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Global Ecosystem Dynamics Investigation (GEDI) instrument alignment and test.

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ABSTRACT

NASA's Global Ecosystem Dynamics Investigation (GEDI) instrument was launched Dec. 5, 2018, and installed on the International Space Station 419 km from Earth. The GEDI is a Light Detection and Ranging (LIDAR) instrument; measuring the time of flight of transmitted laser beams to the Earth and back to determine altitude for geospatial mapping of forest canopy heights. The need for very dense cross track sampling for slope measurements of canopy height is accomplished by using three individual laser transmitter systems, where each beam is split into two beams by a birefringent crystal. Furthermore, one transmitter is equipped with a diffractive optical element splitting the two beams into four, for a total of 8 beams. The beams are reflected off of the features and imaged by an 800 mm diameter Receiver Telescope Assembly, composed of a Ritchey-Chrétien telescope, a refractive aft optics assembly and focal plane array which collects and focuses the light from the 8 probe beams into the 8 science fibers, each with a field of view on the Earth subtending 300 μ rad. The dense cross-track sampling mandated a custom designed dual-fiber interface. The science fibers had to be aligned to the nominal, projected laser spots. The alignment was highly dependent on optimization and co-positioning of the fibers pair-wise due to mechanical constraints. This paper presents the end-to-end alignment and metrology of the full optical system from transmitter elements through receiver telescope, aft-optics, focal plane and receiver fibers performed at NASA Goddard Space Flight Center.

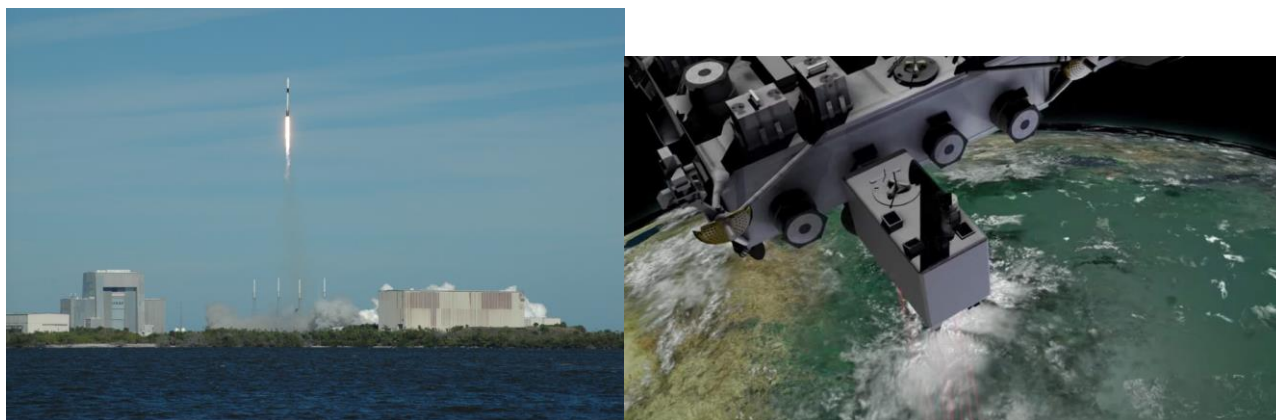


Figure 1. a) GEDI launching on a SpaceX Falcon from NASA's Kennedy Space Center December 5, 2018. b) GEDI mounted on the International Space Station.

Keywords: GEDI, Receiver Telescope Assembly, Alignment

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1. INTRODUCTION

NASA GSFC has designed and built several LIDAR instruments with progressively increasing requirements and capability over time. GEDI is the LIDAR instrument with the highest number of science channels to date, and presents challenging and complex requirements for imaging and alignment. GEDI produces the first high resolution laser ranging observation of the 3D structure of the Earth¹. As the highest resolution and densest sampling of any orbiting LIDAR, GEDI makes precise measurements of forest canopy height, canopy vertical structure, and surface elevation, thereby greatly improving the ability to characterize carbon and water cycling processes, biodiversity, and habitat information. The mission duration is planned for 2 years aboard the ISS. See Figure 1.

The sole GEDI observable is the waveform, and all other data products are derived from this. Signal processing is used to identify the ground within the waveform. The distribution of laser energy above the ground can be used to determine the height and density of objects within the footprint. The view geometry and active use of light by LIDAR allows the ground to be identified through small gaps in the tree canopy, enabling unsaturated measurements of much denser forests than is possible with either passive space borne cameras or with short wavelength radar systems. In addition, uniquely amongst satellite remote sensing, the height and vertical distribution are direct measurements that can be compared to field observations. The GEDI instrument is designed to map the 3D structure of the Earth with emphasis on forest canopy height, canopy vertical structure, and surface elevation. Of the three GEDI lasers, the two canopy lasers each produce 10.5 mJ, and the coverage laser produces 4.2 mJ. The transmitters are equipped with internal 2.5x mini beam expanders, and external 11.3x refractive beam expanders which further increase the beam diameter to 50-60 μ rad.

The GEDI telescope was manufactured by General Dynamics, originally as a spare for the Advanced Topographic Laser Altimeter System (ATLAS) instrument for the ICESat-II mission, but was found to fulfill the specifications for the GEDI mission, and was transferred to GEDI after the ICESat-II mission had determined that the ATLAS mission did not need the spare telescope². The optical prescription for the receiver telescope utilizes a two-mirror axis-symmetric Ritchey Chretien design. The 0.8 meter diameter light-weighted primary mirror was diamond turned from beryllium, electroless nickel plated and polished with a small tool. The secondary mirror is also diamond turned from beryllium and electroless nickel plated and small-tool polished. Both mirrors were then coated for performance at 532 nm and 1064 nm wavelength. The telescope itself is optimized for the performance obtained for a field point on the center-axis of the telescope. It has been equipped with a 3-element refractive aft-optics assembly corrector unit which improves the off-axis performance of the telescope, as the 8 GEDI field points are located off-axis in a pattern around the on-axis field. The on-axis field is not used by the GEDI Instrument on-orbit, but has been used during part of the initial ground testing.

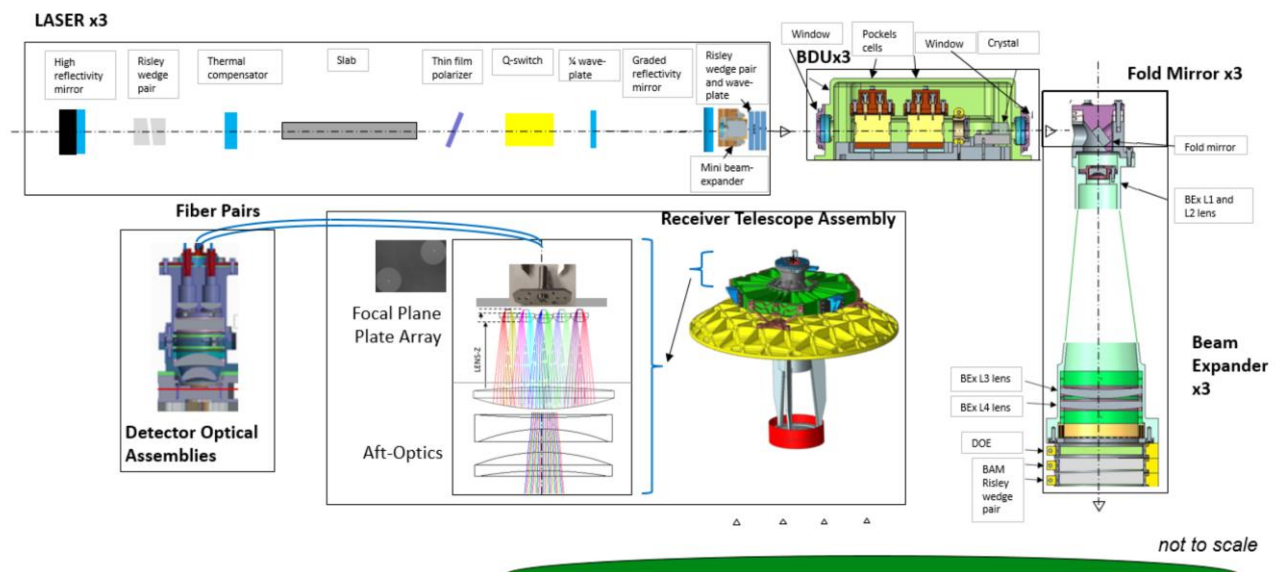


Figure 2. GEDI optical block diagram.

The Aft Optics was designed, assembled and tested interferometrically at NASA GSFC using fused silica lenses fabricated by Optimax. A narrow dual-band transmission coating was applied to all surfaces to minimize out of band stray light and allow transmission at 1064 nm as well as 532nm. The GEDI focal plane plate assembly is mounted directly to the back of the Aft Optics Assembly, and it consists of eight 600 μm diameter multimode fused silica fibers aligned to eight field lenses which reduce the 3.6 m focal length telescope to 2 m. The fiber optics in the focal plane must be aligned to within 30 μrad of the transmitted laser beams, and the receiver telescope must have an image quality that provides a sufficiently small focused image. Figure 2 shows the GEDI optical block diagram. The hardware was provisioned for a total of 10 field points, as Diffractive Optical Elements were manufactured for both Transmitter (Tx) path #1 and #3, but it was chosen to only install DOE on Tx#1 and benefit from the higher output power in each of the two channels provided by Tx#3.

2. GEDI SYSTEM OVERVIEW

Early on in the Flight hardware building phase of the GEDI mission, Ground Support Hardware (GSE) necessary for the test and alignment of GEDI was moved to the cleanroom assigned to GEDI for test and integration. The GEDI Instrument comprises a number of subsystems, all installed on a composite panel Optical Bench with mechanical inserts for each subsystem. GEDI is a LIDAR instrument and therefore comprises both transmitter and receiver subsystems. The transmitter subsystem consists of 3 separate transmitters, which must be aligned individually⁶.

- Lasers (3)
 - 1064 nm, equipped with a Risley-pair, waveplate (for polarization contrast ratio optimization), and mini beam expander. Pointing into the Beam Dithering Unit (BDU).
- Beam Dithering Units (BDU) (3)
 - BDU, a novel type of unit conceived, developed and flight qualified at GSFC separates the incoming beam in two beams (time multiplexed), angularly separated 18.85 mrad. BDU sets the distance between two field points in a group.
- Fold Mirror (FM) (3)
 - Brings the two signals from the BDU output on the $-Z$ side of the OB to the $+Z$ side of the OB where they enter the Beam Expander (BE).
- Beam Expander (BE) (3)
 - A 4-element refractive, afocal 11.3x Beam Expander (BE) which reduces the divergence of the transmitted beams and the field angles of the BDU beams is mounted in a Transmitter Optical Assembly housing.
- Diffractive Optical Element (DOE) (1)
 - Splits a beam pair into two beam pairs, setting the distance between field point groups.
 - DOE is installed on canopy transmitter path 1.
- Boresight Alignment Mechanism (BAM) (3)
 - Consists of a pair of motorized Risley prisms which allow for adjustment of the boresight. The Risley's are primarily used to adjust boresight after launch during commissioning, but can be activated occasionally between science operations, if necessary.

The GEDI receiver subsystem consists of

- Receiver Telescope Assembly (RTA) (1)
 - A two mirror axis symmetric Ritchey Chretien telescope design with a hyperboloid primary mirror (0.8 m diameter) and secondary mirror pair. The reflective telescope has an Aft-Optics Assembly (AOA) mounted near its focal plane to improve off-axis performance. The GEDI RTA optical design is telecentric which is required for efficient fiber-coupling, and it operates at $f/2.5$ (corresponding to 2m EFL/0.8m clear aperture), slower than the fiber $f/2.27$ (0.22NA).
- Focal Plane Plate Assembly (FoPPA) (1)
 - The GEDI Focal Plane Plate Assembly (FoPPA) provides the interface to the 600 μm diameter science fibers which connect the received signals to the Detector Module (DM) installed in the GEDI box structure. FoPPA has a field lens for each science field point to reduce the original EFL from 3.6m to 2.0m.
- Detector Module (DM)
 - DM is fiber coupled and installed directly into the GEDI box structure enclosure, and no alignment at the optical Alignment Integration & Test level is required. Figure 3 shows a schematic of GEDI channel configuration.

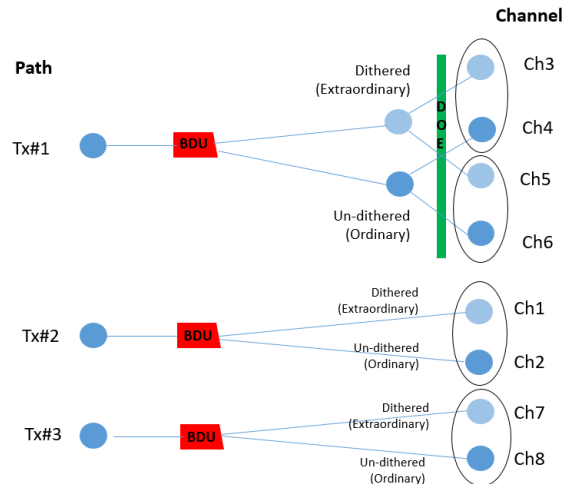


Figure 3. Conceptual Path to Channel association (but does not show the exact to scale physical path and only those optical elements which affect the number of beams).

3. GEDI RTA IMAGE QUALITY TESTING

The GEDI RTA wavefront error was measured using a double-pass interferometry test setup. The double-pass interferometry test system consists of the gimbal mount for the RTA, an ESDI (Intelliwave) interferometer, Ball Alignment Fixture and a large flat mirror; the Horizontal Autocollimation Flat (HAF), which is a 36" diameter flat mirror which wavefront has been characterized at Arizona Optical Systems, such that the HAF mirror figure can be analytically subtracted from each RTA wavefront map at each field position measured. The WFE interferometry measurement was performed at 632 nm. This measurement was performed as shown in Figure 4.

The optical-axis horizontal interferometry test allows independent verification of the measurements performed at General Dynamics where the telescope was held vertically and was gravity-offloaded by mechanical paddles. The GEDI RTA was mounted in a modified commercial gimbal mount which allows for precise angular tip/tilt adjustment to allow measurement of the wavefront at selected field points. To control interface stress, the RTA is mounted on a diamond turned interface plate on the gimbal. The interface plate is diamond turned at the three RTA interface pads, and the opposite side accommodates a diamond turned optical reference flat indicating the RTA boresight. RTA was mounted to 0.0005" coplanarity to the interface plate on the gimbal mount.

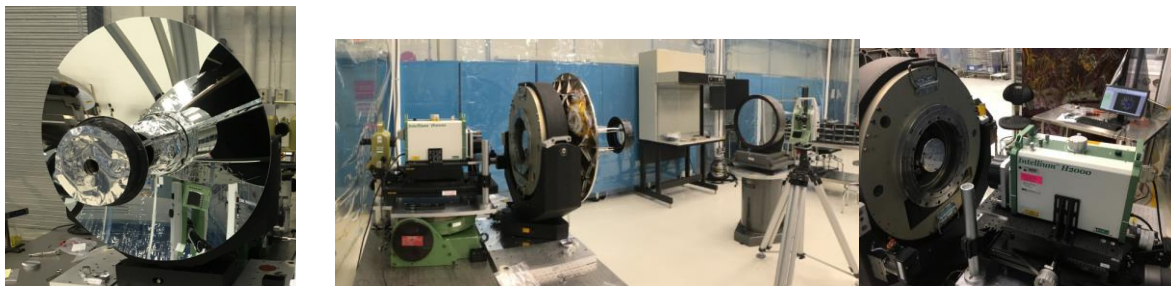


Figure 4. GEDI telescope (left) and interferometer test setup (right)

3.1 GEDI RTA Zero Gravity Wavefront Error

Alignment of the interferometer to the RTA was performed by utilizing a Ball Alignment Fixture (BAF) consisting of a diamond turned flat with holes drilled at precise points which are populated with removable high-sphericity high-precision

tooling balls placed in delrin inserts. The tooling balls can be precisely positioned along focus relative to the diamond turned datum surface. The BAF is detachable and re-insertable to allow the same field point to be measured at different RTA clocking orientations. It replaces the GEDI focal plane plate that resides on the Aft Optics and is an alignment aid for positioning the interferometer and mapping out the RTA focal plane for determining placement of the flight optical fibers, the Receiver Fiber Optic Assemblies. The interferometer is mounted on a stage that is adjustable in the focus axis as well as laterally to interrogate the instrument field of view. A fast transmission sphere (lower f/#) on the interferometer allows overfilling the secondary mirror to eliminate the need to tilt the interferometer during wavefront testing across the field of view. Figure 5 shows the processed 0-G wavefront map for the 180 degree-clocking pair after the surface residual error of the autocollimation flat mirror has been subtracted.

The gimbal mount includes a manual rotation stage to allow clocking around the optical axis of the RTA for alignment purposes and in order to allow the wavefront to be measured in 180 degree opposite orientations to provide a zero gravity (0-G) wavefront map of the precise focal surface. To measure the 0-G wavefront error, wavefront maps are acquired at 180-degree clocking RTA intervals, for 5 field positions, including on-axis, which is not a science field point, but measured for reference. Wavefront maps for 180-degree rotated wavefront measurement pairs should average out gravity induced deformations, and by processing and averaging the 180 degree averaged pairs a zero gravity figure can be estimated. The RTA is clocked in the gimbal mount and wavefront measurements are acquired at each field for each RTA clocking angle. At each RTA clocking angle the BAF is counter-rotated to allow field sampling to stay in the plane of the interferometer horizontal translator. The measurements were repeated after the GEDI AOA was installed.

The GEDI 0-G measurement includes clocking angles of 0 degrees and 180 degrees, respectively, which was found to provide sufficient information from previous testing of the ‘sister-RTA’ telescope, which General Dynamics manufactured for NASA’s ATLAS mission. The ATLAS RTA had undergone a measurement series including 6 different clocking rotations, and as the end result was insignificantly different from the 0 to 180-degree clocking orientation results, it was decided to measure the GEDI RTA in only two different clocking orientations, 0 degrees and 180 degrees ².

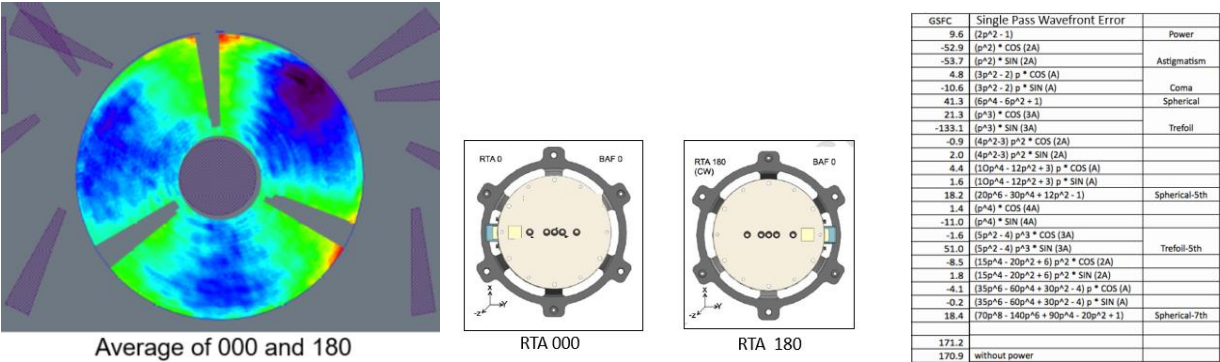


Figure 5. GEDI RTA 180 degree clocking WFE test and resulting 0-G figure. BAF shown in the center.

The estimated zero gravity wavefront error is 171 nm rms at the 632 nm test wavelength which compares favorably to the 224 nm rms single pass wavefront error measured at General Dynamics in a cup-up vertical double-pass interferometry test with the telescope gravity offloading system activated. The largest difference between the measurements is due to the uncertainty in the HAF mirror astigmatism; consistent with changes measured after moves during characterization at Arizona Optical Systems

3.2 GEDI RTA focal surface mapping and focus setting

Mapping of the GEDI RTA focal surface was performed in a double-pass interferometry test setup with a 20” subaperture flat where the wavefront error was minimized to locate the correct focus position. The RTA was held in the 6 DOF gimbal mount as shown in Figure 4. Interferometry was required to allow placement of each fiber at their nominal focus position prior to performing plate scale measurements of the RTA. In order to ensure that the plate scale measurements which are to be performed later will not be biased by defocused images, care has been taken to position the optical fibers as precisely as possible on the focal surface. The Ball Alignment Fixture is critical in determining the offset between the zero-power position of the interferometer at each field point and in determining the placement of the science fibers along the z-axis

relative to the aft optics assembly mechanical datum surface. See Figure 6 for an image of the Ball Alignment Fixture.. After achieving a null on the ball, the ball is removed, and the initial axial and horizontal translation readings on the micrometers that are used to align the interferometer are captured. The interferometer is then translated along the focus axis to minimize power in the RTA double pass wavefront, and the new micrometer position, as well as the wavefront error, is recorded. Different field points were accessed for testing after tilting the transmission flat the desired amount.

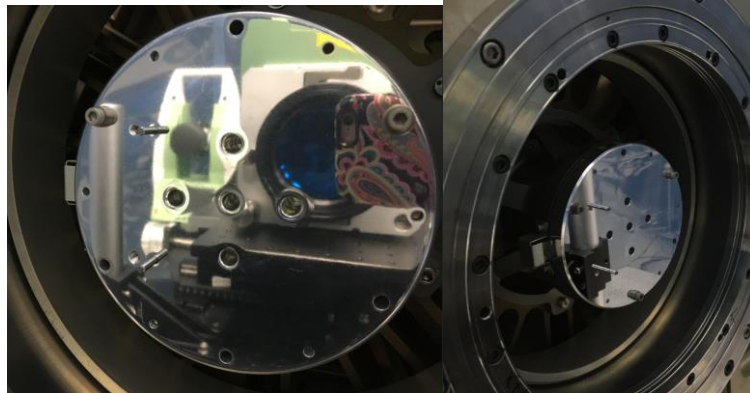


Figure 6. The GEDI BAF plate used in focal surface mapping.

The GEDI RTA focus was set using the focal surface mapping performed with the interferometer offset for the difference between the nominal science laser wavelength of 1064 nm and the interferometer test wavelength of 632 nm. Knowledge of the diamond turned surface, the AOA datum surface and the measured null produced extremely repeatable and consistent results with very little change in focus with orientation. Based on analysis this degree of uncertainty results in changes in the expected encircled energy diameter of less than 1 μm and focal surface position of less than 50 μm , which is within the required accuracy to align the fibers to the focal surface (in Z). The Focal plane plate assembly allows for the GEDI Receiver Fiber Optic Assemblies to be individually positioned and shimmed on the focal plane plate. However, if individual shimming is not necessary, the system will be less complicated. With the nominal 'global' shim of 3.505 mm installed on the AOA, the measured field points were found to be aligned to within +3 μm and -12 μm of the required setting, thereby not requiring individual shimming.

The plate scale measurements of the RTA followed the focal surface mapping and focus setting. The fibers are mounted into ultra precision custom adapters developed by NASA GSFC. Positioning of the adapters was performed using a Vertex MicroVu optical coordinate measuring machine after a local focal plane coordinate system was established. The GEDI focal plane plate being configured for measurements with the MicroVu system is shown in Figure 7.

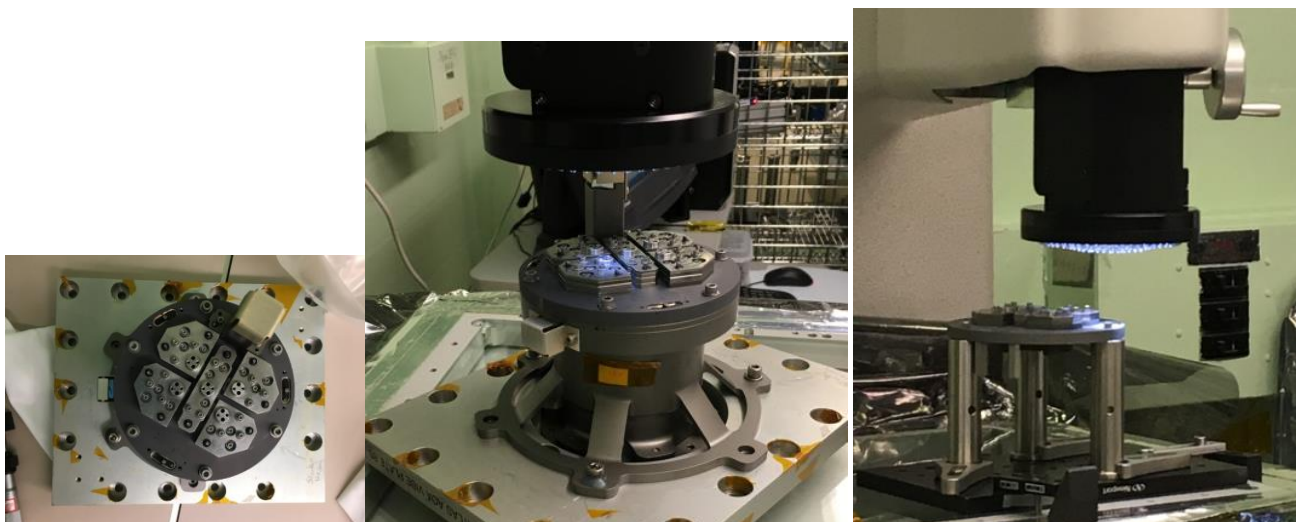


Figure 7. The GEDI Focal Plane Plate Assembly being measured in the MicroVu.

A local coordinate system on the focal plane plate is defined in the MicroVu instrument. The origin of the coordinate system is at the central hole on the focal plane plate. Once this coordinate system is defined the MicroVu displays the position of the center of the image in the field of view. Illumination of the adapters from below the focal plane allowed for very accurate determination of the center of the fiber in the local coordinate system. It was possible to adjust the adapter positions by loosening the fasteners and sliding the adapters on the interface and tightening them down. The purpose of this pre-alignment was to place the adapters close to nominal to limit the amount of adjustment required in the integration facility, where the focal plane would be vertical during alignment. The use of high magnification and adaptive lighting on the MicroVu allowed placement of the fiber adapters to better than 5 μm accuracy in each degree of freedom. However, since the fiber-pair adapters on the focal plane plate are mechanically coupled, the positioning was inter-dependent, and there was a penalty realized based on that, but the alignment budget accommodated this. The change in fiber-pair distance from pre-to-post thermal test of the focal plane plate had been measured to the less than 8 μm .

3.3 GEDI RTA plate scale and focal length determination

The GEDI focal plane plate was installed on the back of the Aft-Optics Assembly of the telescope in the integration facility. The GEDI focal plane plate assembly (FoPPA) has a field lens installed for each science field point to reduce the ATLAS RTA EFL from 3.6m to 2.0 m to yield a 300 μrad diameter Instantaneous Field of View (IFOV) with a 600 μm diameter fiber.

The GEDI RTA field mapping was performed with a 1064 nm light source connected to two multi-channel integrating spheres to cover all field points, illuminating the RTA from the back via the EM fibers between the integrating spheres and the Engineering Test Unit (ETU) focal plane plate assembly, as shown in Figure 8. A theodolite equipped with a Basler camera capable of IR imaging was installed in front of the primary mirror of the telescope, viewing three fiber pairs at a time on the camera screen. Using an average of 3 readings per channel, the Azimuth and Elevation positions of the illuminated spots was noted. The EFL and plate scale, respectively, are reported as the average of each of the tested fiber pairs. The plate scale was measured with the RTA clocked 0 and 180 degrees with no discernable difference. The focal length and plate scale before FoPPA installation was measured to 3610 mm and 277 $\mu\text{rad}/\text{mm}$, respectively. The IFOV was measured to 302.3 mm, corresponding to an Effective Focal Length (EFL) of 1.985 m, which is in the specified range of 2.0 m $\pm$ 0.018 m.



Figure 8. GEDI Focal plane plate assembly with fibers during plate scale measurement.

The focal plane design incorporating the field lenses was created in order to be able to keep the existing aft-optics assembly design and optical prescription for the 3 refractive corrective lenses. The GEDI Aft-Optics Assembly and the focal plane plate assembly (FoPPA) underwent optical performance test at flight qualification temperatures, as well as vibration test, before integration to the GEDI telescope.

The thermal optical behavior of the sister RTA was well known prior to the GEDI RTA. For the GEDI Instrument the individual elements such as lasers, detectors, fibers, beam expanders etc. were TVAC tested before integration to the GEDI Optical Bench, and the entire GEDI was TVAC tested at Instrument level. The telescope design is athermal, as all optical components are made of beryllium, and Zemax modeling showed that the telescope stays focused as a function of bulk

temperature change. The RTA design is also athermal over a 20 ± 20 C bulk temperature operating environment, if the telescope axial and primary radial gradients are kept within <2 C axial and <1 C based on the 11.4 ppm/C Beryllium thermal expansion coefficient. Therefore, it was experimentally verified in the GEDI program that when all the GEDI telescope/RTA components have the same temperature and exemplified by establishing small temperature changes around the ambient temperature in the integration facility clean room. The test was performed by measuring the GEDI RTA Instantaneous Field of View (IFOV) of the image captured by the Basler camera, at different temperatures, and verified that the IFOV diameter, and thereby focus position, was unchanged.

The 5.1772m m EFL Parabola (which was later used in the GEDI Collimator) is in the clean room, and is pointed towards the RTA. A Basler camera is installed on a stage mounted on a tripod, and is positioned at the focal point of the Parabola, where it captures a set of spots (Ch1 and Ch2) from the GEDI RTA back-illuminated through the EM fibers with a 532 nm laser source. A visible laser source is used for convenience, as the athermal behavior of RTA is independent of test wavelength. At the three test temperatures, 22.2 C, 20.5 C and 23.5 C, the stage is moved in Z (along the optical axis) to verify that the image is correctly in focus. Figure 9 shows images acquired with the stage positioned at the parabola focal point.

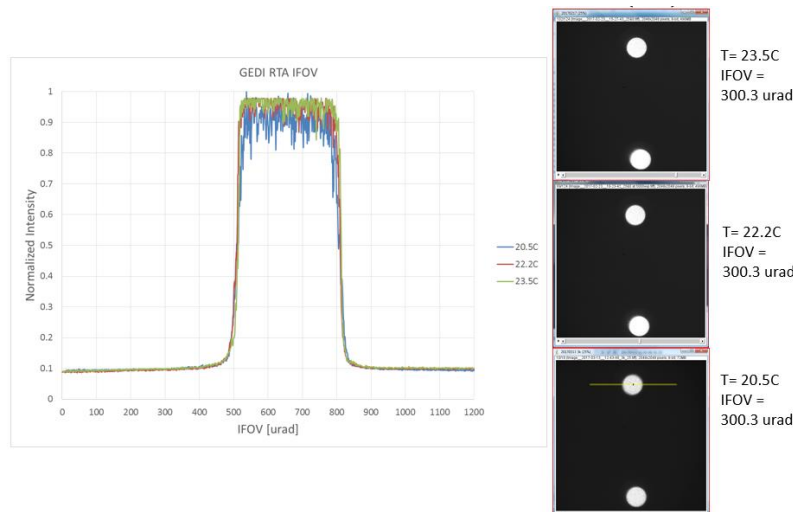


Figure 9. GEDI IFOV during temperature change test.

3.4 Encircled Energy

The encircled energy (EE) is a measure of concentration of energy in an optical image, and determines how efficiently light is coupled into the instrument science fibers and how much pointing boresight margin is available. The EE for the GEDI RTA was determined at ambient at an early stage in the program. For the primary mirror, spindle wobble during diamond turning produced high frequency figure errors that were not completely polished out. Encircled Energy measurements were performed at the RTA level where the configuration included the telescope with aft-optics unit (but not the FoPPA with the field lenses) combined with interferometry using subaperture analysis was performed to determine the optical performance.

The EE was tested in a collimator using a 40" diameter parabolic mirror, an elliptical fold mirror and a laser source. The 40" diameter parabola figure was measured at its center of curvature using an interferometer, and the elliptical flat fold mirror was measured interferometrically as well, allowing a model of the collimator to be created. The reference for the collimator primary mirror boresight is the back surface of the mirror, which allows for a repeatable alignment reference.

A LUPI compact interferometer placed at the source table is used for illumination of the parabola in characterization of the system in a double pass configuration using a 36" diameter flat mirror, the Horizontal Autocollimating Flat (HAF). The HAF was characterized at Arizona Optical Systems to allow for the WFE of the HAF to be subtracted from the RTA measurements.

The collimator used for testing of the RTA undergoes periodic characterization to satisfy critical ground support equipment requirements of the wavefront error and power to be minimized. For this purpose, a precision tooling ball is translated

into position and adjusted until it is nulled to the interferometer, providing a reference. The tooling ball resides on a two-axis stage that also holds the fiber source and collimator-imaging camera. For encircled energy measurements the precision tooling ball is translated out of position and the launch fiber is translated into position. A theodolite monitoring the collimated LUPi laser beam acquires the single mode fiber, which is then translated to the same boresight angle as the interferometer point source. Focus of the fiber is achieved by maximizing the amount of energy retro reflected back into the fiber. When the collimated fiber point source is aligned, the cart holding the HAF mirror is rolled out of the optical path, allowing the beam to reach the RTA in the gimbal mount. The diamond turned mounting plate holding the RTA to the gimbal mount is used to align each RTA field position to the collimator.

The best focus RTA images average an encircled energy of $77\text{ }\mu\text{m}$, well within the $90\text{ }\mu\text{m}$ goal. See Figure 10². The impact of a $100\text{ }\mu\text{m}$ focus error is less than $1\text{ }\mu\text{m}$ on encircled energy – insignificant when RSS'ed with a $77\text{ }\mu\text{m}$ EE telescope. The impact of the HAF mirror on the encircled energy is less than $1\text{ }\mu\text{m}$, which also is insignificant to the measured EE. The difference in the average encircled energy measured for RTA in 000 degree orientation and in 180 degree orientation is less than $2\text{ }\mu\text{m}$.

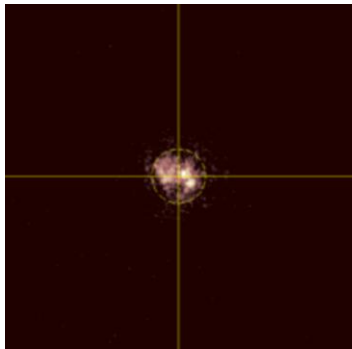


Figure 10. RTA 80% Encircled Energy measurement example²: $74\text{ }\mu\text{m}$, at best focus, RTA clocking orientation 0 degrees.

4. GEDI RECEIVER BORESIGHT ALIGNMENT

The task of the GEDI Receiver Telescope Assembly fibers in the telescope focal plane is to collect the transmitter light after it has been reflected off respective footprints on the Earth, then deliver the collected light to the detectors in the detector assembly. The alignment of the laser, BDU, fold mirror, Beam Expander and DOE (for Tx#1 specifically) in each transmitter path determine each transmitter beam direction. The DOE is a holographic element that diffracts the E and O beam exiting the BDU into primarily 4 spots, each pair separated by 5.985 mrad . The Receiver Fiber Optic Assembly fiber adapters connecting and holding the fibers to the focal plane plate assembly require adjustment capability in order to match the center of the field of view for each fiber at the location corresponding to the appropriate transmitter. The output beam divergence for the transmitters is $50\text{--}60\text{ }\mu\text{rad}$ for GEDI, and the IFOV of the RTA is $300\text{ }\mu\text{rad}$. The nominal size of the laser beam on the ground is approximately 22 m ($\pm 3\text{ m}$). Common path alignment errors between the spots in each transmitter and the receiver can be corrected using the BAM. System dimensioning offers this option, primarily intended for use in commissioning after launch, but the BAM's can be run via the flight software during on-orbit 'housekeeping' sessions of the instrument. The purpose of the receiver to transmitter boresight alignment is to minimize the uncorrectable alignment errors and demonstrate margin that is consistent with expected changes from ground to on-orbit.

The BAM does not offer a better alignment than what can be obtained on the ground; as the radial distance between the spots are restricted from being reduced or increased, and inter-channel alignment cannot be changed, but the spot pattern within each transmitter system/group can be moved to optimize the match to its corresponding receiver channels.

As the individual GEDI optical subsystems became ready after performance and environmental testing, they were transferred to the GEDI AI&T facility for integration to the GEDI Instrument. All GEDI alignment sensitive subsystem components were installed on the optical bench. The detector modules are not alignment sensitive at the system level, as they are Diamond AVIMTM fiber coupled. At optical bench level, there is access to all the subsystem components, which is important during the integration and alignment phase. By the end of integration and alignment the optical bench would be carefully lowered into the GEDI box structure.

4.1 Collimator

A key element in the GEDI integration and alignment phase was the large collimator needed in order to boresight the GEDI Transmitters and Receiver. A 5.1772 m EFL on-axis parabola is located (optical axis horizontal) at the end of the GEDI cleanroom. A 6" x 9" flat fold mirror is positioned in front of the parabolic mirror, angled 45 degrees in order to fold the beam out of the GEDI optical path and onto an optical table holding a Basler CMOS camera capable of detecting visible and IR signals. The GEDI Collimator setup is shown in Figure 11.

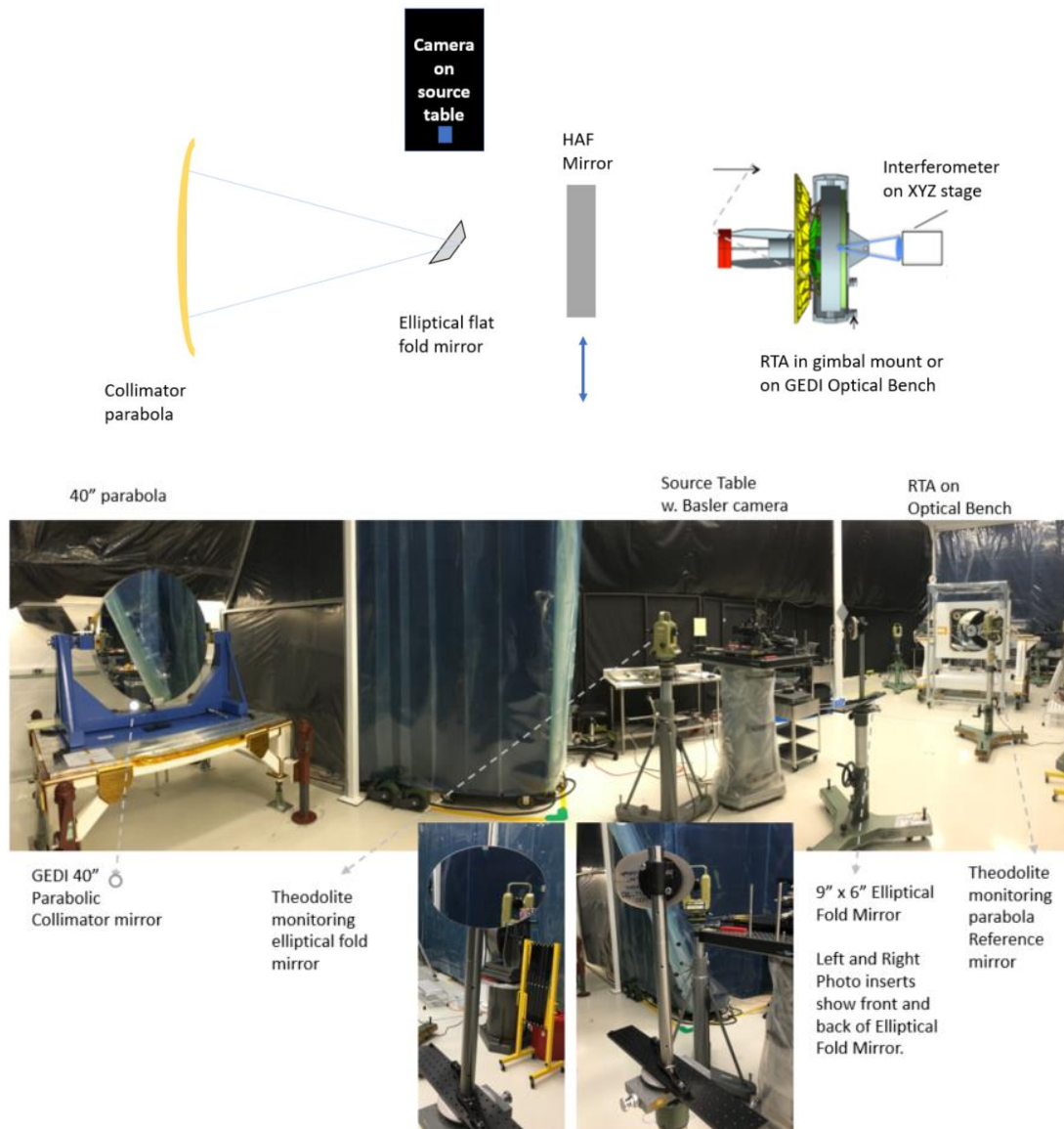


Figure 11. GEDI Collimator: Schematic diagram shown at top. Photos show from left: 40" diameter parabola, flat fold mirror (center), source table and GEDI on Optical Bench in Instrument dolly (right).

The collimator is characterized and calibrated before use, and stability over time is ensured. The camera at the focal point of the collimator has a field of view which allows one pair of field points to be viewed at a time. Transitioning between field point pairs is done by lateral shift of the GEDI Instrument in its dolly combined with tip/tilt action of the dolly to point the proper pair of field points into the collimator. Theodolites were used to ensure that the collimator setup itself is un-altered, in order to maintain its calibration. By back-illuminating the RTA, which was done by injecting light into the

GEDI receiver fibers, collimated beams were transmitted out through the telescope and into the collimator, and these beams were displayed on the collimator focal plane camera screen. In order to align the transmitter to the receiver, the transmitted spots from the transmitter under alignment were sent into the collimator as well, and the transmitter spots were displayed on the collimator focal plane camera screen. The camera screen covers an area of about $2100 \mu\text{rad} \times 2100 \mu\text{rad}$, and once the transmitter spots were located on the screen with the back-illuminated receiver spots, the work to actively co-center the beam pairs began. The collimator focal plane camera screen provided excellent visual feedback during alignment, with the spots easily distinguishable, due to the expected differences in size and brightness of the transmitted beams (small, bright) versus the back-illuminated receiver spots (large, dim). See Figure 12.

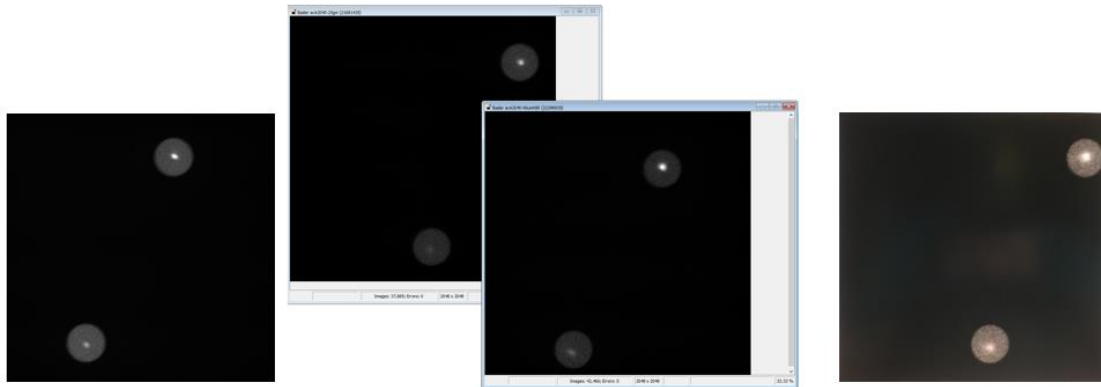


Figure 12 Bore sight alignment of all three Tx/Rx systems.

Two low power alignment lasers (COTS fiber coupled laser with a launcher boards fitted with adapters that mount to the Flight laser inserts on the Optical Bench), seen in Figure 13, were used in preliminary alignment work for proof of methodology.

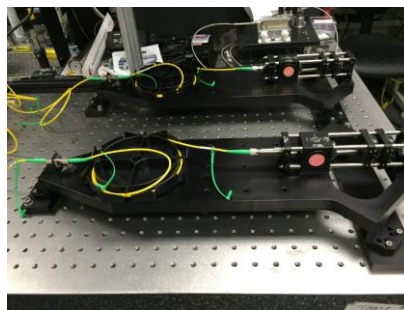


Figure 13 The two GEDI alignment lasers on boards.

4.2 Optical Bench

The GEDI Optical Bench was fabricated at the Goddard Space Flight Center and consists of an aluminum core with composite panels epoxied to the core. This structural panel was machined to accommodate titanium fittings that allow integration of the instrument components on the Optical Bench. A laser tracker (LT) and LT targets are used to measure the three RTA inserts together with other LT targets mounted on the $-Z$ side of the OB. After RTA is installed on the OB, the pin holes will no longer be visible. By measuring several targets along with the RTA pin holes before RTA installation, the knowledge of the position of the pin holes will be maintained when the rest of the targets in the group are later measured.

The RTA inserts on the OB have high co-planarity ($1/1000''$), and adjustability of the RTA to OB interface is not provided. Since it is unfeasible and unnecessary to shim under the RTA, it has been chosen to let the RTA inserts (which are at the

+Z side of the optical bench) determine the OB reference frame. The other optical components align relative to RTA. Therefore, RTA is the first subsystem to be installed on the optical bench, and the transmitters are aligned to the RTA.

The primary datum that defines the GEDI coordinate system is the RTA interface plane and is defined by the 3 mounting pads and pins that RTA interfaces to. The RTA datum is controlled to 0.0005" to minimize mounting strain to the RTA flexures to ensure adequate co-planarity². The GEDI Optical Bench was equipped with 4 optical reference cubes, positioned near the edge of the optical bench, and distributed to allow Line Of Sight to one or more cubes in different bench orientations throughout the integration and alignment process. The GEDI Optical Bench coordinate system was established during CMM characterization at GSFC using the RTA interface datum normal to establish the Z axis. The origin of the coordinate system is at the center of the RTA hole on the Optical Bench at the intersection with the Z plane. This coordinate system knowledge was transferred to the cubes on the Optical Bench. Since the Optical Bench is sequentially loaded with many subsystems it is critical that the alignment of each subsystem and characterization of the instrument coordinate system with gravity orientation be performed. A view of the fully integrated GEDI Optical Bench is shown in Figure 14.

The RTA primary mirror and secondary mirror are on the +Z side of the OB, together with the Beam Expanders (and BAMs) from each transmitter, facing the Earth. The Focal Plane Plate Assembly and the Aft-Optics of the RTA are on the -Z side of the Optical Bench, together with the Laser modules, BDUs and Fold Mirrors. The Fold Mirrors direct the transmitter signal through the Tx holes in the Optical Bench.

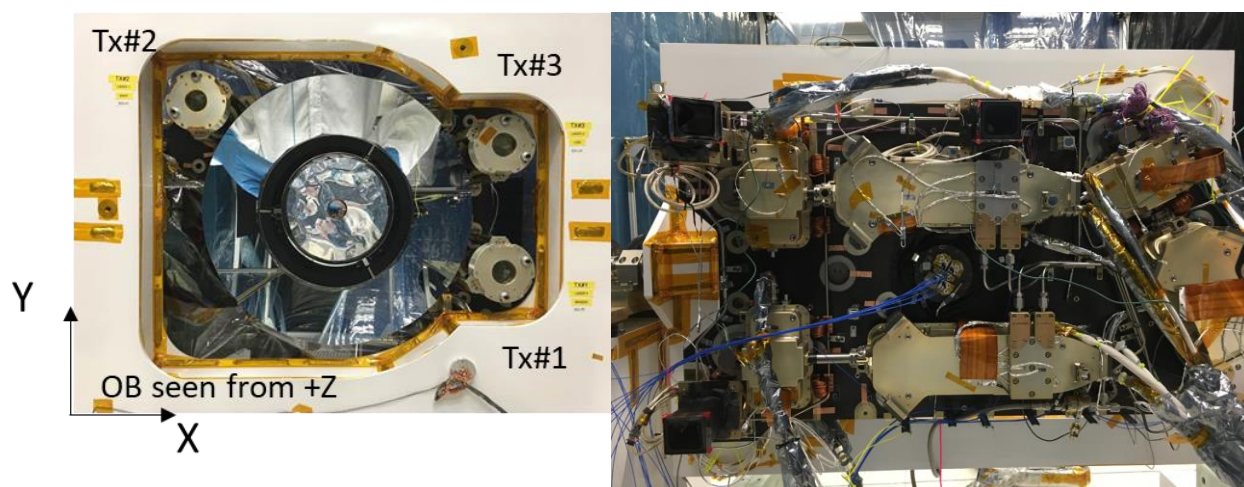


Figure 14 : The populated GEDI Optical Bench (in dolly). A (left) Transmitters installed around the telescope, OB +Z side. B (right) Lasers, BDUs, Fold Mirrors for Tx#1, Tx#2 and Tx#3 on the -Z side of the Optical Bench.

Before installing and aligning components to the Optical Bench a reference frame on the Optical bench is established. The origin of the Optical Bench mechanical reference frame is the center of the RTA pinhole circle (through which the optical axis of the telescope passes). The 2.68-inch diameter raised bosses on the three RTA inserts on the OB define the XY plane. The center of each insert is determined by the 1/4 inch RTA pin position. The X_{OB} - Y_{OB} plane is parallel to the OB, and Z_{OB}=0 is at the side of the OB that holds the telescope (surface of OB facing +Z). The +Z axis is aligned with the telescope boresight, normal to the optical bench and defines the pointing direction for the primary coordinate system. The X and Y axes are in the plane of the optical bench, nominally aligned with the GEDI +X and +Y axes, respectively.

Theodolite measurements of the reference cube on the component module provides the pointing information, and Laser Tracker metrology with CAD model information provides the beam position in the XYZ coordinate system on the OB. The RTA interface datums are best-fit to CAD nominal values, and related to the OB Primary Reference Cube (OB PRC) and LT metrology references. LT and theodolite measurements ensure that the Tx path optical components are mounted to within pre-set alignment tolerances, and that no component will require shimming outside its hardware adjustment range. A network of theodolites were used to perform crosschecks of the alignment of the GEDI OB, RTA (small reference mirror on the back of the RTA secondary mirror mount) and collimator. Ten (10) spherically mounted retro reflectors

(SMR) laser tracker targets were mounted on the $-z$ side of the OB and were used to establish the OB Master Reference Frame after the RTA installation. The targets were removed before integration into the GEDI box structure.

The engineering test unit (ETU) focal plane plate assembly (FoPPA) was installed next. The ETU FoPPA was used in the first part of the instrument alignment, but exchanged with the Flight FoPPA once it became available. The RTA measured plate scale was used to calculate the nominal positions for the center of each fiber in the RTA focal plane, after the focal plane plate had been measured and the fiber adapter receptacles pre-aligned in the Vertex Micro-Vu optical coordinate measuring machine (CMM). With the ground test (EM) fibers installed in the ETU FoPPA on the RTA, the RTA was back-illuminated, and the IFOV spots projected into the collimator was used to adjust the dolly to line RTA up to the collimator.

5. GEDI INSTRUMENT ALIGNMENT

The GEDI instrument optical alignment was challenging for several reasons: No less than three transmitters needed to be co-aligned to a single receiver with multiple, pair-wise dependent sampling channels, the beams exiting the GEDI instrument are all pointing in different directions, and the alignment and transmission efficiency of the laser and BDU subsystems are inter-dependent. However, with careful planning of the process and collaboration between alignment, design and test disciplines, it was possible satisfy all the requirements and to deliver the GEDI Instrument on time. It should be mentioned that GEDI was an aggressive, short schedule development effort. An overview of the main instrument alignment sequence is shown below.

- 1) EM fibers installed on RTA FoPPA
- 2) Laser and BDU installation on nominal shims on OB and inter-alignment to optimize throughput, polarization contrast ratio and image performance in near-field / far-field test setup.
- 3) Beam Expander Shim installation on OB using theodolite and collimator
- 4) Beam Expander installation on the Shim (DOE pre-installed and aligned, ± 2 degree clocking adjustment possible)
- 5) GSE BAM (manually adjustable Risley pair) installed on Beam Expander (allows for manual adjustment of DOE under the GSE BAM, unlike the Flight BAM)
- 6) Fold mirror installation and optimization using collimator
- 7) Transmitter/Receiver alignment for each transmitter using collimator and back-illuminated receiver telescope
- 8) Optimization using compensators
- 9) Exchange to flight fibers
- 10) Swap helicoils and fasteners, stake fasteners
- 11) Check alignment
- 12) Exchange GSE BAM's for Flight BAMs and option to optimize boresight alignment
- 13) Check alignment with Bench Checkout Equipment after GEDI Instrument vibration test.
- 14) Perform GEDI Instrument thermal vacuum test, where alignment is monitored using the BCE. Option for BAM re-adjustment of boresight alignment.

5.1 Alignment error sources and compensators

Many factors affect the boresight alignment of the GEDI instrument: In addition to the residual alignment errors from integration, alignment and test, the system experiences one-time shifts and static shifts during launch, thermal effects, as well as jitter. The alignment error sources can be divided into uncorrectable and correctable errors. The uncorrectable error terms are

- Plate scale changes due to pressure, temperature or alignment (RTA, DOE)
- Clocking (BDU, FoPPA dual fiber adapter receptacle)
- Beam separation angle error for the BDU
- Workmanship (alignment process, e.g. fastener torque, staking).

Error sources that affect all channels from a transmitter source equally, such as small tilts or decentrations, are generally correctable on the ground, or on orbit, with the BAM. The ground support equipment BAM will facilitate confirmation

that the OB optical alignment is close to nominal within the Flight BAM allocated range for ground alignment, and that the transmitter path system level boresight alignment can be optimized using the BAMs.

A roll-up of all the predictions and assessments of the contributors leaves the integration and test phase with an allocation for the science channels to have a boresight alignment error no larger than 30 μ rad for the ground alignment (pre-system vibrate and TVAC). The contributors are primarily the static shifts and thermal shifts and gravity release experienced in all subsystem optical components such as the RTA, laser, Beam Expander, and fold mirror, plus the optical bench itself, as well as jitter (from ISS, lasers and pointing mechanism motors). See list in Table 1.

Boresight Alignment Errors				
Contributors		μ rad		μ rad
Integration and test		30		
RTA	Post launch (thermal hyst., 1G-rel.)	60	Thermal shifts	55
Laser	1-time / static shifts	20	thermal shifts	10
BDU	1-time / static shifts	11	thermal shifts	10
Beam Expander	1-time / static shifts	75	thermal shifts	10
Fold Mirror	1-time / static shifts	100	thermal shifts	35
Optical Bench		60		

Table 1 Boresight alignment errors.

The estimated boresight change realized under thermal conditions, partly based on modeling and telescope TVAC testing at subsystem level indicated a 3.5 μ rad/degreeC boresight change. The on-orbit boresight alignment budget takes this wander of the spots into account, but the spots from the ground will still be received well within the 300 μ rad diameter IFOV 'window', if the other contributors are within budget.

In order to perform the boresight alignment of the GEDI subsystem, a number of alignment compensators are built into each subsystem, to counter effects from mechanical tolerances. A list of the alignment compensators is found in Table 2 GEDI alignment compensators.

Compensators	X	Y	Z	Rx	Ry	Rz
Subsystem	mm	mm	mm	deg	deg	deg
RTA	NA	NA	NA	NA	NA	NA
FoPPA						
Assembly			+/- 2.0			+/- 2.5
Adapters	+/- 0.45	+/- 0.45				+/- 2.5
Fibers			+/- 1.0			
Laser						
Assembly	+/- 0.5	+/- 0.5	+1.5/-3.0			
LOS					+/- 1.0	+/- 1.0
Polarization				0-90		
BDU	+/- 0.5	+/- 0.5	+/- 1.0			
Fold Mirror					+/- 3.0	+/- 3.0
TOA						
Assembly	+/- 0.75	+/- 0.75		0-0.5	0-0.5	
DOE						+/- 2.0
Shim	+/- 0.02	+/- 0.02				
BAM						+/- 360

Table 2 GEDI alignment compensators.

The GEDI optical model in Zemax was used to support the alignment work and was used to determine the alignment sensitivity in various test cases ⁶.

Components are installed to the optical bench to tolerances, and with a nominal mechanical shim placed between the component and the optical bench in order to accommodate adjustments of shims in both positive and negative direction later, if needed. The canopy lasers are responsible for the furthest off-axis channel sets, 3, 4, 5, 6 and 7, 8, respectively. The two canopy laser transmitter systems are extra challenging, because the physical location of the beam expanders on the optical bench, combined with the position of the channels in the ground pattern, require the beam expanders to be pointed at an angle compared to the optical axis, i.e. not normal to the optical bench.

5.2 Transmitter Alignment

There are three lasers on the GEDI Instrument installed on $-Z$ side of the optical bench. All lasers are used during alternating time slots during science operations, with a 242 Hz repetition rate⁴. The lasers were fabricated by NASA Goddard Space Flight Center^{3,4}. As with all GEDI optical components and subsystems, the lasers are characterized prior to delivery to the optical bench for installation. To optimize the integration and test flow, the lasers were delivered one at a time after they completed environmental testing. Integration and alignment of the three separate transmitter systems to the receiver on the GEDI instrument was performed sequentially.

Alignment of each transmitter system began with inter-alignment of the laser and BDU module pairs in order to ensure maximum performance. This was accommodated in the optical integration facility after initial nominal installation of the laser and BDU to the optical bench. The OB, mounted in a rotation dolly, was turned horizontal for the output after the BDU to be conveniently captured by a laser beam profiler camera. The alignment process was iterative using the profiler as feedback while optimizing the performance of both dithered beams.

In order to establish the pointing of the two canopy lasers, the canopy Beam Expanders (BE#1 and BE#3) are each equipped with a wedged shim between the optical bench and the BE mounting interface in order to provide the pointing from the RTA optical axis (in opposite directions). The pointing angles are $R_x = +0.2573$ degrees and $R_y = -0.1485$ degrees for BE#1, and $R_x = +0.2970$ degrees and $R_y = -0.1715$ for BE#3. Since the BE shims had to be checked before the BE's could be installed, the angle between the two beams was $11.3 \times$ larger than the flight angle, and pointing into the collimator was therefore not feasible. The implementation of the wedged shims are open rings, such that the beam expander is supported under the entire perimeter. For each transmitter, the shims were measured and adjusted/modified if necessary. The metrology and alignment of the pointing of these beam expanders required separate steps which will be described in the following section.

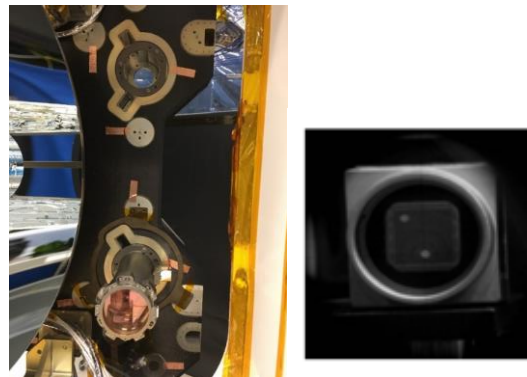


Figure 15. The optical bench (+z side) with one Beam Expander installed at the bottom, and an open Beam Expander slot. The Primary mirror of the RTA seen to the left. Insert to the right shows the IFOV spot pair on the collimator camera.

After the beam expander shim was installed on the optical bench +z side, a theodolite was positioned in the path between the beam expander shim under alignment and the collimator. A Parallel mirror was held to the shim in order to create an optical return. The theodolite equipped with a camera was aligned to the return from the Parallel mirror, referencing the shim. Next, the theodolite was clocked 180 degrees in Azimuth in order to view the spots from the telescope - back-illuminated with the receiver IFOV spots to which the Transmitter spots should be aligned - received in the Basler camera at the focal plane of the collimator. The theodolite measurements were used to calculate if the shim angle and orientation was correct, and the information was used to modify shims if needed.

Figure 15 shows the OB with one beam expander installed at the bottom, and an open slot at the top, ready for beam expander installation. The Primary mirror of the Receiver Telescope is seen to the left. Insert to the right shows the IFOV spot pair viewed on the theodolite camera imaging the active area of the collimator camera. For initial alignment with the Flight laser, low power mode was used. When the transmitter paths had been well-aligned, full power mode (Flight mode) was used for the lasers, with proper attenuation between the transmitter output and the collimator. The alignment laser illuminated the DOE pattern (and higher order). The image on the collimator camera through the BE was overlaid with the back-illuminated RTA image of the focal plane. The GSE BAM Risleys were manipulated until the images from the Tx side and the Rx side were overlaid, with the spots positioned in the field of view at their correct

distance from the center of the field of view. See Figure 16. The open mechanical mount of the GSE BAM allows for manual adjustment of the DOE mounted at the end of the beam expander. The DOE has a ± 2 degree clocking capability and was manually rotated - through the access port in the GSE BAM - to position the spots from the Tx side on the designated channel spots generated from the Rx side. Each of the transmitters' beam expanders were required to obtain their pointing angle within ± 0.03 degrees (0.52 mrad), and that was achieved. The DOE was liquid pinned once system alignment was achieved, and before the Flight boresight alignment mechanisms were installed on the optical bench over the BEs. The transmitter across track separation achieved was 1.521 mrad, which was within the narrow requirement band of 1.5 mrad ± 0.095 mrad.

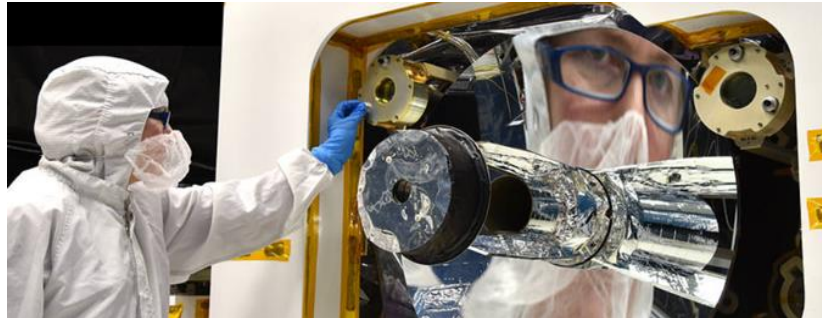


Figure 16. Adjustment of the GSE BAM on Tx#2.

For rough initial alignment of the GEDI Instrument pointing to the Collimator, the light from the back-illuminated receiver was used as a guide to move the GEDI Instrument dolly into place. The tip/tilt of the Optical Bench is adjusted to allow the beams from the particular transmitter under alignment to be sent into the parabolic mirror and reflected towards the elliptical fold flat mirror and on into the focal plane camera aperture. For Transmitter #1 which has 4 channels, two cameras placed adjacent in the collimator focal plane are used to increase the view to the two channel pairs, one in each camera.

The Flight BAM is the last component in the Tx-Rx system to be installed on the OB. Once it is installed, there is no access to the DOE. 1000 μ rad of the total 2000 μ rad provided by the GEDI BAM is allocated to the optical boresight alignment during integration, however, the philosophy being that the optical boresight alignment will be performed to the best alignment possible before the BAM range is used, and that the BAM range should be viewed more as a time saver than an alignment planning tool. The installation and adjustment of the BAMs, and subsequent full end-to-end test in the collimator of all Tx-Rx alignment, concludes the Tx/Rx flight hardware installation and alignment.

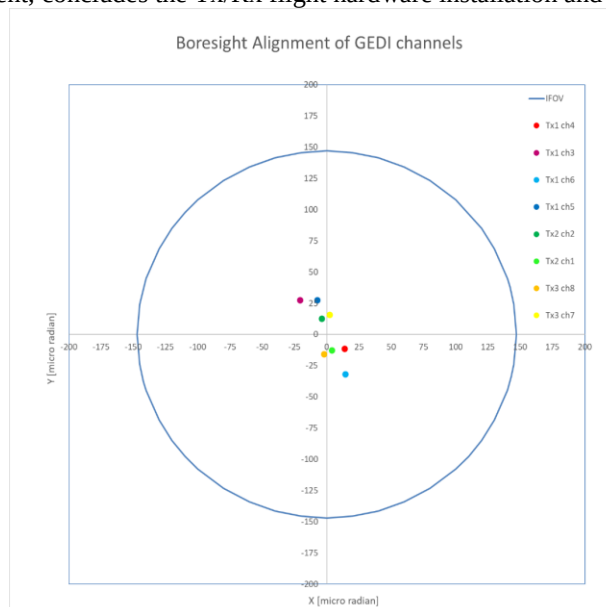


Figure 17. Boresight alignment of all channels. Each spot represents a channel. The blue circle indicates the IFOV.

As the channel pairs were required to be very densely spaced, the custom fiber adapters were installed in a dual fiber housing. This meant that a fiber pair was installed simultaneously, and that the two fiber positions could not be individually and independently adjusted. This known error source was accounted for in the error budget. Optimizing each fiber pair using the camera at the focal plane of the collimator was an iterative process which required significant dexterity. The transmitter with 4 channels, i.e. two channel pairs, did – as expected – require the most attention, and had the highest residual boresight alignment error.

As indicated in Figure 17, the residual on-ground alignment errors goal were $< 30 \mu\text{rad}$ which was achieved with large margin for Tx#2 and Tx#3, and with narrow margin for Tx#1. In most cases the residual channel alignment error was much on average only $15 \mu\text{rad}$, but the average was driven up by the two outliers driven by the 4 channel transmitter, Tx#1, where the coupling between the channels constrained the split of the difference among the channels, and resulted in the larger overall error. The measured boresight error in the integration lab was corrected for the beam expander focus error for ambient pressure, showing the as-built uncorrectable boresight error to fulfill the requirement of being $< 30 \mu\text{rad}$.

Without the GSE BAMs, the alignment of each would still have been possible, but would have taken longer time, as more iterations had been required regarding especially the shimming angle and fold mirror adjustment. For a short schedule development like GEDI, the BAMs were a necessary tool. In some cases, the BAM only needed to contribute about $60 \mu\text{rad}$ to dial a channel pair into optimal boresight alignment, and in the worst case a couple hundred μrad was needed, - still well within the 1mrad ground alignment allocation for the BAM.

The fully integrated and aligned GEDI is subjected to environmental testing: Vibration test, Electromagnetic Interference (EMI) test and Thermal Vacuum Testing (TVAC). Once removed from the integration and test facility housing the collimator, no direct visual alignment is possible, but the BAMs were used by purposely driving the transmitter beam out of its corresponding IFOV to each side, whereby it was possible to determine to optimum centration of the beam on the IFOV. The BAM's were used to test the boresight alignment after during TVAC, in the same way that the BAM's are used on -orbit. The boresight shifts associated with environmental changes are between $70 \mu\text{rad}$ and $80 \mu\text{rad}$ per channel, corresponding well to the predictions in Table 1.

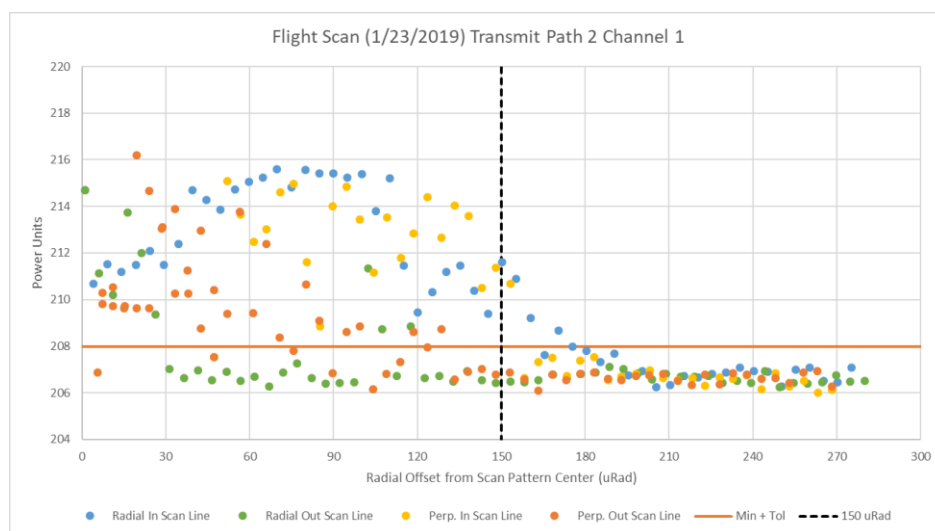


Figure 18. Example of on-orbit detector response versus position.

The BAMs were used as planned during on-orbit commissioning of GEDI. Figure 18 exemplifies on-orbit alignment data of a single transmitted beam to its corresponding receiver IFOV. BAM scans like this have been performed on-orbit to gain knowledge and confidence in transmitter to receiver boresight alignment. The returns from real Earth features and cloud cover account for the uneven noise floor and limit the uniformity of targets returned intensity and accuracy ($\sim 30 \mu\text{rad}$). The boresight shifts associated with launch changes are between $95 \mu\text{rad}$ and $110 \mu\text{rad}$ per channel, in good accordance with the predictions in Table 1. GEDI boresight alignment on-orbit exhibits very satisfactory stability: Since commissioning several months ago, no further boresight alignment has been necessary, corresponding to system model predictions.

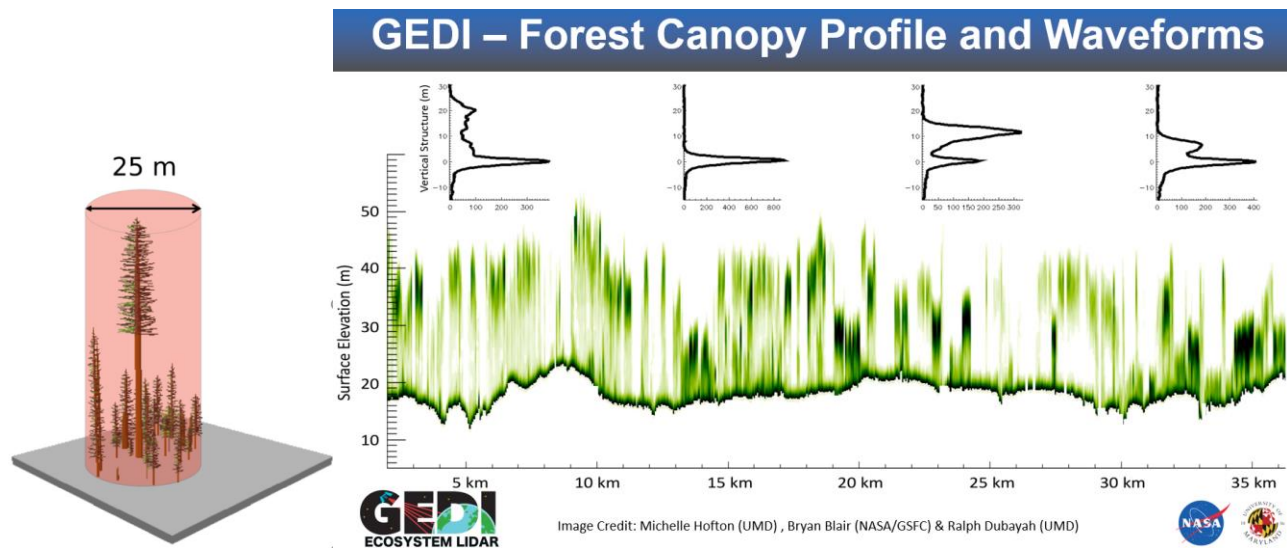


Figure 19. Example of real on-orbit GEDI data product: Forest Canopy Profile and Waveforms ¹.

6. CONCLUSION AND SUMMARY

The alignment and test, as well as the design and implementation, of the GEDI instrument was challenging, but with careful planning of the process and collaboration between alignment, design and test disciplines, it was possible to deliver the GEDI Instrument on time for the December 5, 2018 planned launch date, and on a record-short schedule. The required performance and alignment of the system was achieved, and has also been proven on-orbit. Since commissioning in March 2019, high quality science data has been collected with GEDI (see Figure 19), and GEDI is hitting the reference ground track to ± 64 meters, well within the 200 m requirement. On-orbit pointing stability has been excellent with < 1 arcsecond variation among all 8 ground tracks.

The authors wish to thank NASA for the support throughout the GEDI project.

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