system used to operate the instrument and collect data is based largely on heritage from the Cloud Physics Lidar (CPL) instrument.[McGill *et al*., 2002] Operating on the ER-2 platform requires fully autonomous capability and rugged design. Data is stored to a solid-state hard drive that is removed after flight for data retrieval. A Novatel model HG1700 inertial measurement unit (IMU) is mounted directly to the telescope assembly to permit accurate determination of instrument pointing.

The overall schematic of the MABEL instrument is shown in Figure 3, and a photo of the completed instrument ready for flight is shown in Figure 4. As-built the instrument weighs 550 lbs and is accommodated in the nose of the ER-2 aircraft.

The MABEL viewing geometry can be changed by rearranging the connections on the receiver and transmitter fiber select boxes, as described above. For the initial flights in December 2010, we used a symmetric narrow measurement swath, with the 532 nm channels illuminating the 0, ±0.1, ±0.2, ±1.0, ±1.9, ±2.0, ±3.0, ±4.0, and +5.0 microradian angles. The 1064 nm channels were set at ±0.1, ±0.2, ±1.9 and ±2.0 microradians. From the nominal 20 km measurement altitude, this resulted in a cross-track width of ±100 m.

To provide precise ranging accuracy, small differences in the optical transmit/receive path must be characterized. Path differences in the transceiver path will correspond error in ranging. Thus, it is important to properly characterize the instrument offsets. The optical path differences, known from design and from measurement of the optical path, are summarized in Table 2.

5. Initial flights and data results

To meet the needs of the ICESat-2 project, MABEL development was on a highly accelerated schedule. Instrument development began in October 2009 and initial demonstration flights were expected by November 2010. By the target date the instrument was completed and was shipped to the aircraft for integration. First demonstration flights occurred December 1-7, 2010, with completion of five flights on consecutive days.

For the initial flights, the etalon filter was not yet in place. Thus, the December 2010 flights were conducted late day and into evening, to minimize effects of solar background. The very first flight produced satisfactory results, demonstrating that all subsystems functioned properly. The second flight then resulted in acceptable demonstration data, and subsequent flights were used to optimize system performance and to sample over differing terrain types.

After the initial flights, the etalon filter was received and installed. With the etalon filter in place, a series of daytime flights was planned for March 2011 to conclusively demonstrate expected count rates during daytime operation. For expediency and cost effectiveness the demonstration flights were flown out of Dryden Flight Research Center in California, with emphasis on obtaining useful surface returns rather than obtaining measurements over specific cryospheric targets. Future flights will focus on measurements over ice and snow cover.

One of the first data images collected with MABEL is shown in Figure 5, from December 9, 2010. The image shows a single MABEL channel (the 532 nm, nadir-pointing channel). The data shown is raw, with no corrections for aircraft pointing or other offsets. Of immediate notice is the multi-layered structure in the 5-10 km altitude region. For reference, the CPL instrument was flown with MABEL, and the CPL quick-look image immediately reveals the presence of multiple cloud layers over the surface (in fact, the clouds are dense enough on the left side of the image that the ground is obscured). This initial data image was a surprise to some, as there was a belief that the small pulse energy being transmitted would not permit detection of diffuse targets (i.e., clouds). In fact, as verified by the CPL measurements, MABEL, and therefore the ICESat-2 instrument, are quite capable of detecting cloud layers. Because this data was being plotted in-field with minimal processing, display capabilities were limited to one channel at a time. Work is now underway to develop contouring graphics that will utilize the full multi-channel capability of the MABEL data.

One early flight of MABEL went over Lake Mead, east of Las Vegas, NM, on March 22, 2011. On this flight, it happened that circumstances allowed a good demonstration of the cross-track measurement capability. As shown in Figure 6, the aircraft skirted the lake shore, with part of the MABEL swath over the open water of Lake Mead and part of the swath over land then going out over water. In this image, two of the 1064 nm channels are shown. One channel, #44, is pointed -21 mrad off-nadir. This channel remains over water for the duration of the image. Because water is a dark surface, the background signal is low when over water. The second channel, #47, is pointed +47 mrad off-nadir. This channel sees an increase in background over the brighter land surface, with the background dropping once that channel moves out over the water. As noted on the figure, the separation between the two channels is about 1.32 km. Prior to correction for angle offset, the data also showed the proper 17 m altitude offset between the two channels, which is correct for the 26 mrad pointing difference from the aircraft altitude.

6. Summary

The initial ICESat mission, launched in 2003, demonstrated the unique capability of spaceborne laser altimetry for a variety of advances in the Cryospheric and Earth Sciences. The second-generation ICESat-2 mission will represent a substantial advance in terms of ice sheet coverage, measurement precision, and change detection capability over steeply sloping outlet glaciers, along with improved lead detection for sea-ice freeboard measurements.

Moreover, the ICESat-2 measurement concept of photon-counting detection is a major shift in measurement approach from previous NASA altimetry missions. The laser technology required to support the photon-counting approach is considerably different from that required for analog altimetry. The optical co-alignment and pointing requirements are also more stringent than in previous NASA applications. The success of the technical approach to the ICESat-2 mission will enable a new era in precision laser altimetry measurements for science applications.

To verify and validate the ICESat-2 concept, an airborne simulator was developed. Dubbed MABEL, the airborne instrument was developed in a mere 12 months and was first deployed for engineering test flights in December 2010. A subsequent series of flights were conduced in March 2011. Initial results from MABEL conclusively demonstrate that the concept of photon-counting detection for surface ranging is a viable approach for the ICESat-2 mission. This paper details the MABEL instrument design, as reference for forthcoming papers that will describe in detail the surface measurements, measurement errors, and other results from upcoming MABEL science flights.

7. Acknowledgements

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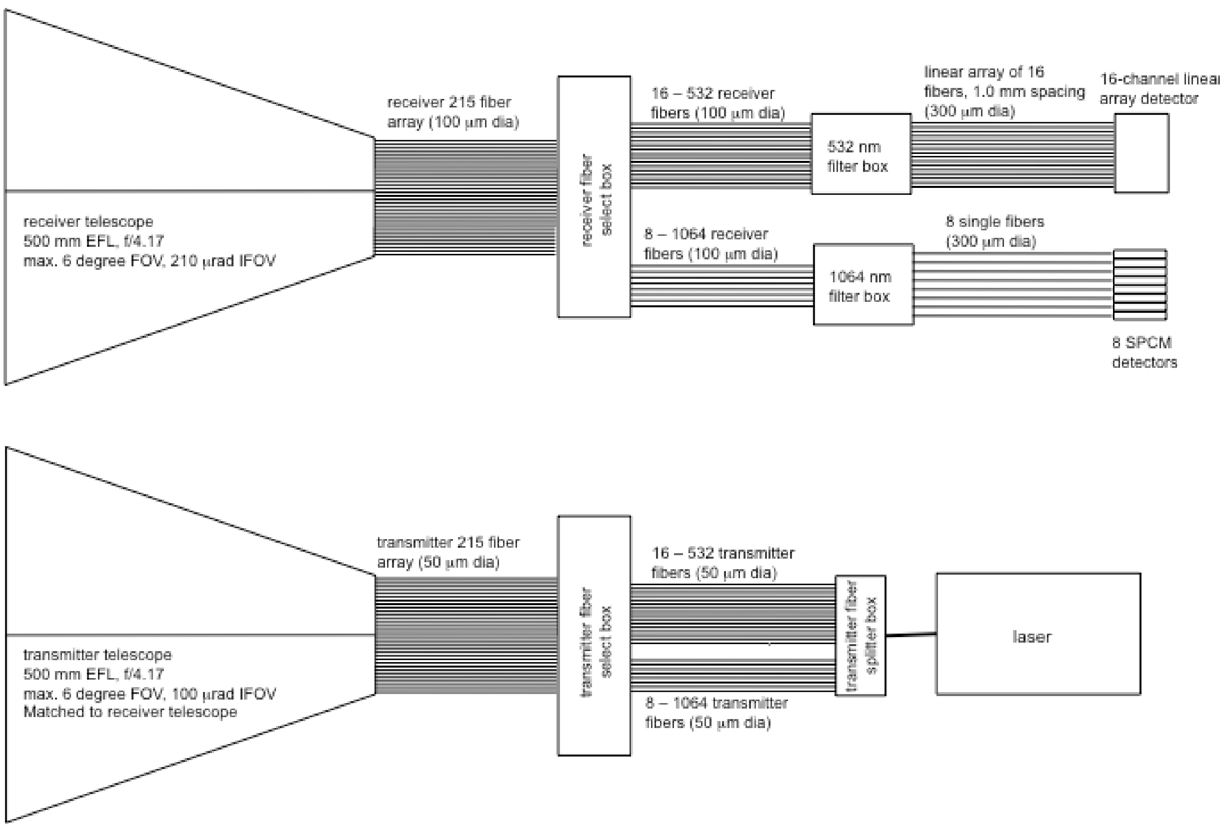

Figure 1: MABEL instrument optical layout. Key to the instrument design is a pair of matched telescopes, one to transmit and one to receive. Selecting which fibers in the transmitter fiber select box are active, and matching to the identical fibers in the receiver fiber select box, determines the instrument viewing geometry.

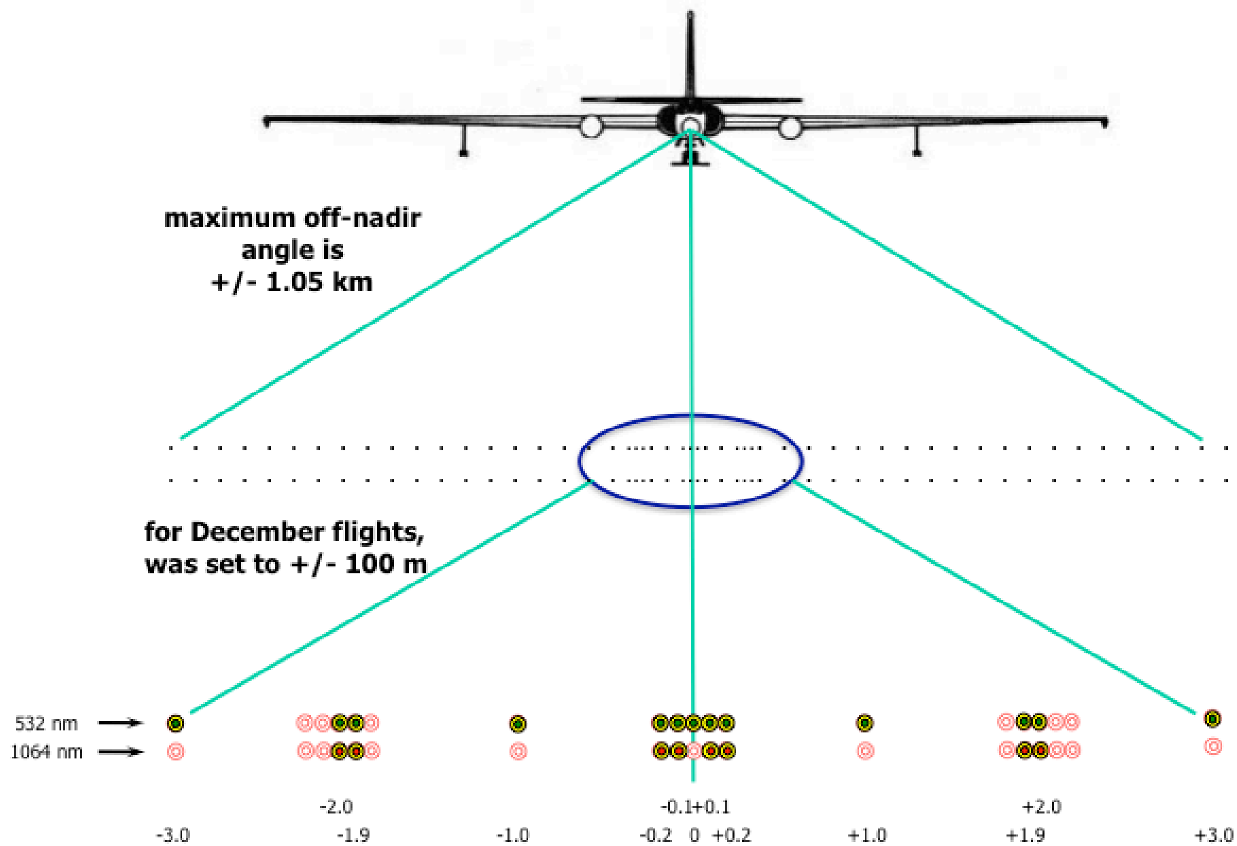

Figure 2: MABEL viewing geometry as defined by fiber arrays. If the outermost fibers were illuminated the swath width would be 1.05 km. For the December flights, only the tightly arranged inner fibers were used, resulting in a ground swath of ±100 m.

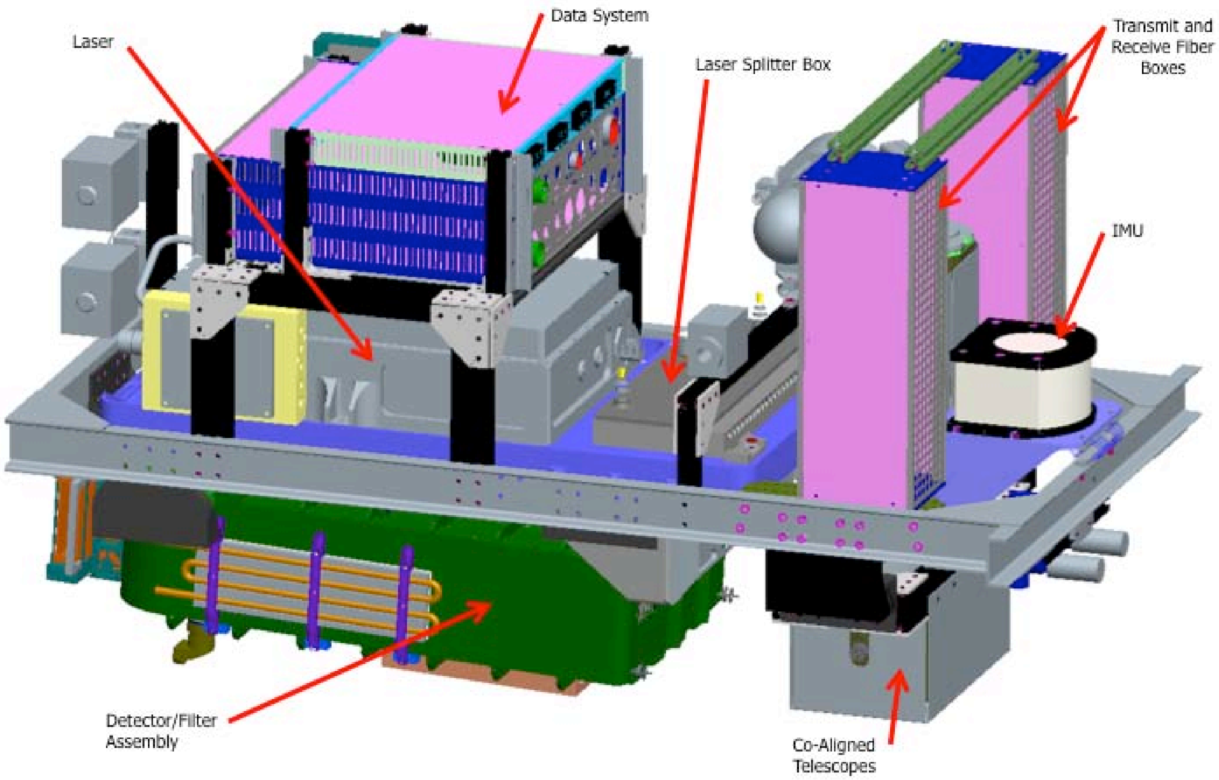

Figure 3: MABEL instrument configuration. Overall dimensions are 52 x 26 x 30 inches.

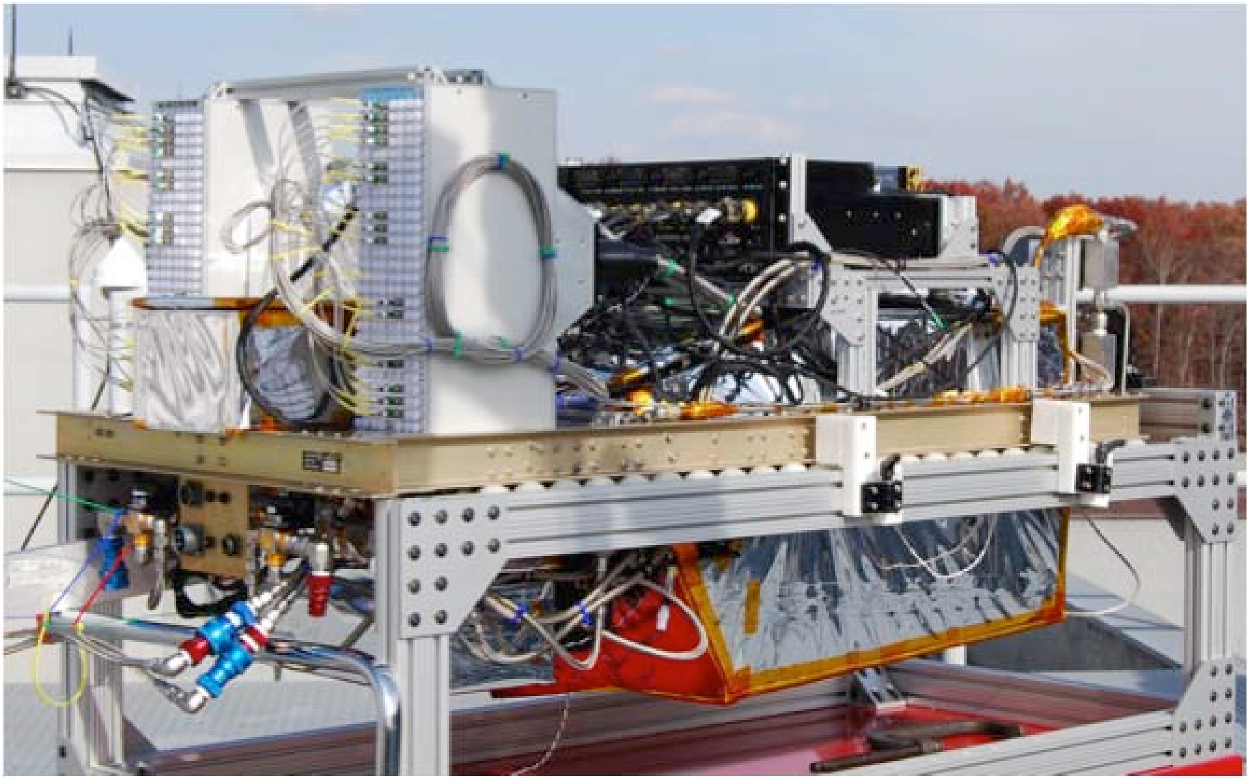

Figure 4: MABEL instrument, in flight configuration.

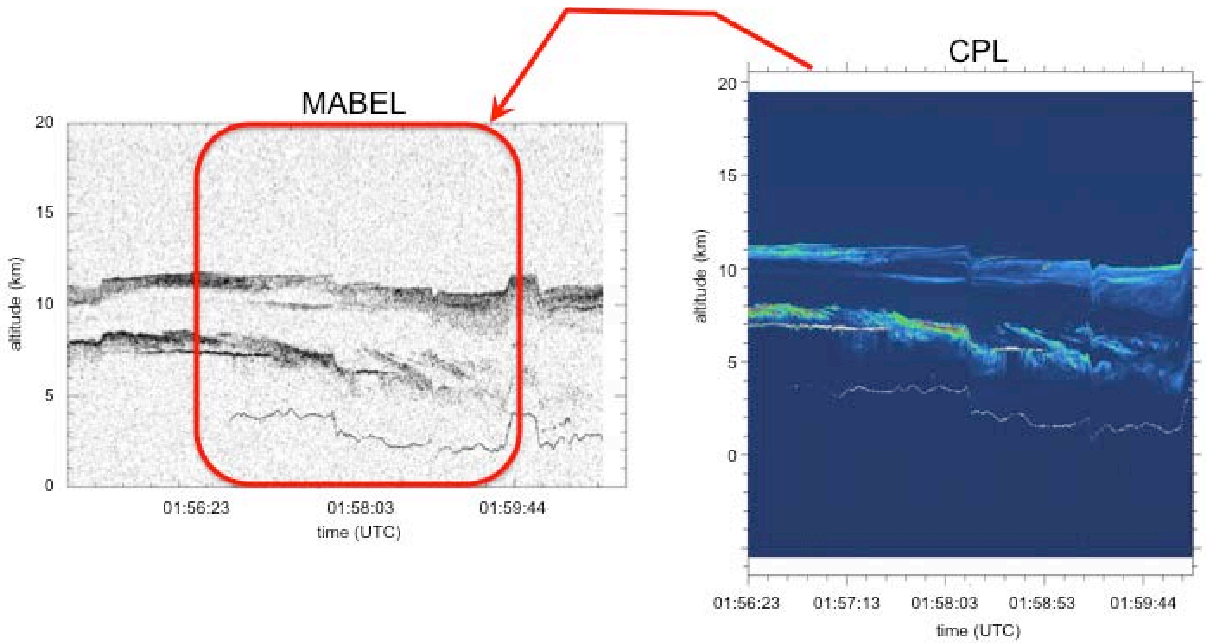

Figure 5: Data from a single MABEL 532 nm channel, acquired December 9, 2010. The data is raw, uncorrected. Vertical jumps in the images are due to aircraft pitch/roll that were not yet corrected in the data. The right-hand image is from the CPL instrument, verifying presence of cloud layers and quite nicely confirming the scene and structure observed in the MABEL data. The portion of the MABEL image circled corresponds to the CPL image.

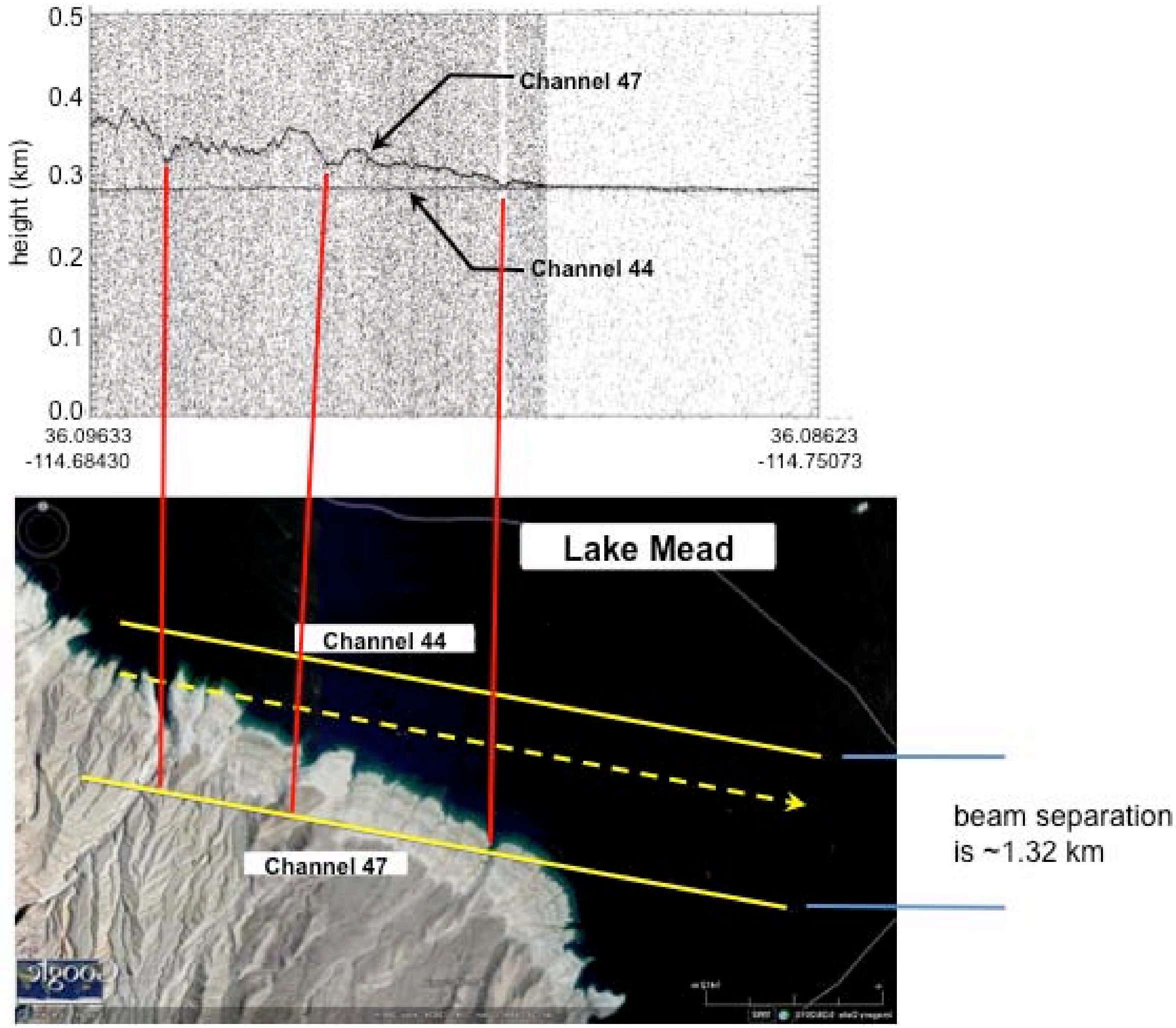

Figure 6: MABEL data from March 22, 2011 over Lake Mead, NM, collected at 17:01 UTC. Although for clarity only two channels are shown, the image provides a good demonstration of the cross-track capability. A Google Earth image provides context for the MABEL tracks. The channel #47 is pointed +47 mrad off-nadir while the channel #44 is pointed -21 mrad off-nadir.

Table 1: MABEL instrument parameters

parameter	value
operational altitude	20 km
wavelength	532 and 1064 nm
telescope diameter	6 inches
laser PRF	variable 5 – 25 kHz
laser pulse energy	variable, nominal 5-7 μJ per beam
laser footprint ($1/e^2$)	100 μrad (2 m)
telescope field of view	210 μrad (4.2 m)
filter width	532: ~150 pm 1064: ~400 pm
detector efficiency	532: 10-15% 1064: 1-2%
swath width (variable)	up to +/- 1.05 km

Table 2: MABEL channel offsets

transceiver channel number	path length difference (mm)
R1 (1064 nm)	0
R2 (1064 nm)	16.1
R3 (1064 nm)	32.3
R4 (1064 nm)	48.4
R5 (1064 nm)	64.5
R6 (1064 nm)	80.6
R7 (1064 nm)	96.8
R8 (1064 nm)	112.9
G1 (532 nm)	27.1
G2 (532 nm)	43.3
G3 (532 nm)	59.4
G4 (532 nm)	75.5
G5 (532 nm)	91.6
G6 (532 nm)	107.8
G7 (532 nm)	123.9
G8 (532 nm)	140.0
G9 (532 nm)	156.2
G10 (532 nm)	172.3
G11 (532 nm)	188.4
G12 (532 nm)	204.5
G13 (532 nm)	220.7
G14 (532 nm)	236.8
G15 (532 nm)	252.9
G16 (532 nm)	269.1