The GNSS Space Service Volume (SSV): Expanding the Future of GNSS Navigation in Space

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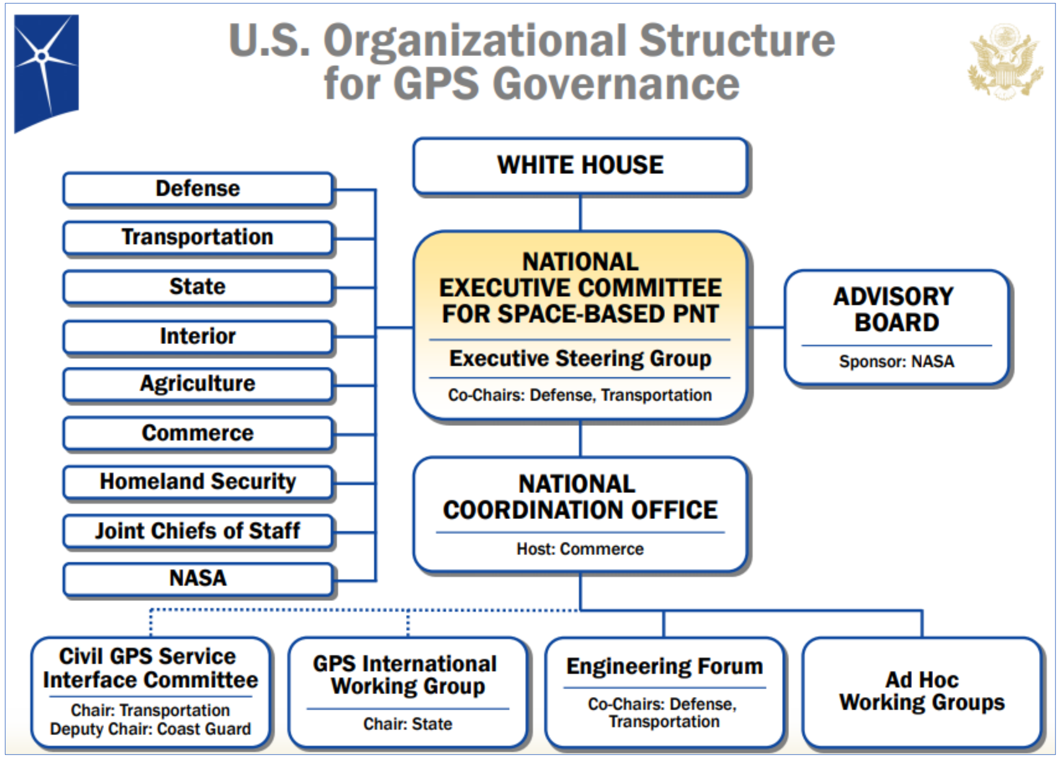
The Gateway, a potential application of international collaboration on GNSS beyond the SSV

NASA's Role in U.S. PNT / Space Policy

- The U.S. Space-Based Positioning, Navigation, and Timing (PNT) Policy tasks the NASA Administrator to develop and provide requirements for the use of GPS & its augmentations to support civil space systems
- NASA works with the Air Force to contribute making GPS services more accessible, interoperable, robust, and precise
- The 2010 National Space Policy reaffirmed PNT Policy commitments to GPS service provisions, international cooperation, and interference mitigation
- In 2018 the National Space Council recommended to develop protections for the radiofrequency spectrum [such as that used by GPS] facilitating commercial space activities

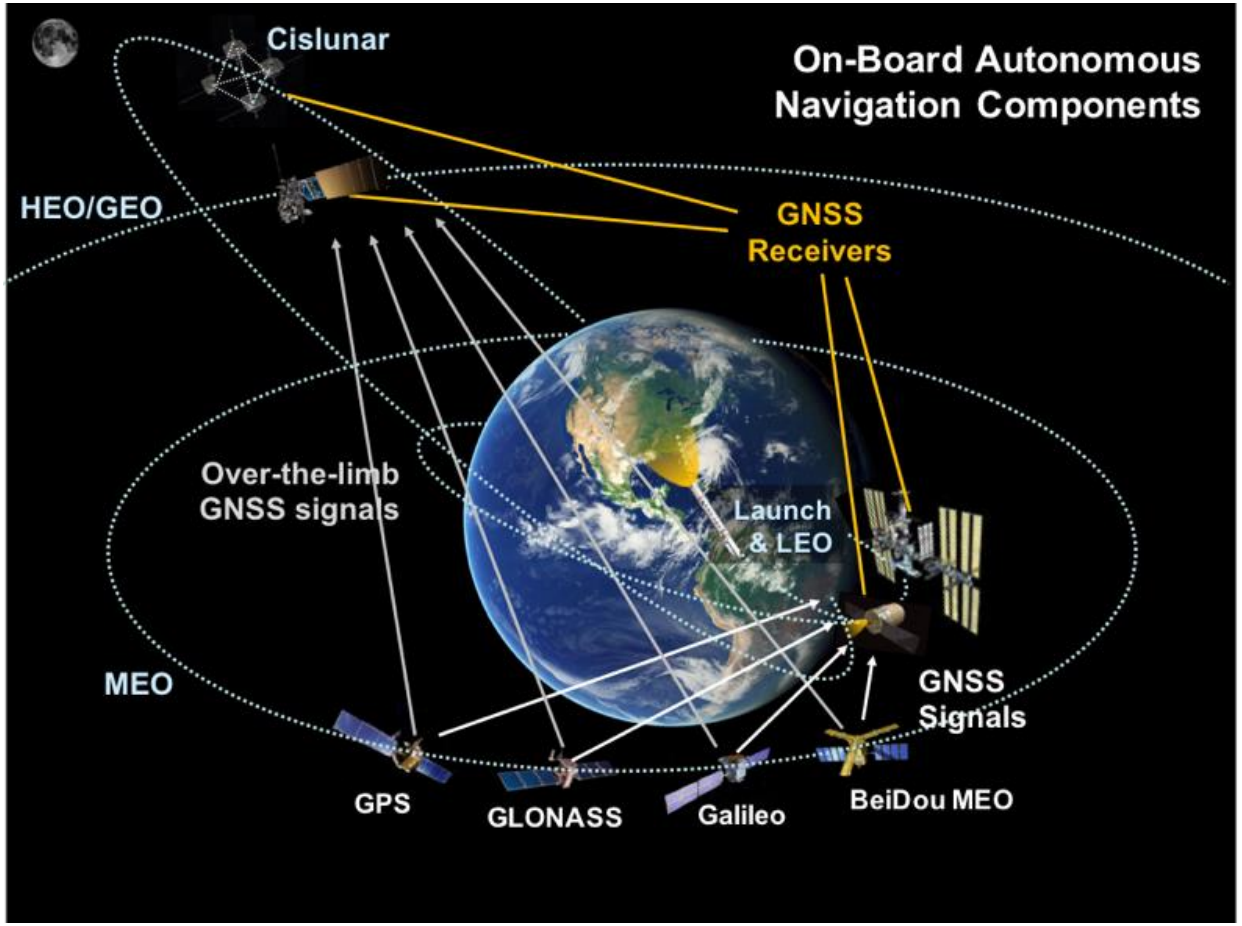
The PNT Advisory Board has implemented a "**PTA**" program to:

- **Protect** the radio spectrum + identify + prosecute interferers
- **Toughen** GPS receivers against natural and human interference
- **Augment** with additional GNSS/PNT sources and techniques



Space Uses of Global Navigation Satellite Systems (GNSS)

- **Real-time On-Board Navigation:** Enables new methods of spaceflight ops such as precision formation flying, rendezvous & docking, station-keeping, Geosynchronous Orbit (GEO) satellite servicing
- **Earth Sciences:** Used as a remote sensing tool supporting atmospheric and ionospheric sciences, geodesy, geodynamics, monitoring sea levels, ice melt and gravity field measurements
- **Launch Vehicle Range Ops**: Automated launch vehicle flight termination; providing people and property safety net during launch failures and enabling higher cadence launch facility use
- **Attitude Determination:** Enables some missions, such as the International Space Station (ISS) to meet their attitude determination requirements
- **Time Synchronization:** Support precise time-tagging of science observations and synchronization of on-board clocks

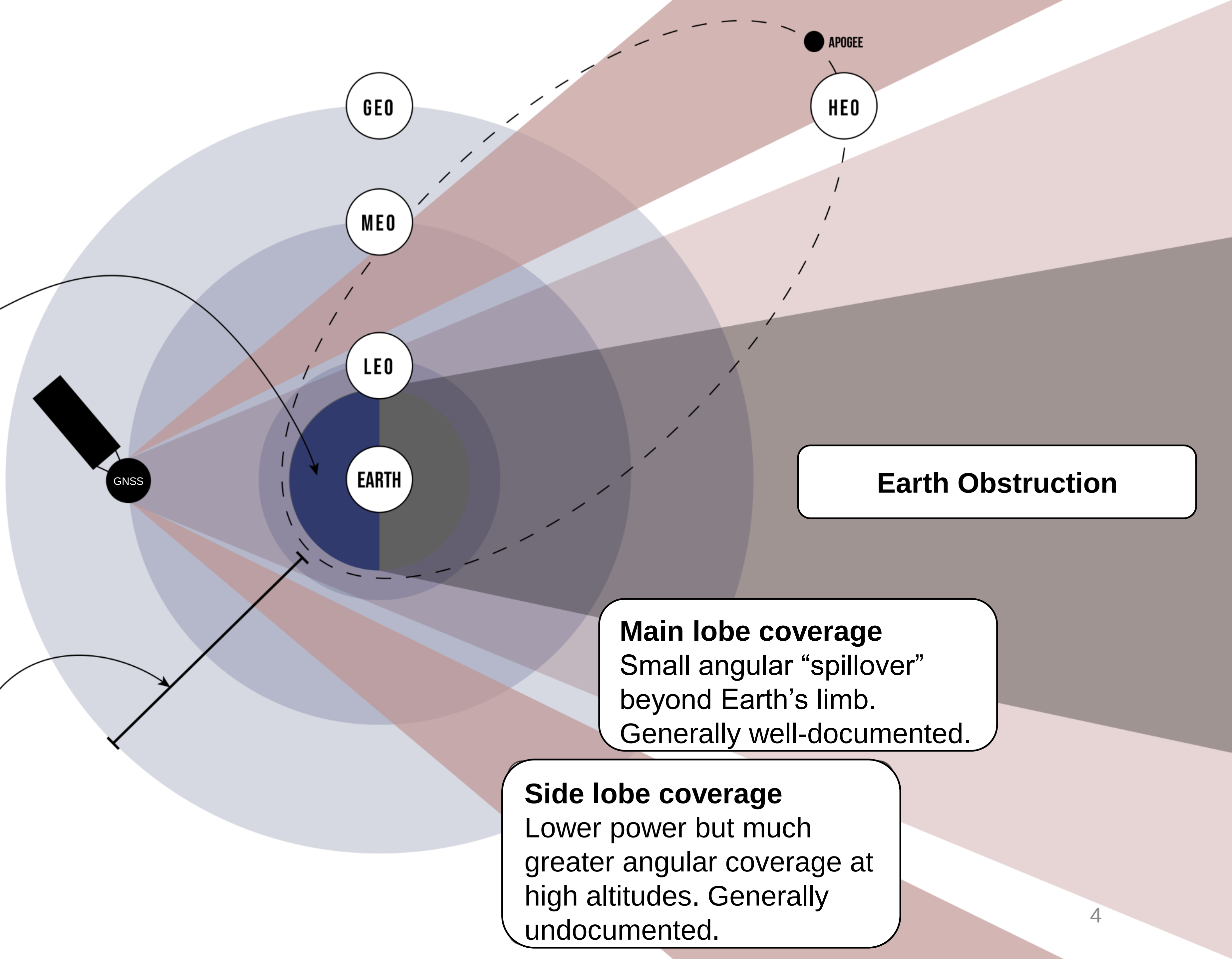


The capabilities of individual GNSS to support space users will be further improved by pursuing compatibility and interoperability among the various GNSS

SPACE SERVICE VOLUME

Terrestrial Service Volume
0–3,000 km altitude

LEO = low-Earth orbit region
MEO = medium-Earth orbit region
GEO = geosynchronous orbit
HEO = highly elliptical orbit



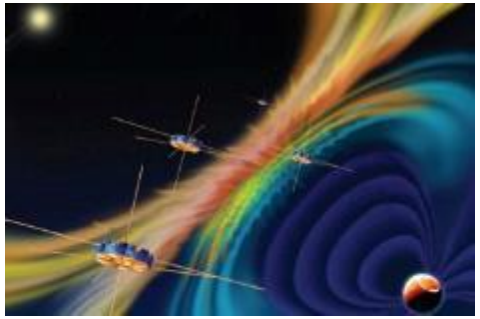
Space Service Volume
3,000–36,000 km (GEO) altitude

The Growing Promise of GNSS for Real-Time Navigation in the SSV & Beyond…

Benefits of GNSS use in SSV:

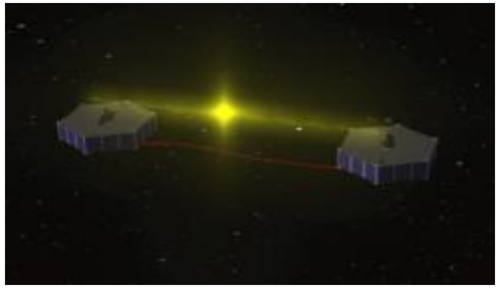
- Significantly **improves real-time navigation performance** (from: km-class to: meter-class)
- Supports **quick trajectory maneuver recovery** (from: 5-10 hours to: minutes)
- GNSS timing **reduces need for expensive on-board clocks** (from: $100sK-$1M to: $15K–$50K)
- Supports **increased satellite autonomy**, lowering mission operations costs (savings up to $500-750K/year)
- Enables new/enhanced capabilities and better performance for **High Earth Orbit (HEO) and Geosynchronous Earth Orbit (GEO) missions,** such as:

Earth Weather Prediction using Advanced Weather Satellites

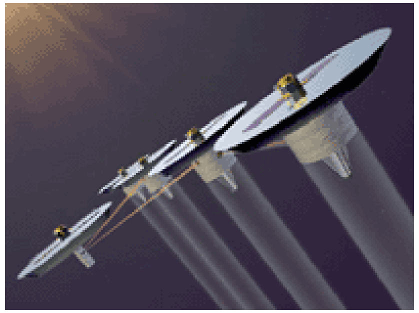


Space Weather Observations

Precise Relative Positioning



Precise Position Knowledge and Control at GEO



Formation Flying, Space Situational Awareness, Proximity Operations

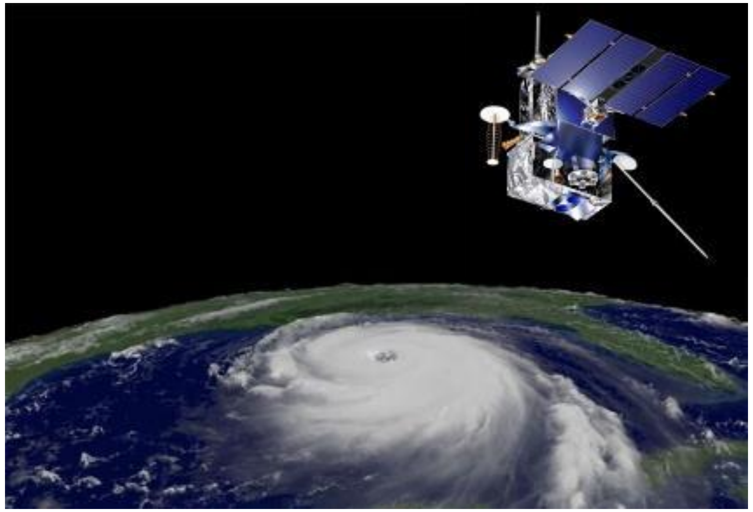
Beyond GEO / Cislunar Space

Recent SSV Achievements in the USA

Operational U.S. Missions using GNSS in the Space Service Volume & Beyond

GOES-R Weather Satellite Series:

- Next-generation U.S. operational GEO weather satellite series
- First series to use GPS for primary navigation
- GPS provides rapid maneuver recovery, enabling continual observation with <2 hour outage per year
- Introduction of GPS and new imaging instrument are **game-changers to humanity, delivering data products to substantially improve public and property safety**



GOES-16 GPS Visibility:

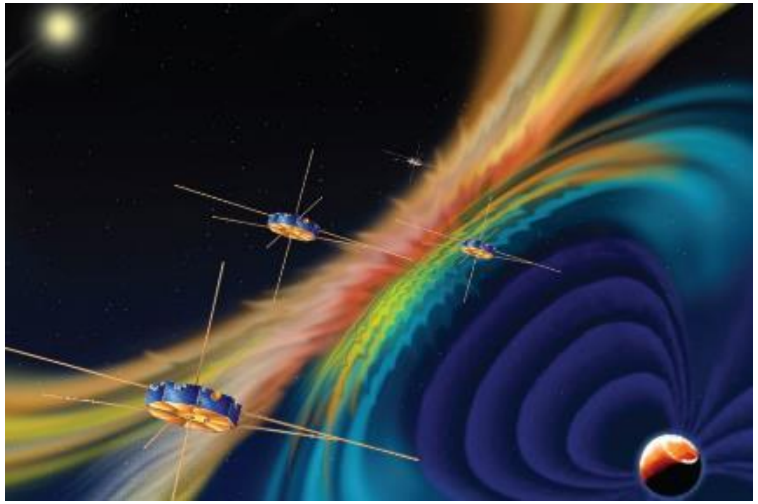
- Minimum SVs visible: 7
- DOP: 5–15

GOES-16 Nav Performance (3σ):

- Radial: **14.1 m**
- In-track: **7.4 m**
- Cross-track: **5.1 m**
- Compare to requirement: (100, 75, 75) m

Magnetospheric Multi-Scale (MMS) Mission:

- Four spacecraft form a tetrahedron near apogee for magnetospheric science measurements (space weather)
- Highest-ever use of GPS
  - Phase I: 12 Earth Radii (RE) apogee (76,000 km)
  - Phase 2B: 25 RE apogee (~150,000 km) **(40% lunar distance)**
  - Apogee raising beyond 29 RE **(50% lunar distance)** completed in February 2019
- GPS enables onboard (autonomous) navigation and potentially autonomous station-keeping



MMS Nav Performance (1σ)

Description	Phase 1	Phase 2B
Semi-major axis est. under 3 R_E (99%)	2 m	**5 m**
Orbit position estimation (99%)	12 m	**55 m**

Feasibility of GNSS for Lunar Navigation

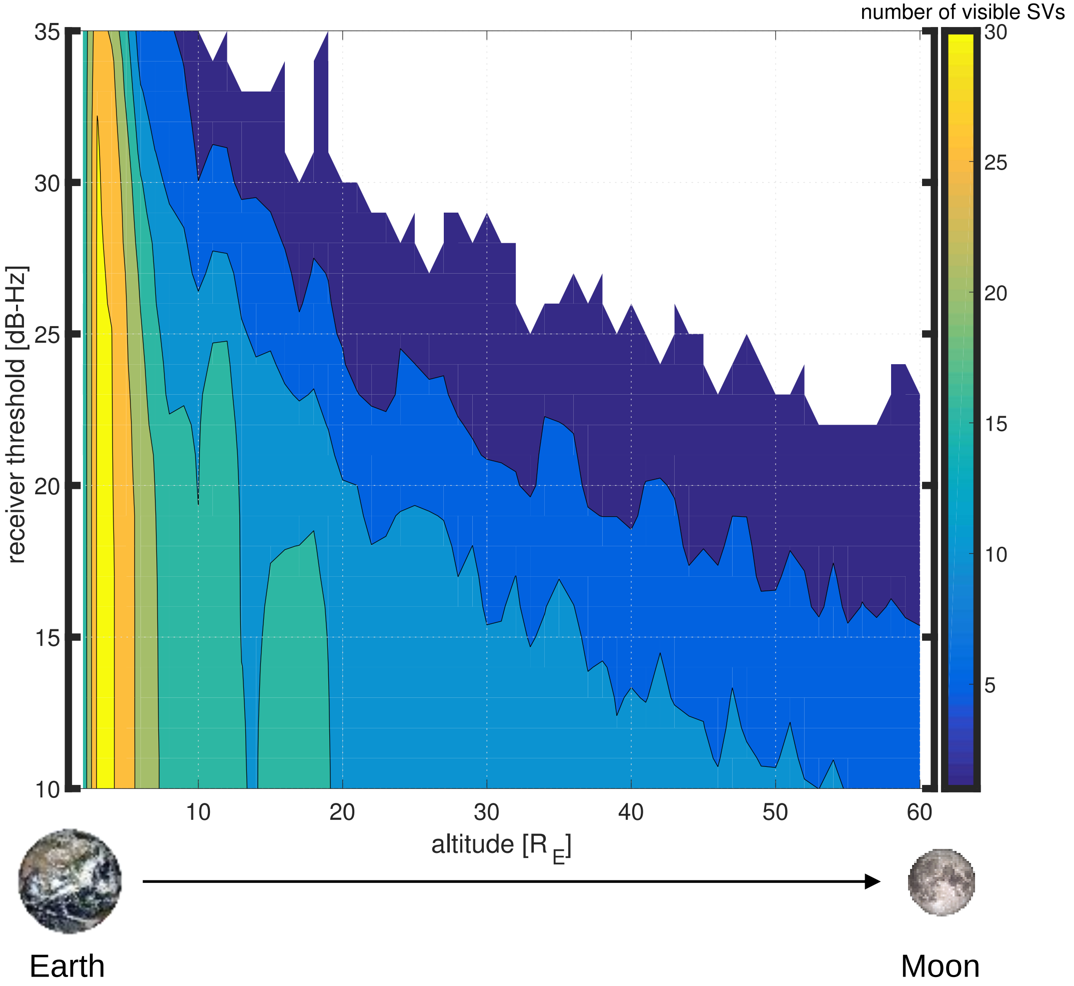
2018 Lunar Visibility Study

- GPS constellation modeled as accurately as possible, including sidelobe signals; validated with GOES-16 and MMS flight data
- Calibrated models applied to outbound lunar near-rectilinear halo orbit (NRHO) GPS receiver reception with 22 dB-Hz C/N_0 threshold

Peak Antenna Gain	1+ Vis.	4+ Vis.	Maximum Outage
7 dB	63%	8%	140 min
10 dB	82%	17%	84 min
14 dB	99 %	65%	11 min

- Use of sidelobes and modest amount of additional antenna gain or receiver sensitivity increases coverage significantly
- **Results show useful onboard GPS navigation at lunar distances is achievable *now* using *currently-available* signals and *flight-proven* receiver technology.**

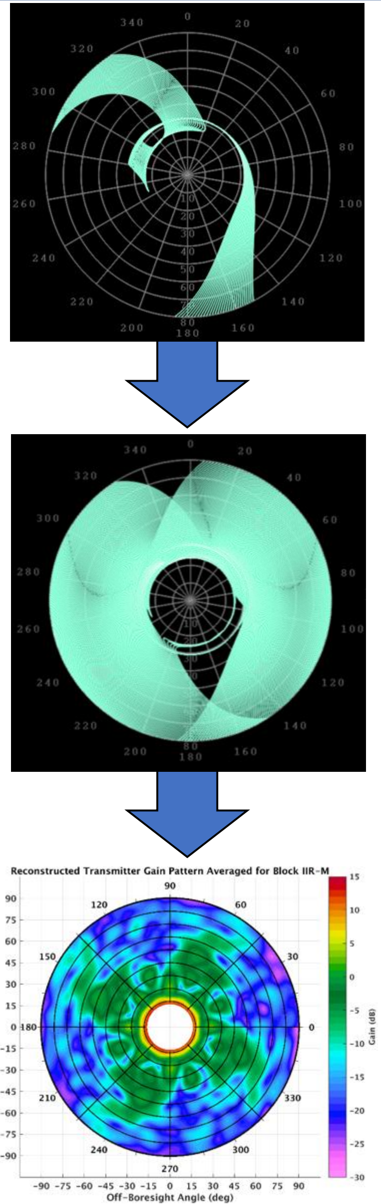
Number of GNSS satellites visible by altitude and receiver threshold



The GPS Antenna Characterization Experiment (ACE)

Objective: Complete first ever mapping of the GPS L1 sidelobes for all GPS satellites to determine signal availability for future missions in the Space Service Volume.

- **GPS ACE architecture permits tracking of extremely weak signals over long duration**
  - 24/7 GPS telemetry provides near continuous tracking of each PRN
- **First reconstruction of full GPS gain patterns from flight observations**
  - Block averages of IIR, IIR-M show remarkable consistency with ground patterns
    - Demonstrates value in extensive ground testing of antenna panel
  - Characterized full gain patterns from Blocks IIA, IIF for the first time
  - Patterns permit more accurate simulations of GPS signal availability for future HEO missions
- **Additional analysis of pseudorange deviations indicate usable measurements far into side lobes**



Dataset available at: **https://esc.gsfc.nasa.gov/navigation**

NASA-USAF SSV Collaboration

- **Oct 13 2017: Joint NASA-USAF Memorandum of Understanding (MOU)** signed
  - MOU addresses civil Space Service Volume (SSV) requirements
  - Scope relevant to GPS IIIF acquisition process
    - Civil space early insight into Block IIIF design relevant to SSV performance
    - Access to Block IIF, III, and IIIF technical data
- **MOU results to-date**:
  - US civil space rep. from NASA supported GPS IIIF source selection team as SSV technical expert
  - Built positive, collaborative relationships with IIIF acquisition team; provided civil space insight continuing through design and production
  - NASA received released GPS IIF antenna pattern measurements per MOU and to support NASA Space Launch System need
  - Participating in GPS IIIF design reviews

MOU supports SSV signal continuity goals for future space users

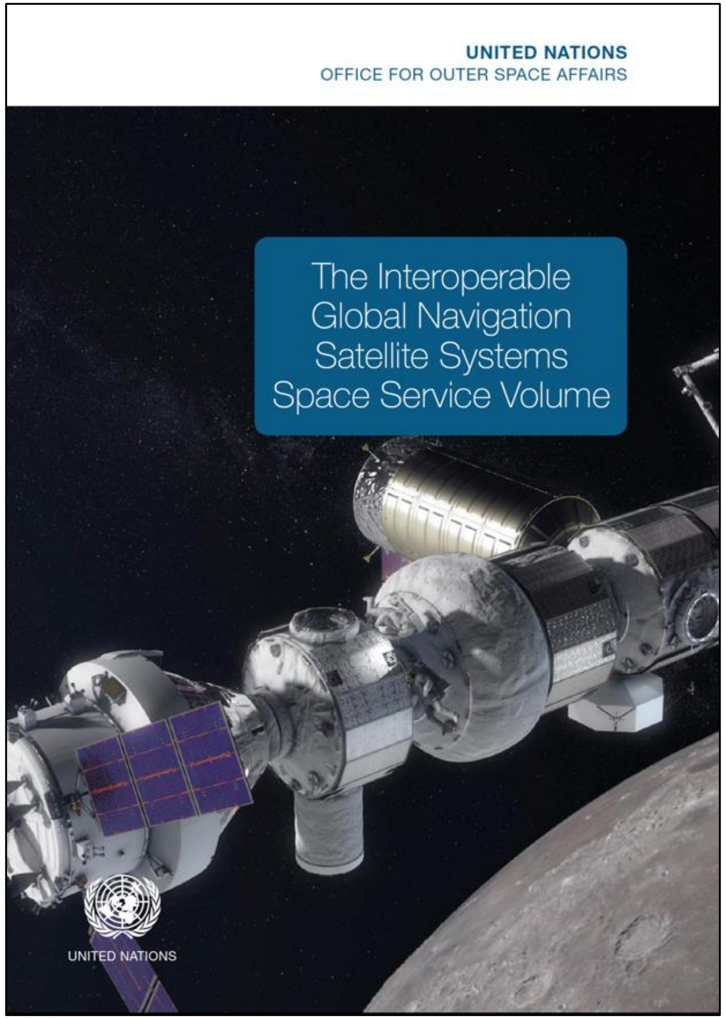
SSV International Collaboration

International Committee on GNSS (ICG)

- **The ICG emerged from 3rd UN Conference on the Exploration and Peaceful Uses of Outer Space July 1999 to:**
  - Promote the use of GNSS and its integration into infrastructures, particularly in developing countries
  - Encourage compatibility & interoperability among global and regional systems
- **Members:** GNSS Providers (U.S., EU, Russia, China, India, Japan), Other Member States of the United Nations, and International organizations/associations (including the Interagency Operations Advisory Group) & others
- **Annual Meetings**:
  - 13th ICG hosted by China in Xi'an, November 4-9, 2018 (http://icg13.beidou.gov.cn/)
  - 14th ICG to be hosted by India in Bangalore, 2019 (https://www.icg14.org/)
  - 15th ICG to be held at the UN in Vienna, Austria, 2020

http://www.oosa.unvienna.org/oosa/en/SAP/gnss/icg.html

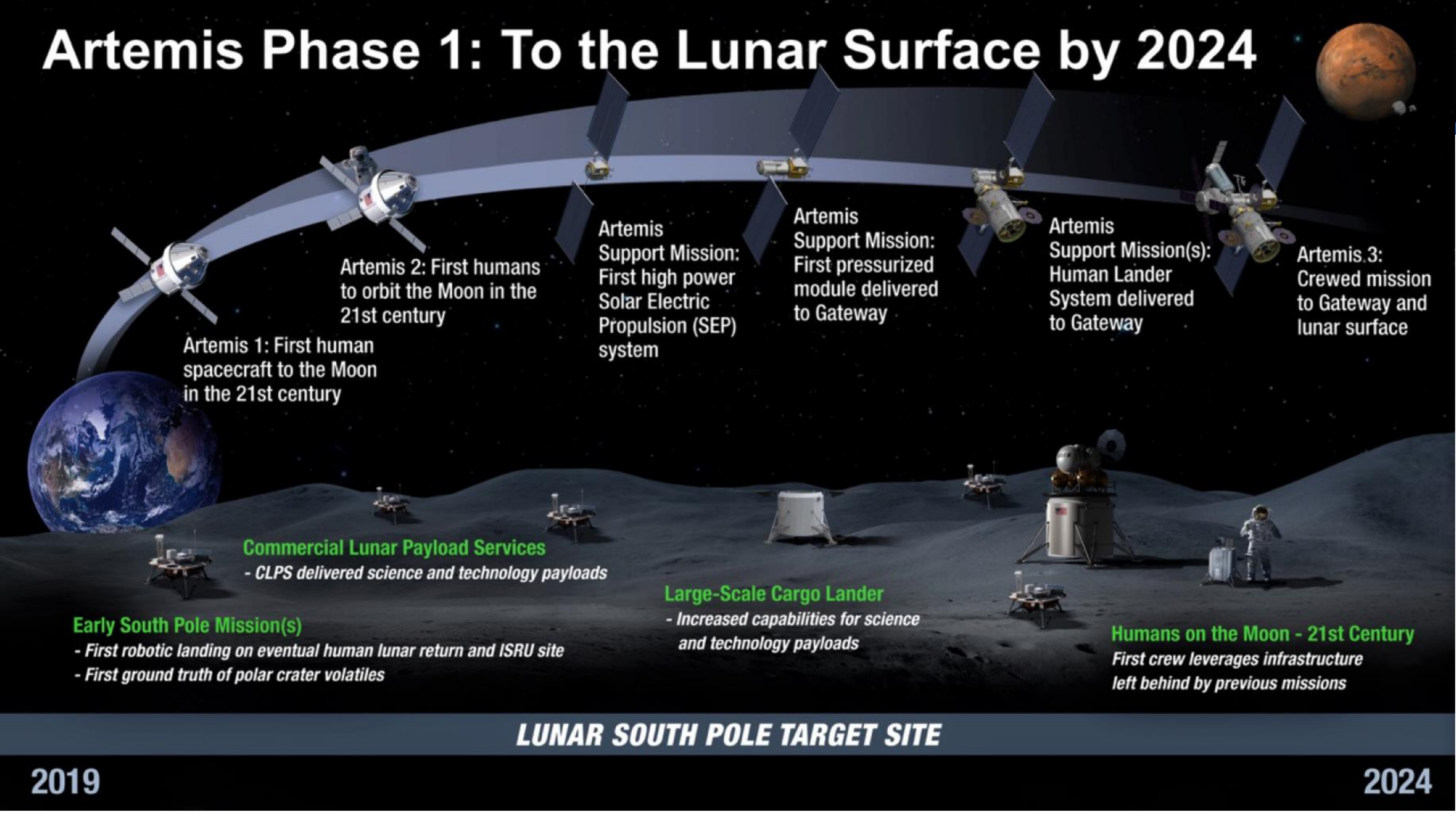
ICG WG-B SSV Booklet & Ongoing Development



https://undocs.org/ST/SPACE/75

- **December 2018: First publication of SSV performance characteristics for each GNSS constellation**
  - Received signal power, signal availability, pseudorange accuracy to GEO distance for each band
  - Conservative performance for main lobe signals only
- **Global and mission-specific visibility analyses**
  - GEO
  - Highly-elliptical
  - Lunar
- **Proposed expansion in 2nd edition:**
  - Addition of DOP analysis
  - Release and analysis of high-fidelity antenna patterns
  - Inclusion of real-world flight experiences
- **Future "Beyond-SSV" complementary activities:**
  - Identification and analysis of major Moon and Mars use cases
  - Analysis of benefits of GNSS augmentations for lunar activities
  - Collaboration with international exploration community

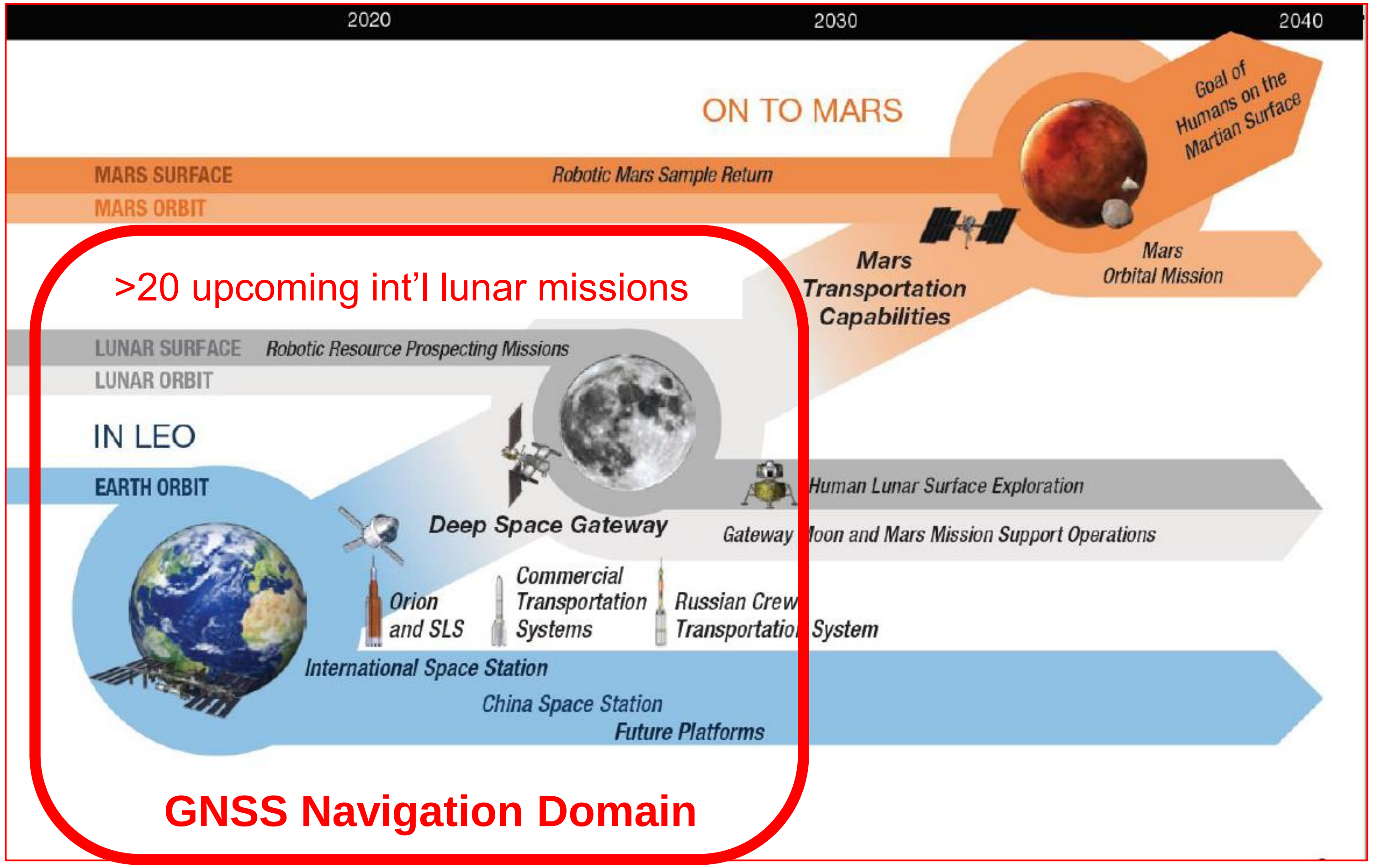
Next SSV Opportunity: Employing GNSS for Lunar Exploration


Artemis Phase 1: To the Lunar Surface by 2024
Artemis 1: First human spacecraft to the Moon in the 21st century
Artemis 2: First humans to orbit the Moon in the 21st century
Artemis Support Mission: First high power Solar Electric Propulsion (SEP) system
Artemis Support Mission: First pressurized module delivered to Gateway
Artemis Support Mission(s): Human Lander System delivered to Gateway
Artemis 3: Crewed mission to Gateway and lunar surface
Commercial Lunar Payload Services
- CLPS delivered science and technology payloads
Early South Pole Mission(s)
- First robotic landing on eventual human lunar return and ISRU site
- First ground truth of polar crater volatiles
Large-Scale Cargo Lander
- Increased capabilities for science and technology payloads
Humans on the Moon - 21st Century
First crew leverages infrastructure left behind by previous missions
LUNAR SOUTH POLE TARGET SITE
2019
2024

Employing GNSS for Lunar Exploration

- ICG WG-B studying use of GNSS *beyond the SSV* (i.e. beyond GEO), such as for lunar-vicinity navigation for exploration
- GNSS on lunar missions would address multiple GER technology needs:
  - **Autonomous Vehicle System Management**
  - **Autonomous rendezvous & docking**
  - **Proximity ops; Relative Navigation**
  - **Beyond LEO Crew Autonomy**
  - **Lunar Lander (100 m accuracy)**
  - **In-space Timing and Navigation**
- ICG initiated ISECG-ICG coordination to employ global exploration roadmaps which will identify ICG study mission profiles
  - Insight into roadmap developments within ISECG would ensure studies are directed at most applicable mission set.

International Space Exploration Coordination Group (ISECG) Global Exploration Roadmap (GER)

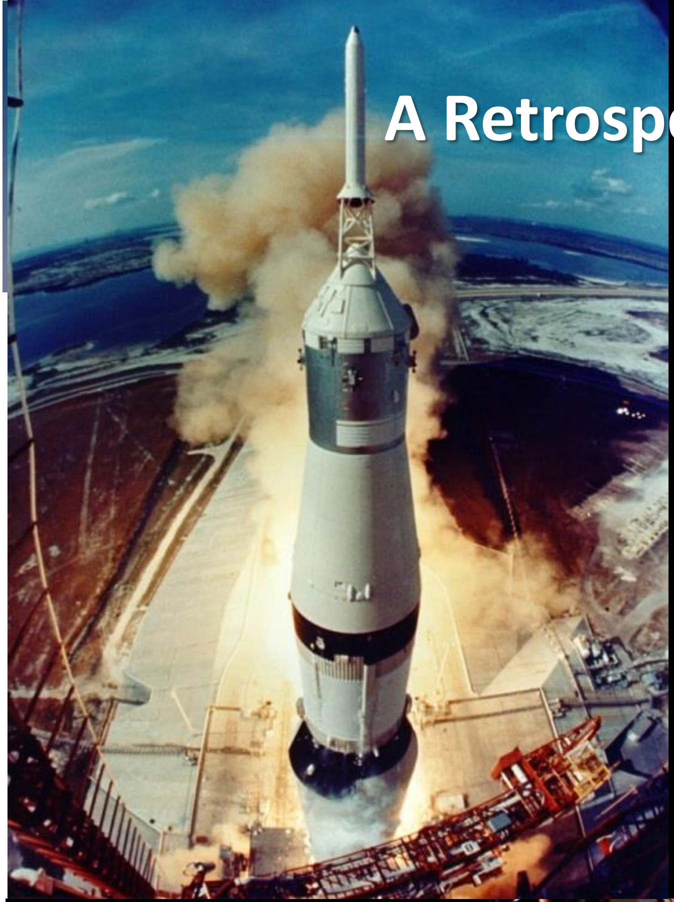


Lunar Missions Represent a Ripe New Frontier for High Altitude GNSS

Conclusions

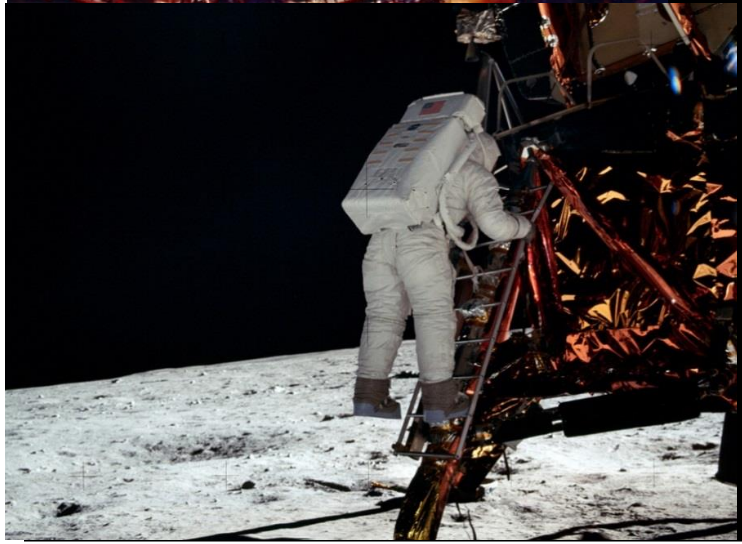
- Current and future space missions in the SSV are becoming increasing reliant on near-continuous GNSS availability to improve their mission performance
- Today, we continue to work to ensure that the SSV keeps pace with user demands, including its expansion into lunar space:
  - Results derived from MMS and GOES data show useful onboard GPS navigation at lunar distances is achievable *now* using *currently-available* signals and *flight-proven* receiver technology.
  - Future work must extend these specific studies to full navigation analysis of lunar spacecraft, and utilizing the *full capability* of multi-GNSS signals
  - ICG is a natural forum for these discussions and analyses
- Developing and evolving an interoperable multi-GNSS SSV is a critical space utility, improving on-board PNT resilience and ensuring wider capabilities are available as needed
- NASA and the U.S. Government are proud to work with the GNSS providers to contribute making GNSS services more accessible, interoperable, robust, and precise for all users, for the benefit of humanity.

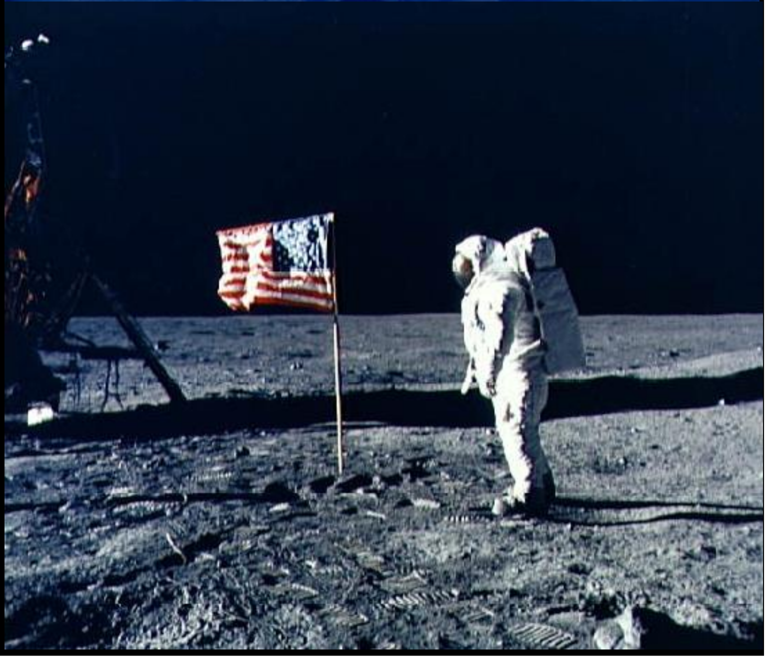
Apollo 11: 50 Years
A Retrospective View of Space Communication and Navigation



First Humans on Lunar Surface
Neil Armstrong, Edwin (Buzz) Aldrin
Michael Collins in Lunar Orbit
July 20, 1969

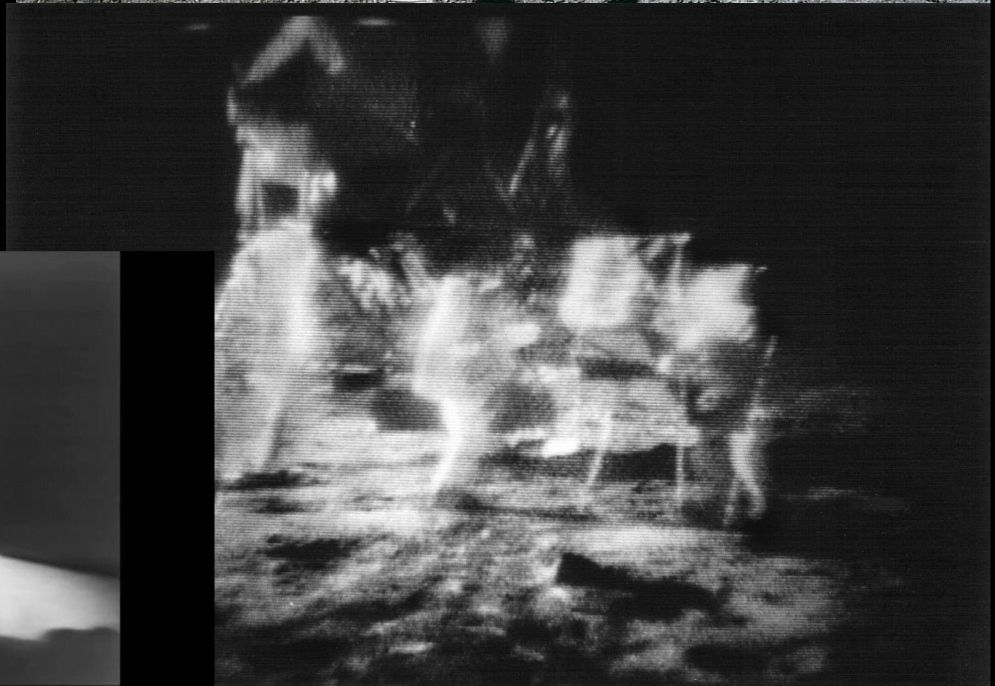
Neil Armstrong
First Person to Walk on
Surface of the Moon





Apollo Unified S-Band Communication & Navigation System

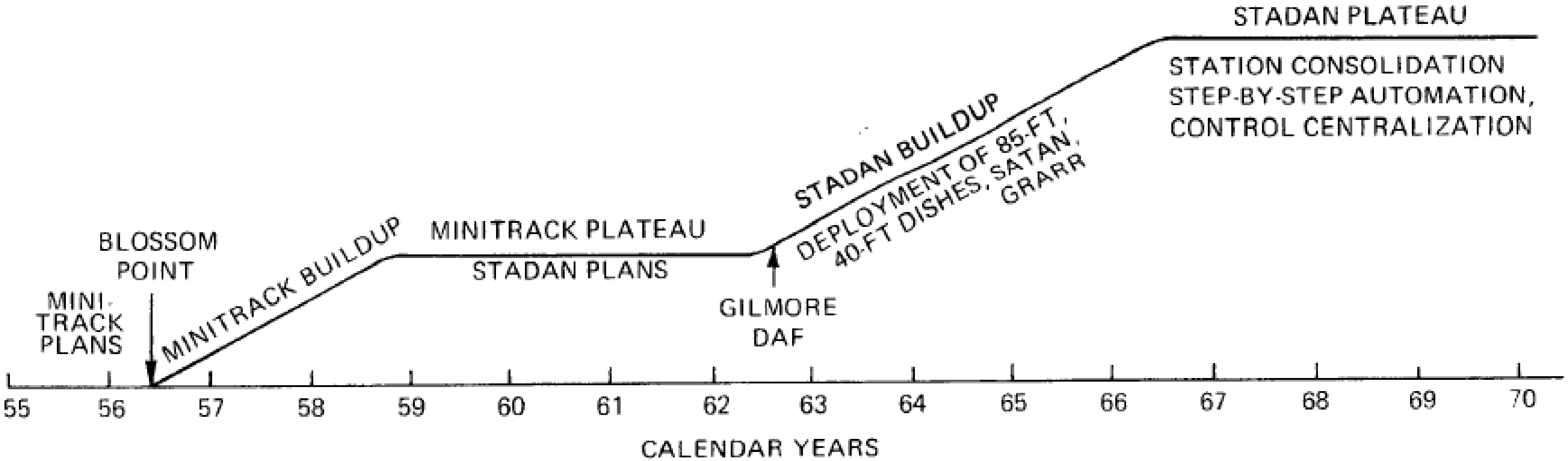
(Some Slides courtesy of Jim Schier, NASA Space Communications and Navigation Program--SCaN)



Early 1960's: First Transformational Era of Space Communication and Navigation

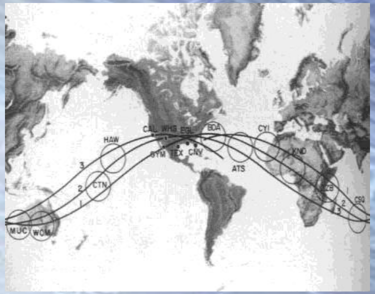
A person would have to stand at the computer and interpret the read-out paper

- Minitrack stations developed in the late 1950's to support early NASA & DoD satellites
- In 1960, Goddard Space Flight Center starting testing Tracking, telemetry and command (TT&C) approaches which quickly turned operational
- Minitrack was upgraded & new stations added to improve geometry, resulting in the new Satellite Tracking and Data Acquisition Network (STADAN)
- New parabolic antennas were installed to accommodate more bandwidth in the higher spectrum of the S-band.



Manned Space Flight Network (MSFN)

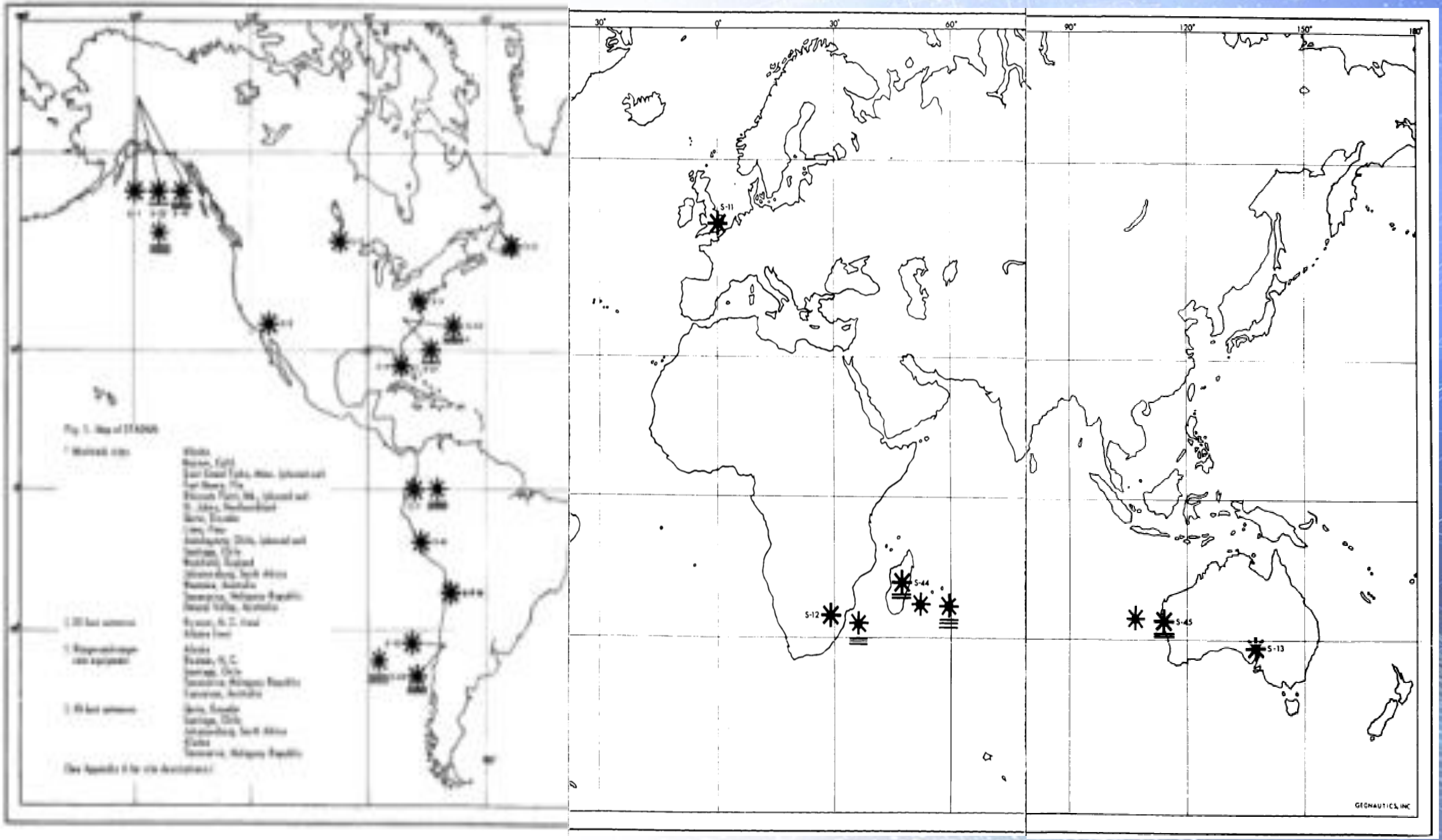
- Gemini III (March 1965) tested the new upgraded Manned Space Flight Network (MSFN)
  - Unified S-band (9 m and 26 m antennas)
  - UHF and C-band antennas for tracking and communications
- The MSFN added new stations and used five ships and eight Apollo Range Instrumentation Aircraft (ARIA) to supplement coverage
- Some components of the MSFN were used until the retirement of the Shuttle in 2011
- Computers were becoming a more prominent part of the network and began to streamline (compress) the data
  - This relieved the need for a person to stand next to the machine and analyze the data



MSFN Map

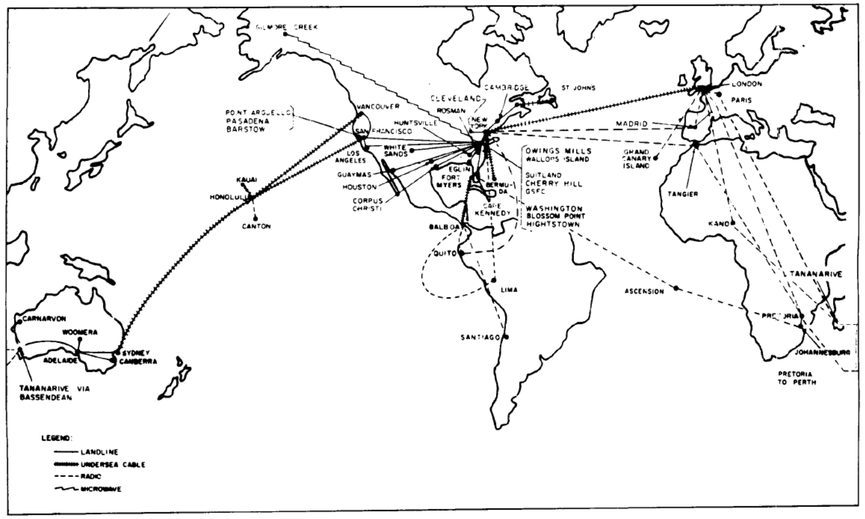
Gemini III crew

MSFN and STADAN Combined



Centralizing Ground Communications

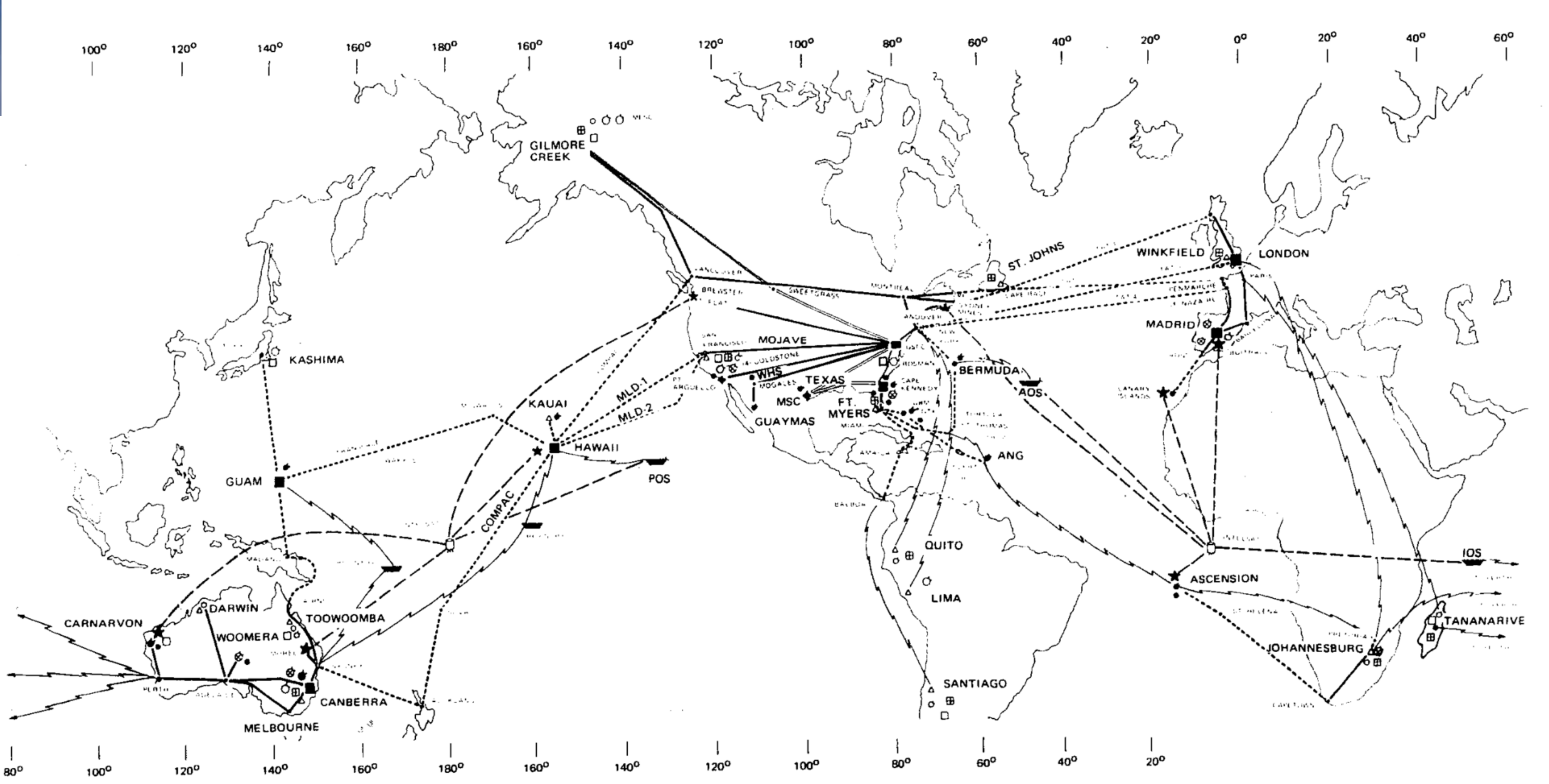
NASCOM 1980’s



NASCOM Map: 1970’s

- **NASA Communications (NASCOM) system was officially combined into one central program in 1964.**
- **NASCOM connected components (voice, television, commands, and telemetry) of all three networks, Satellite Tracking and Data Acquisition Network (STADAN), Manned Space Flight Network (MSFN), and Deep Space Network (DSN) which fed into Goddard Space Flight Center.**
- **Switching, Conferencing and Monitoring Arrangement (SCAMA) was the telephone switchboard that handled all voice communications and connected all ground stations.**

NASA Communications (NASCOM)



- **By 1969, 2.0 million miles (3.2 million km) of circuits had been laid. By 1974, NASCOM was the largest broad-band, real-time communication network in the world, linking all the continents except for Asia and Antarctica, and allowing for a two-way "dialog" with spacecraft from a centralized mission control center.**
- *Corliss, William R. (June 1974). Histories of the Space Tracking and Data Acquisition Network (STADAN), the Manned Space Flight Network (MSFN), and the NASA Communications Network (NASCOM)*

Genesis of Unified S-band System (USB)

- **Mercury & Gemini, operating in Low Earth Orbit (LEO), had separate radio systems for voice, telemetry, and tracking.**
  - > **Voice, command, and telemetry data sent via UHF and VHF systems.**
  - > **Tracking was done by a C-band beacon interrogated by a ground-based radar.**
- **Apollo needed a single communications & navigation system to save Size, Weight & Power (SWaP) and simplify lunar operations**
  - > **Unified S-band (2-4 GHz) combined voice, television, telemetry, tracking and command (TT&C) into single system**

USB Basic Concepts

- **The USB consisted of four technical elements:**
  - **Unification of carriers: Channel unification was a relatively new concept but the advantages far outweighed the risks**
  - **The move to the S-band: Only above 1000 MHz was there sufficient room in the spectrum to use subcarriers on a single carrier for all information.**
  - **The phase-lock loop (PLL): Electronically "locking" a transmitter and receiver together via a coherent radio signal.**
  - **Pseudorandom Noise (PN) ranging employing precise timing: Now a standard on all GNSS systems**

USB Development

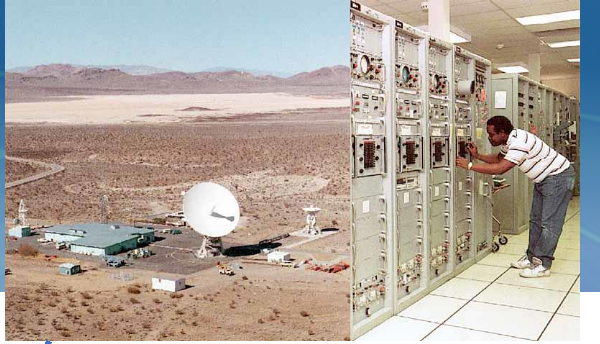
- MIT Lincoln Laboratory designed the USB system starting with a concept presented in a report on July 16, 1962 titled "Interim Report on Development of an Internal On-Board RF Communications System for the Apollo Spacecraft"
- USB tracking and communication system developed for the Apollo program by NASA and the Jet Propulsion Laboratory (JPL)
- USB ground network was managed by Goddard Space Flight Center (GSFC)

USB Ground Stations

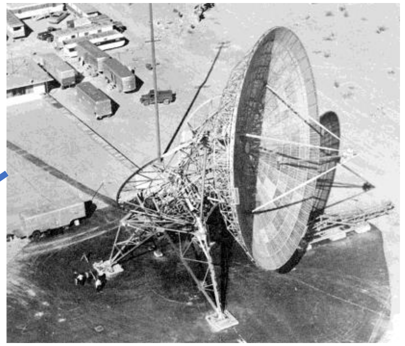
	SITE	CODE*	LAUNCH	INSERTION	NEAR EARTH	INJECTION	LUNAR	RE-ENTRY
MSFN Sites	CARNARVON	D,S			X	X		
	BERMUDA	S	X	X	X			
	TEXAS	S			X			
	CAPE KENNEDY	D,S	X	X	X	X		
	GUAYMAS	S			X	X		
	HAWAII	D,S			X	X		
	GUAM	D,S			X	X		
	ASCENSION	D,S			X	X		
	CANARY ISLANDS†	S			X	X		
	ANTIGUA†	S		X	X			
	GRAND BAHAMA I.†	S	X	X	X			
MSFN & DSN Sites	GOLDSTONE	D,L					X	
	CANBERRA	D,L					X	
	MADRID	D,L					X	
ARIS Ships	SHIP NO. 1	D,S		X		X		
	SHIP NO. 2	D,S				X		
	SHIP NO. 3	S				X		
	SHIP NO. 4							X
	SHIP NO. 5							X
ARIA A/C	AIRCRAFT (8)					X		X

*CODE
D - Dual Stations
S - 30 Foot Ground Antenna
L - 85 Foot Ground Antenna

†Canary Islands, Antigua, and Grand Bahama Islands are proposed sites only.

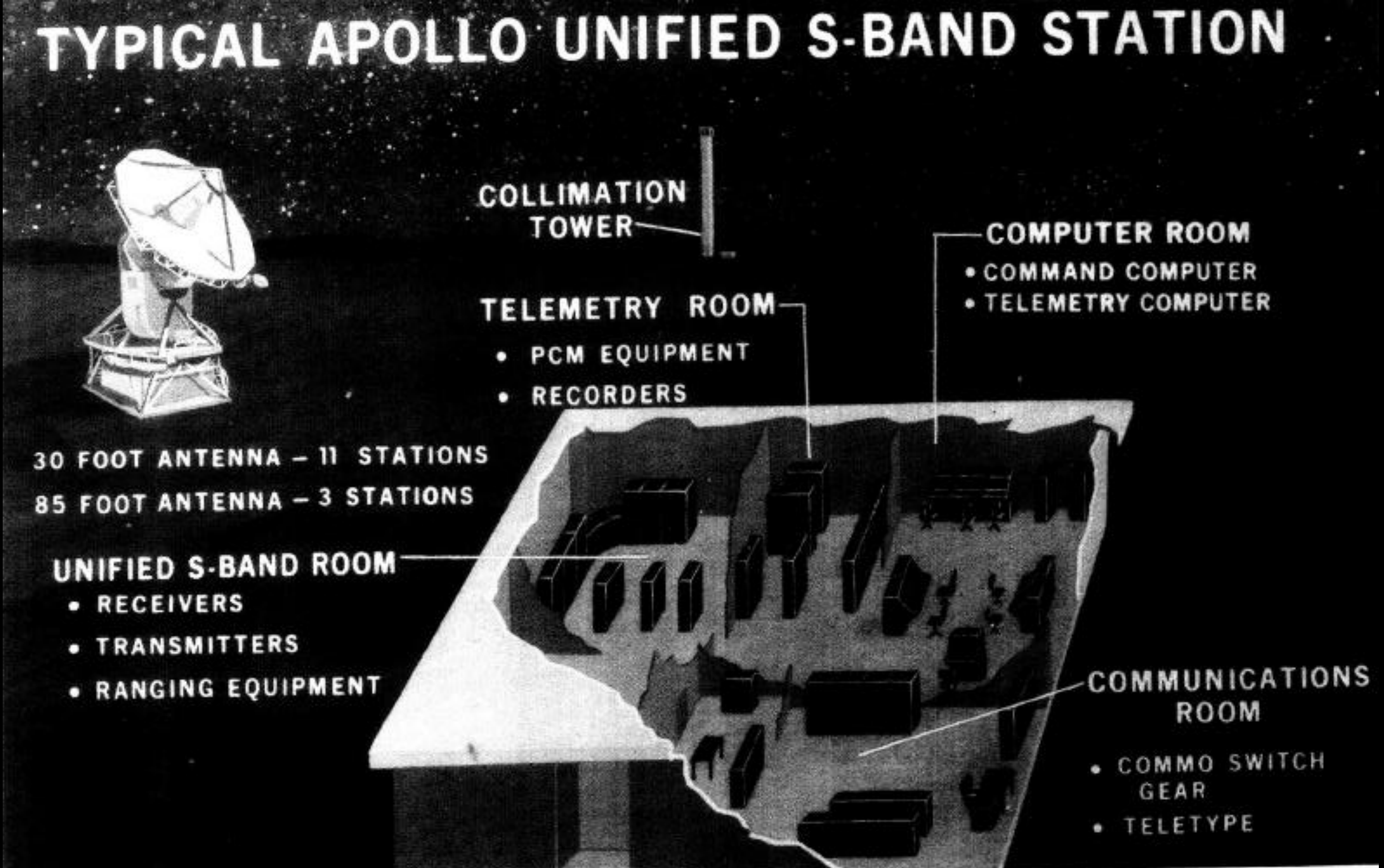


DSN Apollo Antenna & Processing Center, Goldstone

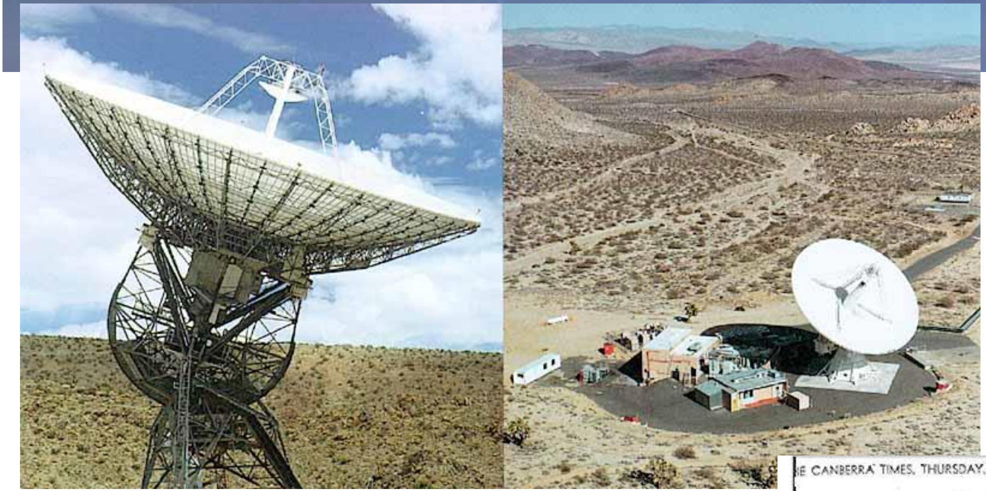


DSN Pioneer Antenna, Goldstone

DSN 26-m, Honeysuckle Creek


TYPICAL APOLLO UNIFIED S-BAND STATION
COLLIMATION TOWER
COMPUTER ROOM
• COMMAND COMPUTER
• TELEMETRY COMPUTER
TELEMETRY ROOM
• PCM EQUIPMENT
• RECORDERS
30 FOOT ANTENNA – 11 STATIONS
85 FOOT ANTENNA – 3 STATIONS
UNIFIED S-BAND ROOM
• RECEIVERS
• TRANSMITTERS
• RANGING EQUIPMENT
COMMUNICATIONS ROOM
• COMMO SWITCH GEAR
• TELETYPE

USB Ground Stations



Echo antenna and Goldstone administration center

DSN Madrid wing with 642-b & 1218 computers, 1299 switches, MSFTP 2 decommutation equipment, & telemetry processors

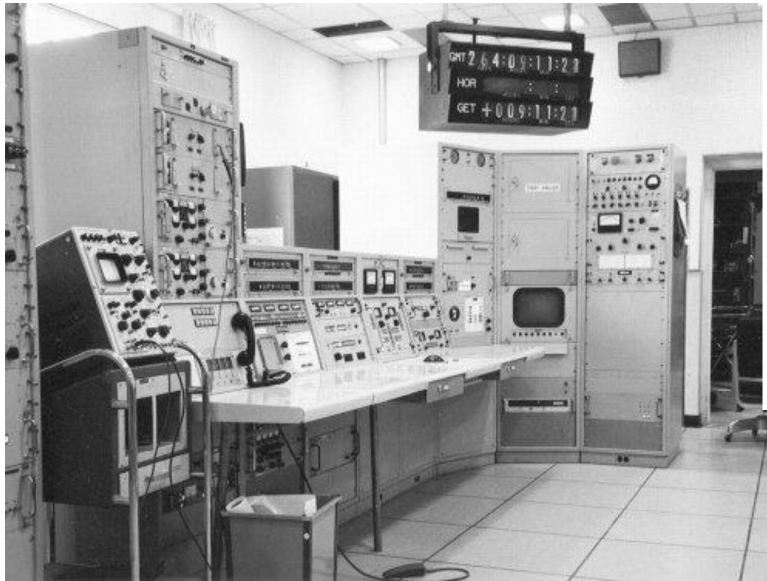
E CANBERRA TIMES, THURSDAY, APRIL 9, 1970

A LIFELINE TO THE MOON

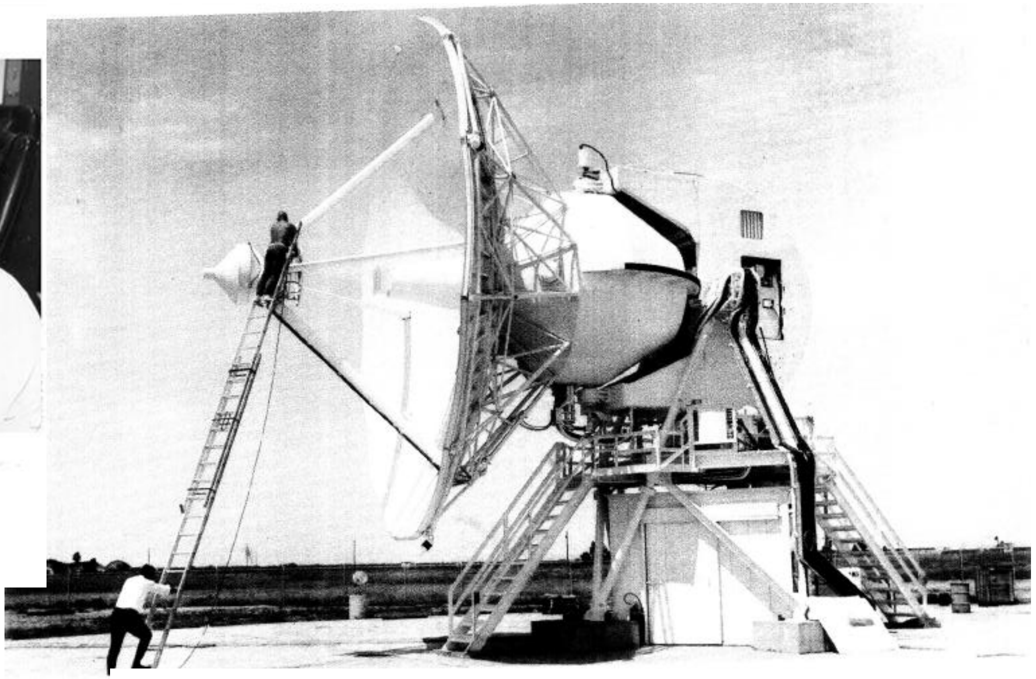
Mr Mike Dinn, left, and Mr John Saxon, at the Honeysuckle Creek tracking station console during simulation exercises this week.

Another perfect emergency for the Apollo team

The lunar module Aquarius had only just lifted off the hill north of Fra Mauro crater yesterday when Honeysuckle Creek tracking station control



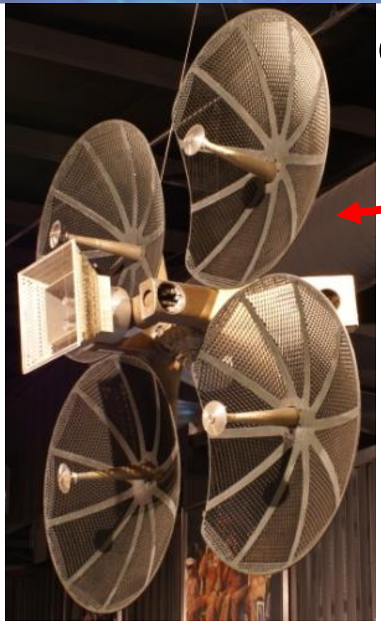
Madrid USB Antenna Servo Console



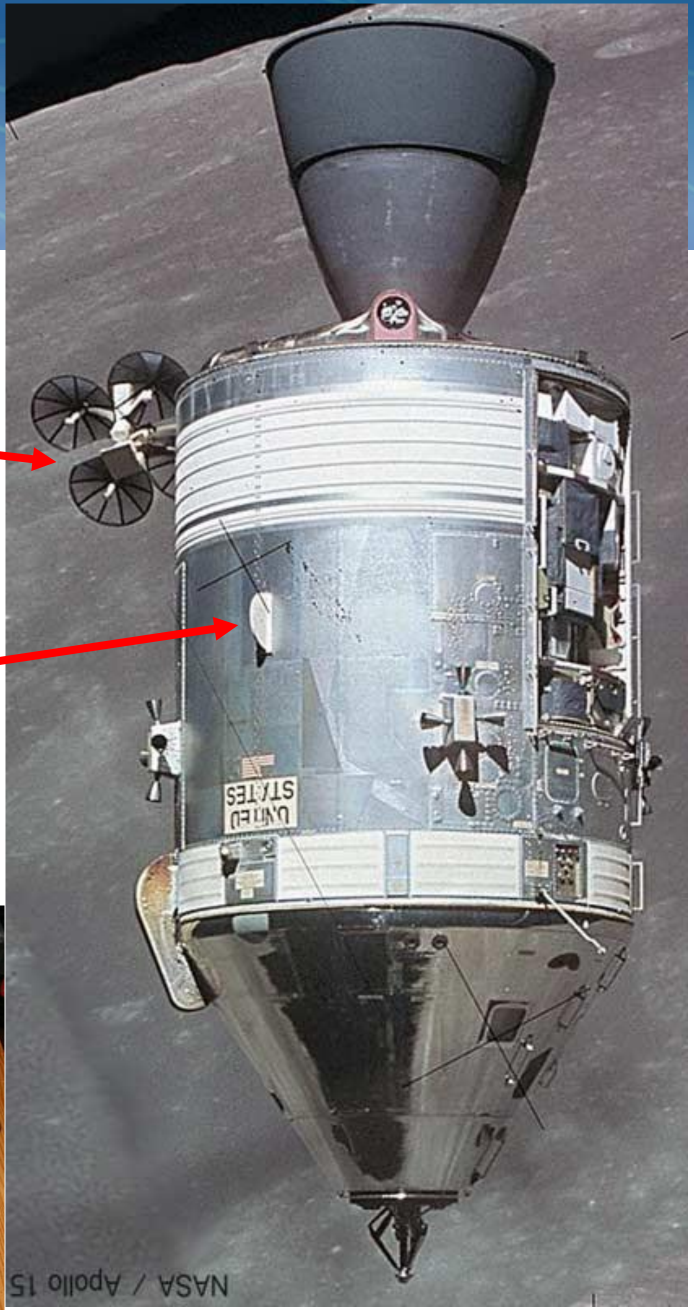
Apollo USB 9-m antenna at Corpus Christi

Apollo Command and Service Module (CSM)

- Short-range CSM-Lunar Module communications used two VHF antennas mounted on the SM
- Steerable USB high-gain antenna for long-range CSM-MSFN communications
  - Four 31-inch (0.79 m) diameter reflectors surrounding single 11-inch (0.28 m) square reflector
- Four omni S-band antennas supported low rate comm when vehicle attitude not optimal for high-gain antennas



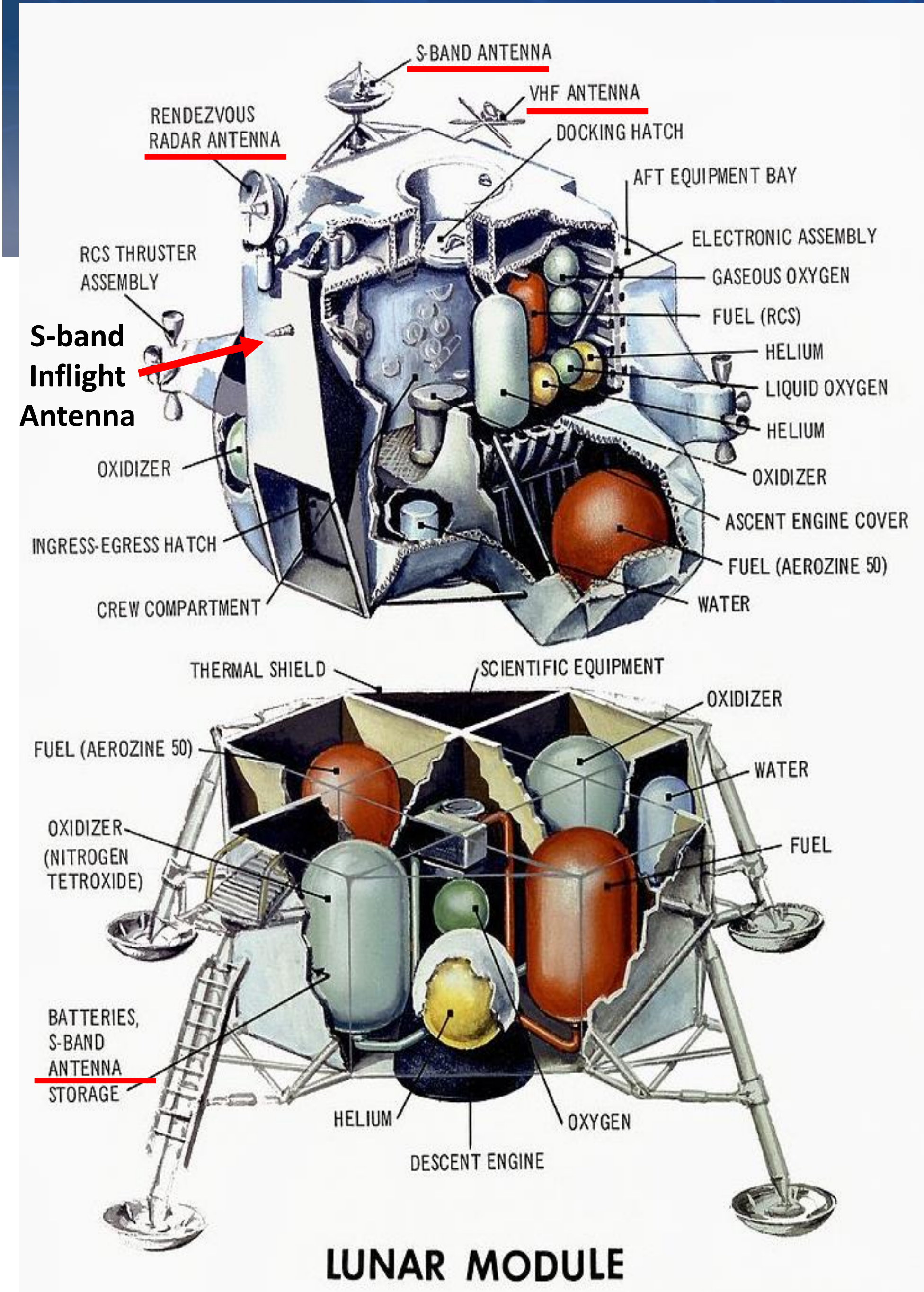
CSM S-band Antenna Array



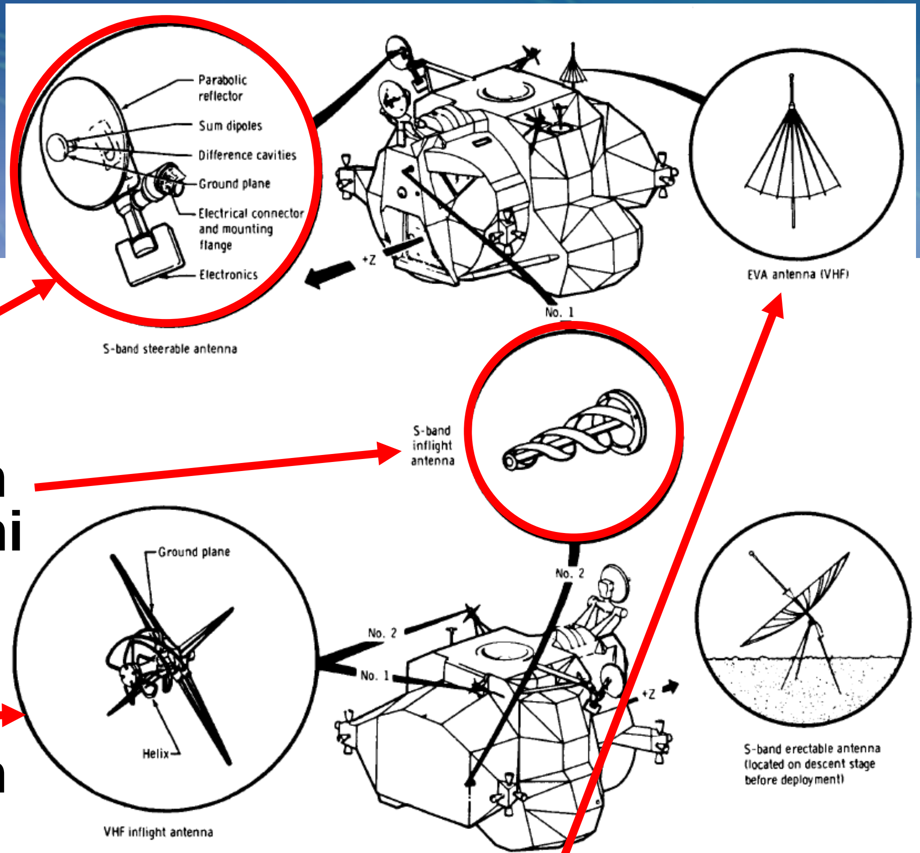
VHF Antenna

CSM USB Transponder

Apollo LM Comms



- **USB system and steerable dish antenna for long range communication with MSFN (helix omni antenna backup)**
- **VHF with two antennas for short range communication with orbiting Command Module**



- **EVA antenna resembling a miniature parasol to relay comm from astronauts' Portable Life Support Systems through the Lunar Module**

Navigation using USB: Range & Range Rate Measurements

Range:

- USB provided distance measurements accurate to within 30 meters.
- The tracking station generated a pseudo-random-noise (PN) sequence at 994 kbps and phase modulated it on uplink carrier; transponder echoed PN signal back to Earth on downlink
- PN sequence repeated after about 5 seconds, enough to measure distance out to 540,000 miles

Range Rate:

- Uplink/downlink frequency pairs were allocated in a fixed ratio of 221/240 permitting the use of coherent transponders on the spacecraft
- A precise "two way" Doppler shift was measured using coherent transponders to within a few centimeters per second
- Uplink signals were derived from extremely precise time and frequency standards, and received downlinks were analyzed in phase and frequency based on these same standards

Conclusion

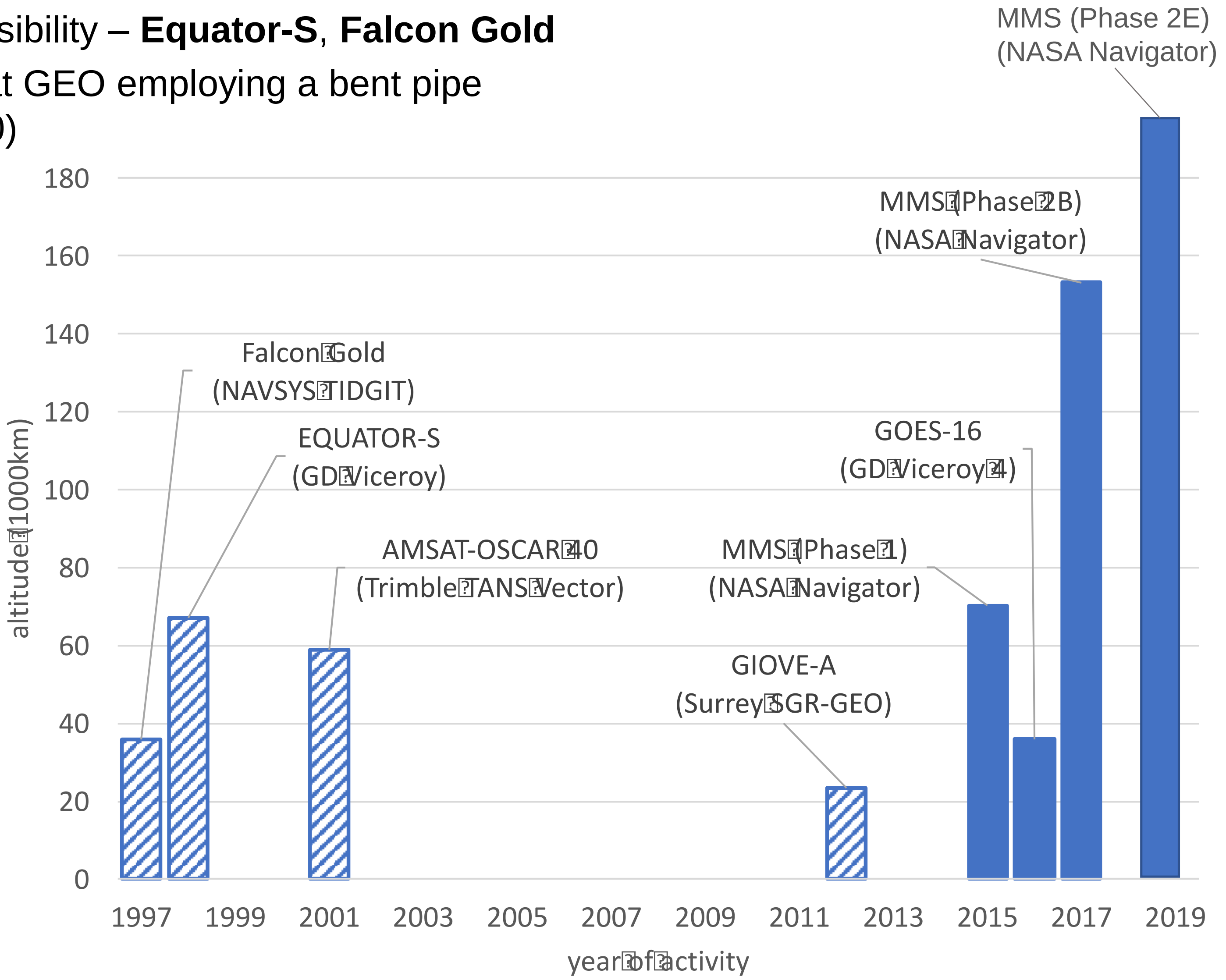
- **Unified S-Band represented a significant technological advance in communications and became the primary communications system on the first human landing on the Moon in July, 1969**
- **System proceeded rapidly from idea (1961) to demo (1962) to operational flight test on Gemini III (1965) to operational system for Apollo (1968)**
- **Tremendous amount of infrastructure on Earth was required to enable the success of Apollo including 18 ground stations, 5 ships, 8 aircraft, and 2 million miles of telecommunication lines across 5 continents**
- **USB used on all elements of the flight systems: Saturn V, Apollo CSM, Apollo LM, Lunar Rover, Surface experiments, and small lunar satellites**
- **These capabilities helped drive major advances in commercial communications & computers that created rapid growth in the US economy from the 1960s through the 1970s**
- **Apollo communication and navigation technological advances have become instrumental elements of our current-day GPS and GNSS systems**

The Development of High-Altitude GNSS

Transition from experimentation to operational use:

- **1990s**: Early flight experiments demonstrated basic feasibility – **Equator-S**, **Falcon Gold**
- **2000**: Reliable GPS orbit determination demonstrated at GEO employing a bent pipe architecture and ground-based receiver (Kronman 2000)
- **2001**: **AMSAT OSCAR-40** mapped GPS main and Side lobe signals (Davis et al. 2001)
- **2015**: **MMS** employed GPS operationally at 76,000 km, then 153,000 km, now 186,500 km
- **2016–2017**: **GOES-16/17** employed GPS operationally at GEO

	Altitude [km]	Altitude [R_E]
GPS	20,200	3
GEO	36,000	5.6
MMS 1	76,000	12
MMS 2	153,000	24
MMS 3	186,500	29.3
Moon	378,000	60



ICG Working Group Structure

- The ICG brings together all GNSS providers and other voluntary participants to:
  - Promote the use of GNSS and its integration into infrastructures, particularly in developing countries
  - Encourage compatibility and interoperability among global and regional systems
- Key technical activities in the following Working Groups (WG):

WG-S: Systems, Signals and Services

Major topics:
- Spectrum compatibility
- Interference detection & mitigation
- Service interoperability
- Performance standards & monitoring

WG-B: Enhancement of GNSS Performance, New Services and Capabilities

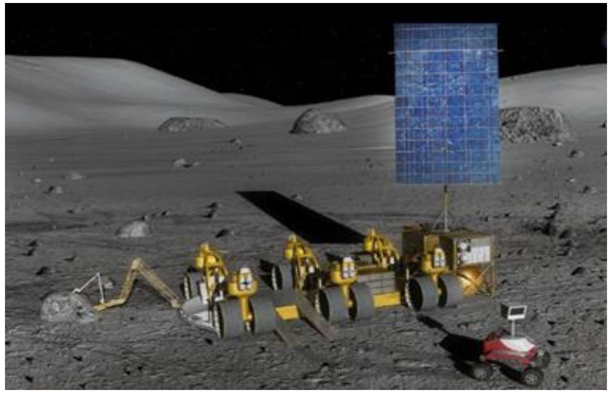
Major topics:
- Development of interoperable multi-GNSS SSV
- GNSS-hosted search-and-rescue payloads
- Space weather and ionosphere modeling

WG-D: Reference Frames, Timing and Applications

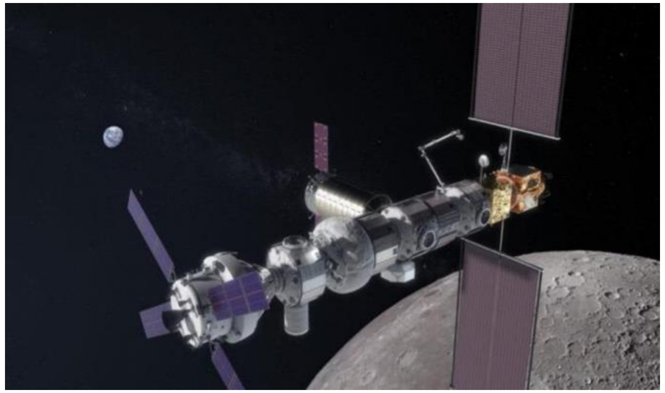
Major topics:
- ITRF, geodetic reference frame interoperability
- Time standards & multi-constellation offsets
- Constellation orbit modeling & technical data

* Fewer technical activities in WG-C: Information Dissemination and Capacity Building

Lunar Exploration Mission Classes Benefited by GNSS Navigation & Timing

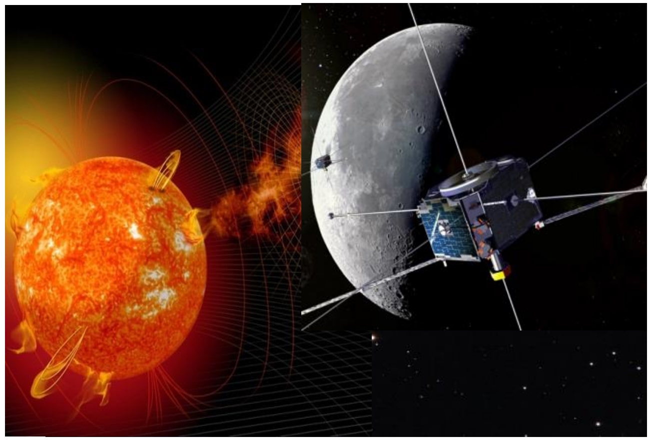


Lunar Surface Operations,
Robotic Prospecting,
& Human Exploration

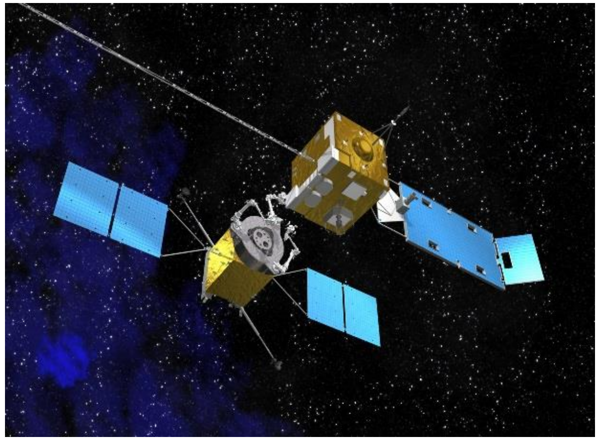


Human-tended Lunar Vicinity Vehicles
(Lunar Orbital Platform-Gateway)

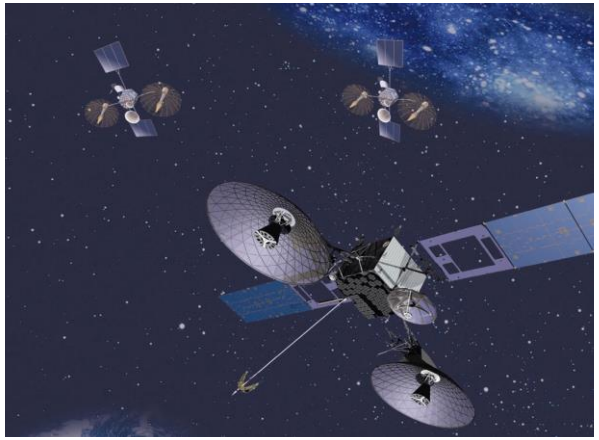
Robotic Lunar Orbiters,
Resource & Science Sentinels



Earth, Astrophysics, & Solar
Science Observations



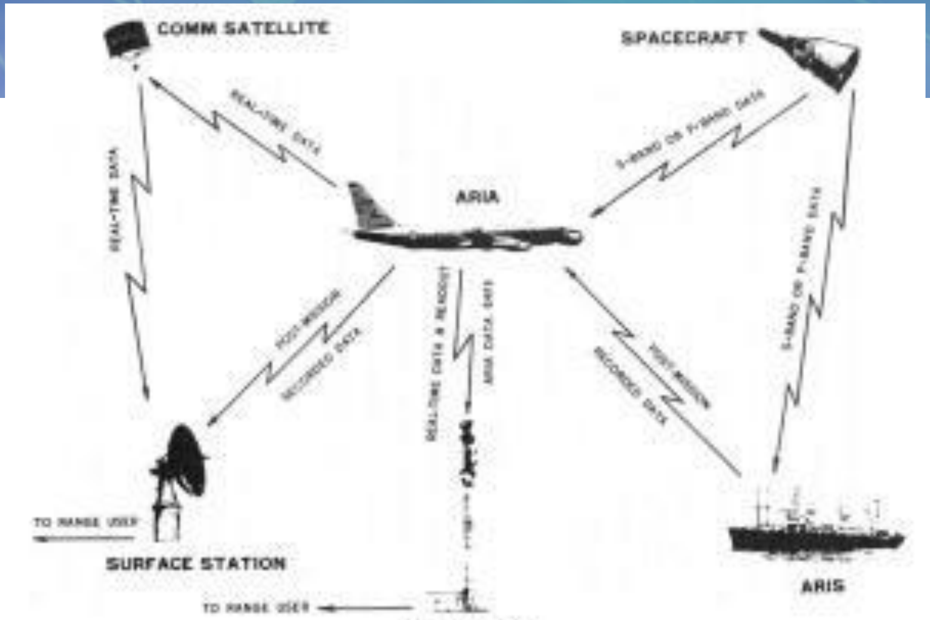
Satellite Servicing



Lunar Exploration Infrastructure

Apollo Range Instrumentation Aircraft (ARIA)

- **Spacecraft global tracking difficult over the Atlantic & Pacific oceans**
- **Developed high speed aircraft (modified C-135) containing instrumentation to assure spacecraft acquisition, tracking, telemetry data recording**
- **Supported Apollo Trans Lunar Injection (TLI) and recovery ops**
- **Operational in January 1968 10’ radome housing a 7’ S-band & P-band dish, the world's largest airborne steerable antenna**



Apollo Range Instrumentation Ship (ARIS)

- Apollo Trans-Lunar Injection may take place over the Atlantic, Indian, or Pacific Oceans, so the Apollo network data coverage is supplemented by three instrumentation ships.
- Two reentry ships pre-positioned in either Northern or Southern Hemisphere landing zones determined 30 days before launch
- Five ARIS ships built
- Performance:
  - 30 days on-station time
  - Stabilization to 0.5°