National Aeronautics and
Space Administration

LunaNet Overview

Presented to NESC Unique Science from the Moon in the Artemis Era Workshop

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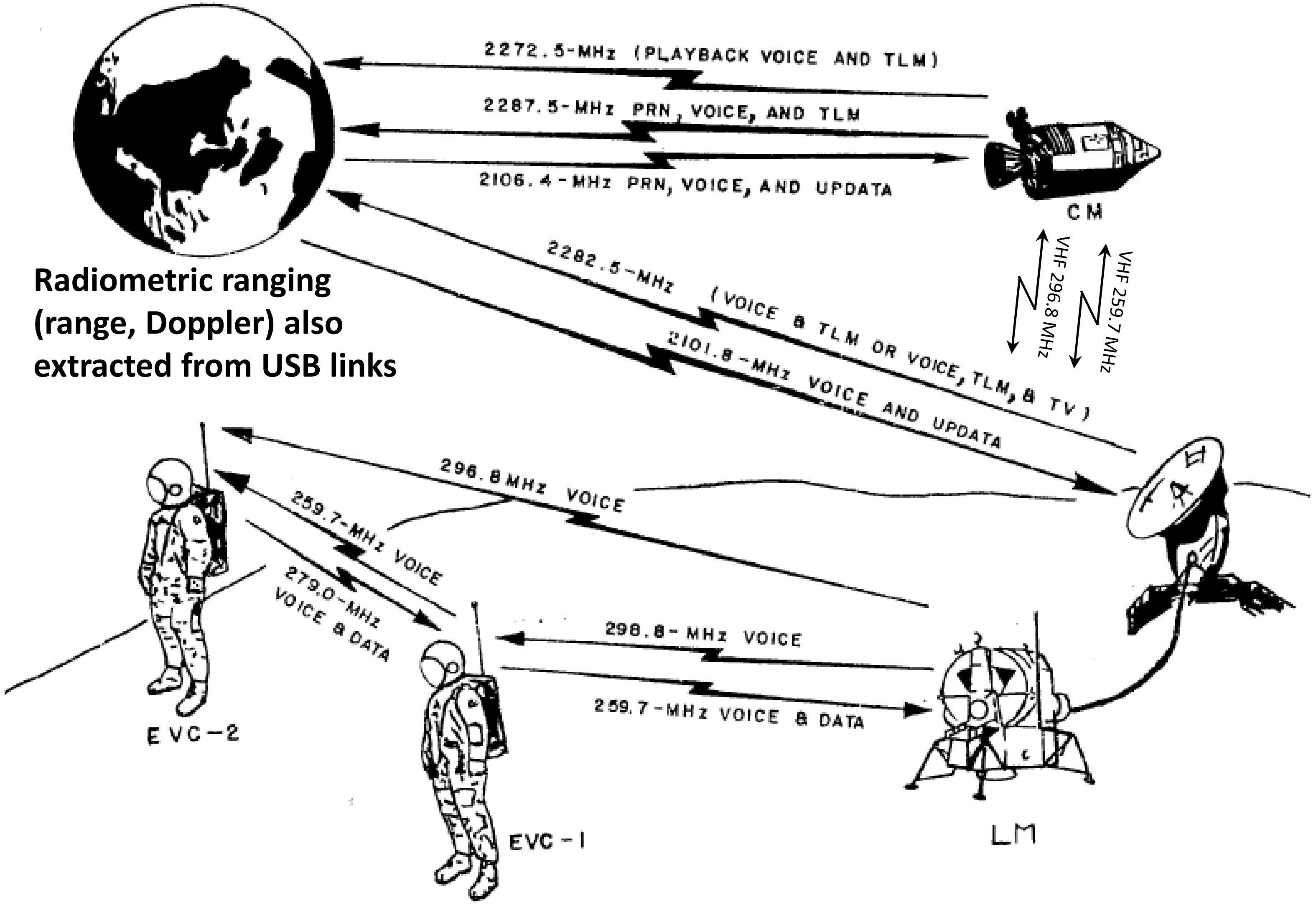
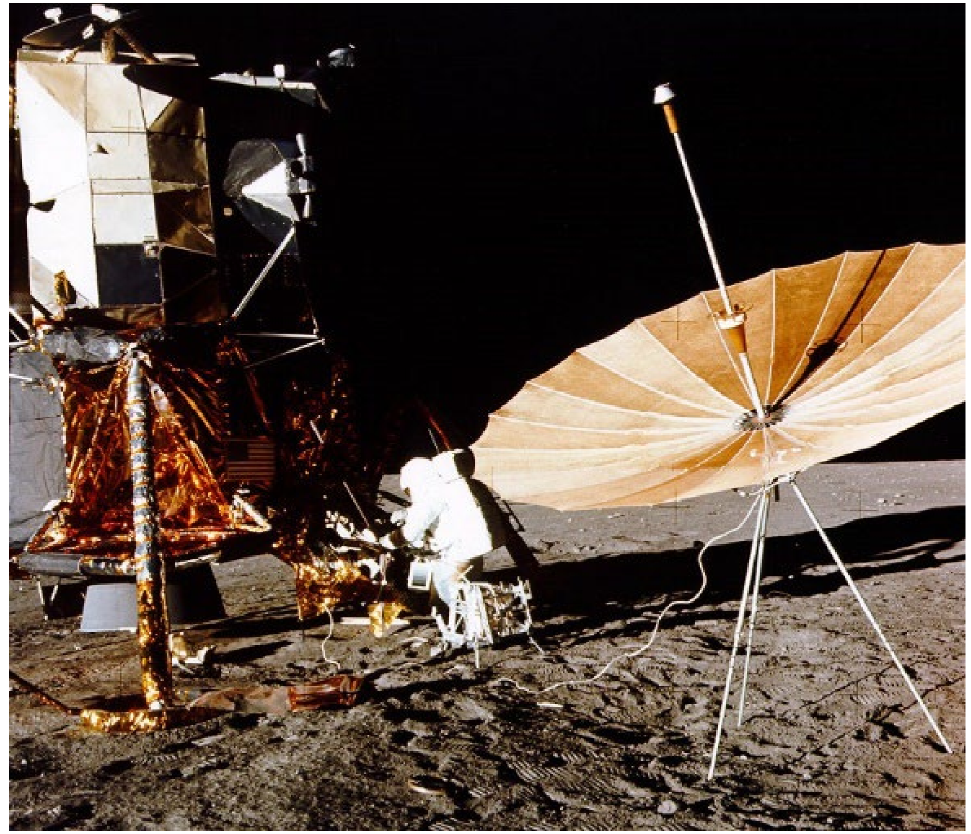
Apollo Capability: Unified S-band (USB) and VHF



Radiometric ranging (range, Doppler) also extracted from USB links

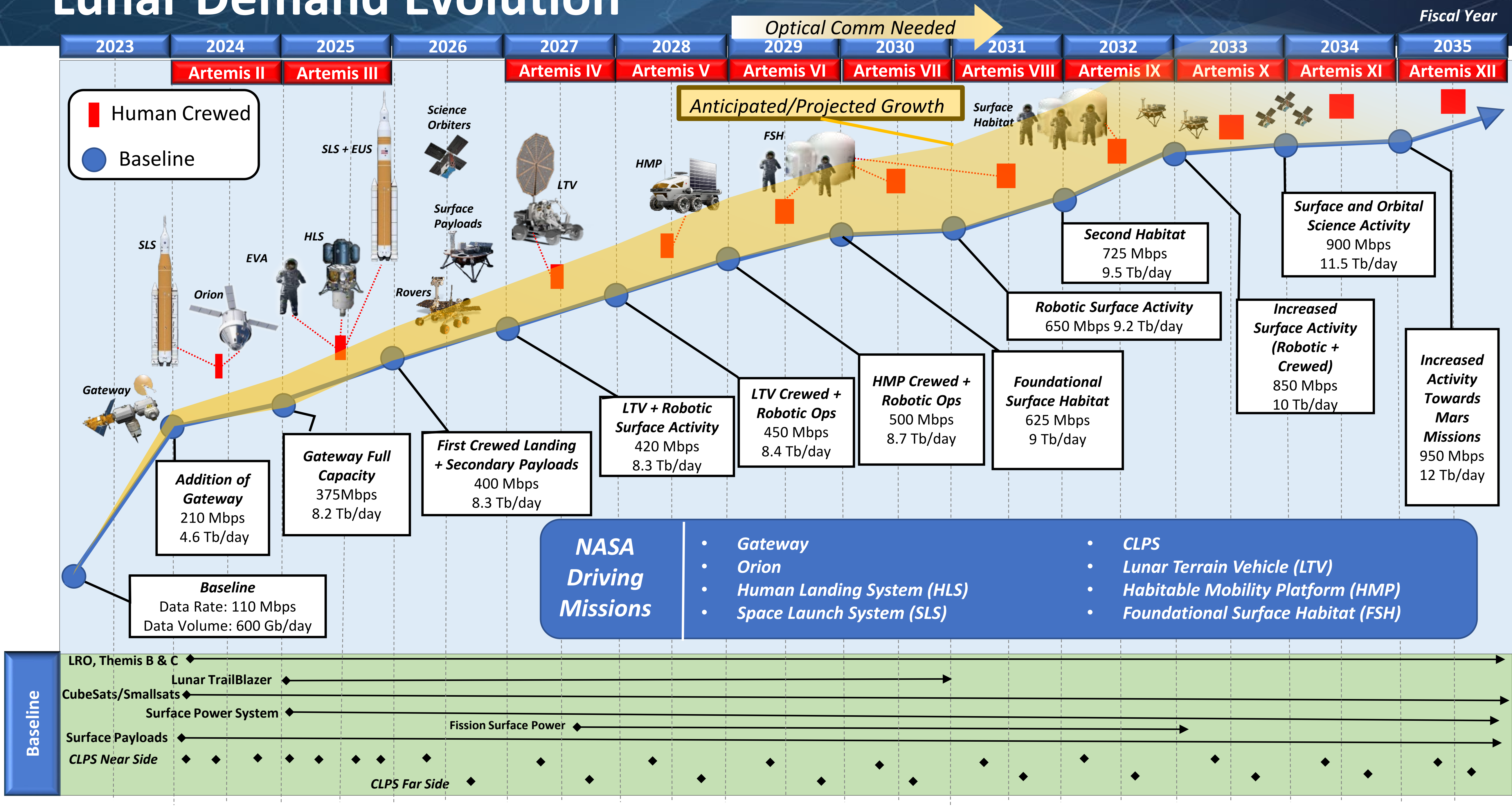


Left: Apollo Surface Links Between Lunar Module, Extravehicular Crew, and Erectable Antenna.

Right: Erectable Apollo Unified S-Band (USB) Surface Subsystem Connected to Lunar Module by Cable

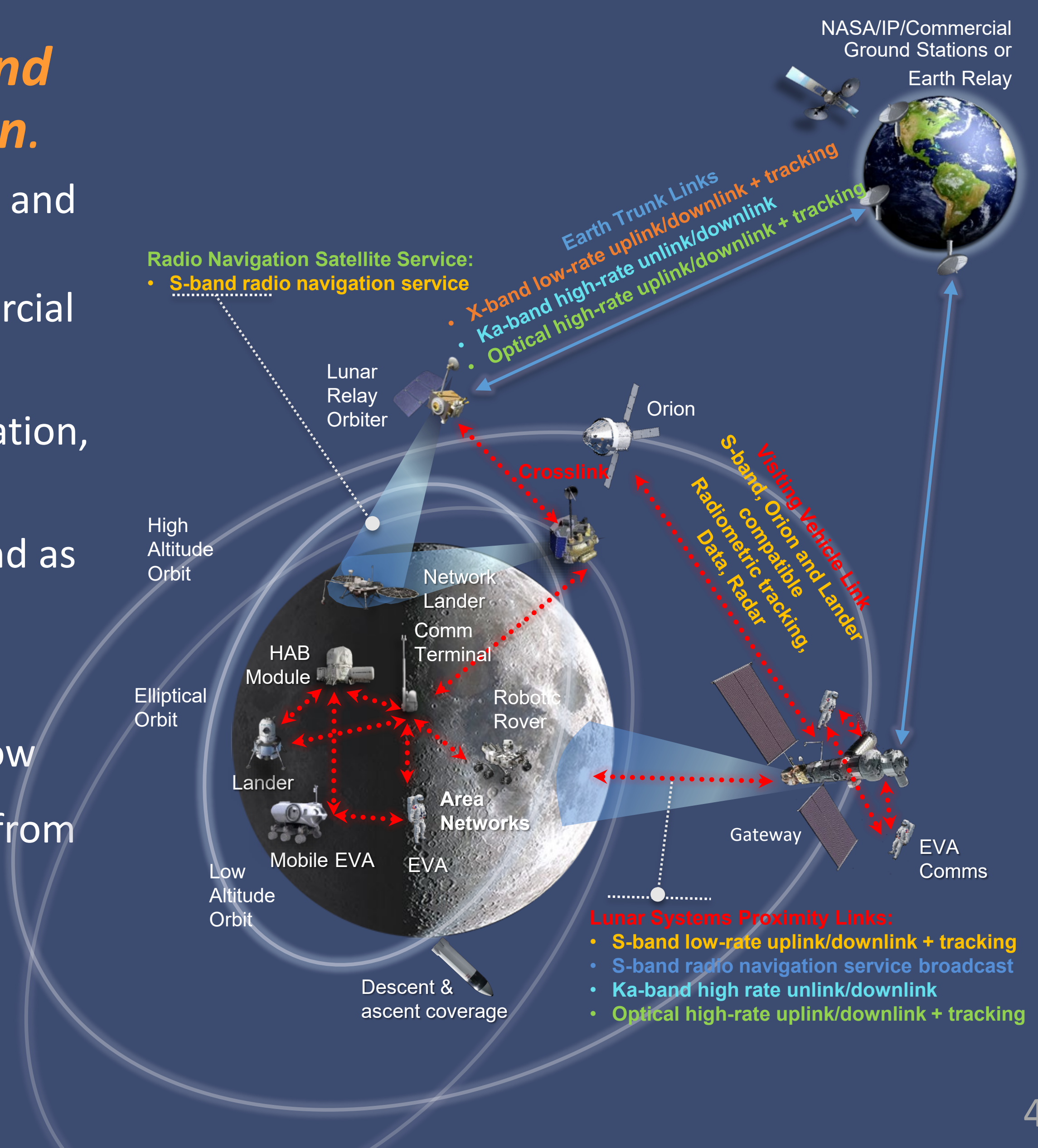
- **Diagram shows capability used on Apollo 11, 12, and 14**
- **Lunar Rover added on Apollo 15-17 with USB to Earth and VHF to EVC**
- **Uplink: ~2 kbps command channel + 2 kbps voice channel**
- **Downlink: ~51 kbps telemetry channel + 2 kbps voice channel**

Lunar Demand Evolution



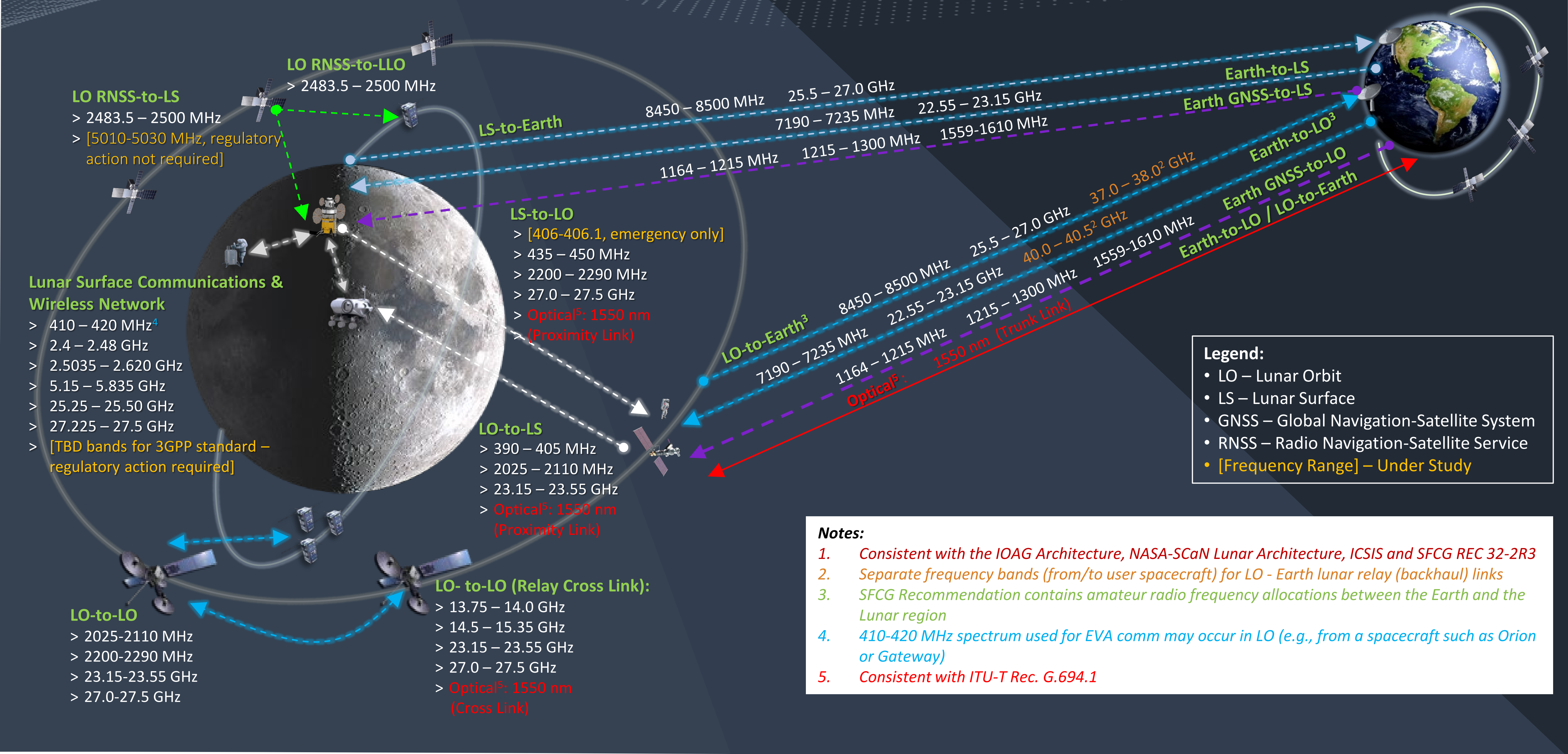
LunaNet, the Lunar Internet

- ***LunaNet is the lunar Internet – a set of cooperating networks providing interoperable communications and navigation services for users on and around the Moon.***
  - Based on a framework of mutually agreed-upon standards, protocols, and interface requirements that enable interoperability
  - Allows many mission users to benefit from services of diverse commercial and government service providers
- **Service-Oriented:** Services include data transmission; Position, Navigation, and Timing (PNT); and situational awareness information
- **Scalable**: Introduce minimal capability for earliest missions and expand as needed for new users and service providers
- **Open**: Based on open international standards like the Internet
- **Resilient**: Resilience to failures and outages increases as networks grow
- **Secure**: Protect sensitive data while preventing or rapidly recovering from cyber threats
- **Extensible**: Apply the LunaNet concept to any planetary body



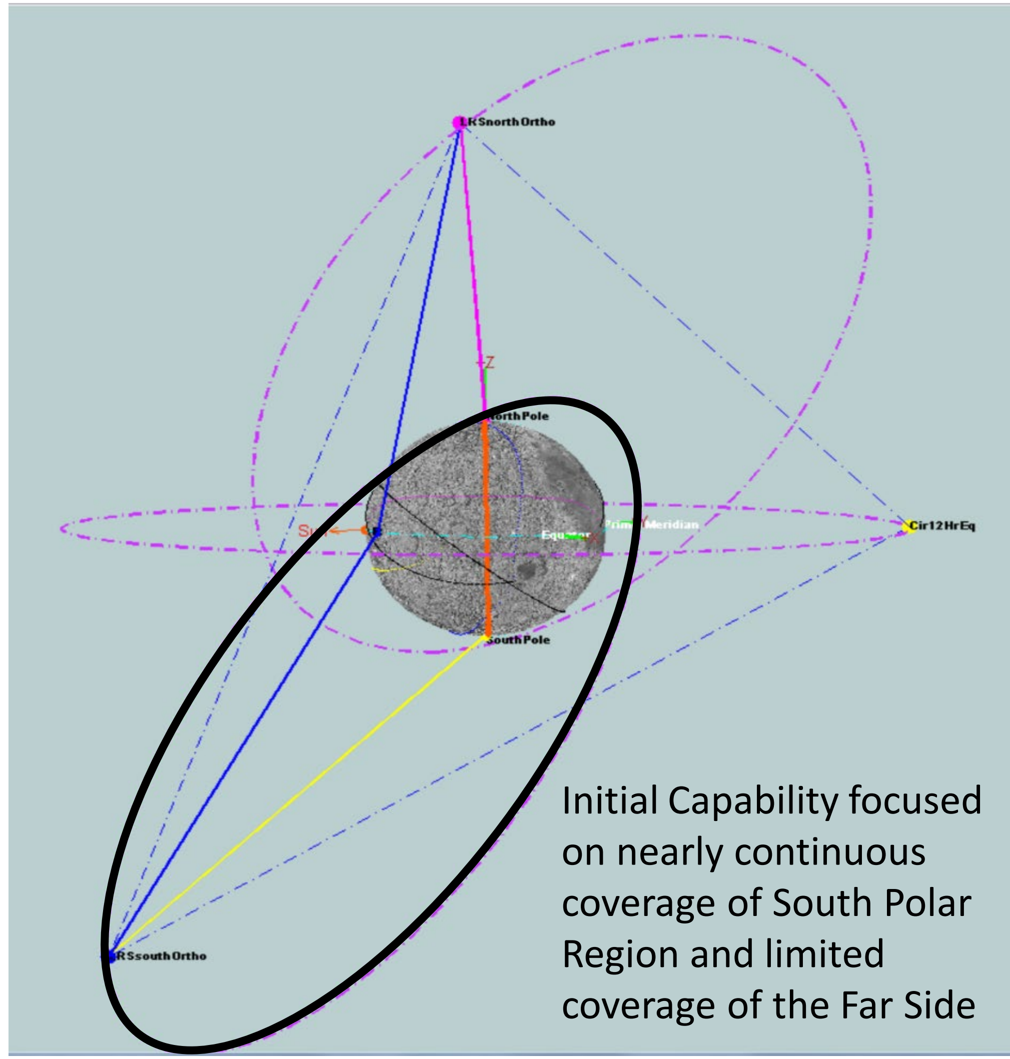
Spectrum Architecture for Lunar Region Communications & Navigation

Radio Frequency[1] and Optical



Lunar Communications Relay and Navigation Network

- **Each LunaNet Service Provider (LNSP) designs its own set of orbits**
- **Figure shows notional constellation characterized by a combination of circular orbits and elliptical orbits, including:**
  - **12-hour Elliptical Lunar Frozen (ELF) orbit with its line of apsides librating over the South Pole;**
  - **12-hour ELF orbit with its line of apsides librating over the North Pole; and,**
  - **12-hour circular orbit around the equator**
- **Initial partial coverage can commence with a single relay orbiter. To achieve full coverage, the minimal constellation would include:**
  - **Two relay orbiters phased 180° apart on the 12-hour southern ELF orbit → covers south polar region**
  - **Two relay orbiters phased 180° apart on the 12-hour northern ELF orbit → covers north polar region**
  - **One relay orbiter on the 12-hour circular orbit around the equator → good but not complete far side coverage**
- **Constellation can be built out in any order to meet changing mission needs**
- **Number of relays per orbit can be increased by reducing phasing angle, e.g., 180° to 120°**
- **Sufficiently rapid motion across the sky to assist surface users in determining their position using Radionavigation Satellite Service (RNSS) broadcast (similar to GPS)**

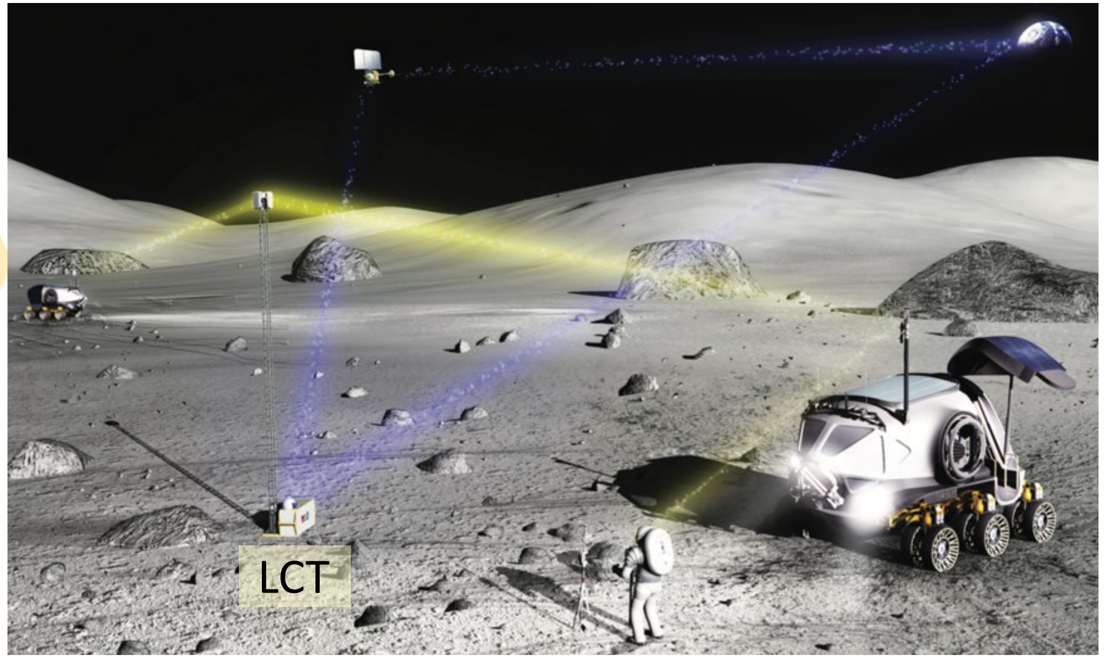


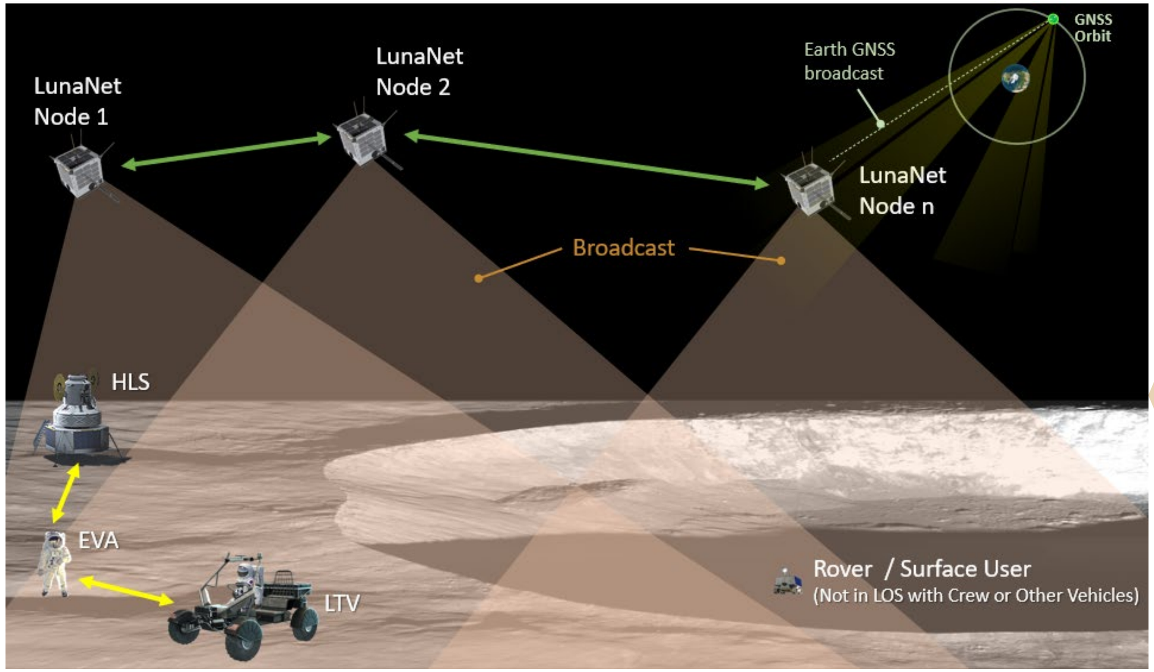
Initial Capability focused on nearly continuous coverage of South Polar Region and limited coverage of the Far Side

Lunar Surface Communications & Navigation

Surface Communication & Networking

- Point-to-point links between surface systems & Lunar Communication Terminal (LCT) that multiplexes & demultiplexes among users and links to overhead relays
- Initial capability limited to specific sites, e.g., Outpost
  - IP and DTN network protocols supported
  - UHF, WiFi and 4G/5G options being evaluated; Nokia 4G demo on CLPS
  - LCT may be relocatable so crew can move it to work sites
- Future capability adds enhanced services and increases assets to improve coverage and resilience





Surface Navigation

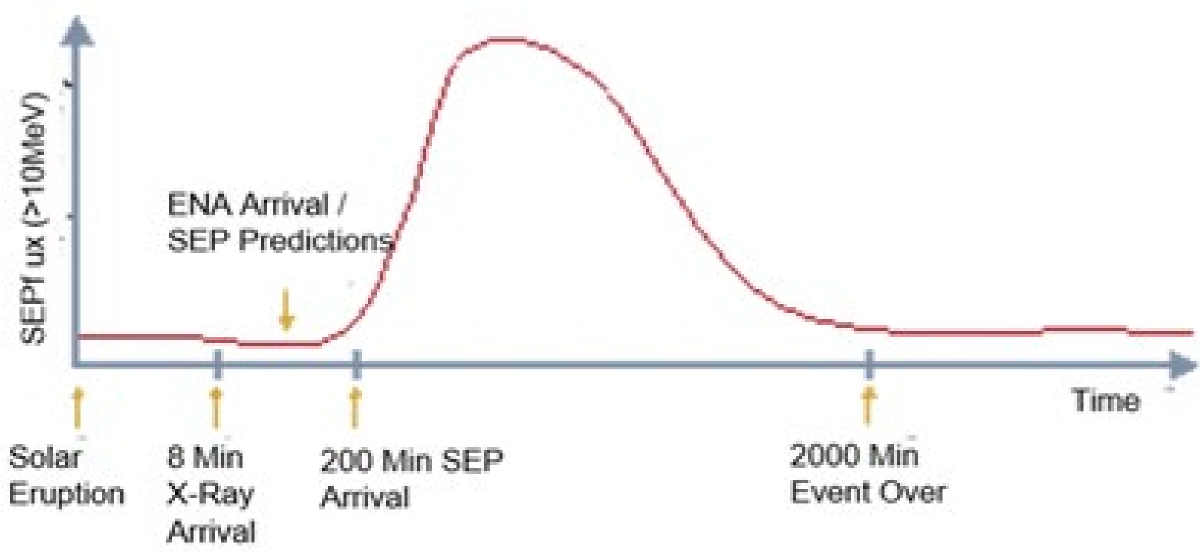
- Range & bearing to users extracted from surface links
- Overhead relays broadcast RNSS navigation signal that user equipment processes like GPS to determine position & velocity
  - Weak signal GPS receiver demonstration on CLPS
  - Initial broadcast capability limited to 1-2 relays requiring long user integration time
  - Full constellation enables instant position calculation & adds optical PNT
- Augmented by science aids to get sub-cm accuracy at sites of geologic interest

<u>Legend</u>

Blue links = Ka-band | Yellow links = S-band, WiFi or 5G (trade in work) | Orange = Navigation broadcast (2.5GHz) | Green links: Crosslinks for PNT Calibration

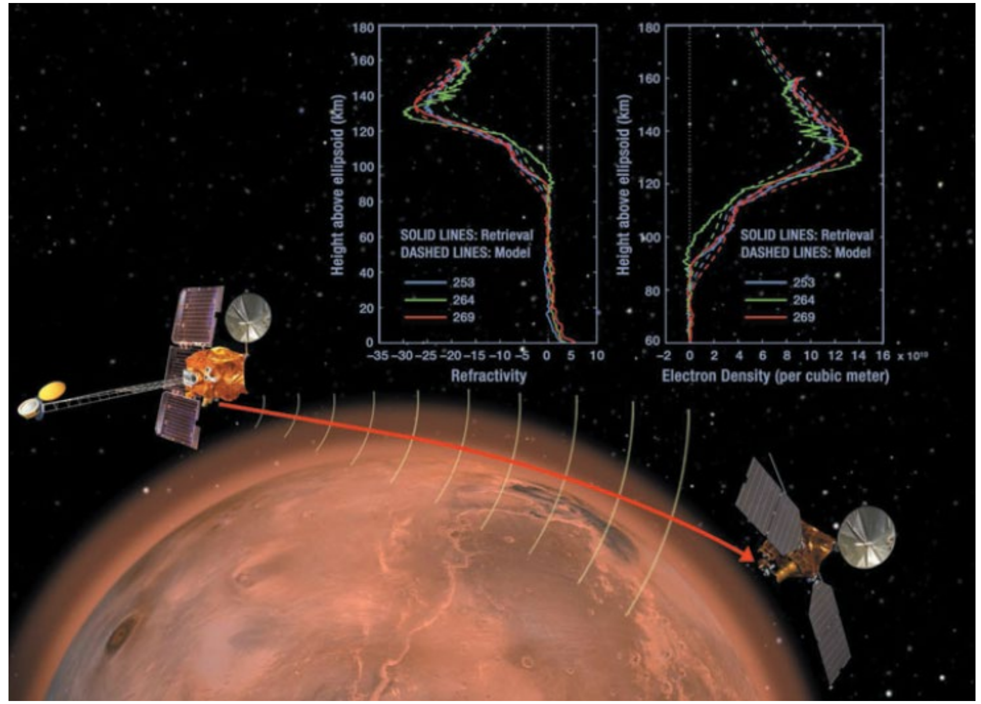
LunaNet Detection and Information Services

- **In-space user can subscribe to information stream published by in-space sensor for point-to-point or broadcast service. Example:**
  - **Space weather sensor located in S-E L1 monitors solar X-rays to sense Solar Energetic Particle (SEP) / Energetic Neutral Atom (ENA) events; broadcasts event & streams data on flux & particle energy**
  - **Crew receives event notice & data stream**
  - **Crew relocates to protective storm shelter within ~30 minutes of event onset**



LunaNet Science Services

- **Proximity, crosslinks & trunk links can be used to conduct a variety of scientific investigations such as geodesy (e.g., rotational variations including precision & nutation) and atmospheric density and composition (e.g., Mars crosslinks and prox links to rovers; GPS experiments)**
  - **The DSN supports Radio Science, Radio Astronomy / Very Long Baseline Interferometry (VLBI), and Radar Science services**
- **Using these links to support science may impose additional requirements on link performance such as open-loop recording, higher accuracy time source, higher SNR than communication links, & capturing parameters not involved in CPNT services**
- **The incremental cost of improving performance of communications and/or PNT links to support science objectives may be worthwhile**
- **Hence, the LunaNet architecture allows for the potential to perform scientific experiments using LunaNet links**
  - **RF has been used to date but optical measurements may be added**
- **This service schedules links between cooperating spacecraft (LunaNet-LunaNet or LunaNet-mission user) to capture signals of interest and transmit them to Earth**



First radio crosslink occultation experiments were conducted between Mars Odyssey & MRO in 2007 using the MRO Electra transceiver to acquire open-loop recording of UHF signal transmitted by Odyssey.

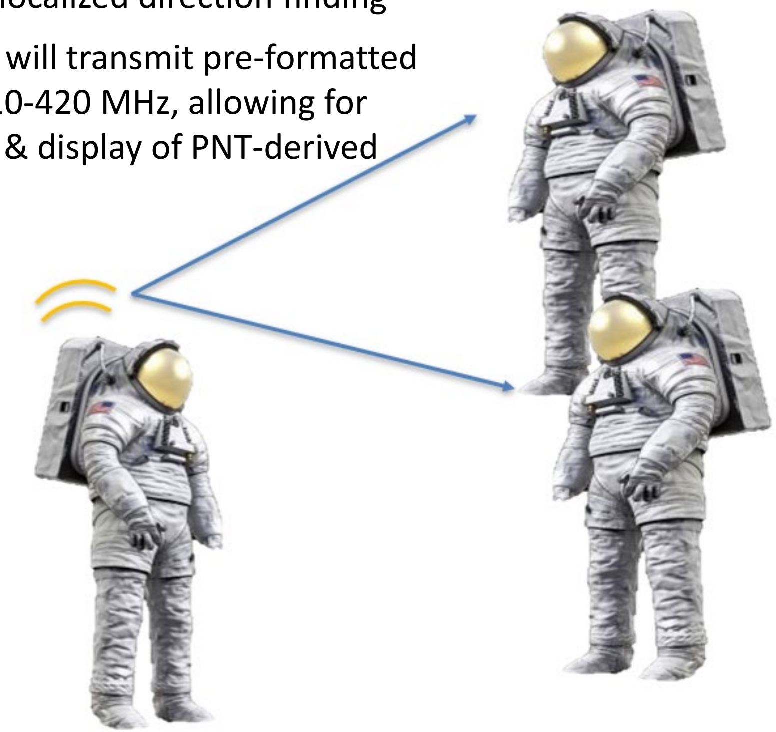
Search & Rescue: LunaSAR Dual-Mode Conops (UHF & S-Band)

Not Baselined but being explored – Proposed use of 406.0-406.1 MHz for Distress Alert Signal

UHF-Surface Transmissions (Local Data Transmission & Homing)

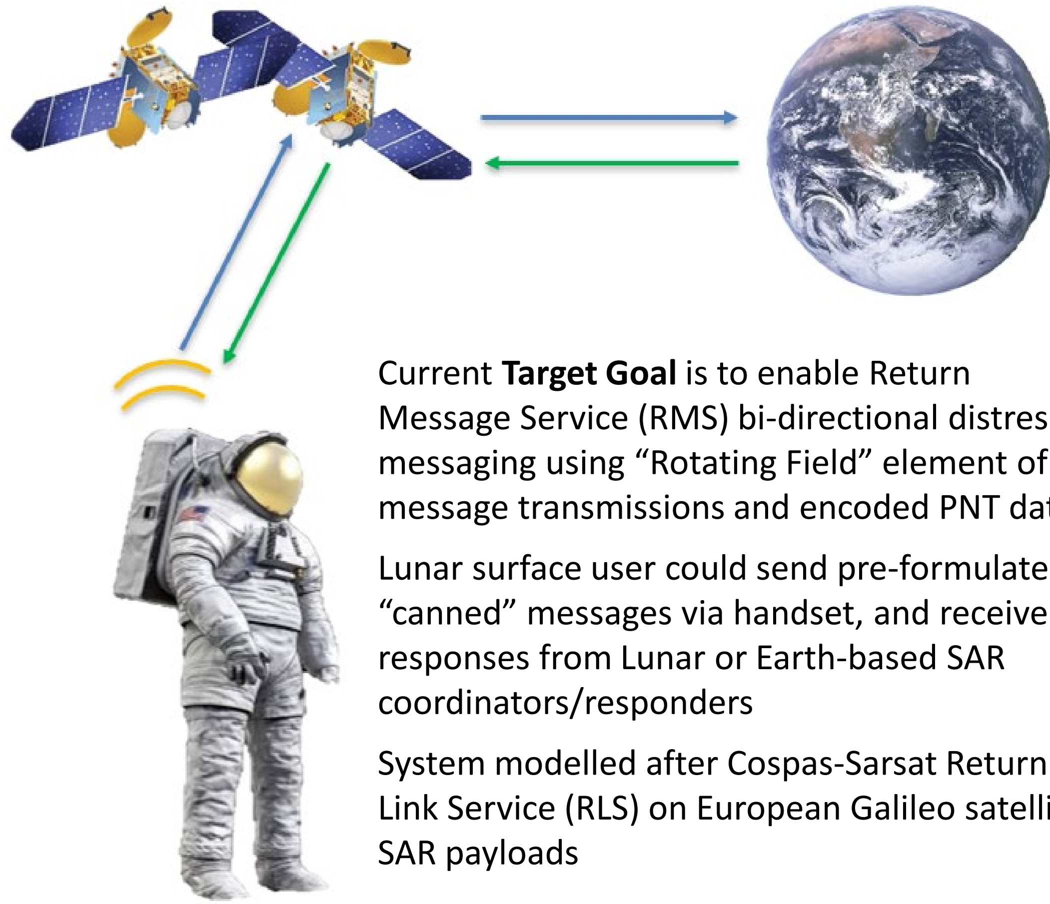
Current **Initial Goal** is to enable UHF point-to-point surface transferal of information as well as potential swept-tone transmission for localized direction finding

LunaSAR beacon will transmit pre-formatted messages on ~410-420 MHz, allowing for direction finding & display of PNT-derived location



Localized direction finding – key to the "last 100 yards" of a SAR operation, especially in a Position, Navigation, and Timing (PNT)-degraded environment

S-Band Transmissions (Bi-Directional Messaging Capability)



Current **Target Goal** is to enable Return Message Service (RMS) bi-directional distress messaging using "Rotating Field" element of message transmissions and encoded PNT data

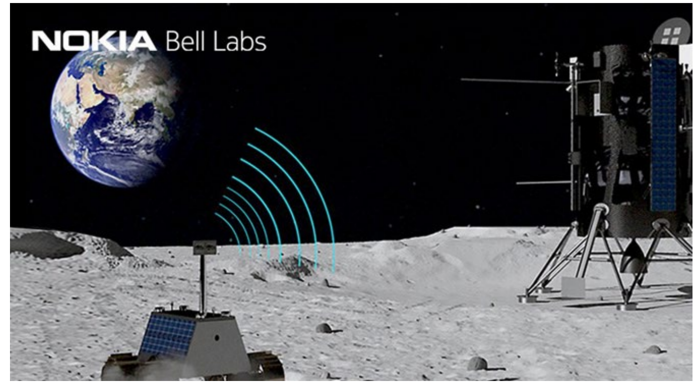
Lunar surface user could send pre-formulated "canned" messages via handset, and receive responses from Lunar or Earth-based SAR coordinators/responders

System modelled after Cospas-Sarsat Return Link Service (RLS) on European Galileo satellite SAR payloads

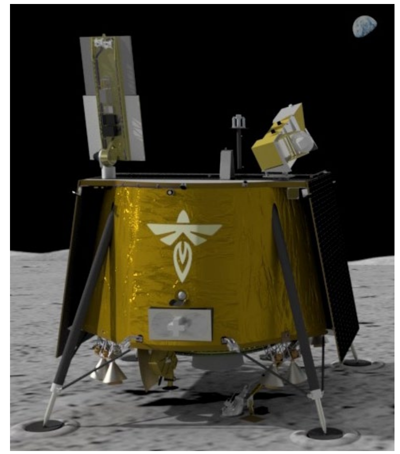
Assured survivor communications – key to bringing the right survival/medical/technical supplies in a timely manner

Technology Development

- **Space Mobile Networking (SMN):**
  - **Wideband SW-Defined Radio for frequency & waveform agility**
  - **Delay/Disruption Tolerant Networking (DTN) using Bundle Protocol (BP)**
  - **Autonomy from Earth control**
- **Demonstrate optical communications on Artemis II (2024)**
- **4G/Long Term Evolution (LTE): Nokia to demonstrate the first LTE system in space by late 2022/early 2023**
  - **Nokia's lunar network consists of an LTE Base Station with integrated Evolved Packet Core (EPC) functionalities, LTE User Equipment, RF antennas and high-reliability operations and maintenance (O&M) control software.**
- **Position, Navigation & Timing (PNT)**
  - **Lunar GNSS Receiver Experiment (LuGRE) funded for Commercial Lunar Payload Services (CLPS) mission in FY23 to characterize weak-signal GNSS reception (GPS & Galileo)**



Nokia's rover talks to the base station on the lander via LTE
Photo: Nokia Bell Labs



Firefly Aerospace's Blue Ghost lander will carry Next Gen Lunar Retro-reflectors (NGLR), Reconfigurable, Radiation Tolerant Computer System (RadPC), & LuGRE ***Credit: Firefly Aerospace***

Architecture Solution to Meet ***Capacity*** Drivers

Deep Space Network (DSN) Lunar Exploration Upgrades (DLEU)*

- Upgrades to two 34-m DSN antennas at each of the three complexes (totaling six upgraded antennas)
  - Simultaneous operations – S+Ka-band or X+Ka-band, simultaneous Ka-band
  - Low latency data processing for > 150Mbps
  - Increased data rates – greater than 100Mbps downlink in Ka-band

Lunar Exploration Ground Segment (LEGS)*
(18-Meter Class Antenna Subnet)

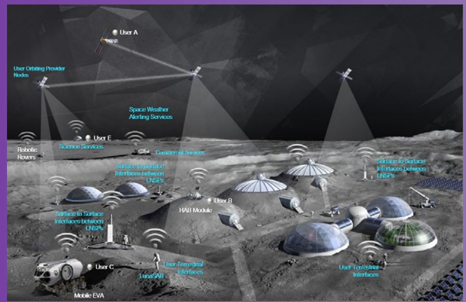
- NASA pursuing build of LEGS sites #1-3
  - Dedicated new set of antennas– 18m or greater equivalent capability– designed to support lunar missions
  - Alleviate the user load on the current 34-meter subnet, to allow for a focus on deep space support
  - Minimum of three sites around the Earth for continuous coverage
- Commercial services for LEGS 4-6 and beyond – add assets as demand grows and to meet redundancy / resiliency needs

Lunar Communications Relay and Navigation Services*

- Initial relay deployment targeted at South Pole and Far-Side, with range and range rate services – nominal commercial service procurement approach
  - Removes DTE line-of-sight comm constraint– reduces user burden
  - Continuous communication during HLS descent is easier supported through a relay link than a DTE link
- Growth in relay satellite nodes / associated services to provide more robust service and coverage
- Alternate options for a government-developed solution

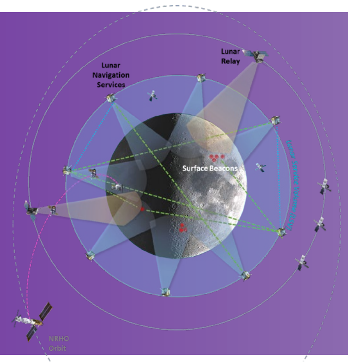
* DLEU, LEGS, LCRNS, surface wireless, LNS and optical are components of a future cooperative lunar network → LunaNet

Architecture Solution to Meet ***Capability*** Drivers



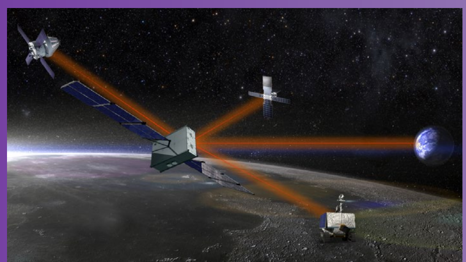
Surface Wireless Communications*

- 3GPP/5G cellular technology for a robust lunar surface C&N infrastructure that is scalable to meet long-term needs
- Essential to address surface and orbital link proliferation
- Enables direct surface/local communication and aggregates data for transition to backhaul
- Technology demonstration on Artemis III
- Fully implemented for Artemis V – connectivity between HLS, LTV, and EVA



Lunar Navigation Services*

- “Like GPS, but at / for the Moon”
- Support near term needs for 10-m surface positioning and 50-m HLS landing knowledge requirements
- Long-term support of complex surface ops, Search and Rescue (SAR) functionality, situational awareness, prediction and avoidance
- LNS deployment of minimum nodes for Artemis V



Lunar Optical Communications*

- Operational optical communications between the Earth and Moon (coherent, multi-gigabit) supports high bandwidth needs, data aggregation and relieves spectrum pressure
- LunaNet compatible, with high-speed Disruption Tolerant Networking (DTN)
- 1 m class operational optical ground station w/ adaptive optics
- Complete prototype (TRL 6) optical relay payload system

* DLEU, LEGS, LCRNS, surface wireless, LNS and optical are components of a future cooperative lunar network → LunaNet

NASA Procurement and Inter-Agency Collaboration

- **Commercial service procurement approach for Lunar Communications and Navigation Relay and Direct To Earth (DTE) in preparation**
- **ESA has contracted with Surrey Satellite for use of their Lunar Pathfinder relay on a joint effort with NASA SMD**
  - **Collaborating with ESA Moonlight initiative on lunar interoperability**
- **Defining strategic relationships between NASA and Other Government Agencies (OGA) regarding Beyond GEO (xGEO) and cislunar domain**
- **DoD is formulating roles and responsibilities that will require new capabilities in the next decade**
  - **Space Domain Awareness (SDA) from GEO to cislunar region defined as critical mission for US Space Force**
  - **Joint requirement to define PNT standards to enable navigation in collaboration with US Naval Observatory (time, lunar reference frame) and National Geospatial-Intelligence Agency (NGA) (geodetic & gravity models)**
- **International civil space agencies collaborating through the Interagency Operations Advisory Group (IOAG) and associated organizations (e.g., SFCG, CCSDS, IETF, ISECG)**
  - **Adopted LunaNet approach based on prior and ongoing IOAG studies**
  - **Voted to establish committee to explore how to govern LunaNet**

Take-away Points

- **LunaNet is architected to be open, interoperable, and scalable enabling it to grow and evolve as the lunar economy expands**
- **LunaNet moves the networks into space for space users – not just “uplink/downlink”**
  - **Communications & networking standards exist; PNT standards need to be developed**
- **Growing national and international acceptance**
  - **Upcoming NASA & ESA RFPs will acquire commercial lunar communication & PNT services**
- **Spectrum architecture deals with frequency band bottlenecks & unique limitations**
  - **Protects far side Shielded Zone for radio astronomy – no emissions below 2 GHz except safety/emergency**
  - **Establishes lunar region equivalent to near Earth region – primary links are between cislunar systems**
  - **Earth←→Moon links become trunk / backhaul links for low-rate TT&C and high-rate mission data focused through relays for higher spectral efficiency and frequency reuse**
    - **S-band reserved for lunar proximity links to limit increase in congestion; X-band used for Earth-Moon TT&C**
    - **Earth→Moon link capacity increases by 1000x (10s kbps → 10x Mbps) due to human presence**
  - **Projected demand leads to congestion in RF bands before 2030 requiring start of operational optical communications**

Worksite Design & Lighting

Charles Dischinger
Technical Lead,
NASA Engineering & Safety Center

Assessment of Effects of Lunar Polar Light Environment on EVA Astronaut Performance

NESC Assessment (study)

Humans lack experience operating on planetary surfaces and for long durations in complete darkness, or when lighted, with harsh sun angles and long shadows

Apollo 12, Ocean of Storms, EVA 1, 19 November 1969, frames A12-46-6738 to 6740 : Apollo 12 landing site

What are the lighting concerns?

- There is no color video footage of Apollo 12 because the video camera was inadvertently pointed at the Sun, burning out its sensor
- Sun angle of Apollo 12, EVA1 = 7.5° (lowest of the Apollo EVAs)
- Sun angle in Polar Area of the Moon ≤ 5° (2-3° is typical)
- Shadow at 2.5° is ~3X as long as shadow at 7.5°
  - 6' object casts ~137' shadow, with Sun at 2.5°
    - All black
- Ambient lighting on the Moon too bright for EVA operations …
  - And too dark

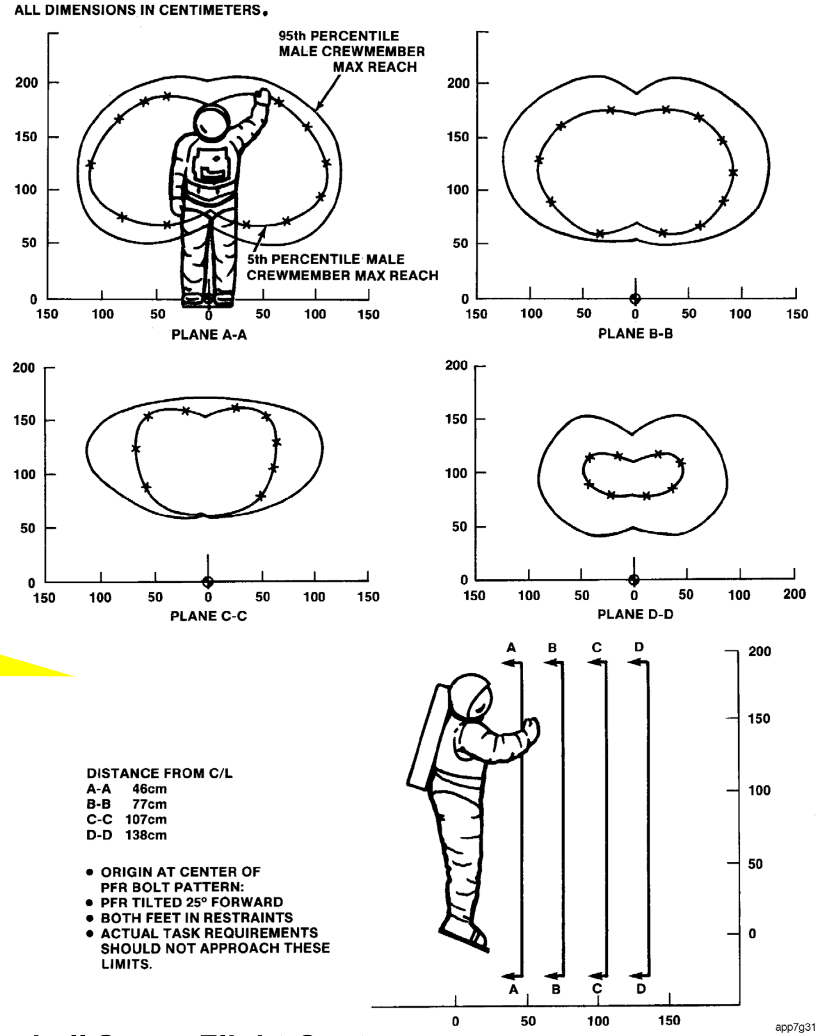
SVS video

https://www.youtube.com/watch?v=aD1OQ9UBwuU

Worksite design

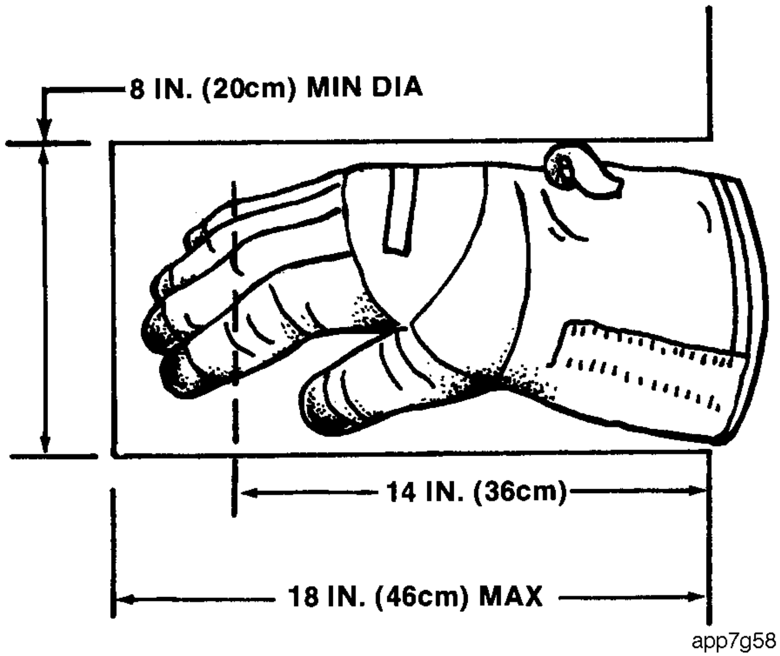
- **General considerations 1: astronaut reach envelopes**

If she cannot reach it, she cannot actuate, remove, or insert it



Worksite design

- **General considerations 2: suit glove & sleeve envelopes**



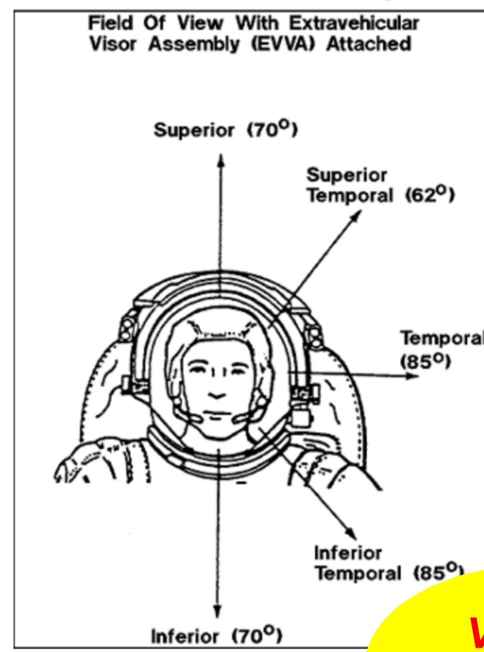
If the glove cannot fit into an opening, or the sleeve is constrained by the opening, she cannot work there.

Worksite design

- **General considerations 3: other suit concerns**

Can the astronaut bend to reach a task site?
Is there a risk that the suit will tear?
Will additional lighting be required?
Can the astronaut see the task site?
Will the needed tool fit into the task site?
Can an astronaut grasp it (does it have a handle?)?

Knee flexion (kneeling)



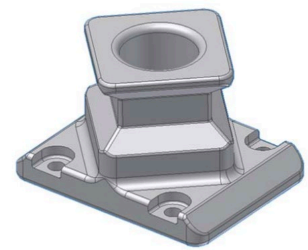
Visual envelope definition

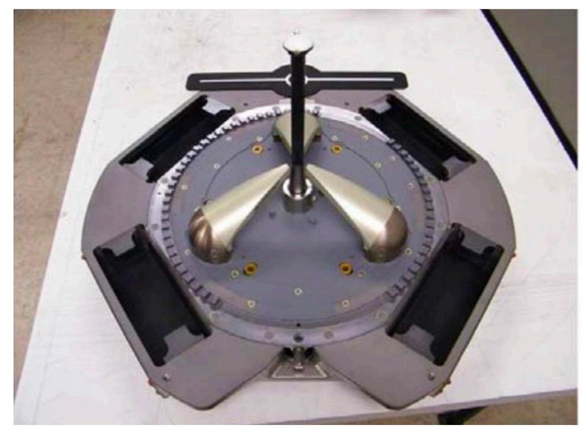
Worksite design robots

- Same considerations as for people

Worksite design robots

- Same considerations as for people
  - Work envelope
  - Visual envelope
  - Reach envelope
  - Tool (end effector) envelope
  - Need a “grasp” interface





Examples of robotic grapple interfaces

Two robots