HUMAN FLIGHT TO LUNAR AND BEYOND – RE-LEARNING OPERATIONS PARADIGMS

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ABSTRACT[3]

For the first time since the Apollo era, NASA is planning on sending astronauts on flights beyond LEO. The Human Space Flight (HSF) program started with a successful initial flight in Earth orbit, in December 2014. The program will continue with two Exploration Missions (EM): EM-1 will be unmanned and EM-2, carrying astronauts, will follow.

NASA established a multi-center team to address the communications, and related tacking/navigation needs. This paper will focus on the lessons learned by the team designing the architecture and operations for the missions. Many of these Beyond Earth Orbit lessons had to be re-learned, as the HSF program has operated for many years in Earth orbit. Unlike the Apollo missions that were largely tracked by a dedicated ground network, the HSF planned missions will be tracked (at distances beyond GEO) by the DSN, a network that mostly serves robotic missions. There have been surprising challenges to the DSN as unique modern human spaceflight needs stretch the experience base beyond that of tracking robotic missions in deep space. Close interaction between the DSN and the HSF community to understand the unique needs (e.g. 2-way voice) resulted in a Concept of Operations (ConOps) that leverages both the deep space robotic and the Human LEO experiences.

Several examples will be used to highlight the unique challenges the team faced in establishing the communications and tracking capabilities for HSF missions beyond Earth Orbit, including:

- *Navigation. At LEO, HSF missions can rely on GPS devices for orbit determination. For Lunar-and-beyond HSF missions, techniques such as precision 2-way and 3-way Doppler and ranging, Delta-Difference-of-range, and eventually possibly on-board navigation will be used. At the same time, HSF presents a challenge to navigators, beyond those presented by robotic missions – navigating a dynamic/"noisy" spacecraft.*

- *Impact of latency – the delay associated with Round-Trip-Light-Time (RTLT). Imagine trying to have a 2-way discussion (audio or video) with an astronaut, with a 2-3 sec or more delay inserted (for lunar distances) or 20 minutes delay (for Mars distances).*

- *Balanced communications link. For robotic missions, there has been a heavy emphasis on higher downlink data rates, e.g. bringing back science data. Higher uplink data rates were of secondary importance, as uplink was used only to send commands (and occasionally small files) to the spacecraft. The ratio of downlink-to-uplink data rates was often 10:1 or more. For HSF, a continuous forward link is established and rates for uplink and downlink are more similar.*

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[3] The work reported in this paper was partially conducted at the JPL/CIT under contract with the National Aeronautics and Space Administration and at NASA HQ.

1. Introduction

The last time NASA (or any other agency) sent humans beyond low-earth orbit (LEO) was in December 1972, during the Apollo-17 mission. Since then, human presence in space has been restricted to LEO, primarily through the International Space Station (ISS), Space Shuttle, and the Mir space stations. In the last decade there is significant interest in, and related planning for, human exploration beyond LEO. For NASA, there are plans to send humans to lunar distances, to be followed by human flights to Mars and asteroids. Specifically, the Human Space Flight (HSF) program started with a successful initial non-crewed flight of the Multi-purpose Crew Vehicle (MPCV) in Earth orbit in December 2014, and will continue with two Exploration Missions (EMs): EM-1, an uncrewed mission, is planned for a 2018 launch while EM-2, carrying a crew, will follow in 2021. Both missions will spend most of the time at lunar distances and will use a similar launch system and payload.

The launch configuration for EM-1/EM-2 will serve as a basis for future missions. It is based on a Space Launch System (SLS) powerful rocket, carrying an upper stage, and a payload. The upper stage will initially be the Interim Interim Cryogenic Propulsion System (ICPS) that will eventually be replaced by the Exploration Upper Stage (EUS). The payload will be the MPCV, supported by a Service Module (SM). This configuration is shown in Figure 1. The initial design reference capability for Exploration Mission 1 (EM1) includes a >20 day Distant Retrograde Orbit (DRO), shown in Figure 2.

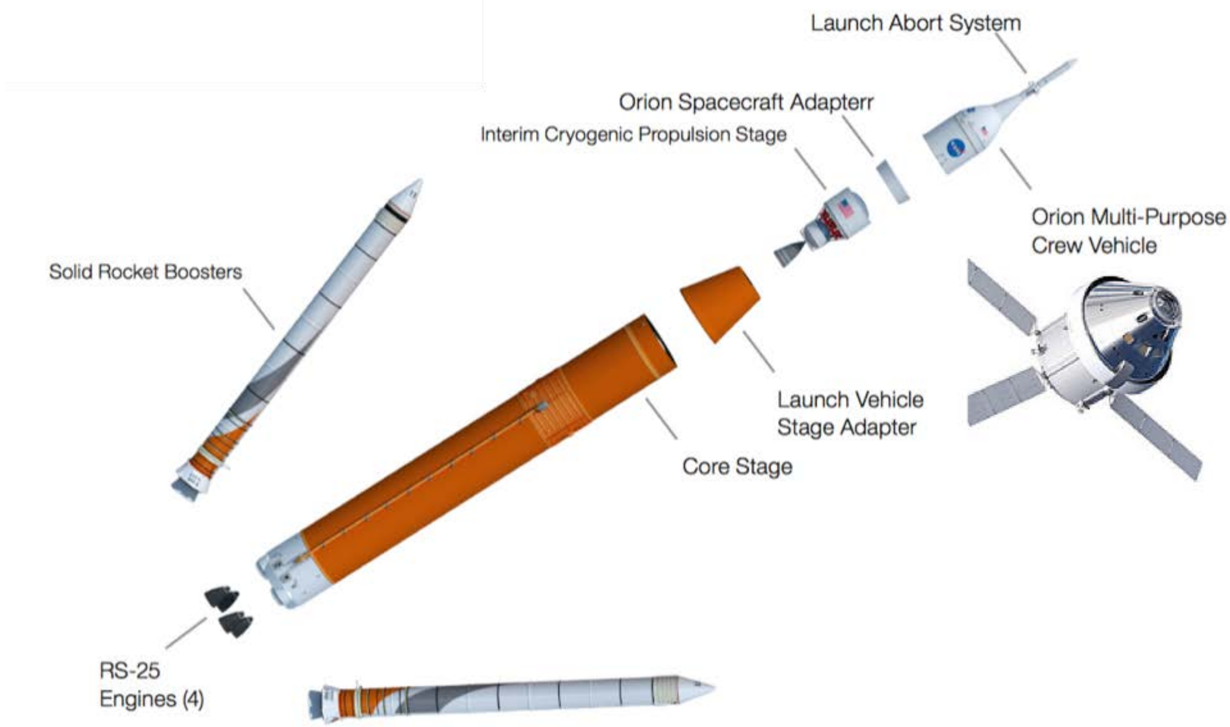

Figure 1 – Components of the Exploration Mission System

In the intervening years, NASA (and its partner agencies) continued to develop equipment and operational experience for LEO crewed missions. However, many of the beyond-LEO technical and operational lessons, learned during the Apollo era, must be re-learned. While the general outline of the Apollo-era technical and operations approach at above-LEO distances has not changed, the details have changed; this is primarily due to technical progress as well as recent budgetary limitations. For example, unlike the Apollo missions that were largely tracked by a dedicated Manned Space Flight ground network, the HSF missions will be tracked by existing tracking networks, shared with other crewed and robotic missions. Figure 3 shows the planned mission profile and assets for communications and tracking of EM-1/2.

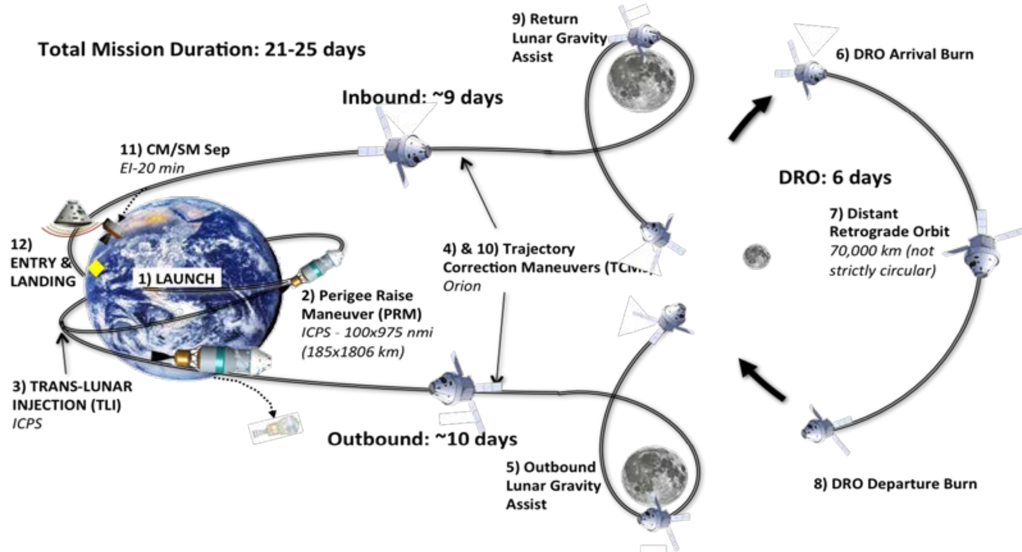

Figure 2 – Exploration Mission 1 (EM1)
Uncrewed Distant Retrograde Orbit (DRO)

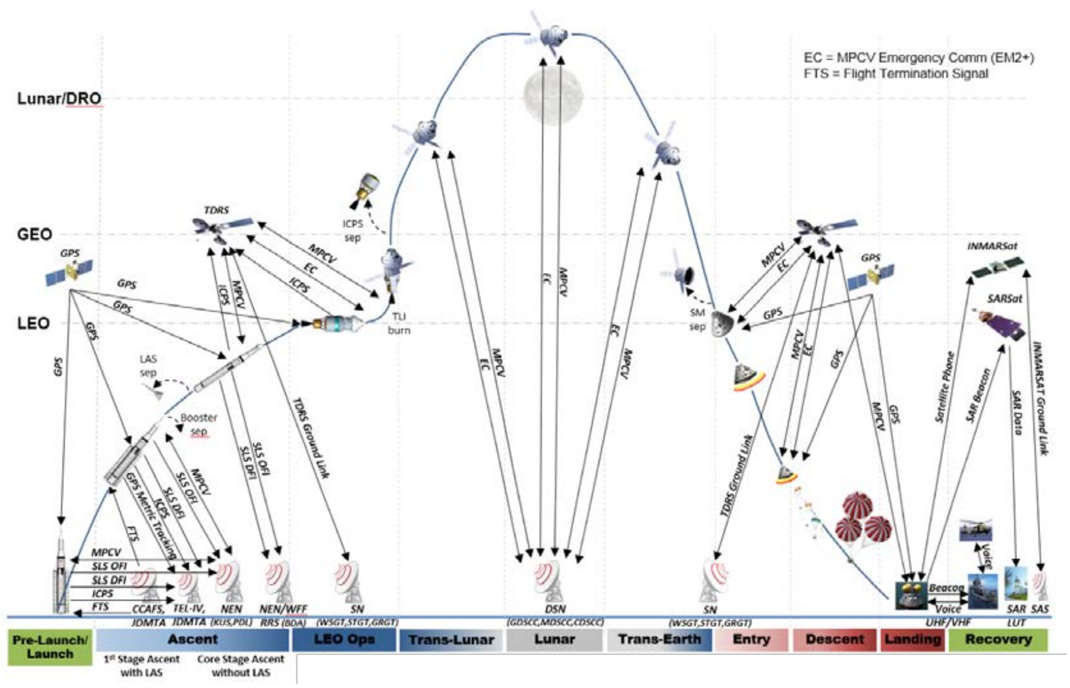

Figure 3 – Communications and Tracking Approach for the Exploration Missions 1 and 2

In particular, at distances beyond the Geo-Stationary Orbit (GEO), HSF missions will be tracked primarily by the Deep Space Network (DSN) antennas. As shown in Figure 4, the DSN has three sites spread approximately 120 degrees of longitude apart, near Goldstone, California, Madrid, Spain, and Canberra, Australia. Each of these sites has several antennas designed specifically to support missions at large distances from Earth: large steerable antennas (34m to 70m in diameter), powerful transmitters (typically 20 kW continuous power) and cryogenic sensitive front-ends. The DSN sites are positioned to operate primarily above GEO: Figure 5 shows a simplified model where the sites and the spacecraft are in equatorial plane, and the sites separated exactly 120 degrees of longitude apart. For such a case, continuous coverage starts at ~30,000 km. Below GEO, NASA relies on the capabilities of the Space Network (SN, aka, Tracking and Data Relay System, TDRS) and the Near Earth Network (NEN).

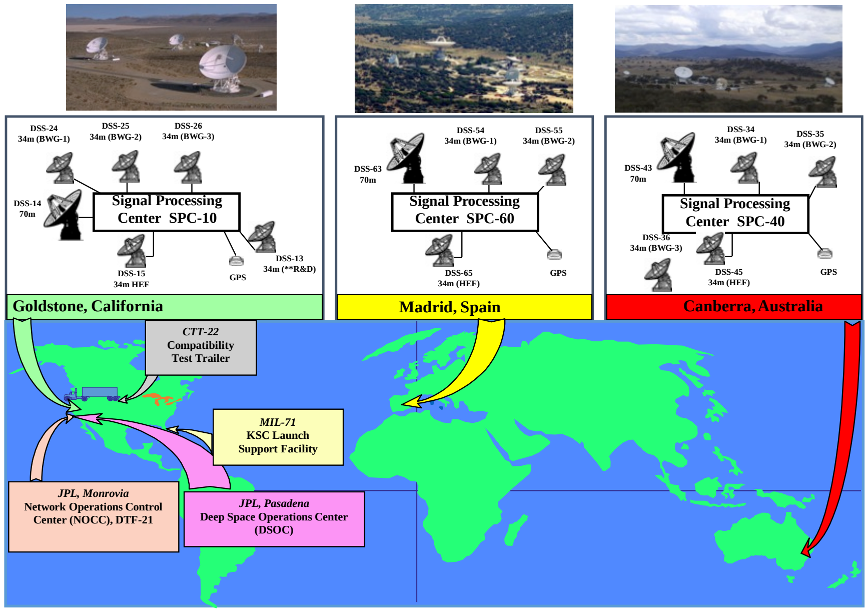

Figure 4 – Configuration of the Deep Space Network

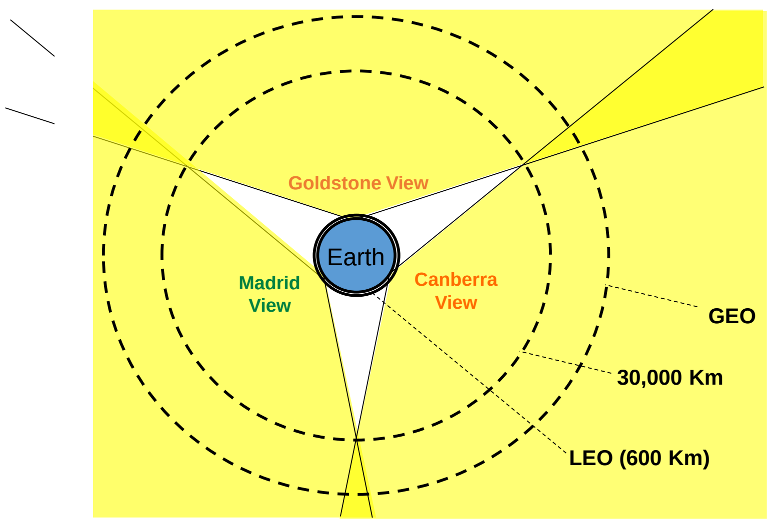

Figure 5 – Simplified Spacecraft Visibility from DSN Sites

This paper will discuss aspects of lunar mission support, as well as future missions to Mars and asteroids, with a focus on Concept of Operations (ConOps) beyond GEO distances. This data is based on several years of close interaction between the DSN and the HSF community that defined the unique needs (e.g. 2-way voice) of Human missions, incorporated the realities of beyond-GEO operations (e.g. round-trip-light-time latency, non-GPS navigation), which lead to development of a ConOps that leverages both the deep space robotic experience and the Human LEO experience.

2. Approach

NASA established a multi-center team to address the communications, ground networks, and related tacking/navigation needs. This team, known as the Integrated Communications, Networks, and Tracking (ICAN) team, is coordinated from the Johnson Space Center (JSC) and has representatives from all organizations involved in the communications and networks aspects of the HSF programs. Figure 6 shows the organizational composition of ICAN. The ICAN team meets weekly and operates as a cross-program coordinator. While having no direct budget or authority to act as a formal control board, the members are the leads for their respective areas. They can thus work together to ensure the combined organization's baselines work together and the leads can affect any needed effort through their home organization or joint efforts.

Figure 6 – ICAN Roles and Structure

An example for the ICAN approach is the method of achieving compatibility between the S-band transponder (SBT) baselined for HSF missions and the DSN antennas. The SBT was designed to be compatible with Tracking and Data Relay Satellite (TDRS) data rates, modulation formats and error-correcting coding. The DSN largely uses Consultative Committee for Space Data Standards (CCSDS) data rates, modulation formats, and error-correcting coding. ICAN worked to identify a solution that meets mission requirements, while minimizing cost involved to make the systems compatible. The result was that:

- Some changes were made to the SBT, e.g. to enable residual carrier modes and non-regenerative ranging.

- Some changes were made in the DSN, e.g. adding downlink Low Density Parity Coding (LDPC) decoding and uplink Enhanced Forward Command Link Transfer Unit (EFCLTU) formats

- Other changes, such as uplink error-correcting coding, were determined as desired but not required, and were not implemented

One of the challenges, and successes, for ICAN is bridging the language and culture differences between elements of the community. Let us use two examples:

a. The DSN uses the term "3-way Doppler" to denote sending a forward signal from one antenna and receiving the reverse signal at another antenna. The EM navigation team uses the same term to denote sending a forward signal from one antenna, receiving the reverse signal at another antenna, and receiving the reverse signal also at the antenna sending the forward signal. (Section 5).

b. The DSN uses the term “timely” to denote the smallest latency possible for a given, incoming signal. It is specified at 10 seconds (assuming lower data rates), which is acceptable for a signal that originates at a Mars distance of 20 light-minutes away. But this “timely” latency of 10 seconds is more difficult to accept for a signal that originates much closer to Earth (lunar distances), especially if the link carries voice traffic. Using assessed work case times based on system performance (not spec) may have as much as 5-8 seconds of time for full round trip signal to/from LRO distances when include all sources of latency. With worst case spec latency (such as the DSN 10 seconds) end to end latency for a conversation could be much longer (Section 6).

ICAN served as a forum where the terminology associated with space operations for beyond LEO crewed missions could be made clear and consistent.

3. Concept of Operations

Crewed missions levy special requirements on the ConOps for a communications architecture. Let us focus on the requirements that impact support from DSN antennas:

a. Human-in-the-loop design. Robotic spacecraft are designed to operate fully based on pre-programmed sequences. These can be very detailed (e.g. drive 4 ft north then 2 ft east then 4 ft north) or higher level (e.g. drive from rock A to rock b). Missions can benefit from strong participation by crew members.

b. Dealing with vehicle emergencies. A robotic spacecraft allows for loss-of-mission (albeit at low probability) and usually can recover slowly from mission anomalies. A crewed vehicle generally needs to be recovered quickly since sustaining the crew has limits to consumables such as food, which crews require. This will affect the design of the communications link (Section 4) and the voice/video capabilities (Section 6).

c. Dealing with Aborts and Return to Earth. Except for rare missions, such as Hayabusa, a robotic spacecraft will rarely be required to return to the Earth’s surface. Crewed Missions nominally have a planned return and re-entry to Earth. Additionally, crewed missions need to account for an ability to abort from the planned mission and return (e.g., if the Trans Lunar Injection burn is off-nominal this might place the crew on a path which is not sustainable and burns would be required to abort the planned mission profile to ensure return to Earth in a timely manner). This will effect planning for the tracking (Section 5) and voice/video capabilities (Section 6)

d. Crew Support and Utilization. Robotic missions can sustain very long periods of time without contact from Earth. Having crew on a mission provides some significant advantages, but also drives special needs. On the International Space Station and Space Shuttle, crew medical conferences and private family conferences were routinely planned to provide contact by the crews back to their family and support groups – similar activities are expected to continue in exploration fights.

   Both crewed and robotic missions include command and telemetry as well as software uploads and return of science data and imagery. However, the number, frequency, and types of files transferred to/from the vehicle for crewed missions is greater than robotic craft.

   Crewed missions that leverage the advantage of crew interactions also need to include procedures and support data in a human legible form with graphics and images, as well as video (imagine working to do maintenance on your washing machine from a text-only file or trying to explain how to judge the color of a complex science experiment’s operations with no diagram).

   Other unique needs for a crewed mission can include items such as stowage tracking file/information (normal daily usage or for items such as calculating cg movement when assessing reentry), video file download of experiments, supporting transfer of email, and even providing the crew a movie file or video of news or other events to help keep them connected with the Earth.

These crew-related aspects will affect the design of communications link (Section 4) and the voice/video capabilities (Section 6).

e. Educational Mission and Public Engagement – Robotic spacecraft are designed and operated to support NASA's education and public engagement in STEM (science, technology, engineering and mathematics) goals. Examples of these effort includes Voyager's official twitter account, it's taking of the "Pale Blue Dot" photo and Curiosity's playing the first song from Mars (recorded by Will.i.am).

Crewed missions extend this support to more direct actions by the crew; for instance, robotic spacecraft are not designed to write and post their own tweets. Engagement is mission unique, but has almost always includes talks with schools, local and national media interviews, participations in conferences or events (e.g., a video from ISS kicked off a TED conference and many others), recorded videos of life in space (e.g., How one cuts hair on the ISS) and engaging science demonstrations (e.g., Google ISS Don Petitt Saturday Science).

These aspects of crewed missions will affect the design of a communications link (Section 4) and the voice/video capabilities (Section 6).

4. Design of Communications Link

Extending the communications link beyond-GEO has resulted in technical advances since the Apollo era and the increased international cooperation, especially in the area of standards.

A key factor is the development of the international standards under the Consultative Committee for Space Dada Standards, CCSDS. CCSDS (www.CCSDS.org) is an international organization that was formed in 1982 and currently has 11 Member Agencies, 30 Observer Agencies, and 98 Associates. It serves as the clearing house for standards that enable international interoperability. One advantage in moving to the CCSDS standards for the spacecraft-to-ground link is greater compatibility with existing interfaces to the various Mission Control Centers (MCC). The DSN has converted many of its formats to be highly-compatible with CCSDS.

In the same time frame, NASA has launched the TDRS satellites. TDRS satellites use spacecraft-relay formats that overlap with the CCSDS formats for spacecraft-to-ground link, but have significant differences. It is important to note, however, that the TDRS formats are now recognized as a CCSDS standard for spacecraft-to-relay communications.

The SBT was initially designed to use TDRS formats that have only modest overlap with the CCSDS formats used by the DSN. As a result, the key challenges in adopting the EM-1/2 communication link to beyond-GEO operations were:

- Moving to CCSDS data rates and modulation formats
- Moving to CCSDS ranging & Doppler formats
- Evaluating frequency bands
- Determining approach to handling of emergencies
- Adding newer coding methods
- Balancing uplink and downlink capabilities

a. Moving to CCSDS data rates and modulation formats. For EM-1/2, the solution to this incompatibility was to restrict the data rates and modulation formats that the SBT will use to those in the overlap between the TDRS and CCSDS formats. Some changes were implemented, in particular adding residual-carrier forward and reverse capability to the SBT (TDRS modes use suppressed carrier exclusively).

A CCSDS capability commonly used for robotic spacecraft is for low data rates, e.g. < 1 Kbps. For above-GEO operations, and especially for above-Lunar operations, such low data rates can be useful during anomalies (e.g., when losing antenna pointing and resorting to Omni antennas). The selected approach for EM was to remain within the SBT data rates and to ensure the ability for the spacecraft to regain pointing. Crewed missions can leverage the onboard crew's capabilities.

b. Moving to CCSDS ranging & Doppler formats. The DSN, consistent with CCSDS, relies on non-regenerative ranging. In this mode, a ranging signal is sent to the spacecraft in the forward channel. The spacecraft transponder, frequency-shifts the forward signal and retransmits it on the reverse channel, with no further processing. The SBT did not have this capability – all ranging is regenerative, processed on-board.

   For EM-1 and EM-2, the solution was to add a non-regenerative capability to the SBT. In addition, a change was made in the DSN to address detection of polarity if ranging occurred when the reverse transmission was in a suppressed carrier mode.

   A related issue is the phase coherence of the forward and reverse signal at the spacecraft. The SBT uses suppressed carrier formats, and uses carrier recovered from the telemetry signals to achieve such coherence. Because of the high accuracy required for deep space navigation (See Section 6) and requirements for inter-operability with non-DSN stations for 3-way Doppler operations, the SBT was also modified to include residual carrier capability in both the forward and reverse channels, enabling derivation of range and Doppler information independent of the data modulation.

c. Evaluating frequency bands. During the Apollo era, communication was primarily at S-band (2.2-2.3 GHz for the reverse channel). Since then, above-GEO communications have migrated to higher frequencies to enable higher data rates and better navigation. The DSN uses S-band as well as X-band (8.4-8.5 GHz for the reverse channel) and Ka-band (25.5-27.0 and 31.8-32.3 GHz for the reverse channel).

   For EM-1 and EM-2, the solution was to retain S-band capability – suitable for lower rate (up to 4 Msps) communications at lunar distances. Options for using higher-frequency bands, as a demo for future missions, are being explored. An optical communications test is also being discussed as an option for EM-2 and future missions.

d. Determining approach to handling of emergencies. For deep space missions, because of the large distances, spacecraft are programmed to enter a "safing" mode, where the spacecraft returns to a known, safe state and slowly (often with commands through the DSN) recovers. This approach requires very low data rates, e.g. <1 Kbps, as the spacecraft orientation may not be known and directional, high-gain antennas cannot be initially used. In addition, virtual channels are used to route the highest-value data first to users.

   For EM-1 and EM-2, the spacecraft will not rely on very-low data rates (e.g. below audio) or virtual channels, during emergencies. The missions do include backup flight software and a safe mode which works to re-establish basic vehicle functionality and regain communications. Also instead of a low data mode, the EM-2 flight will instead have an alternate communication package that is dedicated to emergency communications and has only basic capabilities for voice and ranging.

e. Adding newer coding methods. Since the Apollo era, newer modes of digital communications were developed. In particular these are newer, more powerful error-correcting codes, such as Low Density

Parity Codes (LDPC) and bandwidth-efficient modulation, such as Gaussian Minimum Shift Keying (GMSK).

For EM-1 and EM-2, LDPC coding will be used for the reverse channels (requiring an update to the DSN), but not in the forward channel (due to limited cost-effectiveness). This updated LDPC capability will now also become available to improve performance of future robotic missions since it will be implemented across all DSN assets. The EM-1 modulation formats used are the more traditional QPSK/OQPSK.

f. Balancing uplink and downlink. For robotic missions, there has been a heavy emphasis on higher reverse data rates, e.g. bringing back science data. Higher forward data rates were of secondary importance, as the forward link is typically used only to send commands (and occasionally small files) to the spacecraft. The ratio of reverse-to-forward data rates was often 10:1 or more. For Human missions, a continuous higher-rate forward link must be established (e.g., for 2-way audio/video communications), thus data rates for forward and reverse links are more similar.

For EM-1 and EM-2, the approach (driven by cost-effectiveness) was to remain within the data rates available in the DSN. This meant that the forward data rate is limited to ~250 Kbps for EM-1 while the MPCV capability is capable of larger forward channel at similar rates as the return. However, a path to higher forward rates has been charted and can be implemented as needed.

5. <u>Navigation Approach</u>

In the early 80's the Global Positioning System (GPS) was deployed, offering an excellent navigation capability for terrestrial vehicles and aircraft. The GPS capability is also very useful at LEO, but becomes much less effective once the spacecraft reaches GEO and above distances; and is not usable at all for lunar or Mars distances.

Robotic deep space missions, and Apollo-Era crewed missions, do not rely on GPS. Instead, they use techniques suitable for above-GEO distances, where GPS is either not available or quickly becomes degraded, deriving navigation data from the communications Radio-Frequency (RF) signal itself. There are three radio-metric measurements used for navigation:

- Doppler measurement – this leverages the variation in the carrier-signal frequency due to the Doppler Effect. The DSN sites are equipped with excellent frequency-and-timing references, and allow high-precision measuring of Doppler shift. There are three types of Doppler measurement: 1-way (just a reverse signal), 2-way (a forward signal and a reverse signal, coherent with each other, using the same antenna) and 3-way (a forward signal and one or more reverse signals, coherent with each other, using multiple antennas).

- Ranging measurement – The ranging signal is a broadband (in concept) signal sent to the spacecraft and echoed back. When the forward and reverse versions of the ranging signal are cross-correlated, the distance (i.e. in the radial direction) between the spacecraft and the antenna can be computed.

- DDOR, or Delta-Difference-of-range measurement – is used very effectively to determine the angular position (or the plane-of-sky angle) of the spacecraft with respect to Earth. In DDOR, two antennas and two spacecraft (or spacecraft and Quasar) are used. The double-differencing results in a very precise angular measurement – the biases inherent in the spacecraft and ground system equipment are removed in the double-differencing.

Navigating the EM spacecraft to lunar distances and beyond will use these techniques, with DSN and non-DSN antennas. Redundancy will be employed where practical, consistent with the crewed nature of the missions.

Navigation is particularly challenging for a crewed spacecraft. Navigation, in general, measures the spacecraft position/velocity and extrapolates these forward in time, for as long as practical, based on a mission model. But for a mission carrying humans, the spacecraft is hard to model (aka it is a "noisy" spacecraft) due to the unpredictable human activities and life-maintaining operations (e.g. venting). Because of that, the ability to extrapolate is greatly reduced and more frequent measurements are needed to maintain the orbit determination.

For EM-1 and EM-2, most of the above-GEO navigation will use Doppler and ranging from DSN sites. Under consideration is the addition of a set of 3-way Doppler measurements that involve DSN stations and non-DSN stations. At lunar distances, properly-designed 3-way Doppler measurements are almost as effective as DDOR measurement in determining plane-of-sky position. Such measurements could provide a measure of risk mitigation.

6. Voice and Video Challenges

Unlike robotic missions, crewed missions will carry humans and are expected to have a voice and, preferably, a video connection with Earth. Once the missions move beyond GEO, the operations have to contend with latency. At a minimum, latency will be the Round-Trip-Light-Time (RTLT). Imagine trying to have a 2-way discussion (audio or video) with an astronaut, with a 2-3 seconds or more delay inserted (for lunar distances) or 20 minutes delay (for Mars distances)!

Specifying the acceptable latency and bandwidth for 2-way audio and video will depend on the application. For the EM application, given the latency to the Moon, the tentative maximum round-trip delay for 2-way voice is analyzed to be 5 to 8 seconds (worst case), achievable with the RTLT. It will cause a slightly unnatural discussion, with pauses, but still enable intelligible discussion.

There are no specifications for video conversations with MPCV. But there are natural limits due to the available data rates – 250 kbps in the forward direction and 4 Msps in the reverse direction. With suitable compression, 2-way video could be obtained, with latency and quality restrictions.

7. Conclusions

Sending humans beyond LEO, starting with the EM series, introduced a number of challenges to both the DSN and the human spaceflight design and planning communities. Through collegial collaboration and constant communications between the key organizations, major issues have been resolved in the past years. Furthermore, plans exist to improve capabilities (e.g., increased forward channel bandwidth) and initial testing has started to ensure success as humans once again travel to lunar distances and beyond.