Architectural and Operational Considerations Emerging from Hybrid RF-Optical Network Loading Simulations

Yijiang Chen, Douglas S Abraham, David P Heckman, Andrew Kwok, Bruce E MacNeal, Kristy Tran, and Janet P Wu

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109

ABSTRACT

A technology demonstration of free space optical communication at interplanetary distances is planned via one or more future NASA deep-space missions. Such demonstrations will "pave the way" for operational use of optical communications on future robotic/potential Human missions. Hence, the Deep Space Network architecture will need to evolve. Preliminary attempts to model the anticipated future mission set and simulate how well it loads onto assumed architectures with combinations of RF and optical apertures have been evaluated. This paper discusses the results of preliminary loading simulations for hybrid RF-optical network architectures and highlights key mission and ground infrastructure considerations that emerge.

Key Words: Optical communications, DSN architecture, loading simulations, optical operations

1. INTRODUCTION

Free space optical communication at interplanetary distances is planned for future NASA missions. In order to enable this, development is underway to mature optical communications technology to Technology Readiness Level (TRL) 6 so that risk retiring technology demonstrations on upcoming Discovery or other missions can be hosted. Such demonstrations will "pave the way" for operational use of optical communications on future robotic missions with science payloads that generate large data volumes (e.g. synthetic aperture radar, hyperspectral imagers, large-pixel-area imagers, etc.). Human exploration missions to distant lunar orbits, asteroids, and Mars will also benefit from the large data volumes achievable with optical communications. Such optical communications capability will, for at least the next couple of decades, likely complement rather than supplant existing RF communications capability. Hence, the Deep Space Network (DSN) architecture will need to evolve in a manner that accommodates RF-only, combined-RF-and-optical, and optical-only missions equally well. Preliminary attempts to model the anticipated future mission set and simulate how well it loads onto assumed architectures with various combinations of RF and optical apertures reveal a number of potential architectural and operational trades between mission and ground infrastructure elements that still need to be studied. This paper discusses the results from those preliminary loading simulations for hybrid RF-optical network architectures and highlights some of the key mission and ground infrastructure considerations that emerged as open trades for future resolution.

Before doing so, however, it is important to understand how these preliminary loading simulations were conducted. A decade or so ago, the DSN developed an architecture-oriented tool suite for collecting and analyzing potential future mission customer needs and projecting the DSN infrastructure development required to meet those needs [1]. While this capability has evolved significantly over the years, it has largely been focused on RF communications [2]. With the

advances in deep space robotic missions and plans for human Mars missions alluded to above, an impetus is created to extend the capability of the tool suite to include optical communications. The following section discusses how this newly augmented tool suite is applied.

2. MISSION SET ANALYSIS PROCESS FLOW

The Space Communications Mission Model (SCMM) is the starting point for all the loading analyses (whether with an RF, optical, or hybrid RF-optical network). This NASA Headquarters Space Communications and Navigation (SCaN) Office model provides current, planned, and projected future missions. It gives high-level mission characteristics such as mission launch date, prime and extended mission end dates, science themes, destination, organizational affiliation, supporting network(s), etc. The next step in the mission set analysis process shown in Figure 1 below involves populating the Mission Set Analysis Tool (MSAT) with each mission's detailed telecommunications, tracking, and mission design information as a function of time. In cases where the future missions are poorly defined or are placeholders for competitively-bid missions (Explorer, Discovery, New Frontiers, etc.) the latest National Research Council decadal surveys and NASA roadmaps are used to derive candidate missions -- with the associated mission concept studies being used to determine the necessary telecommunications, tracking, and mission design information.

Figure 1. Mission Set Analysis Process Flow

Because the trajectories of the original concept designs may not correspond to the potential launch dates in more recent roadmaps, an Orbital Trajectory Inference Engine (OTIE) is used to generate updated trajectories. This tool also provides MSAT with range distance as a function of time for

computation of the RF communications links. And, it computes the visibility of each spacecraft relative to each of the DSN's RF ground stations (as well as any other ground stations that may be of interest) as a function of time.

With the data from OTIE in hand, MSAT computes the RF communications links for each spacecraft as a function of time and combines this performance data with each spacecraft's tracking requirement data as a function of time into the requirement file for input into an Architecture Loading Analysis Tool (ALAT). The requirements file includes such headers as mission name, science/exploration theme area, spacecraft Id, operational segment name, operational segment start date, operation segment end date, distance at start, distance at end, destination that identifies visibility file to load for each mission, subnet name, days between tracks, track length, tracking network, link direction, link type, band, frequency, required antenna gain versus noise temperature (G/T), required Effective Isotropic Radiated Power (EIRP), and data rate. Because deep space missions have different requirements depending upon whether or not they are in cruise, performing a critical event like a planetary flyby or an orbit insertion, in prime science, in an extended science mission, or in an extended relay mission, specification of these requirements in the context of the proper operational segment is an absolute necessity.

Based on the visibility identifiers from the MSAT requirements file, ALAT also grabs the corresponding RF visibility files from OTIE. At this point, ALAT has all of the information it needs to analyze the RF portion of the loading on the architecture.

For analysis of the optical portion of the loading on the architecture, however, additional information is required. In particular, a Strategic Optical Link Tool (SOLT) was developed to provide the needed optical link performance and associated parameters as a function of time [3]. In order to use trajectory information in the formation of tracking schedules, data rates as functions of time, for each optical site under consideration, are required. Acquiring such information starts with assessing the site-specific observational geometry associated with a trajectory, examples being the evolving spacecraft range, azimuth, and elevation. To this end, OTIE features a system for processing trajectories and optical site positions into files that contain that information.

For SOLT to be able to accurately calculate optical links and pass the needed metrics to ALAT, the files exported by OTIE are required to include, for each trajectory and each site on the Earth, the time-based evolution of the following data:

- Spacecraft range from the site, azimuth angle, and elevation angle
- Sun azimuth and Sun elevation
- Sun-Earth-Probe angle ("SEP" angle)
- Sun-Probe-Earth angle ("SPE" angle)
- Sun range from the spacecraft
- Flags indicating presence of any major planetary objects in view near the site-to-spacecraft line

SOLT then takes these inputs from OTIE, in conjunction with the spacecraft optical communication system and operational segment requirements from MSAT, and performs an optical link analysis for each mission that is using optical communications. The analyzed results are fed back to MSAT and supplied to ALAT with available data rate, optical visibility time at each site, noise photon flux, PPM

order, signal photon flux, slot width, code rate, wavelengths, and transmitter power at a fixed ground aperture size. If the ground aperture size used in the SOLT analysis differs from the aperture size scheduled by ALAT, ALAT scales the aperture size provided by SOLT to the actual ground aperture size using a scaling law that was developed during the development of SOLT [4]. At this point, ALAT has all of the information it needs to analyze the optical portion of the loading on the architecture.

3. ALAT and Combined RF and Optical Architecture Loading Analysis

The Architecture Loading Analysis Tool enables the DSN to analyze how well the projected future mission set loads up on alternative architectures consisting of both RF and Optical apertures. Specific ALAT functions include:

(1) generating simulated tracking schedules as an input to terrestrial data network performance modeling,

(2) simulating the performance of the current DSN architecture and planned upgrades for alternative mission loading scenarios, and

(3) modeling user-specified, multi-site ground-station architectures and simulating their performance relative to the current DSN architecture plus planned upgrades.

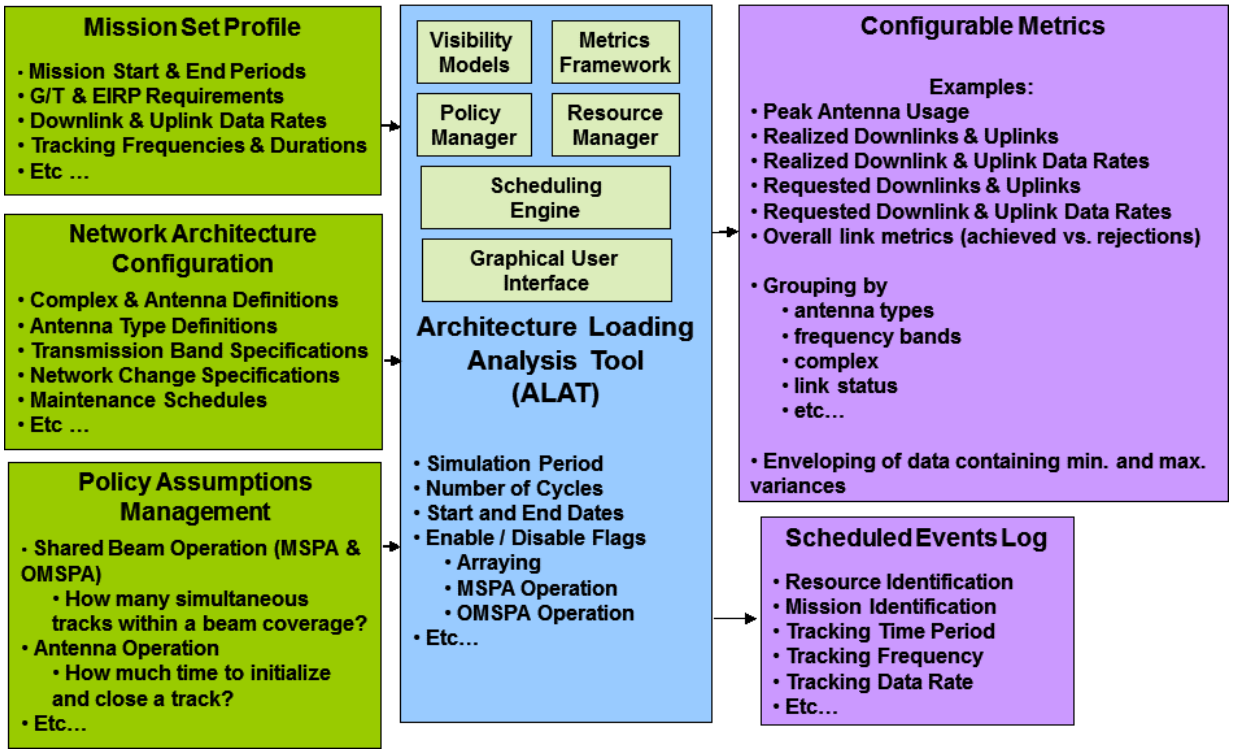

Figure 2. ALAT block diagram of inputs and outputs

ALAT is characterized by:

- An "intelligent" rule-based-automated scheduler that simulates 20-30 years of operations, assuming accurate spacecraft link requirements
- A flexible architecture that allows definition of complexes, antennas, antenna types, network

evolution and maintenance events.

- Customizable output metrics that allow analysis flexibility
- Use of accurate spacecraft and planetary ephemeris data from OTIE assures accuracy in assessing scheduling conflicts in the same sky locations

Figure 2 provides an overview of ALAT via an input and output block diagram. Key inputs to ALAT include the mission set profile, network architecture, and operational policy assumptions.

These inputs, in conjunction with ALAT's OTIE-derived visibility models, determine how the missions are scheduled on the assumed antenna architecture. Here the visibility models refer to spacecraft visibility to Earth ground stations around the globe, and do not account for cloud cover due to weather for optical communications. A graphical user interface allows specification of the network architecture configuration and the operational policy assumptions as well as the nature of the output metrics. In addition to the metrics, the simulated tracking schedule, also known as the "scheduled events log" can be output.

KEY MISSION INPUT CONSIDERATIONS

As alluded to earlier, each mission includes multiple operational segments that treat different phases of mission, e.g., launch, cruise, approach, orbiter science operation, etc. Each operational segment has different requirements including track length, track frequency, and data rate. Track length is the time interval (in hours) for each communication or contact between the DSN and the spacecraft, and track frequency is the number of days, or a fraction of a day, between two contacts.

KEY NETWORK ARCHITECTURE CONSIDERATIONS

The baseline architecture configuration is typically that of the current DSN plus any planned network upgrades and/or antenna retirements. The DSN consists of complexes (e.g. Goldstone, Canberra, Madrid). For optical links, other sites can be included, e.g. Palomar. The complexes are roughly equally spaced around the globe such that a spacecraft beyond geosynchronous orbit will always be in view of at least one complex as the Earth rotates. Each complex contains multiple antennas, including 34m and 70m antennas. Figure 4 is a 34m antenna located at Madrid complex.

Figure 3. 34 m antenna at Madrid complex

Each antenna is characterized by uplink and downlink capabilities at X-band, and various ones are also S-band and/or Ka-band capable. ALAT's GUI can be used to specify these particular band characteristics, as well as any new bands – along with the associated G/T and EIRP performance characteristics. Optical aperture can also be modeled through the GUI to look like antennas operating in an optical band with a certain aperture size and associated data rate capability. Hybrid RF-optical

antennas can be modeled using a combination of the RF and Optical antenna parameters.

THE SCHEDULING ALGORITHM

For each spacecraft, a window of opportunity is created for scheduling each track. The window of opportunity is determined by the tracking frequency of the spacecraft. For example, suppose Spacecraft A requires one track per week. The window of opportunity is defined as the scheduled start time for Spacecraft A to the next scheduled start time (e.g., a week later). Thus, the first track can be scheduled anywhere within this week. This is shown graphically in Figure 4.

In order for a given ground aperture to track a spacecraft, the spacecraft must be "visible" at the aperture site. Visibility files from either OTIE (RF) or SOLT (Optical) provide accurate visibility periods at each aperture site for the entire duration of the analysis. Figure 4 shows the windows of tracking opportunity (red), three actual tracks (blue) and visibility times (green, Figure 5) at a particular site. ALAT places each track within the required tracking window at a time when the spacecraft is visible to the aperture.

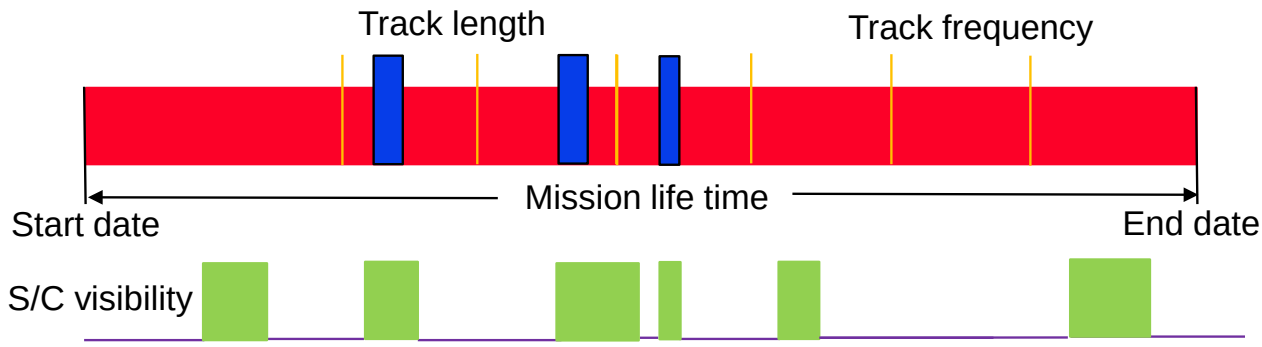

Figure 4. *Window of opportunity*

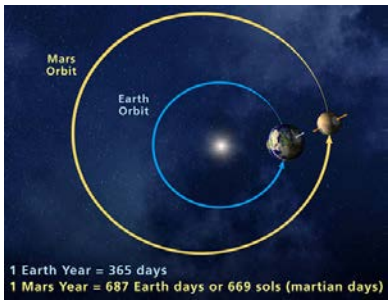

Figure 5. *Trajectories of Earth and a planet for visibility coverage*

For each visible time segment associated with each complex (starting from the longest available), the algorithm attempts to track the Spacecraft at that complex. It gets available time segments from each antenna within the visibility time segment at this complex and goes through each of the antennas at the complex and creates a sorted list (longest to shortest) of available time segments.

For each available time segment, if the time segment is longer than required track length, a list of all antennas that are available during this time segment, and are capable of supporting the spacecraft, is

created. Support means that the antenna supplies at least one of the transmission bands needed for the downlinks or uplinks with the required capabilities. If the time segment is shorter than the required track length, it is stored in a sorted list from longest to shortest. The reasoning here is to first try to fully satisfy a track before conceding to a partial track.

If the resulting list of available antennas can meet the requirements for handling the spacecraft track, the appropriate set of antennas to be used out of the available antenna list is selected. The tracking event is added to the tracking calendar for each antenna. The antenna is removed from availability for the future scheduling within this time period.

If the track requirement could not be satisfied or a track time cannot be identified, the process is repeated for available time segments stored in the partial list. If a track time is still not available, then the track is considered to be rejected, and the next spacecraft track is then processed for scheduling.

A mission requiring certain frequency bands is scheduled with antennas that have the needed frequency band with the needed capabilities. Antennas with RF capability are scheduled to support the RF portions of missions only, and optical antennas (to be built and deployed in the future) are scheduled to support the optical portions of missions only. Hybrid antennas are scheduled for both the RF and optical portions of missions, based on availability. If a mission requires both RF communication and optical communication link support, both RF antennas and optical antennas are scheduled for that mission, if hybrid antennas are not available.

Beyond frequency bands, G/T and EIRP are used as the criteria to test if the RF antenna (or an array of antennas) can support a mission that requires RF link support. Data rate is the criterion to decide if an antenna with optical capability can support an optical mission. This is due to the difference in characterizing RF and optical antenna link performance. The concept of G/T or EIRP for RF communication is not applicable to optical communications because of its link nature and susceptibility to various factors such as background atmospheric noise (not to be confused with cloud cover or other weather). Thus, supportable data rates are calculated for each optical link. These realizable data rates are provided by SOLT, which calculates the rate for each link at a particular ground aperture size.

To reduce the burden on SOLT in performing these calculations, ALAT incorporates an aperture scaling algorithm that can be applied to the optical missions as necessary. In such cases, SOLT provides the data rate for one specific ground aperture size. If a spacecraft is scheduled with a ground aperture size, in the same location, that is different from the aperture size used by SOLT to calculate the date rate, the scaling algorithm is employed to compute the supportable data rate for the new aperture size in accordance with the optical aperture scaling law referenced earlier [4].

Figure 6 shows an example of a requirement input from MSAT. There are two optical link missions in this example of input. One link is “OptScience Operations” which starts on 9-3-2027 and ends on 2-5-2044. Track length is eight hours and track frequency is twice a day. Its visibility and supported data rates are depicted in the visibility file: Mars_2022_2042_12m. The other is “Laser Comm Checkout” starting on 3-15-2027 and ending on 6-22-2027. Track length is four hours and track frequency once every 30.44 days. The visibility is recorded in the visibility file: MarsOptical2026_12m.

Assume that ground optical antennas are placed in Goldstone (12m), Canberra (12m), Madrid (12m), White Sands (1m), Table Mountain (1m), Alice Springs (12m), Haleakala (12m), Hartebeesthoek (12m), La Silla (12m), Mount Graham (12m), Palomar(12m), and Tenerife (12m). ALAT output for the example input is presented in Figure 7. Shown in the figure is the percentage of downlink hours realized, which is defined as

% Downlink track hours realized = downlink realized (or scheduled) track hours / downlink requested track hours *100%

Mission Name	Science/Exploration Theme Area	Spacecraft Id	Op Seg Name	Op Seg Start	Op Seg End	Distance at Start (AU)	Distance at End (AU)	Destination
Mars Optical Relay w/Ka 2026#812	Planetary Science	1	OptScience Operations#10335	9/3/2027	2/5/2044	1.95539	0.81653	V - Mars_2022_2042_12m
Mars Optical Relay w/Ka 2026#812	Planetary Science	1	Laser Comm Checkout#10347	3/15/2027	6/22/2027	0.50521	1.43298	V - MarsOptical2026_12m

Link Specification Name	Subnet Name	Hot Backup Required	Days between tracks	Track Length	Tracking Network	OMSP A Host	OMSPA Time Fraction	Link Direction	Link Type	Band	Frequency (GHz)	G/T or EIRP	Data Rate (kbits)
Science Optical Downlink#28248	Optical#30874	FALSE	0.50	8.00	Optical Network		0.00	DL	Telemetry	Optical	-	0	75,000.00000
Laser Checkout Link#28264	Optical#30890	FALSE	30.44	4.00	Optical Network		0.00	DL	Telemetry	Optical	-	0	100,000.00000

Figure 6. Example of requirement input from MSAT

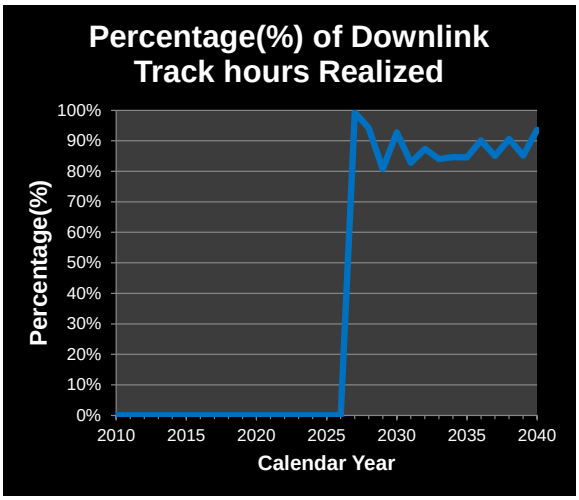

Figure 7. Example of ALAT output for optical link analysis

Comparing the input requirements of Figure 6 with the ground infrastructure assumed, one would expect downlink track hours realized to be 100% (ignoring outages due to weather). However, this is not the case as shown in Figure 7. Downlink track hours realized are 80% to 93% after 2027. This is because the spacecraft is not fully visible to all of the stations. To get downlink tracked 100 percent of the time requires both the ground infrastructure availability and visibility to correspond as shown in Figure 4. Some of the optical ground stations, however, have a northern hemisphere location and some have a southern hemisphere location. Depending upon the season and certain longer-term trends, the assumed Mars spacecraft may be northern or southern-hemisphere biased, leading to a more limited choice of ground stations.

4. FUTURE MISSION ARCHITECTURE LOADING CONSIDERATION

Many other optical and combined RF-optical architecture loading simulations were performed and analyzed to assure proper functioning of the associated software. However, these attempts to model the anticipated future mission set and simulate how well it loads onto assumed architectures with various combinations of RF and optical apertures revealed a number of potential architectural and operational trades between mission and ground infrastructure elements that need to be worked out. In RF communication, how RF missions operate has been well established. However, the knowledgebase for operation with optical communications is scarce. Except for the LADEE Lunar Communications Demonstration (LLCD), no real deep space missions with optical communications capability have been designed and flown. The questions associated with how missions will operate with optical communications need to be worked out and addressed. These questions include:

- Will a mission keep the same tracking and acquire more data when RF is replaced by higher-rate optical communications? Or, will it seek less tracking for the same data volume, thereby minimizing communications time in favor of observation time?
- Should optical communications operate in conjunction with RF and switch to RF in bad weather? This will depend on the site location and weather conditions. If an optical antenna is located within the same view periods as RF antennas operating in the proper band(s), this option might be feasible. But, it could lead to significant asset contention with the RF missions that are also depending upon those antennas. This would be particularly true, if the RF downlink requests were not scheduled until the last minute. These passes would likely have to be significantly longer than the nominal optical passes. On the other hand, if contingency RF downlinks were scheduled far in advance and then not used, the RF antenna utilization would not be very efficient and would shortchange the RF missions that would otherwise have utilized the passes. Another remedy to reduce the weather effect on optical communications without RF backup would be to build optical ground antennas in several sites far away from each other within the same geographical region, so that the link can be switched from site to site in order to circumvent any bad weather. However, this option could be very expensive to implement. And, for both approaches, the operational feasibility can depend significantly on the mission and spacecraft design (e.g., anticipated data volumes and onboard data storage capability for use with Delay Tolerant Networks). Clearly, there is a “chicken and egg” issue implicit in all of this. The mission and spacecraft design tend to be driven to some extent by the RF and optical ground architecture. But, the optimal RF and optical ground architecture tends to depend heavily on the user mission and spacecraft designs.
- To the extent that small Sun-Earth-Probe (SEP) angles can sometimes degrade optical communications performance due to stray light and small Sun-Probe-Earth (SPE) angles can sometimes degrade performance due to difficulties with pointing beacon detection, should optical links be switched to RF links during such time periods? This issue is very similar to the weather issue, though it is a lot more predictable. The solution to weather of switching to RF can probably be applied to small SEP and small SPE angles (when warranted by the link conditions), while the optical ground site diversity solution to weather probably will not help in these instances.
- Will future optical missions come to rely on optical uplinks for commanding, or will they still rely on RF for the uplinks? While ALAT has the ability to schedule optical uplinks, our analyses to date have focused on optical downlinks with the assumption that the optical missions will depend on RF uplinks. The assumption drives dual scheduling of RF and optical ground assets for the optical missions in much the same way that the weather and SEP/SPE angle issues do. However,

if the optical missions assume more risk and embody more onboard autonomy such that weather delays to optical commanding can be tolerated, the RF uplink might not be needed and the loading situation for the RF and optical ground assets would then change significantly. There could be a gradual transition from hybrid RF-optical spacecraft to all-optical spacecraft, but on what timescale?

- A similar question arises for navigation. Will future optical missions still rely on RF for two-way Doppler and ranging and delta-DOR, or will they rely solely on optical ranging? Again, the answer to the question can dramatically impact the RF and optical ground asset loading. If RF is still used for navigation, dual RF and optical ground assets will need to be scheduled. If the optical missions rely solely on optical ranging, then the RF ground assets are freed up. But, in such a case, what then is the required occurrence frequency and duration of the optical ranging sessions? Can these sessions be done as part of the optical communications passes, or do they require separate shorter passes at a different tempo from the communications passes? Again, there could be a gradual transition from hybrid RF-optical spacecraft to all-optical spacecraft, but on what timescale?
- Will the answers to the prior questions be different for missions with humans onboard as opposed to purely robotic missions? For mission safety reasons, will human missions always desire a combination of RF and optical communications capabilities? Whether they do or not, will they always want 24/7 coverage?

Clearly, the answers to all of these questions affect the nature of the RF and optical ground asset mix to be analyzed with ALAT. In the hybrid RF-optical spacecraft cases, hybrid RF-optical ground antennas might load better than trying to schedule separate RF and optical ground assets for the same spacecraft. But, if the preponderance of the future mission set is dominated by RF-only and optical-only spacecraft, then the hybrid RF-optical ground assets will not load efficiently. Hence, before the detailed loading performance of combined RF and optical ground architectures can be analyzed in any detail, a systematic approach to answering the above questions needs to be formulated and executed.

With such answers, proper ground antenna architectures can be postulated and analyzed for their ability to support the projected future mission set. These results will then help inform NASA as it plans for infrastructure development to prepare for human/robotic missions in the coming decades.

5. CONCLUSION

With technology demonstration of free space optical communication at interplanetary distances currently planned for one or more future NASA deep-space missions, it seems likely that we will see significantly more missions, robotic and human, embracing optical communications in the future. Given this, we have augmented our RF-focused architecture analysis tool suite to include optical communications capabilities. This augmented tool suite has been used to make some preliminary attempts at modeling the anticipated future mission set and simulating how well it loads onto assumed architectures with combinations of RF and optical apertures. These attempts culminated in several key questions that potential optical communications users and potential optical communications providers will need to systematically address while postulating combined RF and optical architectures. These questions generally revolve around three key issues: the appropriate mix between additional data volume and tracking pass reduction that becomes possible with the data rate differences between optical and RF, the appropriate RF and optical mix onboard the spacecraft to ensure unimpeded operation and navigation, and the degree to which robotic and human missions can embody the same

types of RF/optical operational assumptions. As the answers to the questions in each of these issue areas become better understood and incorporated into the combined RF and optical ground architectures being postulated, more precise loading performance analyses can be performed to arrive at the most optimal RF and optical ground assets combinations for meeting the projected future demand.

Acknowledgement:

The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. © 2016. California Institute of Technology. Government sponsorship acknowledged.

REFERENCES

[1] MacNeal, Bruce E., Douglas S. Abraham, Rolf C. Hastrup, Janet P. Wu, Richard J. Machuzak, David P. Heckman, Robert J. Cesarone, Raffi P. Tikidjian, and Kristy Tran, "Mission Set Analysis Tool for Assessing Future Demands on NASA's Deep Space Network," IEEE Aerospace Conference 2009, April 2009.

[2] Cheung, K.-M. and D. S. Abraham, "End-to-End Traffic Flow Modeling of the Integrated SCaN Network," *Interplanetary Network Progress Report*, IPN PR 42-189, pp. 1-20, May 15, 2012.

[3] Moision, B. and H. Xie, "An Approximate Link Equation for the Direct-Detected Optical PPM Link," *Interplanetary Network Progress Report*, IPN PR 42-199, pp. 1-14, November 15, 2014.

[4] Moision, Bruce and Hua Xie, "An Analogue to the RF scaling law for an optical link," November 6, 2013, JPL internal memorandum.