Challenges in Communications for Exploration Class Missions

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Abstract

Background

Communication latency and channel capacity constraints pose significant challenges to providing medical care beyond low earth orbit (LEO). Developments such as NASA's Deep Space Optical Communications (DSOC) network provide workable solutions to near-term challenges in channel capacity by utilizing laser (optical) signals in the higher frequency near infra-red spectrum. This network aims to support data transmission at rates 10-100 times higher than currently employed radiofrequency (RF) channel capacities and allow high volume data transfers. Despite such recent advancements however, communication delays and anticipated data downlink limitations - combined with the inability to rapidly return astronauts to Earth in beyond LEO missions - mandate a shift in medical operations towards greater crew autonomy and away from Earth-reliant approaches to medical care.

Description

75 data-producing medical capabilities were identified from among 635 capabilities in NASA's Information Mission Planning via Analysis of Complex Tradespaces (IMPACT)* database. Data file sizes for each capability were estimated. Channel capacity downlink durations were estimated in the context of a 10% channel capacity allocation for data-generating medical capabilities. Downlink durations varied for each medical capability when examined in the context of current RF capabilities as well as near-term and futuristic optical capabilities.

Discussion

As human space exploration moves toward missions beyond LEO, relying on RF-based communications alone will prove insufficient to sustain the current level of ground-based medical support allocated to LEO missions. Advancements in optical communications such as DSOC offer promise in augmenting transmission capabilities, albeit with undeniable constraints. These constraints include limited allocation of channel capacity supporting medical capabilities, data processing time, SME expert evaluation, and slower uplink compared with downlink rates. In addition to variable latency delays, a fixed speed-of-light limitation must also be considered when assessing the impact of latency on medical operations. Reliance on ground support for clinical decision-making during exploration missions could result in delays measuring in hours or days. While some advancements in technology offer latency mitigation strategies, the concept of Earth Independent Medical Operations (EIMO) will be critical for the future of medical care to crew beyond LEO.

*The IMPACT Probabilistic Risk Assessment (PRA) tool is under active development. All results are preliminary, subject to change, and must not be used for mission planning, operational decisions, or formal analysis. These results are provided solely for feedback and discussion purposes to support tool improvement.

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Introduction

Image adapted from NASA.gov.

Communication latency and channel capacity constraints pose significant challenges to providing medical care beyond low earth orbit (LEO). While theoreticians discuss ground-breaking technologies (e.g., "quantum communications"), more realistic developments such as NASA's Deep Space Optical Communications (DSOC) provide workable solutions to the near-term challenges in channel capacity. Despite recent advancements however, communication delays and data downlink limitations - combined with the inability to rapidly return astronauts to Earth in beyond LEO missions - mandates a shift in medical operations towards greater crew autonomy and away from Earth-reliant approaches to medical care.

Image adapted from NASA.gov.

Background

Medical operations on the International Space Station (ISS) are highly Earth-reliant

- Real-time guidance
- Crew recovery back to Earth possible <1 day

The ISS has historically used radiofrequency (RF) networks for data exchange and communication

- Tracking and Data Relay Satellites (TDRS) enable near-continuous signal relay to ground antennas on Earth
- NASA's Space Communications and Navigations (SCaN) program advancements have allowed increasing amounts of data exchange:
    - ➢ Higher radiofrequency transmissions: Ku (12-18GHz) and Ka band (26.5-40GHz) frequencies (surpass the previous Unified S-Band (USB) system used during the Apollo programs)

The Shannon-Hartley theorem of information outlines the maximum theoretical data transfer rate within a specified bandwidth (channel capacity (CC), bps, Figure 1)

- Higher frequency transmissions (greater bandwidth) → increased information transmission per unit time (higher CC)
- CC is influenced by signal power relative to noise (S/N ratio), impacting both data quantity and quality of data transfer
- Frequencies surpassing Ku and Ka bandwidths are expected to offer even greater data harnessing capabilities, particularly beneficial for missions beyond (LEO)

$$C = Blog_2\left(1 + \frac{S}{N}\right)$$

C: Channel Capacity, bps
B: Bandwidth (Hz)
P: Ave Power (W)
N: Ave Power of Noise

Figure 1. Shannon-Hartley Theorem

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Background (Continued)

SCAN's DSOC program:

- Utilizes laser (optical) signals in the higher frequency near-infrared spectrum (higher bandwidth)
- Aims to transmit data at rates 10-100x higher than current RF channel capacities to support high volume transfers (scientific data, high-definition imagery)

Advantages:

- Narrower beam width → reduced power requirements, smaller ground receiver
- Lower mass and volume requirements → lighter & smaller spacecraft infrastructure

Limitations:

- Signal power diminishes with the square of the distance b/t source and receiver ("inverse square law of electromagnetism")
- Requires precise beam focusing
  - Flight laser transceiver stabilization strategies (gimbals) & fast steering mirrors to overcome "jitter"
- Many noise sources
  - Cloudy/misty weather, stray sunlight (necessitates measures like cylindrical sunshade around transceiver's telescope)
  - Scattered light in Earth's atmosphere
- Infrastructure for optimal performance not yet in place (i.e., antennas and power capabilities)

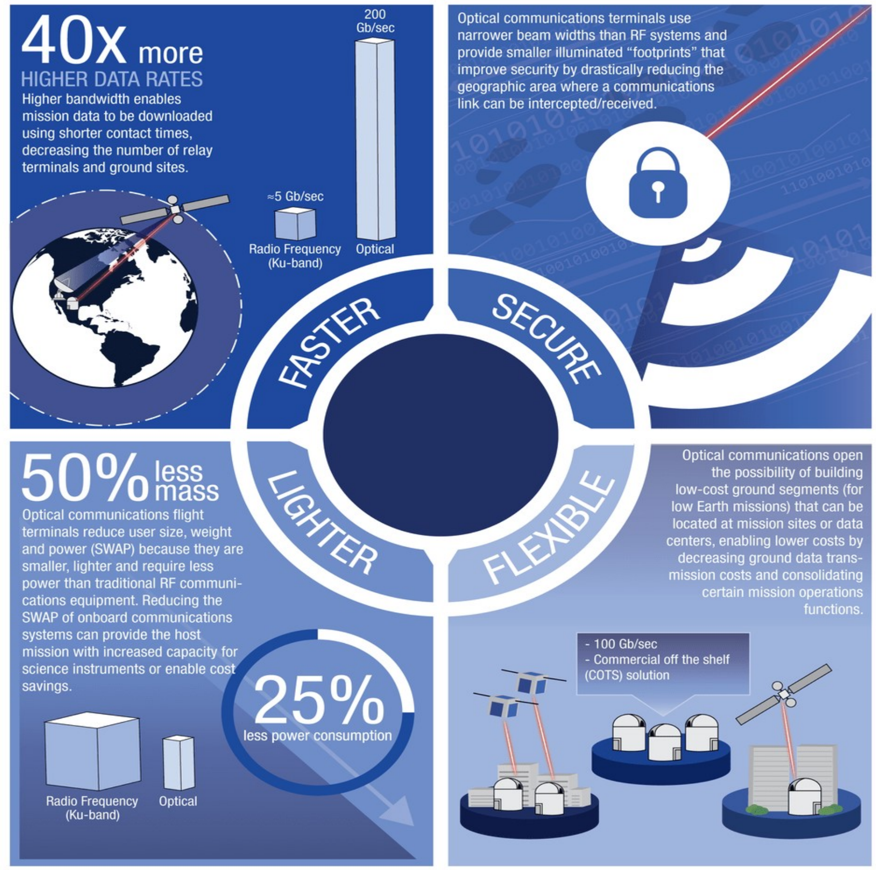

Figure 2. Graphic depicting benefits of Optical Communications. Adapted from NASA.gov.

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Description: Methods

- Identified 75 data-producing medical capabilities from within 635 capabilities in the Information Mission Planning via Analysis of Complex Tradespaces (IMPACT)* database
- Estimated data file sizes for each capability (when available) and consolidated redundant or alike data file sizes into a master list
- Estimated channel capacity downlink durations **assuming 10% of total channel capacity** can be allocated for medical needs (with 90% reserved for continued operational communications)

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Images adapted from NASA.gov

Table 1. Channel Capacities and Downlink Durations for Data-Generating Medical Capabilities

		Downlink Duration (hh:mm::ss)* *image compression and error correction coding not accounted for				
Channel Capacity (CC) Assumption: 10% of Total CC is allocated to data-generating medical capabilities		**0.31Mbps** RF, Ka-bandwidth (3.1Mbps Total CC, Today's technology and Infrastructure)	**1.14Mbps** RF, Ka-bandwidth (11.4Mbps Total CC, Infrastructure not currently in place)	**0.1Mbps** Optical (1Mbps Total CC, Current/achievable capability)	**6Mbps** Optical (60Mbps Total CC, Theoretical: Infrastructure not currently in place)	**10Mbps** Optical (100 Mbps Total CC, Theoretical: Significant progress needed)
Medical Capability	**File Size**					
4K HD Video, 1 hr (3840x2160 pixels)	22GB	157:42::21	42:53::05	488:53::20	08:08::53	04:53::20
HD 1080 Video, 1 hr (1920 x 1080 pixels)	1.4GB	10:02::09	02:43::44	03:06::40	00:31::06	00:18::40
HD 720 Video, 1hr (1280 x 720 pixels)	900MB	06:27::05	01:45::15	20:00::00	00:20::00	00:12::00
Lines of message text (JEDI)	439KB	00:00::11	00:00::03	00:00::35	<00:00::01	<00:00::01
Photo Image (3000 x 3000 pixels)	3.1MB	00:01::20	00:00::21	00:04::08	00:00::04	00:00::02
ECG Image	24.5KB	<00:00::01	<00:00::01	00:00::01	<00:00::01	<00:00::01
Continuous ECG	4GB	28:40::45	07:47::50	88:53::20	01:28::53	00:53::20
SANS/Occular Questionaire (ESA EveryWear App)	1MB	00:00::25	00:00::07	00:01::20	00:00::01	<00:00::01
OCT	650MB	04:39::34	01:16::01	14:26::40	00:14::26	00:08::40
Ultrasound, still image (Butterfly, DICOM)	952KB	00:00::24	00:00::06	00:01::16	00:00::01	<00:00::01
Ultrasound, 6 sec loop (Butterfly, .mp4)	3400KB	00:01::27	00:00::23	00:04::32	00:00::04	00:00::02

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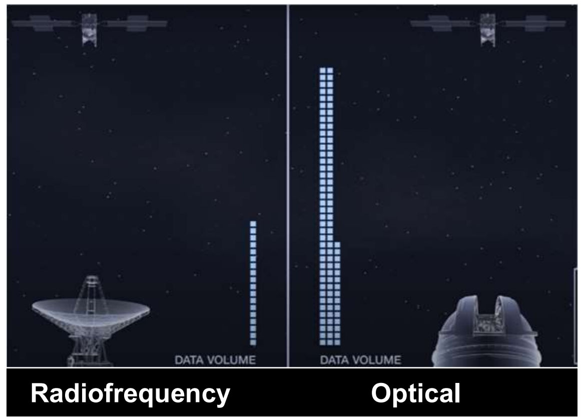
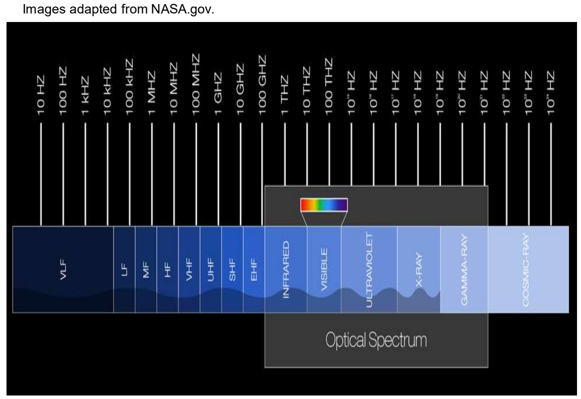
Discussion

As human space exploration moves toward missions beyond LEO, relying on RF-based communications alone will prove insufficient to sustain the ground-based medical support that missions in LEO currently depend on. Advancements in optical communications such as DSOC offer promise in augmenting transmission capabilities, albeit with undeniable constraints.

- Presently, the maximum total channel capacity for Mars missions based on RF Ka-band capabilities would be 3.1Mbps (Table 1).
- Optical communications: potential to provide rates as high as 100Mbps
  - ➢ Necessary technology and infrastructure to achieve such rates is not expected to be available in the near-future
  - ➢ Current/future optical capability predictions for Mars missions → no more than **1-2Mbps** downlink rates
- Some medical communication capabilities may transition entirely to methods typified by "store and forward"
- Others may be minimally affected by channel capacity constraints, such as small or routine data-generating medical capabilities (e.g., OCT data and medical conferences)



Images adapted from NASA.gov.



Determining the "ideal" medical channel capacity requirements for exploration missions is highly complex and multifaceted

- Table 1 demonstrates "time to downlink" medical data assuming the entire channel capacity is allocated to medical requirements (left columns)
- Only a portion of the available capacity, however, can be allocated to medical capabilities (other allocations include life support systems, spacecraft telemetry, EVA or roving surface missions, or non-mission related demands from organizations globally compete for capacity)
- Channel capacity resource allocation is and will continue to be composed of dynamic and mission-focused/mission-driven needs
- More realistic example: if 10% of the available channel capacity was allocated to support medical needs, an US image may still be transmitted in a reasonable amount of time
- Transmission of a larger file such as OCT information or video could take several hours→ may be too long in emergency scenarios (threats to life/limb)

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Discussion (Continued)

Latency Associated with speed-of-light: no current technologies to overcome this latency

- Approximately 22 mins for any form of electromagnetic data to reach Earth from Mars at orbital extremes
  - ➢ Transmission of an US image could take ~ 22 mins+ 5 mins + additional latency from CC relay required to send the data using 10% of a 1Mb optical channel capacity capability (Table 2)
- Other factors contributing to latency: data processing time, SME expert evaluation, slower uplink rates compared with downlink rates
  - ➢ Time to reach clinical decision can quickly become on the order of hours if relying on ground for exploration missions (vs. minutes on ISS)
- This delay could have important implications for crew morbidity/mortality in certain emergent situations

Table 2. Latency Associated with Speed of Light

Location	Max Distance from Earth (km)	Latency (Speed-of-Light)
ISS	408 Km	0.001601 sec
Artemis Missions	432, 210 Km	1.4417 sec
Mars Near Orbit	54.6 million Km	3.0354 min
Mars Far Orbit	401 million km	22.293 min

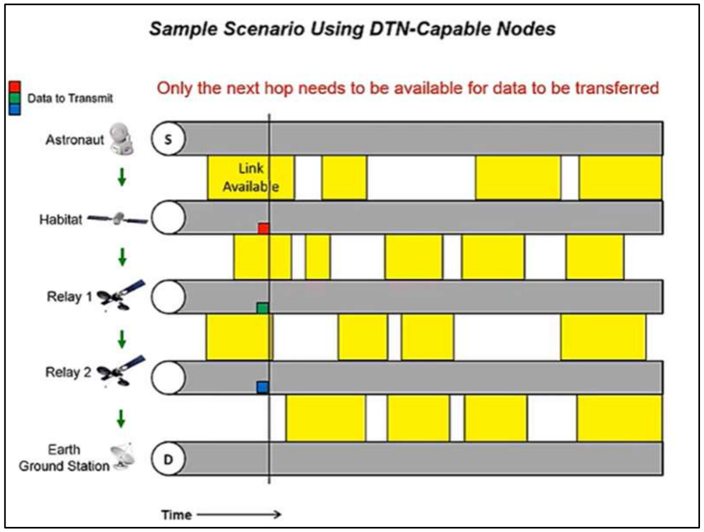

Figure 3. Delay/Disruption Tolerant Networking (DTN). A way to improve store-and-forward capabilities whereby complete end-to-end path does not need to be available for data transmission (decreases latency and mitigates loss of data). Graphic adapted from NASA.gov

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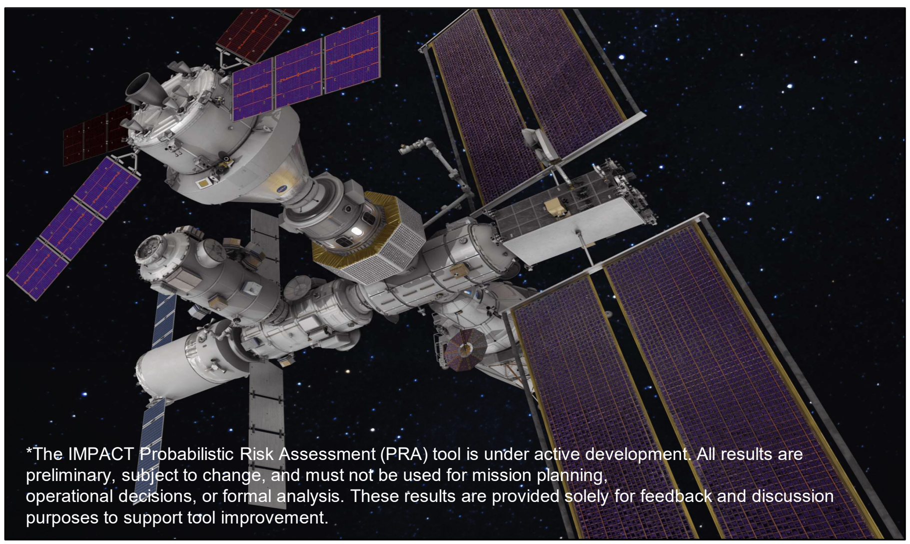
Discussion

- When assessing the impact of latency on medical conditions, at least two communication delays must be considered: fixed speed-of-light delay and variable channel capacity delay
- **Risk Mitigation**: Integrating known speed-of-light latency delays and channel capacity limitations into models such as IMPACT* could help improve risk predictions and inform overall mission risk
- These constraints also present opportunities to leverage technologic advancements to help crew members respond to medical events as seamlessly as if that they were onboard the ISS
- **The advent of exploration class missions requires a re-evaluation of medical care provided to astronauts, in an approach scalable to the available channel capacity and extent of latency**



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Discussion: Future Considerations

While some advancements in technology offer latency mitigation strategies, the concept of Earth Independent Medical Operations (focusing on crew autonomy rather than solely on ground support) will be critical for the future of medical care to crew beyond LEO

- Space braiding (communication technique to mask latency by using multiple conversation "braids" during simultaneous transmission)
  - ➢ Potential applications for medical conferences and psychological therapy
- Earth Independent Medical Operations (EIMO) Concept of Operations (ConOps)
- "Just in Time Training" (JITT) software techniques (AMOS Autonomous Medical Officer Support), Augmented Reality
- Intelligent Medical Crew Assistant (IMCA)-interactive voice intelligence platform
- Augmented Reality techniques to guide procedural skills (OCT, abdominal ultrasound imaging)

Video: Introduction to Space Braiding

Image adapted from NASA.gov; Astronaut Raja Chari

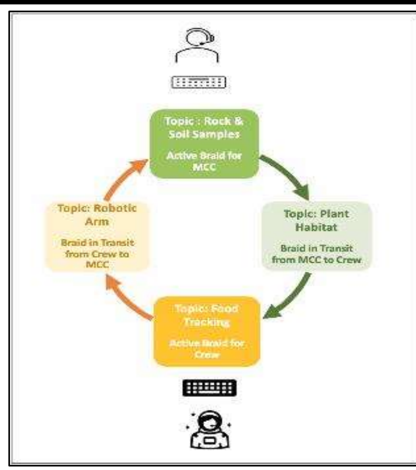
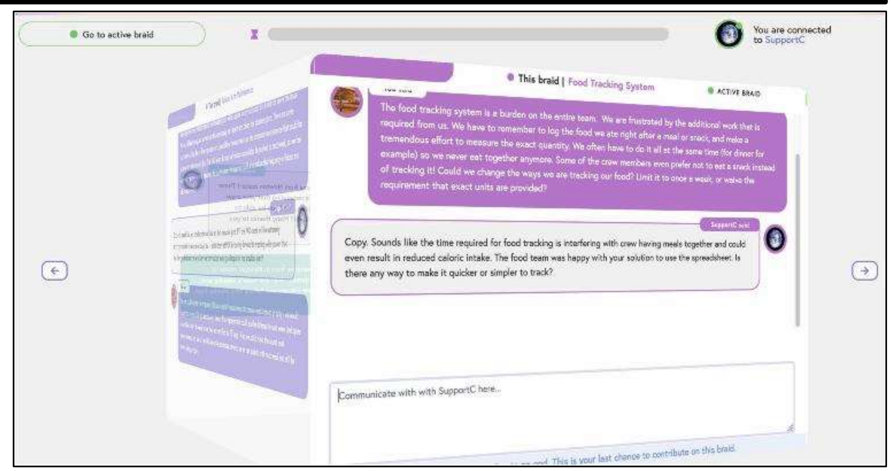


Image adapted from https://braided.space/resources/space-braiding.



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References