



Transmission Telescope Optical Dynamic Alignment

Viviana Vladutescu

New York City College of Technology/City University of New York, Brooklyn, New York

Aaron J. Swank, Dzu K. Le, Calvin R. Robinson, and O. Scott Sands

Glenn Research Center, Cleveland, Ohio

NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program plays a key part in helping NASA maintain this important role.

The NASA STI Program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI Program provides access to the NASA Technical Report Server—Registered (NTRS Reg) and NASA Technical Report Server—Public (NTRS) thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- **TECHNICAL PUBLICATION.** Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counter-part of peer-reviewed formal professional papers, but has less stringent limitations on manuscript length and extent of graphic presentations.
- **TECHNICAL MEMORANDUM.** Scientific and technical findings that are preliminary or of specialized interest, e.g., “quick-release” reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.
- **CONTRACTOR REPORT.** Scientific and technical findings by NASA-sponsored contractors and grantees.
- **CONFERENCE PUBLICATION.** Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.
- **SPECIAL PUBLICATION.** Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.
- **TECHNICAL TRANSLATION.** English-language translations of foreign scientific and technical material pertinent to NASA's mission.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at <http://www.sti.nasa.gov>
- E-mail your question to help@sti.nasa.gov
- Fax your question to the NASA STI Information Desk at 757-864-6500
- Telephone the NASA STI Information Desk at 757-864-9658
- Write to:
NASA STI Program
Mail Stop 148
NASA Langley Research Center
Hampton, VA 23681-2199



Transmission Telescope Optical Dynamic Alignment

Viviana Vladutescu

New York City College of Technology/City University of New York, Brooklyn, New York

Aaron J. Swank, Dzu K. Le, Calvin R. Robinson, and O. Scott Sands

Glenn Research Center, Cleveland, Ohio

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

Acknowledgments

This work was funded by the NASA Space Communications and Navigation (SCaN) Program and the 2017 NASA Glenn Faculty Fellowship Program. Additionally, we would like to thank Paul Greenberg and David G. Fischer for their insightful comments on our testbed. Last but not least, the authors would like to thank their colleagues Eliot Aretskin-Hariton and Michael Lichter from NASA Glenn and Victor Pena from Baruch/CUNY for their input in various stages of the project.

Trade names and trademarks are used in this report for identification only. Their usage does not constitute an official endorsement, either expressed or implied, by the National Aeronautics and Space Administration.

Level of Review: This material has been technically reviewed by technical management.

Available from

NASA STI Program
Mail Stop 148
NASA Langley Research Center
Hampton, VA 23681-2199

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
703-605-6000

This report is available in electronic form at <http://www.sti.nasa.gov/> and <http://ntrs.nasa.gov/>

Transmission Telescope Optical Dynamic Alignment

Viviana Vladutescu

New York City College of Technology/City University of New York
Brooklyn, New York 11201

Aaron J. Swank, Dzu K. Le, Calvin R. Robinson, and O. Scott Sands
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Abstract

The Integrated Radio Optical Communication System (iROC) is designed to transmit data between Mars and Earth by means of radio waves at 32.67 GHz (Ka band) and laser beam (LB) at 1550 nm, both transmitted via a combined telescope/antenna called a teletenna. The iROC terminal will provide “beaconless” operations to allow full function from the outer planets. In order to point without the aid of an uplink beacon, the proof of concept presented here is addressing the need for an accurate determination and control of the relative position of the LB with respect to a reference star.

The experiment presented simulates a surrogate transmission telescope system in a laboratory setting and presents the model used in the correction of the outgoing beam. The results of the model show a nonlinear dependence between the outgoing and the reference beam, indicating the necessity of a minimum of two metrology instruments placed along the optical system for increased pointing precision.

1.0 Introduction

Current and future space exploration endeavors will require new capabilities for large data transfer between Earth and other planets in the solar system. Data communication with Earth from other planets will be completed through Deep Space Network (DSN) arrays on Earth and satellites around Earth (Refs. 1 to 3). In an effort to develop advanced space communication capabilities for large data transfer, NASA John H. Glenn Research Center at Lewis Field is also investing a revolutionary concept named the “Integrated Radio and Optical Communication (iROC),” featuring a space communication terminal, which tightly integrates a compact optical transmitter and radio communication system (Refs. 4 to 11).

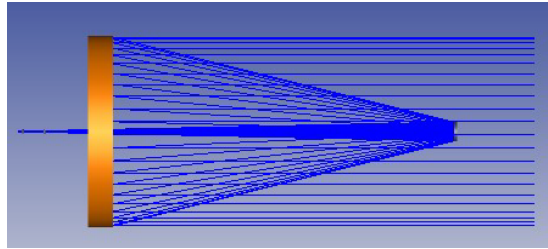
A particular design named “Telescope within RF (radiofrequency) Antenna (teletenna)” for future iROC flight demonstration is being developed at Glenn, in which a laser-transmission telescope is placed at the center of an RF antenna. The combined telescope/antenna called a teletenna system to be

demonstrated include advanced pointing techniques for laser transmission without an uplink beacon. Operating without an uplink beacon is considered necessary for communications from the outer planets. The pointing accuracy ($\sim 2\text{-}\mu\text{rad}$ goal, $5\text{-}\mu\text{rad}$ threshold) required for beaconless optical communication is obtained, in part, through the use of a star tracker (ST). Such accuracy is expected to become available soon and will likely employ an interferometer (Ref. 12). The ST provides information for celestial sensing and optical pointing calculation (Refs. 13 to 16).

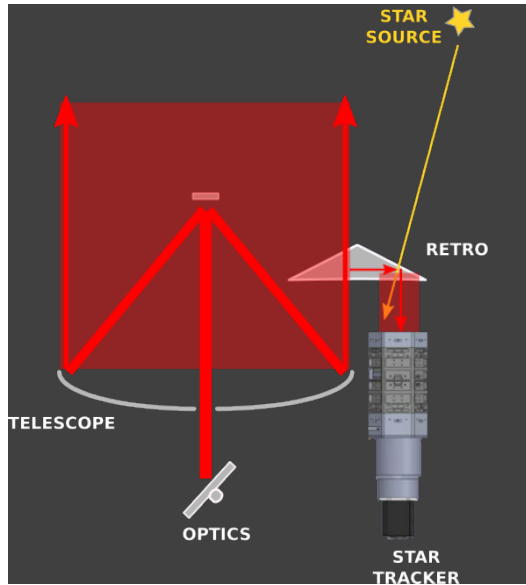
Alignment studies have been conducted in the past to demonstrate the feasibility of different sensing and communication systems between Moon and Earth, Mars and Earth, etc. The complexity of these systems varies and all indicate that this type of communication is possible if certain alignment conditions are satisfied (Refs. 17 and 18).

The outer diameter of the primary mirror (PM) of the telescope (either of Cassegrain or Ritchey-Chrétien type) in the teletenna concept for data transmission from Mars to Earth is 0.25 m, and the secondary mirror (SM) outer diameter is 0.025 m. The laser-transmission tertiary optics behind the PM include the laser-fiber port, collimator lens, focus lens, quarter-wave plate, and a beam splitter in that order; all aligned with the telescope axis. Figure 1 illustrates the beam path outwards from the laser fiber through the tertiary optics and the telescope. The beam splitter within the tertiary optics assembly is needed for directing the return beam from a flat reference reflector in front of the telescope onto a wave-front sensor behind the PM. In place of the wave-front sensor, a simple metrology set consisting of a focus lens and optical sensor can also be used to detect beam misalignment and/or jitter. The illustration in Figure 1(b) shows the path of a beam section sampled through a retroreflector above the PM to be registered on the ST placed below the telescope near the PM edge.

Related to the optical transmission of the laser beam (LB), we need to know with precision: the quality of the transmitted beam profile and divergence and determine and control the relative position of the LB with respect to the star field. The optical quality issues can be understood through the



(a)



(b)

Figure 1.—(a) Optical analysis of the outgoing beam path from the laser-fiber port to the secondary mirror and then reflecting off the primary mirror surface. (b) Outgoing beam path as sampled by the retroreflector and measured by the star tracker.

measurement of M2 factor and Strehl ratio. Beam pointing accuracy must be addressed by ST accuracy and proper internal alignment of the optical train and proper beam stabilization.

Design studies of the iROC beaconless pointing terminal have considered issues related to pointing bias errors and beam jitter (Ref. 10). The results of studies on internal optics alignment metrology for the teletenna concept are presented in this paper for purposes of stabilizing the communications beam in the presence of relative motions among the elements of the optical system, principally motion between primary and SMs. In the case that the structure of the teletenna is not sufficiently damped and stiff, these methods will be employed to suppress beam jitter.

The investigated metrology includes an optics alignment sensing metrology to image a beam reflected from a fiducial on the SM of the surrogate telescope onto a pixelated sensor (PixSen) behind the telescope. Additionally, the metrology

TABLE 1.—TERMS USED

Notation	System Component
LB	Laser beam on Camera 1
ST	Star tracker (represented by Camera 1)
PixSen	Pixelated sensor (represented by Camera 2)
CO	Celestial object (represented by obscuration target)
FB	Fiduciary beam (on Camera 2)
FP	Fiduciary point (on Camera 2)
PiPosX	Piezocontrolled mirror axis X
PiPosY	Piezocontrolled mirror axis Y
Con1X,Y	Autocollimator (Ref. 18) 1 axis X,Y
Con2X,Y	Autocollimator 2 axis X,Y
FSM	Fine steering mirror
DistSTIF	Distance between CO and LB on Camera 1 (ST)
DistPixSen	Distance between FB and FP on Camera 2 (alignment sensor or pixelated sensor)
iROC	Integrated Radio Optical Communication System

includes sampling a portion of the LB and redirecting it onto the ST image plane. We refer to this testing procedure as the indirect method of pointing precision measurement of the iROC system. The objective of this measurement is to determine angular position of an LB as it comes out of the telescope relative to inertial space and to compensate for factors such as thermal drift, aging of components, jitter, etc. The main system components used in this proof of concept are given in Table 1.

The proposed alignment/metrology method is considered risk reduction for the iROC at the baseline to compensate for beam jitter. Beam jitter energy above the ST detector Nyquist rate (the anticipated Nyquist rate for the ST is somewhere in the range of 100 mHz to 10 Hz) will be detected but will be aliased into the passband of the ST. This investigation will inform decisions regarding separate optical jitter suppression subsystem by providing guidance to the final beaconless pointing system design (Refs. 13 to 16).

The paper presents the proposed metrology procedure in Section 2.0 and the postprocessing in Section 3.0. In Section 4.0 we present the statistical analysis and model results. Discussions and conclusions are given in the last sections.

2.0 Proposed Metrology Procedure for Pointing Precision

The process requires external alignment between the telescope and the receiver placed on Earth (also referred to as “pointing precision”) and the internal alignment by means of fiducials placed along the beam path. The external alignment is ensured via the ST, which detects the position of the astral bodies, and based on celestial calculations, it determines with

accuracy the position of the LB with respect to the Earth at the moment of transmission. Due to the lack of need for a beacon in the iROC system, the “point ahead” function is reduced to a simple “deflection shooting” calculation. Limitations on the optical field of view for the telescope, brought by the need to simultaneously detect the Earth beacon and pass the communications beam are, thusly, eliminated. For the internal alignment, we propose a combination of an alignment pixelated sensor (PixSens), placed behind the PM of the telescope, in combination with the ST sensor, which is placed outside the telescope.

In this proof of concept, we used a simplified design of the telescope. The alignment principles are based on the claim that a relative change of the outgoing LB partially captured (via a corner cube) by ST is strongly related to the relative change in the position of a reference beam reflected off the SM into the PixSens, which already detects a portion of the LB on its way to the fine steering mirror (FSM). This relation is mathematically derived based on measurements of these relative positions and their nonlinear interdependence.

The ST is replaced in the experimental setup with Camera 1, which will be replaced by an actual ST for future calibration processes. The observable change in the beam profile due to angular displacement, divergence, and length of path, is minimal considering the beam travel. Our preliminary analysis led to excellent predictions of the beam position of the communication beam on the ST based on the position of the returned beam on the pixelated sensor.

2.1 Optical Setup and Control System

The setup and its components are illustrated in Figure 2. The main components are listed in Table 2. Depicted in Figure 2 is the virtual telescope location. A surrogate telescope is placed at this location in the experimental setup, which is used to generate additional degrees of freedom in the optical path. The surrogate telescope is used in the test setup to emulate operational disturbances and is not a magnification telescope in the current test. Initially, only one autocollimator (Ref. 19) was used (see element 3 in Figure 2). However, we observed a notable improvement in the proposed metrology procedure with the inclusion of the second autocollimator, whose scope was the angular position detection of the SM of the surrogate telescope. The first autocollimator was used to determine the positions of the steering mirror and the second to measure the exact angular misplacement of the telescope SM individually.

The corner cube mirrors located in front of the ST (see element 9 in Figure 2) are replaced with a transparent glass plate containing the fiduciary point (FP), or CO in this case.

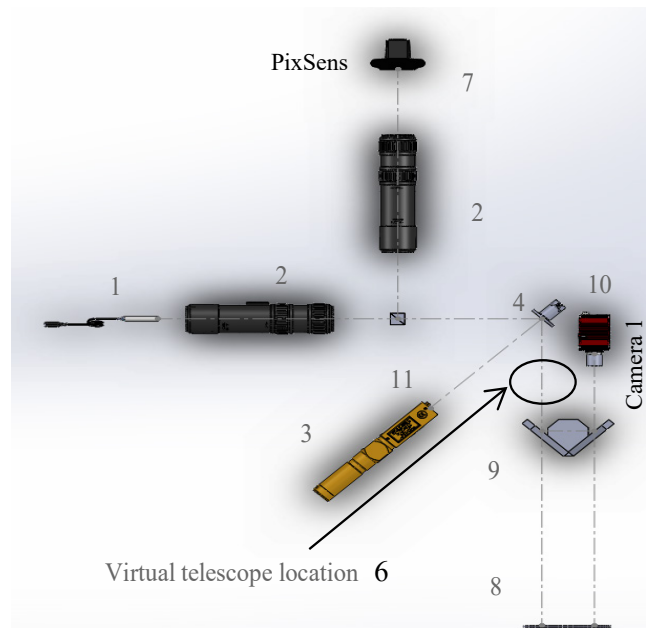


Figure 2.—The conceptual design of the direct metrology of the outgoing laser beam. The metrology design components are listed in Table 2.

TABLE 2.—OPTICAL COMPONENTS IN THE TESTBED

Optical Component	Description of Optical Component
1. Laser	635 nm, 2.9 mm, 2 mW for visible testing (Laser Diode Module: C160105-256, Diam 2.9 CPS635R. In the final design, iROC will use a fiber optic laser source 1550 nm, 13 mW for IR testing)
2. Beam expander	2-in. beam expanders in VIS with mounts. In this case, we used a 2-in. BE-20X Achromatic Galilean Beam Expander, AR Coated: 1050 to 1650 nm and a 1.5-in. BE (30X)
3. Auto-collimator	Autocollimator with Laser Diode: 1 mW; 5-kHz modulation; Detector: 2×2 mm Position Sensing Device, sensitivity 0.003 urad/√Hz and connected to computer or oscilloscope
4. Fine steering mirror	Piezoactuator with 1- to 2-in. mirror (steering mirror) connected to the controller and connected to computer
5. Computer	MATLAB, Python, and proprietary software for the piezocontroller and autocollimator (not shown in Figure 3)
6. Virtual telescope	Surrogate telescope with 6 degrees of freedom
7. Camera 2	Cameras with lens 1:1.4/35 mm
8. Fiducial	Partially reflective or transparent slabs with fiducial: (a) 50 μm and (b) 500-μm-diameter “stars”—used as FB and CO in the metrology design (also referred to as “Obstruction Target”)
9. Corner cube mirror	This mirror is used in the final design—in the current proof of concept, the corner cube is removed, and Camera 10 is placed behind element 8
10. Camera 1	Same as 7
11. Pellicle beam splitter	2 in., 400 to 700 nm (R45% T55%)

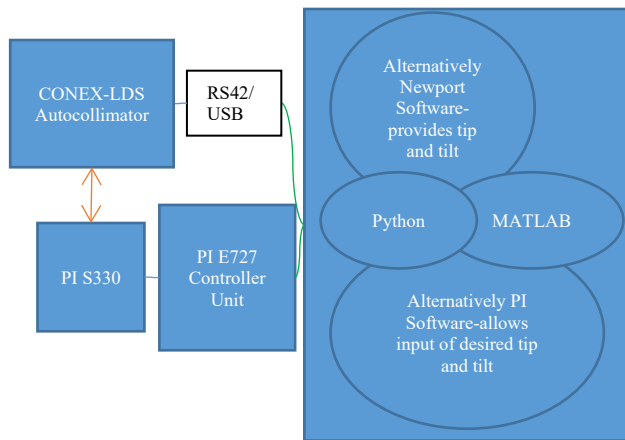


Figure 3.—Control system of the automatic adjustable components (piezocontrol for the fine steering mirror and the autocollimator(s)).

This allows for an additional degree of freedom in the sensitivity calibration process (in addition to the steering mirror). With more piezocontrollers installed on the telescope mirrors, one will induce more nonlinear changes of the beam in other directions to develop a model that accounts for more complete linear and nonlinear misalignments (baseline). Additional piezocontrollers could be used in future setups to augment baseline misalignment models.

The control of the optical actuators and sensors was done via computer control of piezocontrollers and automatic digitization of autocollimators as illustrated in Figure 3. Control of the experimental setup was done using a scripting software program. The autocollimator angular positions were used in repositioning the FSMs in a loop format. For a given range of mirror positions and a step size, the software automated each cycle of mirror position and data acquisition. For data acquisition, the Python3 Asynchronous I/O (asyncio) library was used to implement concurrent data acquisition from all the sensors, including the two autocollimators, the two cameras, and the mirror position sensors integrated into the piezoactuators. While the autocollimator measurements were used as the primary indicator of the mirror positions, the position data from the integrated sensors in the piezoactuators were used as validation. After collection of the sensor data for each configuration of the mirror position, all of the data was saved to a disk for postprocessing and analysis using MATLAB® (The MathWorks, Inc.).

The measurement procedure is given step by step in the next subsection.

2.2 Measurement Procedure

The dynamic alignment measurements are done with two cameras: one intended as a surrogate for the ST and the other as an alignment (pixelated) sensor.

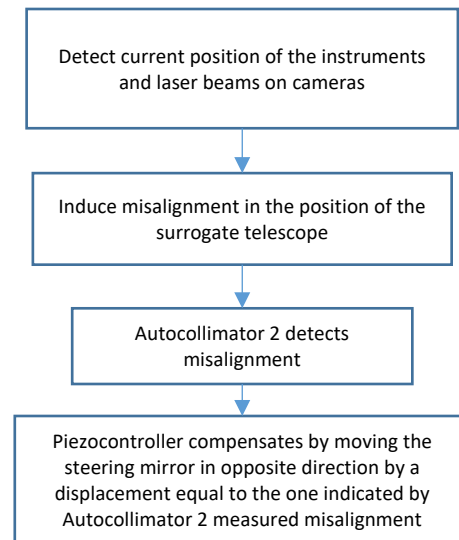


Figure 4.—Steps used in the intentional misalignment and measurement process.

The goal of this procedure is to prove that there is a clear interdependence between the images collected on the ST and the ones collected by PixSens (alignment sensor). Interdependence refers here to the fact that a change in the return beam (as reflected back from the SM) position on the alignment sensor is associated with a change of the beam on the surrogate ST. If carefully analyzed, they will allow for full realignment of the optical train. The steps used in this proof of concept are given below and represented in the flowchart in Figure 4. To our knowledge, this technique has not been implemented yet in space systems.

The following are the details of this procedure as indicated in steps 1 through 7:

1. With the laser, the autocollimator, the two cameras, and the piezocontroller on, set the piezocontroller to autozero the position of the mirror (see Figure 5). This step is necessary for autocalibration of the autocollimator and recording the beam's positions on the cameras.
2. Confirm that the laser signal is centered on both cameras and that the piezocontrolled mirror is aligned with the autocollimator 1, where the autocollimator reading is (0 μ rad, 0 μ rad) and piezocontroller reading is (1,000 μ rad, 1,000 μ rad), which corresponds to the center position, as the piezocontroller range is 0 to 2,000 μ rad. The piezocontroller provides the last position, which is used to move to the next incremental step starting from the previous position. The scanning is covering the total field of view of the cameras.

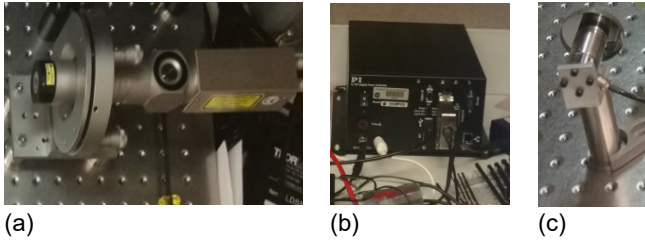


Figure 5.—(a) Autocollimator and laser source. (b) Piezocontroller. (c) 2-in. steering mirror.

If there is an offset in the position of the autocollimator, it will be recorded as the reference starting point. This initial LB position needs to be recorded for each camera (see Figure 6).

3. At the ST end of the alignment system, one can mount a fiducial in the path of the communication beam or other reference. In this procedure, the fiducial was a celestial object (CO) (i.e., the Earth), whose position is known with respect to the satellite and calculated based on the celestial coordinates at the alignment/calibration moment and the previous calibration position.
4. This CO is represented by the small spot (500 μm) on a glass slab placed in front of the ST. This glass slab is also referred to as “observation target.” Therefore, we centered the image of the CO, represented by the 500- μm spot on the obscuration target, in Camera 1 to overlap the LB (if there is an offset from the predetermined beam position on the camera sensor, record its coordinates as reference). For this new position, we collected 30 frames per second (the highest rate obtainable with the camera) with each camera, and 100 readings with the autocollimator, which are necessary for noise reduction. After preliminary measurements, using the proprietary software of the autocollimator, we observed a steady instrument response using this number of readings. Remember that the signal-to-noise ratio improves with the increase in the number of data points or images (N) collected: $\text{SNR} = \frac{N}{\sqrt{N}} = \sqrt{N}$.

In the next step, we changed the surrogate telescope position by a predetermined degree (i.e., 50 μrad) in the counterclockwise (or clockwise) direction. In this proof of concept, we used a two-axis system formed of two nonmagnifying mirrors and an achromatic telescope beam reducer/expander. This induced misalignment led to a change in the position of direction on Camera 1 (surrogate ST) by a displacement, d, which should be determined for the geometry of the optical train. This changed beam position on both cameras and result in a misalignment of the piezocontrolled mirror with respect to the autocollimator. For noise reduction we collected 15 frames with each camera and 15 data points with the autocollimator per new beam position on cameras.

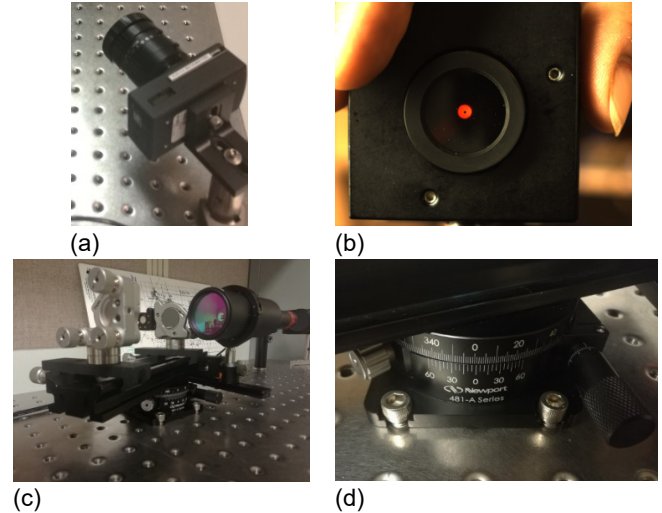


Figure 6.—(a) Camera 1 (surrogate for ST). (b) Camera 2 (surrogate for pixelated sensor behind the primary mirror of the telescope). (c) Image of laser beam and reference celestial object on Camera 1. (d) Micrometer rotation stage to induce misalignment in the position of the surrogate telescope.

5. To realign and bring the LB back to the CO in Camera 1, exact calculations are needed for the beam path length. Based on the geometry of the surrogate system, the angular change in the FSM should be about 2/3 the induced misalignment (see Figure 7 and Figure 8). However, in this proof of concept, we increased the scanning path at the expense of returning the beam back to its initial position. In conclusion, the angular change in the FSM was equal to the angular change detected by Autocollimator 2. Therefore, the FSM brought back the outgoing beam to a position beyond its initial position by approximately 1/3 of its total induced displacement. In the final design, this steering process will be based on exact calculations in order to bring the LB in the predetermined position of Camera 2 and the communication LB overlapping the initial position (that of the CO) on Camera 1. If this is done correctly in a feedback loop, the beam will always point towards the CO, no matter what misalignments might occur in the system, provided that the jitter frequency is lower than the detectable one. The function of the system was verified with an informal experiment in which, after purposefully misaligning the system (by 50 μrad), we manually tried to bring back the beam by the predetermined misalignment, but the instrument readings were too noisy so we relied on the automated realignment process instead.

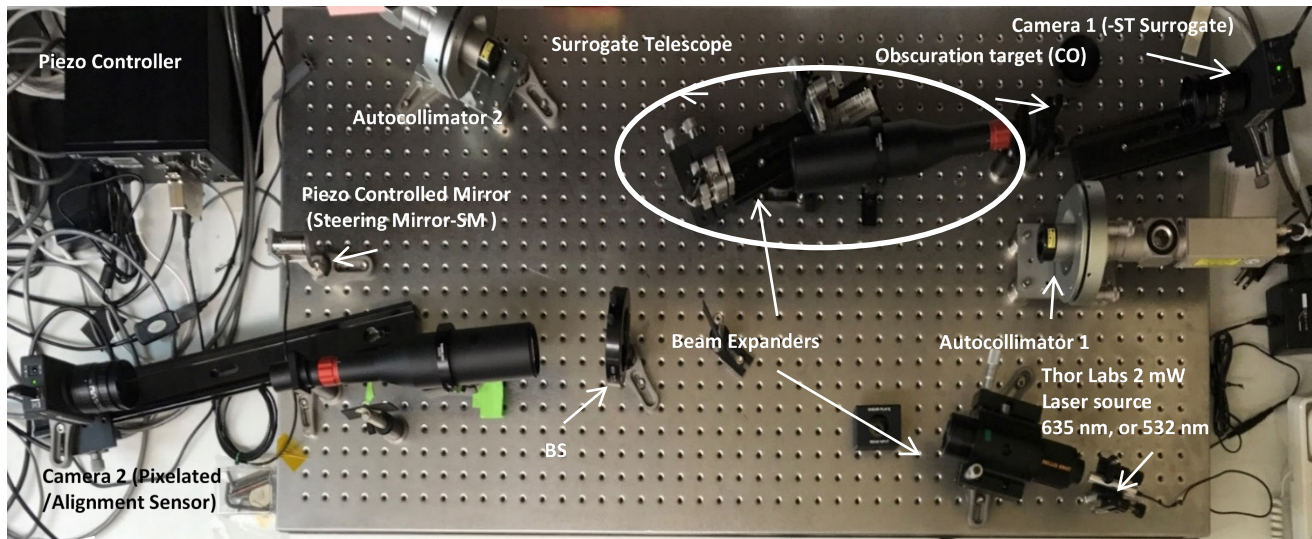


Figure 7.—Actual surrogate system of the transmission telescope and the metrology systems installed on an optical breadboard.

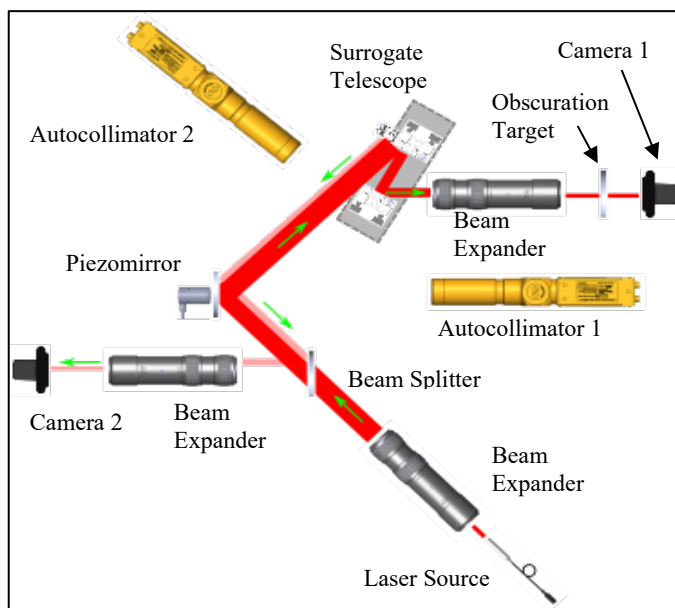


Figure 8.—Schematic of the surrogate system as assembled.

6. In the following step, we continued manually changing the angular displacement of the telescope by the same increment, in the same direction as in step 4, and step 5 to bring back the LB in the initial reference position in the two cameras. The reference position for each alignment step is new, and is the previous position of the beam, for reasons explained in step 4.
7. Repeat these steps until the LB is out of the field of view of the cameras. Note that these steps will give us the angular displacement sensitivity, which is a major factor in the correction decision by means of the SM.

8. Repeat steps 4 through 6 for different levels of intensity of light at the detectors (50 percent, 10 percent), by using OD (optical depth) 0.3, 1, 3, etc.

3.0 Postprocessing

3.1 Image Processing

The images captured by the ST along with the relative distance are illustrated in Figure 9. The relative distance on the ST is calculated with respect to a selected star from a detected constellation, which was simulated in our case with fiducials, a transparent glass plate with round spots of known diameter, placed in front of the surrogate ST sensor. The image collected on the pixelated sensor contains the FP and reference beam as reflected of the SM of the telescope.

In our preliminary measurements, we used the Image Analysis Toolbox in MATLAB to determine the quality of the beam profile (divergence) and accurately control the relative position of the LB with respect to a reference CO (star or Earth). As illustrated in Figure 10, we determined the centroid and diameter of the different clusters in the image (in MATLAB use function “regionprops”). From all centroids detected, select only the ones that correspond to circles with diameters known in the range of the star and LB and with minimal difference between the MajorAxisLength and MinorAxisLength (in this case 20 to 50 px, based on inspection). Given the pixel size, the CO can occupy a variable number of pixels. In the end, we calculated the distance between the centers of the CO and LB using euclidean mathematics (function “pdist”) (Ref. 21).

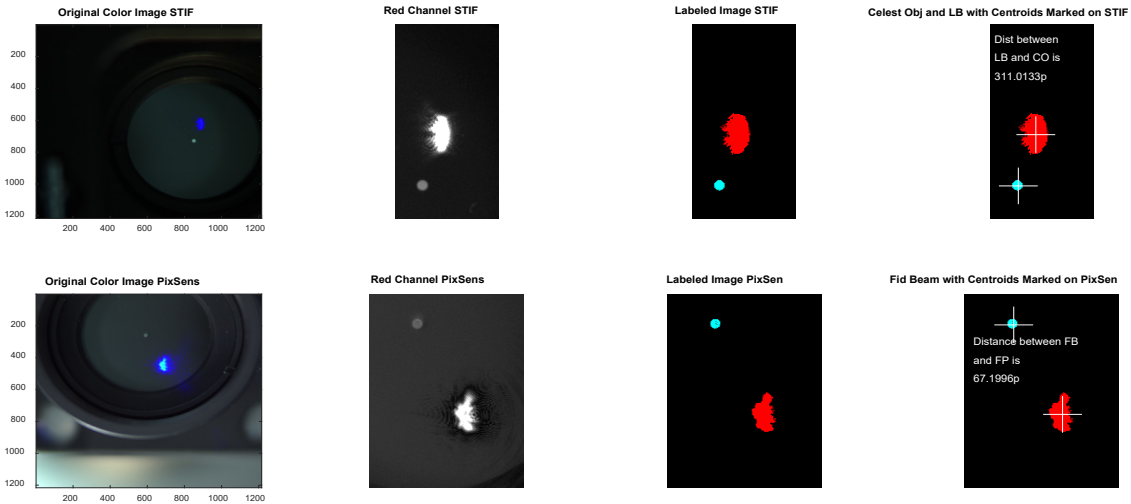


Figure 9.—Sample images collected by the ST (Camera 1 or STIF in the figure) and PixSens (Camera 2) and the corresponding relative positions of the transmission laser beam (LB) and celestial object (CO) on the ST and fiduciary beam (FB) reflected on the secondary mirror of the telescope and the fiduciary point (FP)/shape placed in front of the PixSens.

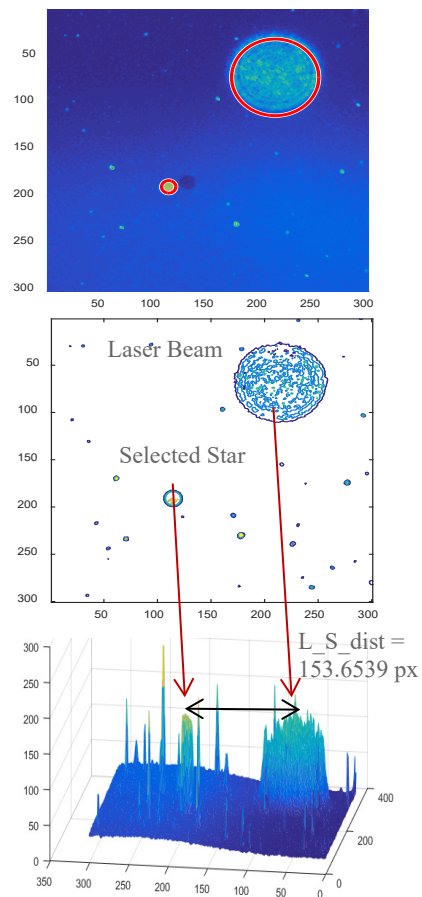


Figure 10.—Preliminary analysis of the relative distance between communication laser beam (LB) and celestial object (CO) on star tracker. Ordinal axis is in units of A/D quanta and X and Y abscissa are in units of pixel index.

3.2 Data Analysis

Selected results of the measurements presented in Section 2.0 are illustrated in Figure 11. As measurements are highly correlated, we illustrate here the most relevant outcomes. The dependence between the relative positions on the PixSens, the angular misalignment detected by the autocollimators, and the piezocontrolled FSM is evident. To minimize the noise associated with each measurement, the data points given in the plots are the average of all collected measurements for a specific misalignment position.

The dependence of the LB–CO distance detected on the ST of the FB–FP distance detected on PixSens is better understood through a fitting line to the averaged data points. This fitting line is noticeably nonlinear as shown in Figure 12(a) and (b). Additionally, the relative error of the fitting line to the data points is clearly increasing as the beam is departing from the optical axis position. This is indicated by the fitting line to the relative error points illustrated in Figure 12(b).

The averaged data points are further used in the prediction models development presented in the next section.

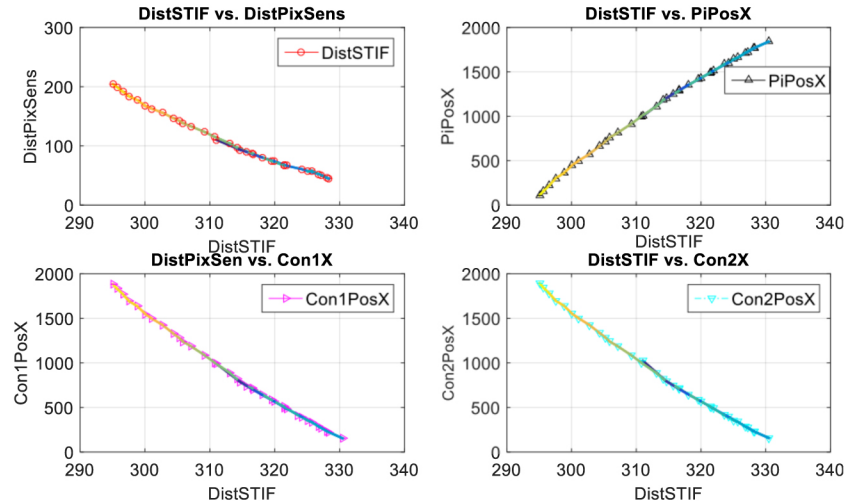


Figure 11.—Dependence of LB–CO distance on ST (denoted by STIF) as a function of FB–FP on the pixelated sensor, the FSM, the autocollimator's (1 and 2) positions.

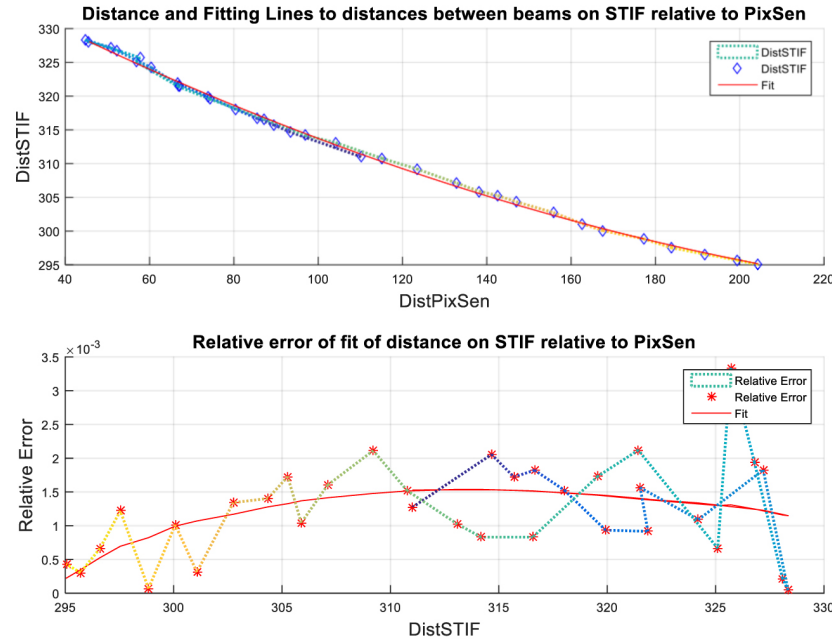


Figure 12.—Dependence of FB–FP distance on PixSens on the distance LB–CO on ST and best fit to the data and relative error of best fit along with the fit to this error.

4.0 Statistical Analysis and Models

4.1 Statistical Analysis

We have tested several prediction models of the beam location on ST as a function of the distance on PixSens using Statistical Analysis System (SAS) software, which gives the best model on several parameters selected. In the first stage, we used all variables listed in Table 1 based on the feasibility of the system and taking into consideration SWaP (size, weight, and power). The model, which requires the least computation, is based on two variables only: the squared relative distance between the FB and FP on the PixSens and the position of the piezocontrolled FSM. This regression model is developed using variables selected on the preliminary Least Absolute Shrinkage and Selection Operator (LASSO) (Refs. 21 and 22), which eliminates all correlated variables (that do not add significant value to the model). This method is based on a constrained form of least squares regression where the sum of absolute values of the regression coefficient is forced to be smaller than a specified limit. The variables were then used as input in the Proc REG (linear regression model). The resulting model is given by

$$\text{DistIST} = 280.26987 + 0.00028294 * \text{Dist_PixSen_Squared} + 0.02671 * \text{PiPosX}$$

The GLMSELECT procedure in SAS, which performs effect selection in the framework of general linear models, such as the LASSO method used here, gives results that also depend on the PiPosY. However, this term was given a 0 coefficient by PROC REG, another linear regression procedure in the SAS.

This is actually in resonance with our measurements, as the changes in the y-direction (the misalignments perpendicular to the plane of incidence of our surrogate telescope system) were not modified during this testing process. However, we observed very small unintentional misalignments in the y-direction in the testing procedure. The performance of this model is given in the following subsection.

4.2 Model Performance

The performance of the linear regression model that predicts the relative difference between the LB and a CO as a function of the FB–FP distance measured on the PixSens is indicated in the graphs of Figure 13. The model has an R-squared of 0.9997 and an adjusted R-squared of 0.9996. According to the leverage plot, there is only one high-residual data point and two leverage points, which are relatively low. Additionally, there are no highly influential points.

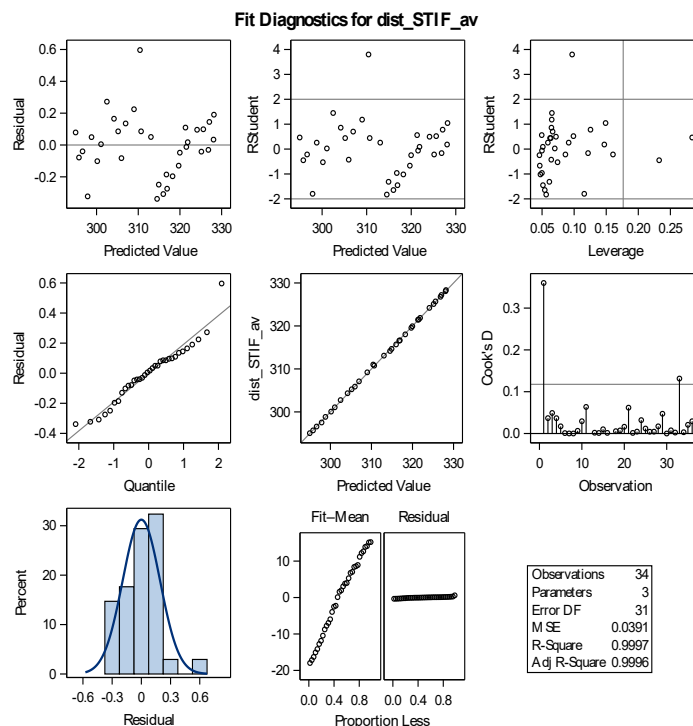


Figure 13.—Output of the linear regression model based on the position of the FSM and the square of the FB–FP distance. Panel provides residual and R-squared of the predicted values leverage points and model performance values.

TABLE 3.—STATISTICAL FIT PARAMETERS USING
MALLOW'S PARAMETERS

M#	C(p)	R-Square	Adj. R-Sq	BIC	Variables in Model
5	5.241	0.9998	0.9997	−107.98	DistPixSens DistPixSensSquared DistPixSensCube DistPixSensQuad PiPosX

The data is also slightly departing from the normal distribution, as can be observed in the residual-quantile plot. This indicates that the measurements could be performed with lower noise levels. Better signal-to-noise ratio is expected to improve the statistical analysis (Ref. 23).

4.3 Alternative Models and Performances

A second model tested is based on statistical parameters C(p) (Mallow's parameter that assess the fit of the regression line), R-squared (coefficient of determination), adjusted R-squared, and BIC (Bayesian Information Criterion), where the values for these parameters were 5.241, 0.9998, 0.9998, and respectively, −107.98 (smallest value in all possible models selected for this run—see Table 3). The root mean square error for this case is 0.17575, and the coefficients for the model are

$$\begin{aligned} \text{Dist_IST_av} = & 290.442 - 0.19840 \cdot \text{dist_Pix_Sen_av} \\ & + 0.002479 \cdot \text{DistPixSensSquared} \\ & - 0.000011615 \cdot \text{DistPixSensCube} \\ & + 2.1796 \cdot 10^{-8} \cdot \text{DistPixSensQuad} + 0.024201 \cdot \text{pi_pos_X_av} \end{aligned}$$

In this model, the y-position of the FSM (PiPosY) is also removed in agreement with the statements in Section 4.1. We would like to mention that removing the fourth power term in the relative distance between FP and FB would not change the performance of the model significantly. Meaning that if we remove the cubic and quartic terms in the model, it will not affect the performance of the model dramatically. Actually, it lowers the chances of overfitting the data.

5.0 Discussions

The alignment measurements performed at the edge of FSM steering range lead to nonlinearity in the relationship between outgoing beam direction (to Camera 1-ST-) and reflected beam direction (to Camera 2-PixSens-), as shown in Section 2.2. Because of this, the adjustment of FSM angular position can realign only one of the beams with its respective camera, but not both, and therefore an additional metrology instrument is required. In the presented proof of concept, this additional

metrology system is the piezocontroller of the FSM or an autocollimator that gives with accuracy the position of the FSM (Autocollimator 1).

The addition of more degrees of freedom in our intentional misalignment procedure would involve at least two more piezocontrollers: one for angular misalignment on a rotation stage and two controllers on the PM and SM to include the nonlinear displacement; followed by the development of a model to extrapolate for all possible misalignments. Additionally, we intend to automatically adjust the position of the SM by means of piezocontrollers to realign the communication beam direction with ST/Camera 1 center/fiducial (CO). The calculation of such adjustment for the SM angular position can be done with on the back-reflection spot on PixSens/Camera 2.

6.0 Conclusion

The analysis supports the metrological method based on mapping of the outgoing communication beam reflections on the same focal plane with the fiducial whose position is known relative to the star tracker (ST) pointing coordinates (based on celestial objects (COs) at the time) being mapped onto the ST focal plane array. Note that the ST is presumed to be rigidly connected to the telescope primary and the entire telescope is assumed to be isolated from spacecraft vibrations.

The output parameters from the presented proof of concept allowed for the determination of the positions and displacements of the beams on Camera 1 (ST) versus Camera 2 (pixelated sensor).

We showed that a model based on the FB–FP square distance and FSM performs with an R-squared of 0.9997 and an adjusted R-squared of 0.9996. Adding more variables is not justified at this point. A model based on higher-order terms of the FB–FP distance on PixSens and all other variables is equal or less than 99.98 percent, which concludes that adding more variables does not improve the regression and requires an increase in power and weight due to the added metrological instruments on the payload.

Among other findings, the work presented here shows that the alignment measurements performed at the edge of the FSM articulation range led to nonlinearity in the relationship between the outgoing beam direction registered on the ST and the fiducial reflected beam direction on an alignment sensor (pixelated sensor) placed behind the telescope. For this reason, the adjustment of FSM angular position can realign only one of the beams with its respective camera but not both, and therefore an additional metrology instrument is required for high pointing precision. In the presented proof-of-concept metrology, this additional metrology component could be the piezocontroller of the FSM and/or an autocollimator that gives the position of the

FSM, with accuracy. In other words, the results indicate that we need at least two optical metrology instruments for the laser communication system. These findings are relevant to the current development and design of the iROC as they indicate that, if necessary, FSM-based steering for optical stabilization appears to be a feasible approach to real-time beam stabilization and optical alignment. While little consideration was given to sensor data rate and actuator bandwidth, this initial proof-of-concept study found no issues with the development of the optical amendments to the iROC optical system to accomplish automatic beam stabilization and alignment using only detection of a return sample of the outgoing beam.

References

1. Boroson D.M.; Biswas, A.; and Edwards, B.L.: MLCD: Overview of NASA's Mars Laser Communications Demonstration System. Presented at the Photonics West: LASE, San Jose, CA, 2004. <https://ntrs.nasa.gov/search.jsp?R=20060043397> Accessed July 28, 2021.
2. Boroson, Don M.: On Achieving High Performance Optical Communications From Very Deep Space. *Proc. SPIE*, vol. 10524, no. 105240B, 2018.
3. Marino, Barbara E.; Tsou, Haiping; and Yan, Tsun-Yee: Earth Beacon Acquisition and Tracking Under Various Illumination Conditions. *Free-Space Laser Communication Technologies XIII Proceedings*, vol. 4272, 2001.
4. Gonzales, Michael A., et al.: Unprecedented Vibration Isolation Demonstration Using the Disturbance-Free Payload Concept. *AIAA 2004-5247*, 2004.
5. Chen, Chien-Chung, et al.: Simplified Lasercom System Architecture Using a Disturbance-Free Platform. *Proc. SPIE*, vol. 6105, no. 610505, 2006.
6. Ramos, Calvin, et al.: Communications Research and Development at NASA Glenn Research Center. *J. Aerosp. Eng.*, vol. 26, no. 2, 2013, p. 377.
7. Raible, Daniel E., et al.: On the Physical Realizability of Hybrid RF and Optical Communications Platforms for Deep Space Applications. *AIAA 2014-4482*, 2014.
8. Hylton, Alan; and Raible, Daniel E.: Networked Operations of Hybrid Radio Optical Communications Satellites. *AIAA 2014-4440*, 2014.
9. Zeleznikar, Daniel; Nappier, Jennifer; and Downey, Joseph: Ka-band Link Study and Analysis for a Mars Hybrid RF/Optical Software Defined Radio. *AIAA 2014-4389*, 2014.
10. Swank, Aaron J., et al.: Beaconless Pointing for Deep-Space Optical Communication. *AIAA 2016-5708*, 2016.
11. Raible, Daniel E.; and Hylton, Alan G.: Integrated RF/Optical Interplanetary Networking Preliminary Explorations and Empirical Results. *NASA/TM-2012-216050*, 2012. <https://ntrs.nasa.gov>
12. Li, Jing, et al.: Dual-Pulse Pulse Position Modulation (DPPM) for Deep-Space Optical Communications: Performance and Practicality Analysis. *NASA/TM-2012-216042*, 2012. <https://ntrs.nasa.gov>
13. Jacoby, Marc T.; and Swank, Aaron J.: Laser Pointing Sensor System for Beaconless Lasercom. *Next-Generation Optical Communication: Components, Sub-Systems, and Systems VII Proceedings*, vol. 10561, no. 105610K, 2018.
14. Swank, A.J.: High-Altitude Balloon Experiments for Advancing Beaconless Pointing Technology. *iROC Project document*, 2015.
15. Swank, Aaron J.; Aretskin-Hariton, Eliot D.: The Influence of Dihedral Angle Error Stability on Beam Deviation for Hollow Retro-Reflectors. *NASA/TM-2018-219946*, 2018. <https://ntrs.nasa.gov>
16. Aretskin-Hariton, Eliot; Swank, Aaron; and Gray, Justin S.: Beaconless Optical Communication System Constraints. *AIAA 2019-2130*, 2019.
17. Fielhauer, K.B.; Boone, B.G.; and Raible D.E.: Concurrent System Engineering and Risk Reduction for Dual-Band (RF/Optical) Spacecraft Communications. Presented at the 2012 IEEE Aerospace Conference, Big Sky, MT, 2012.
18. Ortiz, Gerardo G.; and Lee, Shinhak: Star Tracker Based ATP System Conceptual Design and Pointing Accuracy Estimation. *Proc. SPIE*, vol. 6105, no. 61050D, 2006.
19. DeVoe, C.E., et al.: Optical Overview and Qualification of the LLCD Space Terminal. *Proc. SPIE*, vol. 10563, no. 105630F-3, 2014.
20. Huang, Chien-Yao, et al.: Development of Precision Angle Measurement System. 2016 IEEE International Instrumentation and Measurement Technology Conference Proceedings, Taipei, Taiwan, 2016.
21. Tibshirani, Robert: Regression Shrinkage and Selection via the Lasso. *J. R. Statist. Soc. B*, vol. 58, no. 1, 1996, pp. 267-288.
22. Efron, Bradley, et al.: Least Angle Regression. *Ann. Statist.*, vol. 32, no. 2, 2004, pp. 407-499.
23. Schwartz, Stephen E.; Huang, Dong; and Vladutescu, Daniela Viviana: High-Resolution Photography of Clouds From the Surface: Retrieval of Optical Depth of Thin Clouds Down to Centimeter Scales. *J. Geophys. Res.*, vol. 122, no. 5, 2017.

