Development of an End-to-End Model for Free-Space Optical Communications

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Through funding by NASA's Exploration Systems Research and Technology (ESR&T) Program and the Advanced Space Technology Program (ASTP), a team, including JPL, Boeing, NASA-Glenn, and the Georgia Institute of Technology, will develop an end-to-end modeling tool for rapid architecture trade-offs of high-data-rate laser communications from lunar, martian, and outer planetary ranges. An objective of the modeling tool is to reduce the inefficient reliance on modeling of discrete subsystems or sequential development of multiple expensive and time-consuming hardware units, thereby saving significant cost and time.

This dynamic, time-domain modeling tool will accept measured component and subsystem data inputs and generate "difficult to measure" characteristics required for the performance evaluation of different designs and architectural choices. The planned modeling tool will incorporate actual subsystem performance data to reduce the develop–build–evaluate–refine production cycle. The list of high-level objectives of the program includes (1) development of a bidirectional global link analysis backbone software encompassing all optical communication subsystem parameters; (2) development of a bidirectional global link simulation model encompassing all optical communication parameters; (3) interoperability of the link analysis tool with all relevant detailed subsystem design models; and (4) a validated model that is validated against known experimental data at the subsystem and system levels.

I. Introduction

The urgent need for high transmission bandwidth to relay an ever-increasing volume of information is accelerating the need for lasercomm (free-space optical communication) technology. For human exploration of the Moon and Mars, data rates of several gigabits per second (Gbps) will be required from those ranges. Lasercomm, with its virtually unlimited and unregulated spectrum, is uniquely positioned to meet this requirement. These rates are needed to provide real-time video links, including high-definition television (HDTV); high-data-rate bidirectional monitoring data links; instant telepresence; immersed response; risk reduction for astronauts; Internet connectivity; and many other telecomm applications. Telecommunication at gigabit rates is at best very challenging with the current technology of conventional radio-frequency (RF) communications. Free-space optical communications is capable of delivering

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data rates from hundreds of megabits per second (Mbps) to several Gbps from the Moon and Mars. Hence, optical communication systems are expected to play a major role in the human exploration of Moon and Mars. The planned Lasercomm Modeling Tool will be compatible with emerging model-based system-level design architectures.

Space lasercomm systems are precision opto-mechanical instruments that must meet demanding tolerances. Degraded performance in any of the subsystem blocks or a capabilities mismatch among various blocks will result in less efficient data transmission. Utilizing the current development paradigm, a pair of laser-communication systems would be designed and fabricated to high tolerances through a sequential "build-up" process. Typically, several versions of the system are built, including (1) a breadboard unit (tabletop setup); (2) a brassboard unit (packaged optical head); (3) an engineering model (form, fit, and function, partially qualified parts); (4) a proto-flight unit (qualified parts, used for qualification testing), and (5) a flight unit. We will develop an end-to-end modeling and simulation tool for rapid architecture trade-offs of high-data-rate laser communications from lunar, martian, and outer planetary ranges. Relying on modeling and simulation capability to reduce hardware development multiplicity and costs is an established and accepted methodology [1,2]. Therefore, an objective of the modeling tool is to reduce the inefficient reliance on sequential development of multiple expensive and time-consuming hardware units. Instead, this tool is intended to allow transition from a detailed, integrated design directly to an engineering model, followed by minor refinements leading to the flight unit.

The models will accept measured component and subsystem data inputs and generate "difficult to measure" characteristics required for the performance evaluation of different designs and architectural choices. As an illustrative example, consider the development of a system for laser-beam pointing and control in the thermo-mechanical environment of a spacecraft platform. Although the mechanical transfer function is almost impossible to measure in a truly representative environment, it can easily and accurately be modeled using measured characteristics of the individual actuator and sensor components. Also, interface of the flight terminal and the host platform under a micro-gravity environment is difficult to simulate in the laboratory but is possible in software. The planned modeling tool will incorporate actual subsystem performance data to reduce the develop–build–evaluate–refine production cycle.

The dynamic, time-domain modeling tool will produce end-to-end system performance data as well as required opto-mechanical design tolerances. The tool will be employed at the stage where a substantial portion of the opto-mechanical design is completed and the performance allocations of major subsystems are known and can be characterized for input to the model. The model will be menu driven and generic enough to be useful for most lasercomm link designs. The architecture of the Lasercomm Modeling Tool will be modular, evolvable, and expandable. It will be designed with inherent flexibility and hooks in place to allow convenient integration of modeling tools developed outside the project into the master model. Figure 1 shows a very high level of input/output parameters for the "flight terminal" model component.

The current approach to lasercomm system engineering typically performs design and analysis in an independent, discrete, and disjoint manner. The results from one block are rarely available in a form suitable for direct inclusion in the next part of the flow. The design typically proceeds sequentially from one analysis to another, with the results of each stage often being distilled to a single, and oversimplified, value (e.g., jitter) for input to the next computational design tool. The result is often a design that works in principle but which requires multiple iterations to correct for the inadequacies of the design process.

Figure 2 depicts the optical communication signal flow for downlink and uplink between a probe spacecraft and an Earth-based receiver (ground-based stations or stations located above the clouds). A powerful, integrated software "toolbox" for the modeling and analysis of lasercomm systems is planned, which will encompass detailed simulation of each individual element in the block diagram. It will incorporate simulation modules that may be run independently and in parallel, taking interdependencies into account. A model of the system will be created; it will simulate the dynamic behavior of the structure, the optical train, the control systems for laser beam acquisition, tracking and pointing, the atmospheric

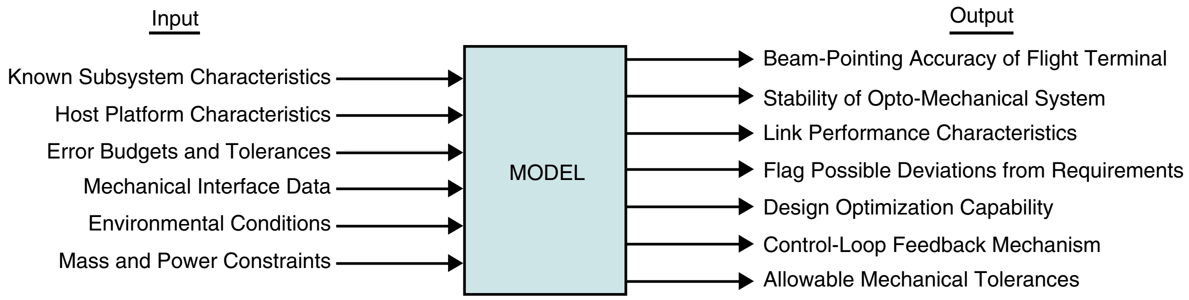

Fig. 1. Example of input/output data from the flight terminal module within the model.

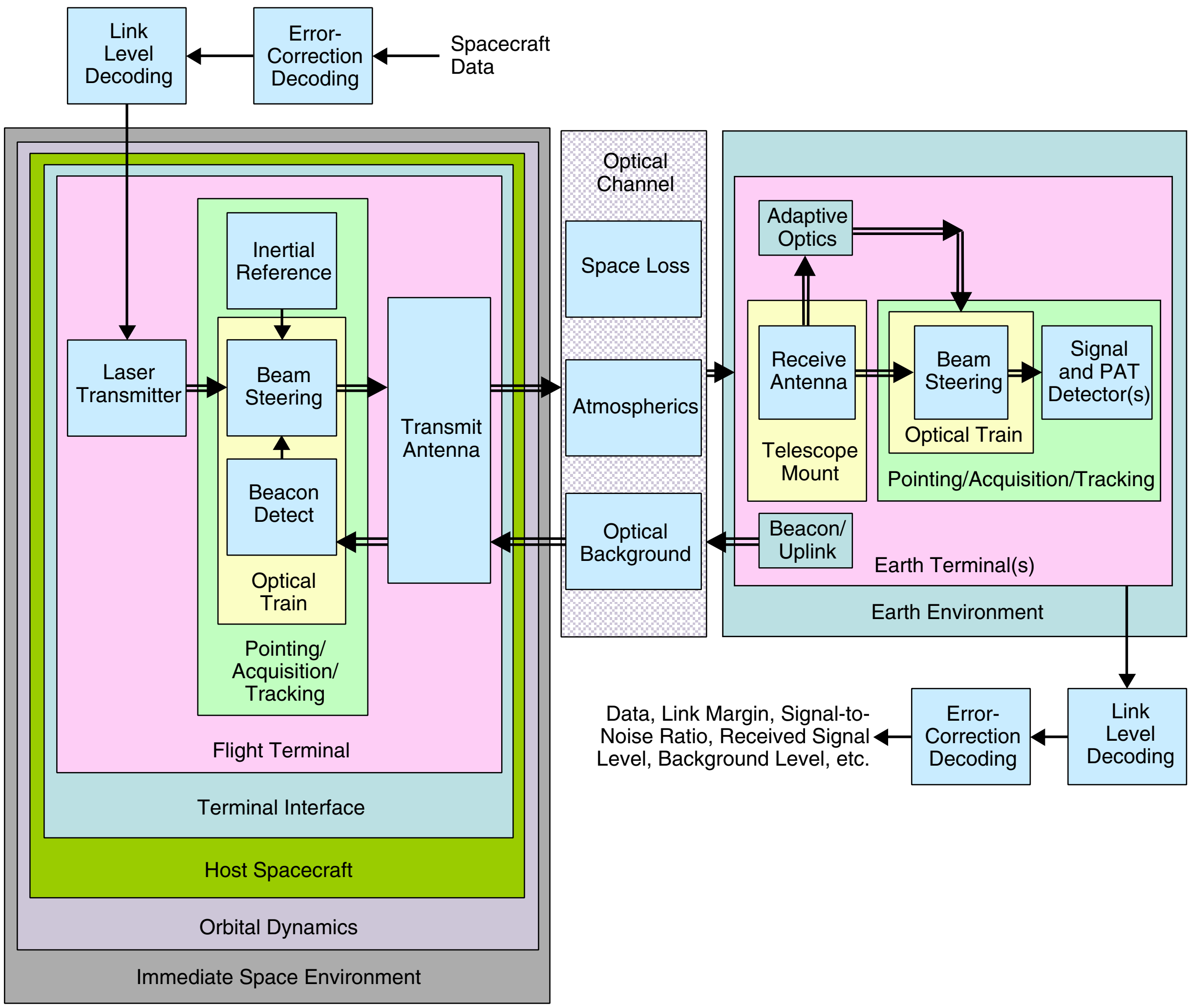

Fig. 2. Example of a communication signal flow between a spacecraft and Earth for free-space optical communication links. (PAT = pointing, acquisition, and tracking.)

channel, expected disturbance sources, and the operational environment in an integrated fashion. This framework will identify the important modal and physical interdependencies of the system that drive the opto-mechanical requirements. The tool will integrate multiple stand-alone software tools developed to address specific needs of lasercomm development and testing. These include software packages from JPL, Boeing, NASA-Glenn, the Georgia Institute of Technology, and commercial developers. The tool will be used to explore high-level design trades, validate design concepts, help guide technology development activities, and predict the performance of designs. The guiding philosophy is to design an optimized system, not just a collection of optimal subsystems. The integrated performance models will quantify thermal, structural control, optics, detector, and system issues in terms of laser-communication impact. Both linear and non-linear relationships are accounted for in the end-to-end performance estimates. The trades and optimization processes will be extended to include cost as a metric.

The specific project goals and objectives are

(1) A bidirectional global link analysis backbone software encompassing all optical communication subsystem parameters

(2) A bidirectional dynamic global link simulation model encompassing all optical communication parameters

(3) Interoperability of the link analysis tool with all relevant detailed subsystem design models (Phase II) and system models

(4) A validated model, validated against known experimental data (Phases I and II)

The linkage of various subsystem modules and the link analysis backbone, as well as the linkage between the modules, is shown schematically in Fig. 3.

II. Implementation Plans

The signal flow (shown in Fig. 1) will be thoroughly modeled in a link analysis program that will be the backbone of the modeling tool. The link analysis program receives subsystem data (e.g., aperture diameters, laser transmitter power) and the required bit-error rate, and calculates such parameters as the link margin, the required power at the receiver, and the background power at the receiver. The data are input manually and with best estimates derived from analysis or prior knowledge. Actual design and/or analysis data for each subsystem not only will improve the accuracy of the link analysis but will propagate changes iteratively throughout the system.

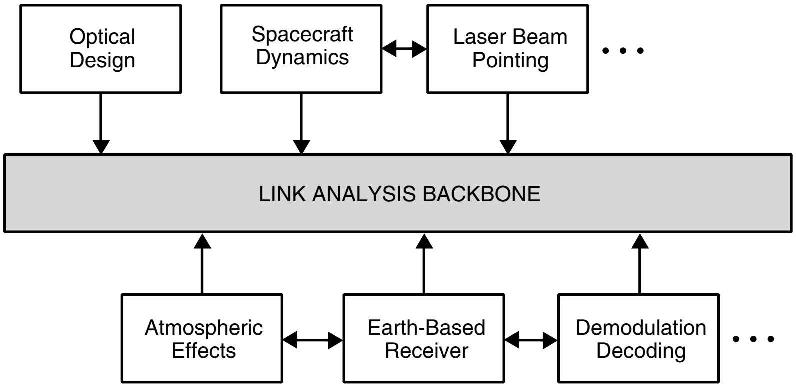

Fig. 3. Link analysis backbone and its interaction with modeled subsystems.

The software modules will be bound together using a suitable software environment. This software environment will provide the core capability to easily manipulate large matrices and to perform numerical analysis in both the time and frequency domains. Central to the tool will be the multidisciplinary capabilities of IMOS (Integrated Modeling of Optical Systems) and MACOS (Modeling and Analysis for Controlled Optical Systems) simulations developed at JPL. They are used for structural and thermal models, optical ray tracing, and diffraction. IMOS also will integrate with "legacy" discipline-specific tools such as NASTRAN (NASA Structural Analysis System) for structures, SINDA (Systems Improved Numerical Differencing Analyzer) for thermal analysis, and FOCAS (Free Space optical Communications Analysis Software) for link analysis. Finally, acquisition/tracking and pointing, atmospherics, networking, and other lasercomm-specific software will be incorporated.

A. Preliminary Software Architecture

The Lasercomm Modeling Tool is a software framework that allows integration of heterogeneous software tools and produces end-to-end system performance data as well as required opto-mechanical design tolerances. The Lasercomm Modeling Tool will be installable on individual personal computers (PCs). There will be an emphasis on reusing existing computational modeling tools and developing new tools only as needed.

In order to facilitate the Lasercomm Modeling Tool design, currently we plan to use the University of California, Berkeley-developed Ptolemy II software system.[2] The Ptolemy II system provides a set of Java packages that support the development of heterogeneous, concurrent modeling and design. These packages allow for

(1) Development of component-based modeling strategies, from state machines to process networks

(2) Development of message-passing schemes

(3) Development of graphical interfaces for developing models as wells as displaying results, including animation of model execution

(4) Development of hierarchical models

(5) Development of interactive models

(6) Integration of/linkage to individual software modules

Ptolemy II's principal role is to provide a mechanism to develop a seamlessly integrated lasercomm simulation platform. Ptolemy II exposes this mechanism through a well-defined set of software packages, including a large library of modeled components that implement several types of modeling, as follows: CT, continuous-time modeling; DE, discrete-event modeling; FSM, finite-state machines and modal model; PN, process networks; SDF, synchronous data flow; and SR, synchronous reactive.

The Ptolemy II system enables the construction of specialized tools with customized interfaces. Using Ptolemy, the Lasercomm Development Team will be able to develop a modeling tool that allows for use of appropriate tools as they become available, without affecting the existing tools or software infrastructure; as individual tools mature or as higher fidelity modules become available, the Lasercomm Team will be able to incorporate them.

B. Phase I

The behavior of the opto-mechanical system depends on a large number of variables that are not directly related to measured quantities. For example, the motion of the optical beam depends on the

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[2] http://ptolemy.eecs.berkeley.edu/

optical design, the control signal that drives the steering mirror, and the mechanical structural motion induced by external stimulus (e.g., platform jitter) [3,4]. The mechanical motion, in turn, depends on the mechanical design and properties of various structural elements. Consequently, simulation of the actual opto-mechanical-control properties is more difficult.

As an example, MACOS (Modeling and Analysis for Controlled Optical Systems) serves as a basis for the development. The simulation process will start with the optical design and the opto-mechanical model. The critical optical surfaces that affect the system performance will be identified. At each time step of the simulation,

(1) The structural-mechanical model with appropriate stimulus inputs (e.g., platform jitter and thermal gradients) will be evolved.

(2) The resulting location (and motion) of the critical optical surfaces will be identified.

(3) The motion and/or distortion will be incorporated into the optical analysis, and the resulting optical field distribution at the detector will be derived.

(4) The detector output signal based on optical intensity and the detector model will be generated.

(5) The detector output will be incorporated into the control system simulator and propagated to the next time step.

1. Block-Oriented System Simulator. Block-oriented simulation tools have been used extensively for simulation of communications systems at the physical layer, when the behavior of the system can be reduced to a discrete number of inputs and outputs. Such a simulation can be mapped to physical connections, e.g., electrical or optical signals. A more complex simulation problem is opto-mechanical control simulation.

This tool will be robust enough to accommodate a variety of lasercomm system designs and links (e.g., downlink, uplink, and crosslink). Each major block in Table 1 and its functions are further defined below.

C. Phase II: Modules Within the Model

Phase II involves development of individual modules, module coupling, and implementation of proper interoperability, followed by characterization and validation. Initial steps prior to utilizing the tool include (1) development of requirements (at level 3 or higher); (2) detailed link analysis; and (3) optical and opto-mechanical design, mostly utilizing JPL-developed tools and legacy software, with subsystems identified and characterized as much as possible. The approaches to developing some of the modules within the tool are described in the following.

Table 1. Major modules of the integrated modeling tool and their corresponding metrics.

Simulator module	Simulator output metric
Flight terminal	Laser beam pointing offset and stability
Optical channel	Link margin for a given bit-error rate
Atmospherics (attenuation/turbulence)	Link availability and fade probability data
Background light, Sun angles	Level of spurious signal (noise) as seen by the photo-receiver
Receiver systems	Precision of the receiver locking onto the downlink signal
Networking	Data latency, link availability, seamlessness of handover

1. Link Analysis, Channel Capacity, Signaling, Modulation, Coding, Formatting, Data Compression, and Buffer Management. Given a statistical model of the receiver output and a set of signaling constraints imposed by each of the physical subsystems (peak and average power constraints, bounds on duty cycle and slot widths), this tool computes the maximum link capacity. With efficient modulation and coding, a link can operate close to the Shannon capacity limit. This capacity can serve as a performance metric independent of the choice of modulation and coding upon changes to various subsystems. Separating subsystem design and coding/modulation design allows independent development, saving resources and time. The tool will include a full suite of error-correction codes (e.g., serially concatenated convolutional codes, low-density parity-check codes, and Reed–Solomon codes) and modulation formats (e.g., pulse-position modulation, multi-pulse-position modulation, and on–off keying). Combinations of these cover most applications.

2. Host Platform Characteristics, Interface Layer, and Space Environmental Conditions. Modeling of the host platform interaction with the laser terminal is one area where integrated modeling has already proved successful [5,6]. The model will accept the host spacecraft's vibration spectrum, anticipated dynamic thermal variations, and thermal gradients, and model the orbital gravity environment under which the system and the host spacecraft must operate. JPL is particularly skilled at modeling of spacecraft in the space environment. The mechanical interface model between the host platform and the laser terminal will include any passive or active isolation mechanisms and will model the dynamic modes of the terminal that interact nonlinearly with the spacecraft modes. The tool will incorporate orbit-analysis and radiation-environment simulation software to generate expected types and dosages of radiation in sensitive components (detectors, optical fibers, lasers, etc.). Rudimentary shielding effects will be incorporated to aid in the design and placement of lasercomm terminals and components.

3. Flight Terminal. At the heart of a flight terminal is the acquisition, tracking, and pointing (ATP) function. The ATP module encompasses all aspects and components that impact the laser transmission. The module will simulate the acquisition and pointing performance of a variety of communication scenarios. Boeing's experience in laser beam control has great breadth and depth. Examples of past work where ATP models were applied include the Airborne Laser (ABL), the Advanced Tactical Laser (ATL), the Space Based Laser (SBL), the High Altitude Balloon Experiment (HABE), the Advanced Discrimination Laser Technology (ADLT), the Tactical High Energy Laser (THEL), and numerous proprietary programs. The performance of the ATP tool has been successfully verified and validated against measured test data. Much of this experience is derived from directed energy systems' and light detection and ranging (LIDAR) systems' ATP design and implementation, and is directly applicable to lasercomm systems. Boeing-SVS's integrated ATP and beam control simulations include world-class capabilities in all areas that potentially can affect system performance, including models for optics, inertial sensors, steering mirrors, focal planes, lasers, structures, and thermal effects. These simulations also incorporate all signal-processing algorithms, including control law, sensor processing, acquisition, tracking, sensor handover, Kalman filters, state estimators, mode logic, and numerous other ATP control algorithms. These simulations have been used successfully to predict performance, develop hardware, integrate and test algorithms, and automatically generate final flight code for real-time processors, including field programmable gate arrays. Table 2 outlines some of the work that will be performed in the development of the modules for the flight terminal.

4. The Atmospheric Path. We will utilize the Boeing-developed OSSIM (Optical Signal Simulation) tool and industry tools such as WaveTrain software for atmospheric propagation and adaptive optics modeling. Other tools to be incorporated or developed are listed in Table 3.

5. Background Light, Sky Radiance, and Stray Light. Earth's atmosphere affects the optical signal from space through attenuation, scattering, and turbulence. Existing software programs (e.g., MODTRAN, FASCODE) will be used to predict the expected transmittance of the atmosphere at specific wavelengths, depending on location of the receiver site, altitude, and visual range. Sunlight scattered by the atmosphere causes unwanted photons to be collected by the telescope aperture, increasing the noise

Table 2. Modules for the flight terminal.

Functions within the module	Module work to be performed
Interface with structural mechanical design and optical design software.	Graphical user interface and interfaces with the JPL-developed optical/structural models will be formed.
Extract dynamic motion of critical optical surfaces.	Mechanical analysis suite needs to be further developed.
Fold motion back into optical design tool to estimate temporal response of the detector output.	Streamlined optical analysis and tolerancing for generation of point spread function distribution relative to detector.
Run the ATP module; control loops that determine the behavior of the ATP subsystem, identify requirements.	Builds upon existing simulation tools built by JPL and Boeing-SVS. Generate new control models as control systems and hardware evolve.
Run structural/thermal analysis and identify motions of critical surfaces.	Finite-element analysis and commercial software.
Generate a temporal behavior model for optical performance. Run optical analysis to identify performance impacts.	New link simulation tools. Interface with commercial software.

Table 3. Modules for the atmospheric channel.

Functions within the module	Work to be performed for the module
Determination of site-dependent atmospheric attenuation and sky radiance	Utilization of commercial software, e.g., MODTRAN, FASCODE, and NASA AERONET
Cloud statistics	Weather forecasting by use of historical data and real-time cloud observation
Atmospheric aerosol and turbulence models	Build upon NASA-Glenn (a project partner), JPL, and commercially developed software
Mitigation of atmospheric turbulence	Build and incorporate models for fade mitigation through multiple beam transmission and adaptive optics (e.g., Arroyo)
Modeling effects of beam wander, beam breakup, signal fade, and blurring (at the receiver)	Wave optics simulation software by teaming with vendors (e.g., tOSC)

level at the receiver and adversely affecting the receiver performance. Sky radiance is dependent on the sunlight's path through the atmosphere, the concentration of aerosol suspended in the atmosphere, and the Sun–Earth–probe (SEP) angle separation. Monitoring and prediction of the sky radiance through dedicated software (e.g., FASCAT) will predict the level of background noise. Atmospheric turbulence degrades the wavefront of the incoming signal, reducing the focusing ability of the receiving telescope and causing a scintillation of the optical signal. Atmospheric turbulence can be mitigated using adaptive optics; however, for optical space communication scenarios, such systems must operate under both daytime and nighttime conditions. Table 4 summarizes the activities for the atmospheric module development.

6. Earth-Based Terminal and a Global Network of Receivers. The optical receiver, meaning the telescopes, as well as the electronic receiver, meaning the photo-detector, the amplifier, and the associated electronics to demodulate and decode the signal, signal processing, and associated effects of clock jitter and drifts, will be modeled. The receiver may be located on the ground or above the clouds (on balloons, planes, or spacecraft) to avoid the negative effects of the atmosphere. A global optical network of telescopes will be required to receive the anticipated high data volume and to provide high link availability. The design and operation of a global optical communication network will rely on link availability and atmospheric channel models described earlier. This module will simulate operation

Table 4. Earth-based receiver.

Functions within the module	Work to be performed for the module
Single aperture Multiple aperture (array), and array of arrays	Build upon existing modeling work at Georgia Tech. (project partner)
Ground-based, air-based (plane, UAV, balloon) Space-based (LEO, MEO, GEO)	Build tools to incorporate receiver platform stability, and include or exclude atmospherics
Electronics receiver—single or array	Build tools; some developed already at JPL/Boeing
Small Sun-angle mitigation	Build upon modeling tools already developed at JPL
Thermal effects for daytime operation	Build upon modeling tools already developed at JPL
Stray-light analysis (due to dust and structure)	Legacy Breault research and JPL tools
Stray-light mitigation models	Build tools that model stops and spatial filters
Data demodulation, decoding, and synchronization	Build upon JPL-developed tools

UAV = unmanned arial vehicle; LEO = low Earth orbit; MEO = medium Earth orbit; GEO = geosynchronous Earth orbit.

scenarios, with emphasis on the Earth, Moon, and Mars, with the intent of allocating a cost-effective network to meet the requirements. By providing real-time data on the global weather and location of the Earth-based (ground-based, air-borne, and space-borne) receiver, the tool will determine the mode of operation that best fits the weather forecasts and indicate the resources needed to make a quality communication link.

7. Uplink Transmission. The model will be bidirectional and will include modules to depict the uplink facility, including optics and modulated lasers. The laser will be utilized for command and communications, navigation, or as a beacon for precision beam pointing by the flight terminal.

III. Test and Verification

The final deliverable is a thoroughly validated, evolvable, expandable, and menu-driven end-to-end simulation and computation platform for laser communications that will greatly cut cost and production-time cycle by evaluating design requirements and tolerances.

The modeling tool, as being developed, and following completion, will be completely characterized and validated at each step of development utilizing known data from the Mars Lasercomm Terminal (MLT). MLT is being developed by the Massachusetts Institute of Technology (MIT) Lincoln Laboratories, JPL, and NASA-Goddard for 2009 launch (2008 hardware delivery). The Mars Telecom Orbiter spacecraft will host the flight terminal. This project will be in continuous interaction with the Mars Laser Communication Demonstration (MLCD).

For the purpose of identifying the approach to test and verification of the Lasercomm Modeling Tool, we will categorize the functionality of the overall system and identify how each element will be tested and verified, as discussed in the following.

A. Development of the End-to-End Laser-Communication System Process

This is what the overall system is modeling. This can be thought of as the roadmap to how a laser-communication system operates and the various elements (e.g., environmental considerations) that affect the data of the entire system. This capability will be validated by review from domain experts.

B. Development of the Simulation Framework Used to Implement the Modeling Process

We plan to use Ptolemy II as the framework. Ptolemy II is widely used, has many industry sponsors, and has been tested and documented by a wide range of users.

C. Development of Subsystem Software Modules for Use in the Modeling Process

A test plan will be written that will include testing requirements for each individual module being developed. We plan to perform the following tests and verification on each subsystem software module that will be used in the modeling process:

(1) Code review: The code for each software module will be reviewed to verify the developer follows conventional coding style and to assist in identifying possible issues in the design and/or coding of the module.

(2) Unit testing: Each module will be unit tested with an emphasis on testing the various subroutines, execution paths, and boundary conditions of the module.

(3) Module testing: Each software module will be tested independently of the Ptolemy II framework. This will be "black box" testing. If necessary, software drivers will be written to test the modules. Expected data for each module will be calculated and compared with the results generated by a given module; the expected data will be documented as part of the test plan for the module.

D. Integration of the Subsystem Software Modules into the Lasercomm Modeling Tool Framework

The test plan will contain a section specifying the requirements/success criteria for integration tests. Once testing of a module has been completed, that module will be integrated into the framework. This will be an incremental process to ensure possible problems in interfaces and/or communication with a module can be easily isolated and identified. Results of executing the integrated module will be compared with expected results documented in the test plan.

E. Generation of Data (System Characteristics) Required for the Performance Evaluation of Different Designs and Architectural Choices

This is what the simulation generates that allows end users to determine the validity of the various components that make up the model:

(1) Scenario development: Based on input from domain experts, a set of scenarios will be created. These scenarios specify how the Lasercomm Modeling Tool will be used, the required input, and the expected output.

(2) Verification and validation test runs: Using the scenarios as test scripts, the end-to-end system will be executed. Results from each run will be documented, reviewed, and compared with expected results.

IV. Conclusion

The Lasercomm Modeling Tool discussed here is expected to provide a complete dynamic view of the communication terminal prior to the time-comsuming stage of precision fabrication and characterization.

Acknowledgments

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References

[1] G. E. Mosier, M. Femiano, K. Ha, P. Y. Bely, R. Burg, D. C. Redding, A. Kissil, J. M. Rakoczy, and L. D. Craig, "An Integrated Modeling Environment for Systems-Level Performance Analysis of the Next-Generation Space Telescope," SPIE, *Astronomical Telescopes and Instrumentation*, vol. 3356-08, pp. 89–97, 1998.

[2] D. C. Redding and W. G. Breckenridge, "Optical Modeling for Dynamics and Control Analysis," *Journal of Guidance, Control, and Dynamics*, vol. 14, pp. 1021–1032, 1991.

[3] D. C. Redding, B. M. Levine, J. W. Yu, and J. K. Wallace, "A Hybrid Ray Trace and Diffraction Propagation Code for Analysis of Optical Systems," SPIE, *Design, Modeling, and Control of Laser Beam Optics*, vol. 1625, pp. 95–107, 1992.

[4] G. E. Mosier, M. Femiano, K. Ha, P. Y. Bely, R. Burg, D. C. Redding, A. Kissil, J. M. Rakoczy, and L. D. Craig, "Fine Pointing Control for a Next-Generation Space Telescope," SPIE, *Space Telescopes and Instruments V*, vol. 3356, pp. 1070–1077, 1998.

[5] J. Spanos and Z. Rahman, "Control Concepts for Active Multi-Axis Vibration Isolation," *Proc. 6th Intl. Conf. on Adaptive Structures*, Key West, Florida, November 13–15, 1995.

[6] B. Bialke, "Microvibration Disturbance Sources in Reaction Wheels and Momentum Wheels," *Proc. Conference on Spacecraft Structures, Materials and Mechanical Testing*, Noordwijk, The Netherlands, March 27–29, 1996.