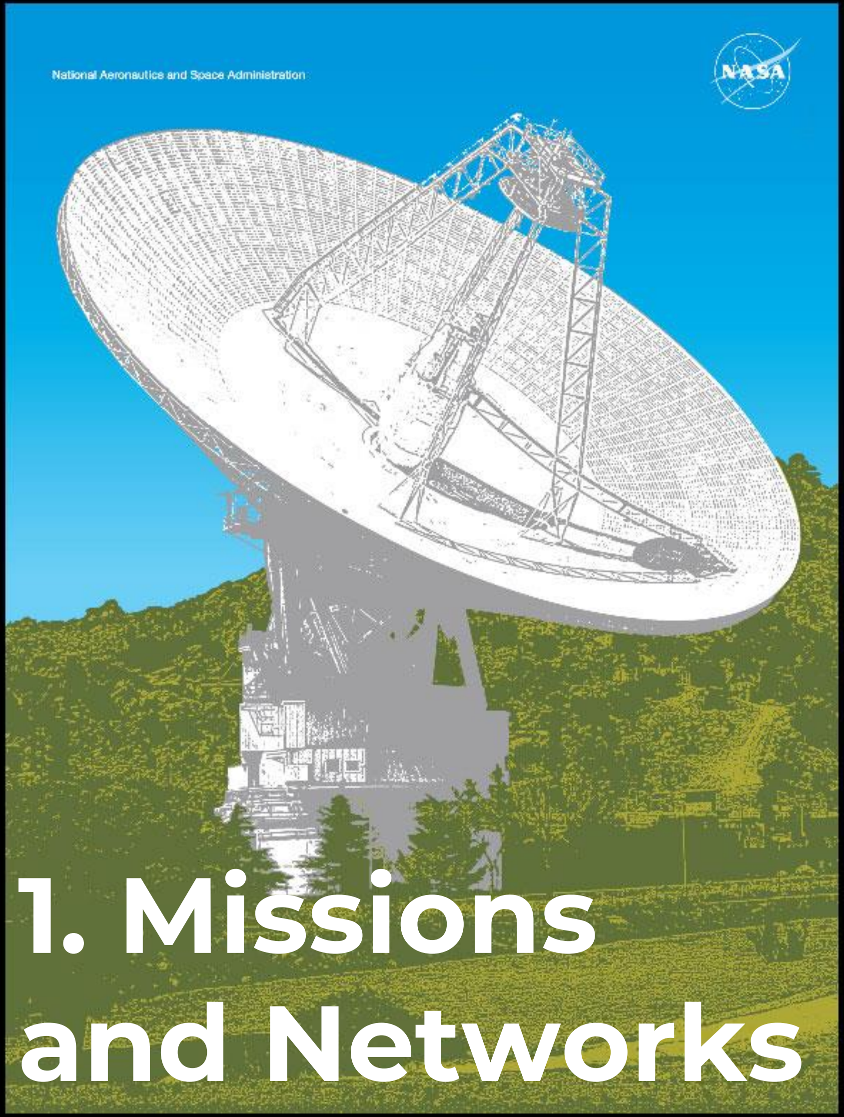
National Aeronautics and Space Administration

SCaN Space Communications and Navigation

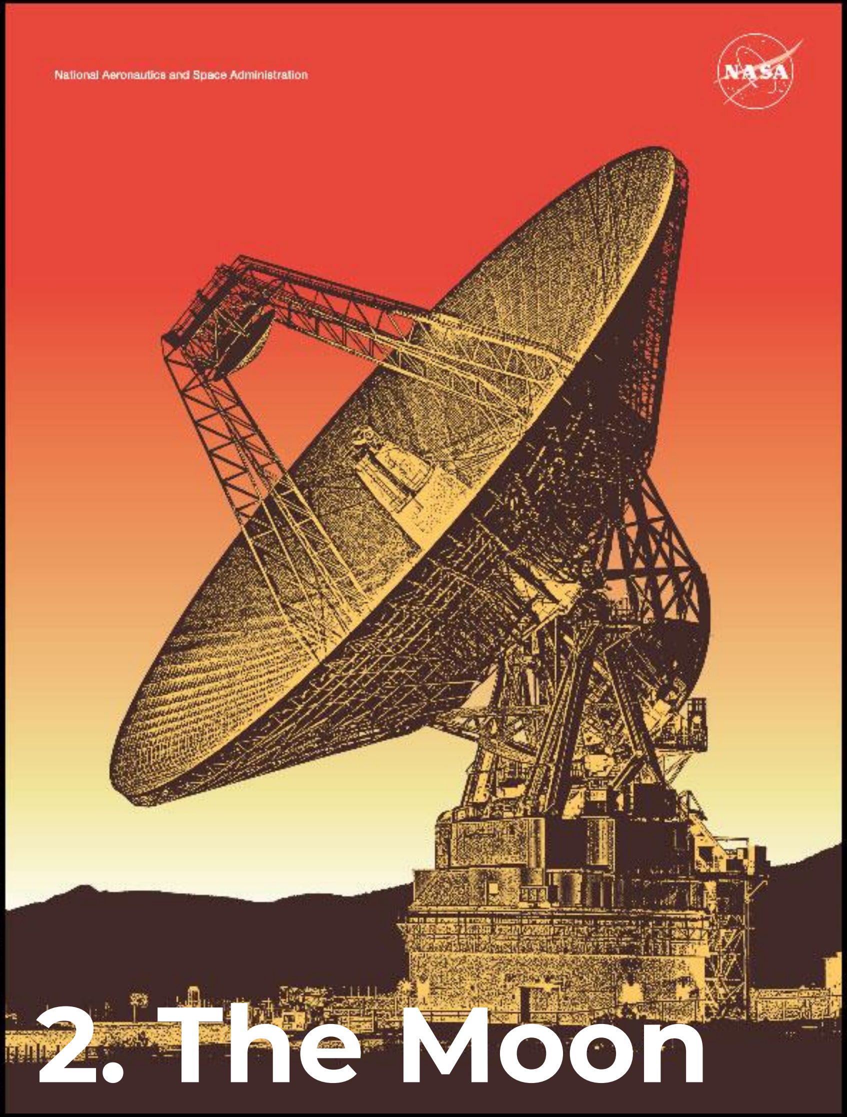
Science and Exploration, Enabled. Together.

Dr. Ben Ashman
Technology Manager
Space Operations Mission Directorate
National Aeronautics and Space Administration

4/30/2024



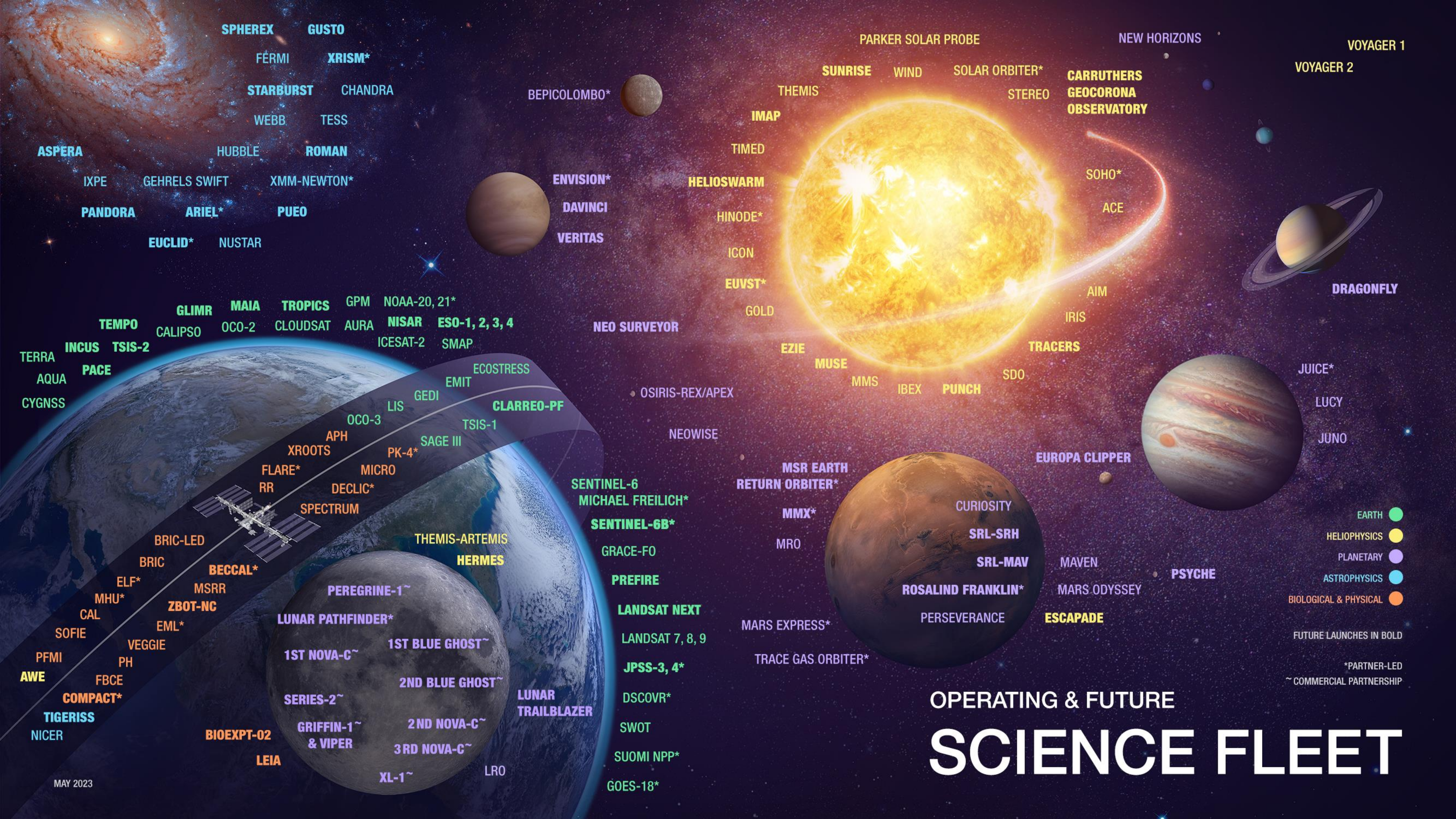
1. Missions and Networks



2. The Moon

3. The Future

1. Missions and Networks



OPERATING & FUTURE

SCIENCE FLEET

SPHEREX **GUSTO**
FERMI **XRISM***
STARBURST CHANDRA
WEBB TESS
ASPERA HUBBLE **ROMAN**
IXPE GEHRELS SWIFT XMM-NEWTON*
PANDORA **ARIEL*** **PUEO**
EUCLID* NUSTAR

GLIMR **MAIA** **TROPICS** GPM NOAA-20, 21*
TEMPO CALIPSO OCO-2 CLOUDSAT AURA **NISAR** **ESO-1, 2, 3, 4**
INCUS **TSIS-2** ICESAT-2 SMAP
TERRA
AQUA **PACE**
CYGNSS

ECOSTRESS
EMIT
GEDI
LIS **CLARREO-PF**
OCO-3 TSIS-1
SAGE III

APH
XROOTS PK-4*
FLARE* MICRO
RR DECLIC*
SPECTRUM
BRIC-LED
BRIC
BECCAL*
ELF* MSRR
MHU* **ZBOT-NC**
CAL EML*
SOFIE VEGGIE
PFMI PH
AWE FBCE
COMPACT*
TIGERISS
NICER
BIOEXPT-02
LEIA

THEMIS-ARTEMIS
HERMES

PEREGRINE-1~
LUNAR PATHFINDER*
1ST BLUE GHOST~
1ST NOVA-C~
2ND BLUE GHOST~
SERIES-2~
GRIFFIN-1~ & VIPER
2ND NOVA-C~
3RD NOVA-C~
XL-1~
LRO
LUNAR TRAILBLAZER

SENTINEL-6 MICHAEL FREILICH*
SENTINEL-6B*
GRACE-FO
PREFIRE
LANDSAT NEXT
LANDSAT 7, 8, 9
JPSS-3, 4*
DSCOVR*
SWOT
SUOMI NPP*
GOES-18*

BEPICOLOMBO*
ENVISION*
DAVINCI
VERITAS
NEO SURVEYOR
OSIRIS-REX/APEX
NEOWISE

PARKER SOLAR PROBE
SUNRISE WIND SOLAR ORBITER*
THEMIS STEREO
IMAP
TIMED
HELIOSWARM
HINODE*
ICON
EUVST*
GOLD
EZIE
MUSE
MMS IBEX **PUNCH** SDO
TRACERS
IRIS
AIM
ACE
SOHO*
CARRUTHERS GEOCORONA OBSERVATORY

NEW HORIZONS
VOYAGER 1
VOYAGER 2
DRAGONFLY
JUICE*
LUCY
JUNO
EUROPA CLIPPER

MSR EARTH RETURN ORBITER*
MMX*
MRO
CURIOSITY
SRL-SRH
SRL-MAV
ROSALIND FRANKLIN*
PERSEVERANCE
MAVEN
MARS ODYSSEY
PSYCHE
ESCAPADE
MARS EXPRESS*
TRACE GAS ORBITER*

EARTH 🟢
HELIOPHYSICS 🟡
PLANETARY 🟣
ASTROPHYSICS 🔵
BIOLOGICAL & PHYSICAL 🟠

FUTURE LAUNCHES IN BOLD

*PARTNER-LED
~ COMMERCIAL PARTNERSHIP

MAY 2023

NASA Networks

- **SCaN operates two networks that support NASA and partner missions:**
  - Near Space Network (NSN) - 0 to 2 million km
  - Deep Space Network (DSN) - 2 million km+

- **Two service types**
  - Direct-to-Earth (DTE) services through a series of ground stations
  - Space Relay (SR) services through the Tracking Data Relay Satellite (TDRS) constellation

NSN Missions Supported

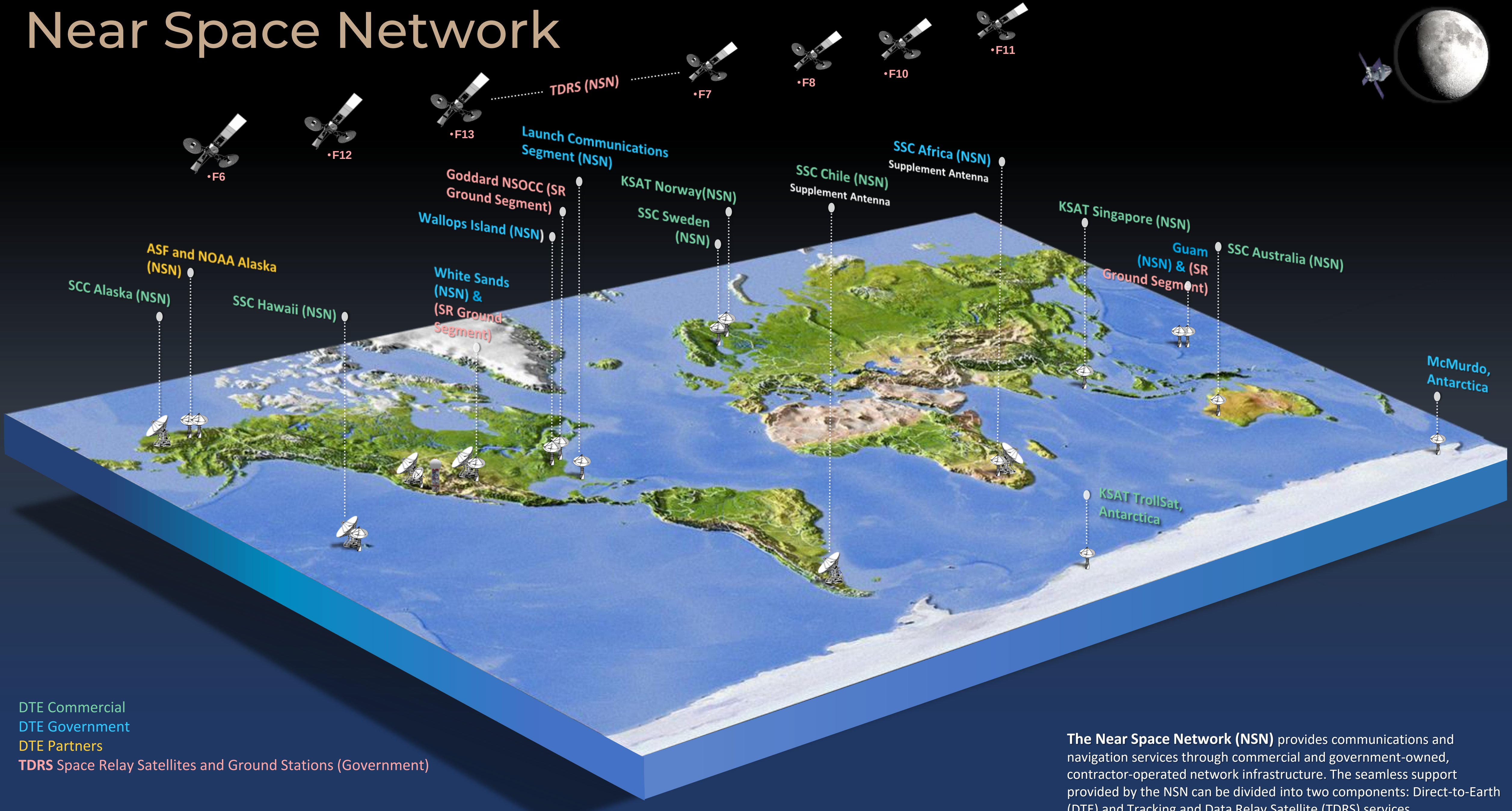
53 DTE Missions Supported

- 31 LEO Missions
- 10 GEO Missions
- 7 HEO Missions
- 3 Lunar Missions
- 2 SEL Missions

43 SR Missions Supported

- 14 Sub Orbital / Launch Missions
- 22 LEO Missions
- 7 HEO Missions (while below GEO)

Near Space Network



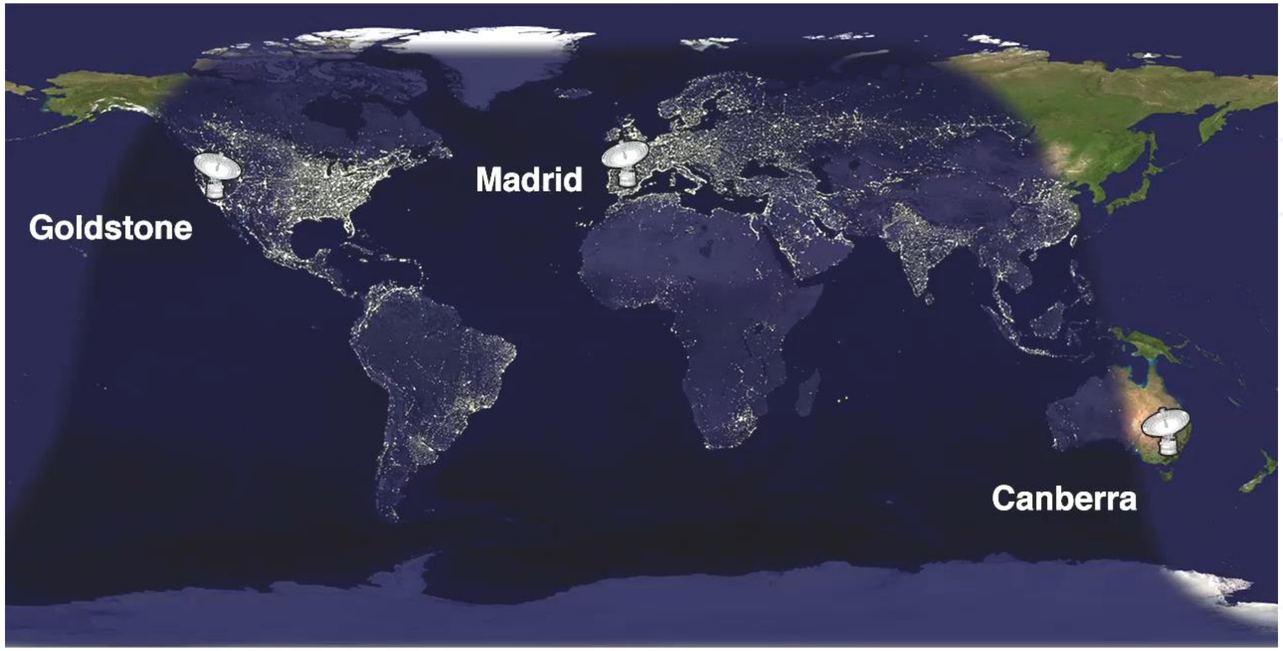
DTE Commercial
DTE Government
DTE Partners
TDRS Space Relay Satellites and Ground Stations (Government)

The Near Space Network (NSN) provides communications and navigation services through commercial and government-owned, contractor-operated network infrastructure. The seamless support provided by the NSN can be divided into two components: Direct-to-Earth (DTE) and Tracking and Data Relay Satellite (TDRS) services.

January 2023

Deep Space Network

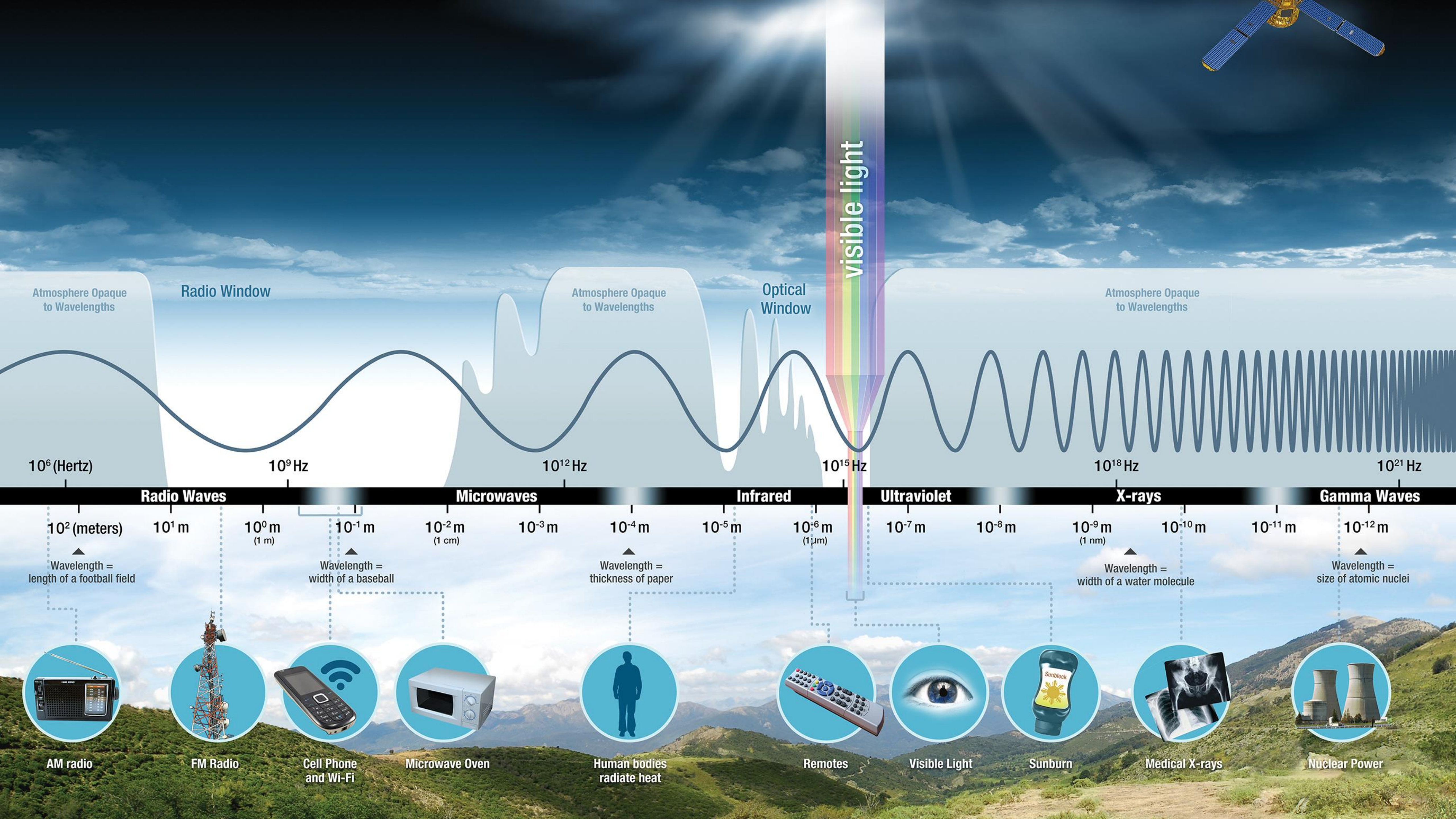
- NASA’s Deep Space Network (DSN) was established in December 1963 to provide a communications infrastructure for all of NASA’s robotic missions beyond Low Earth Orbit (LEO)
- DSN has three complexes, spread across the world to ensure 24/7 coverage
- The NASA Jet Propulsion Laboratory (JPL) develops, operates, and manages DSN



Goldstone Deep Space Communications Complex, California

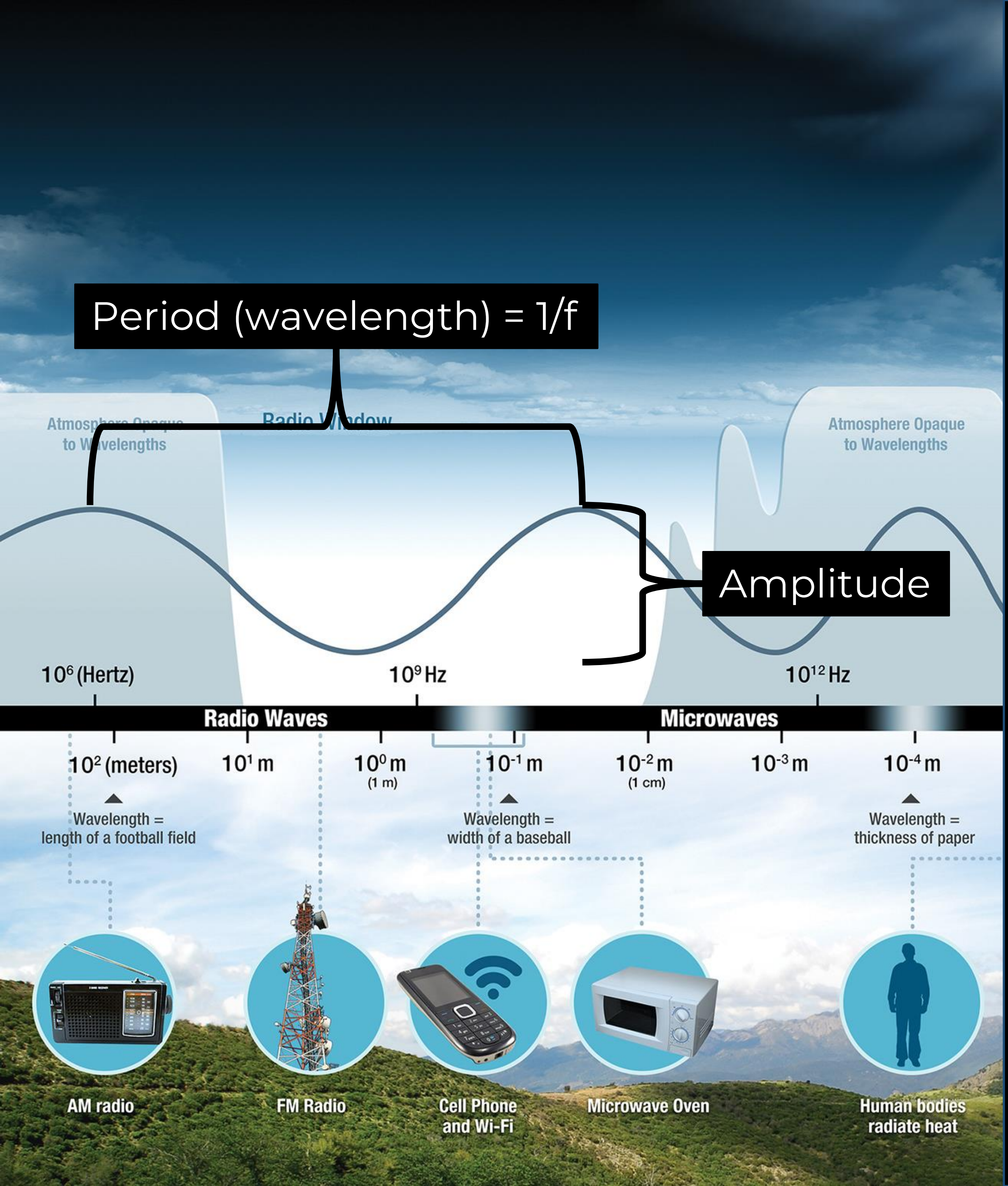
Madrid Deep Space Communications Complex, Spain

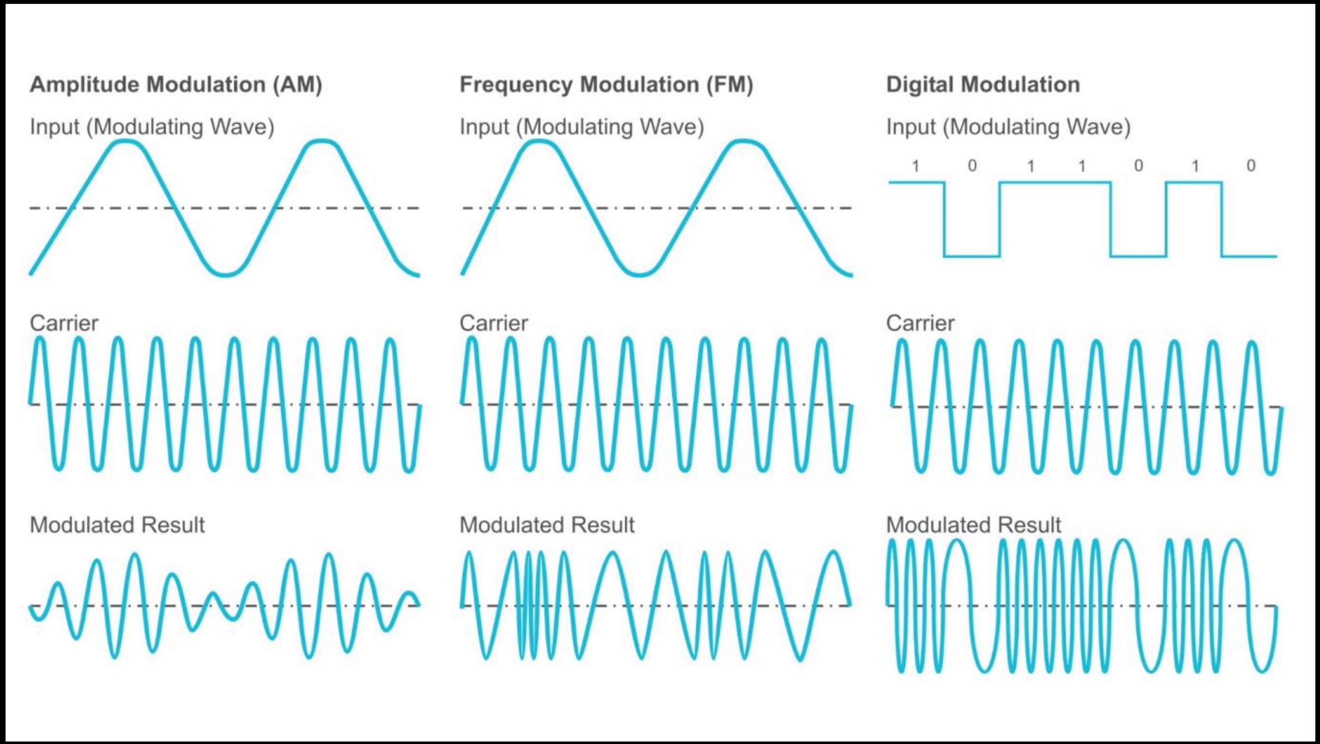
Canberra Deep Space Communications Complex, Australia

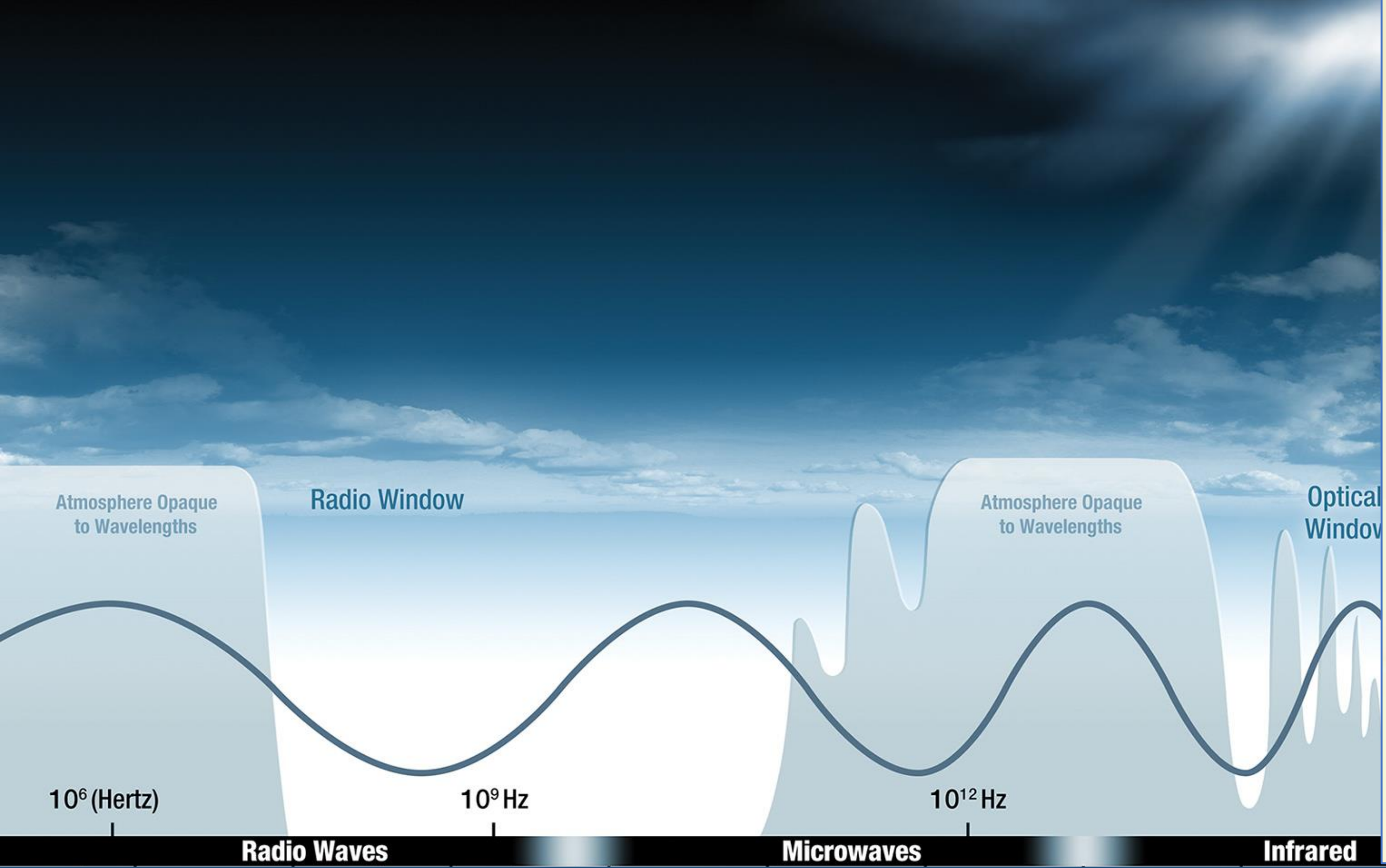

visible light
Atmosphere Opaque to Wavelengths
Radio Window
Atmosphere Opaque to Wavelengths
Optical Window
Atmosphere Opaque to Wavelengths
10⁶ (Hertz)
10⁹ Hz
10¹² Hz
10¹⁵ Hz
10¹⁸ Hz
10²¹ Hz
Radio Waves
Microwaves
Infrared
Ultraviolet
X-rays
Gamma Waves
10² (meters)
10¹ m
10⁰ m
(1 m)
10⁻¹ m
10⁻² m
(1 cm)
10⁻³ m
10⁻⁴ m
10⁻⁵ m
10⁻⁶ m
(1 µm)
10⁻⁷ m
10⁻⁸ m
10⁻⁹ m
(1 nm)
10⁻¹⁰ m
10⁻¹¹ m
10⁻¹² m
Wavelength = length of a football field
Wavelength = width of a baseball
Wavelength = thickness of paper
Wavelength = width of a water molecule
Wavelength = size of atomic nuclei
Sunblock
AM radio
FM Radio
Cell Phone and Wi-Fi
Microwave Oven
Human bodies radiate heat
Remotes
Visible Light
Sunburn
Medical X-rays
Nuclear Power

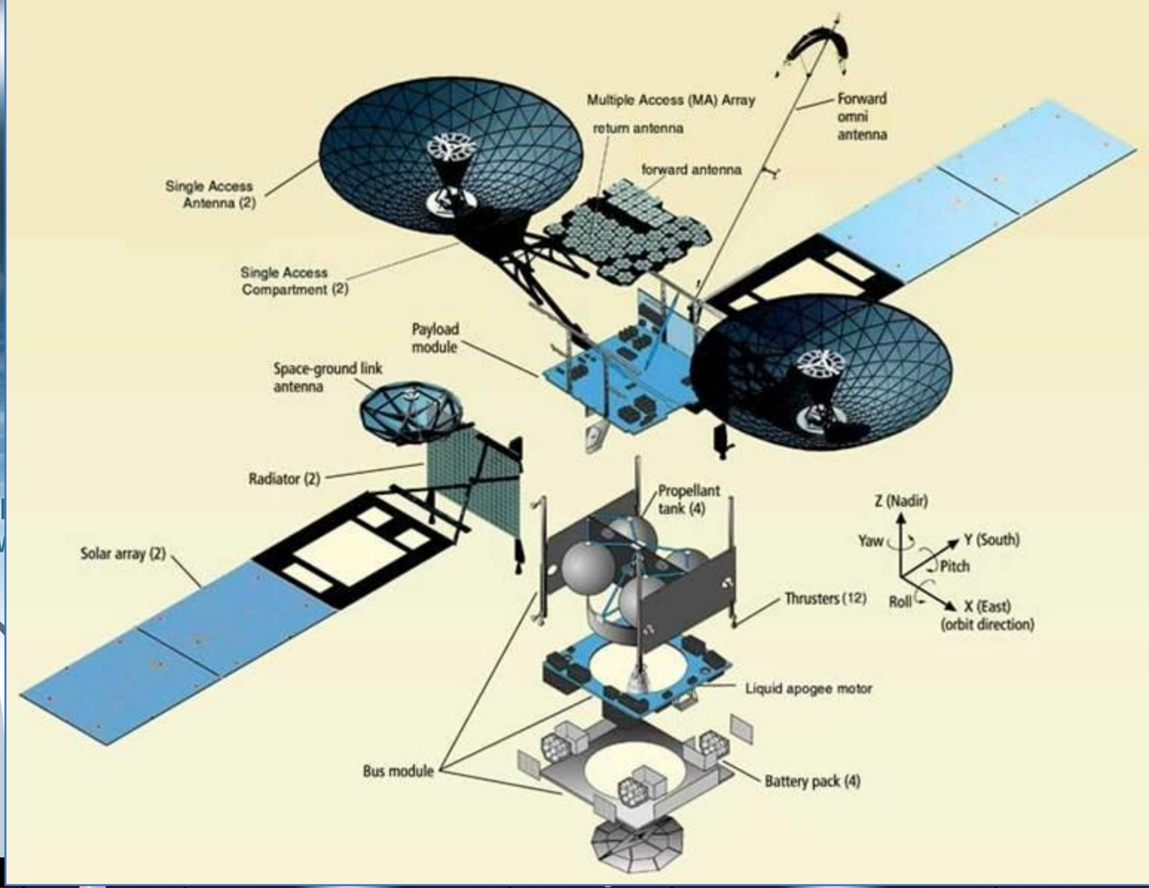
Electromagnetic Spectrum

- Energy travels through space in the form of a wave
- Message is encoded on a carrier (e.g., AM, FM)
- Propagation depends on frequency; only certain bands penetrate atmosphere
- Bands protected for satellite communications and navigation through international agreements

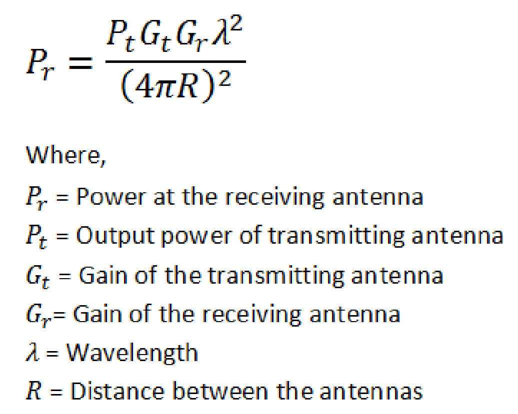








- Data rate depends on bandwidth, which is proportional to carrier frequency
- Communications link formed between spacecraft radio and ground radio
- Ground antenna must compensate for size, weight, and power limitations of onboard communications system



$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi R)^2}$$

Where,

P_r = Power at the receiving antenna

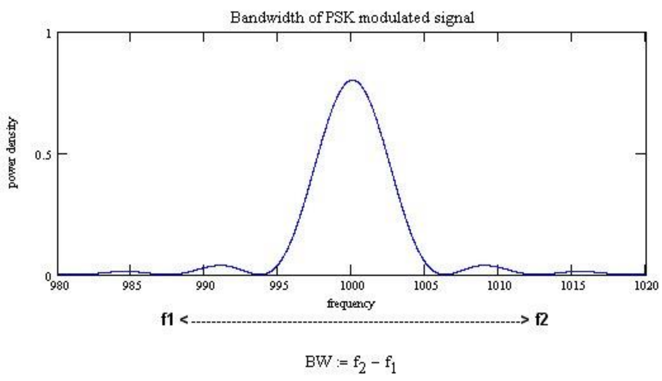
P_t = Output power of transmitting antenna

G_t = Gain of the transmitting antenna

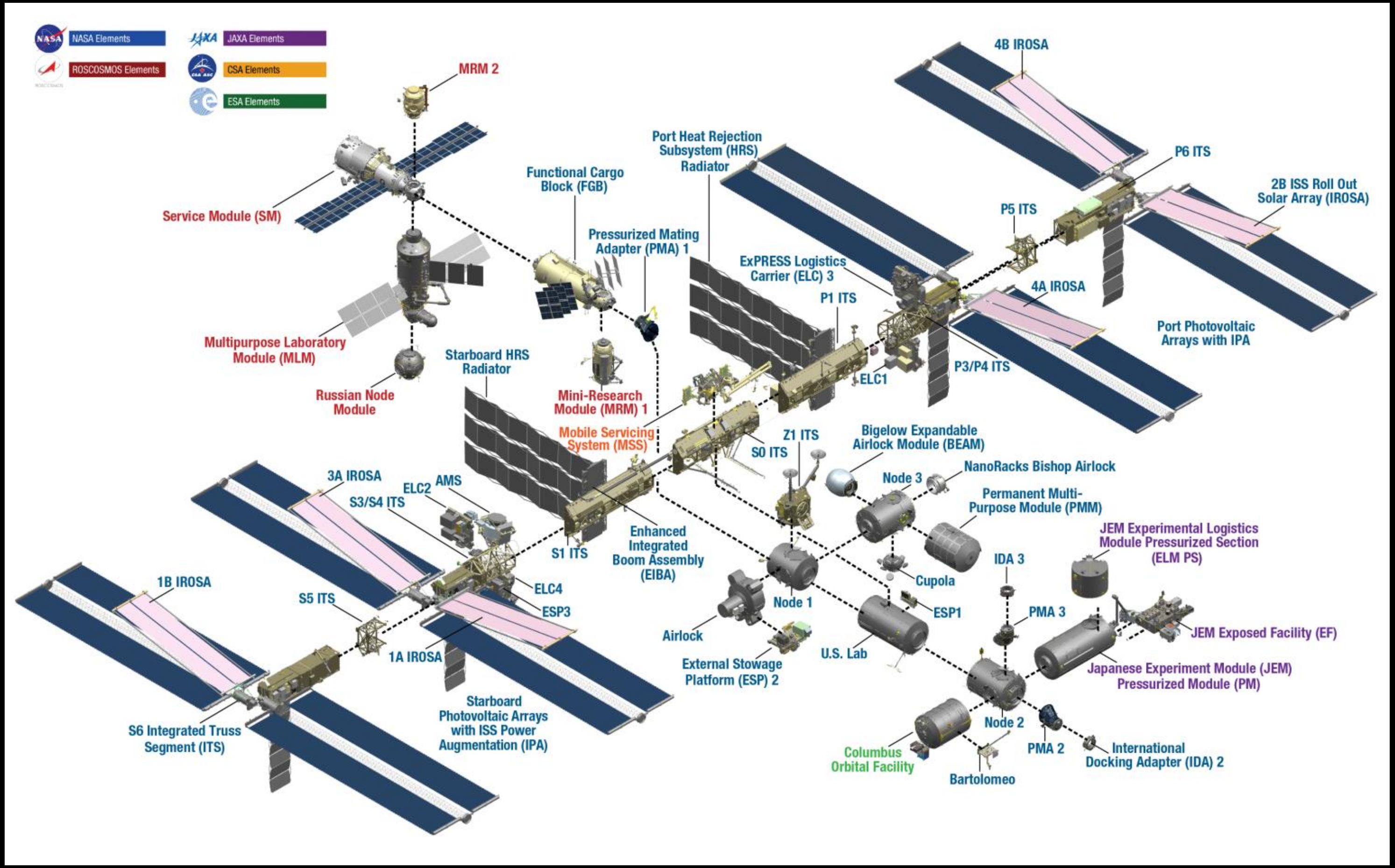
G_r= Gain of the receiving antenna

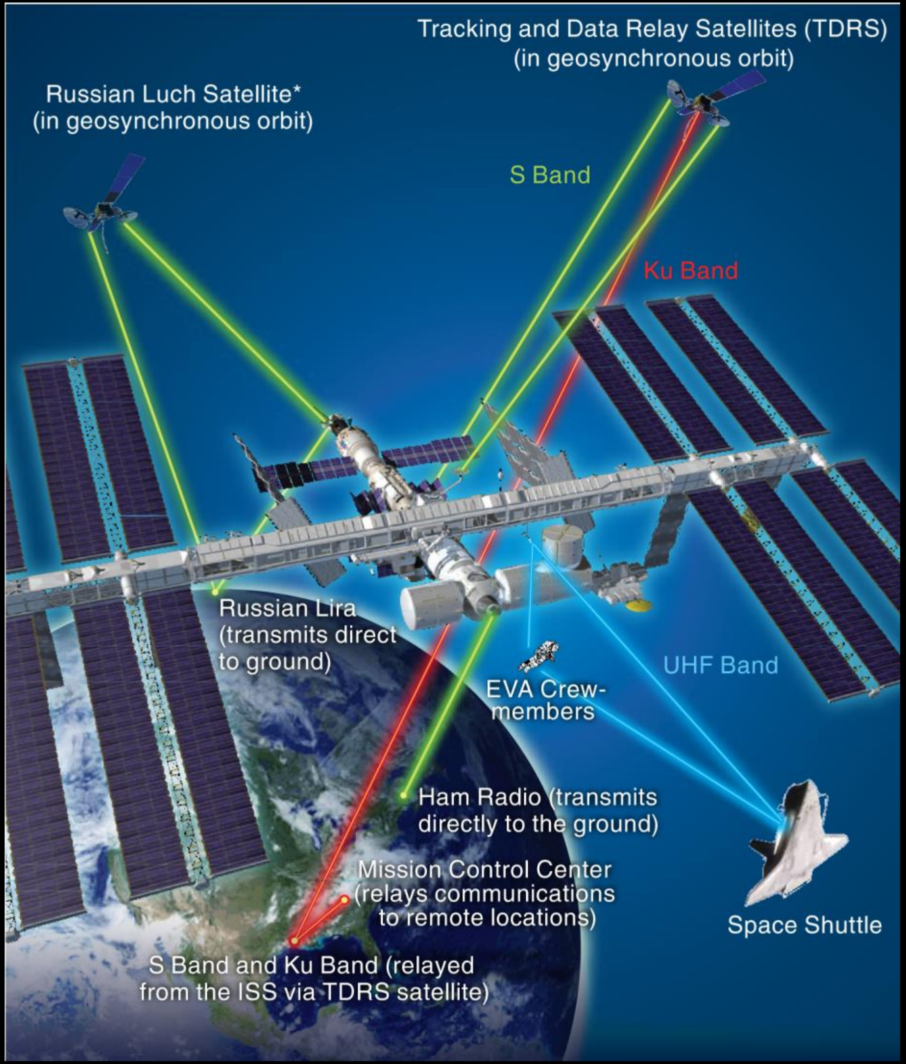
λ = Wavelength

R = Distance between the antennas



Example: International Space Station (ISS)





Introduction to Navigation

- Navigation is the process of determining position and direction
- Generalization of the problem: estimate unknown parameters based on observations

$$\mathbf{z} = \mathbf{h}(\theta) + \mathbf{v}$$

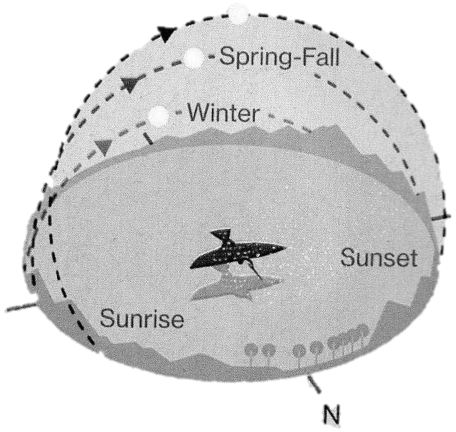
θ = parameter vector (e.g., Cartesian position and velocity, our “state”)

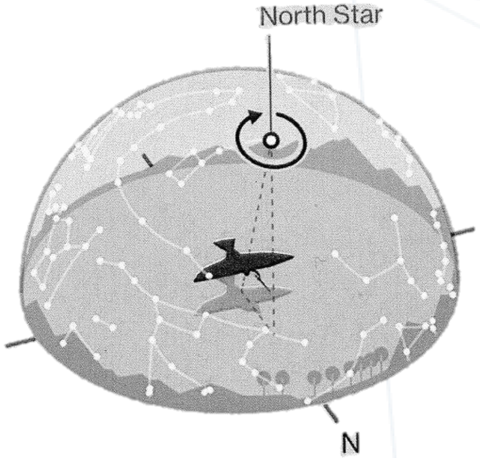
$\mathbf{z}$ = observation vector (i.e., set of measurements)

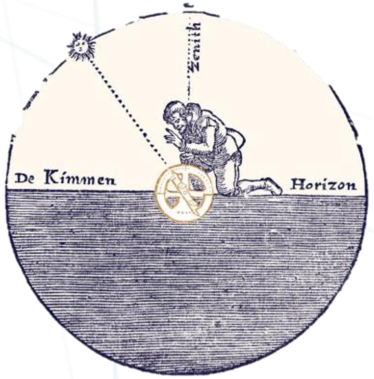
$\mathbf{v}$ = observation noise vector (i.e., measurement error)

$\mathbf{h}(\cdot)$ = relation between parameter set and observation set (i.e., measurement model)

- Given a parameter set, we seek an observation set, a relation between our parameters and observations, and an estimator $\hat{\theta}(\cdot)$, in order to form an estimate: $\hat{\theta} = \hat{\theta}(\mathbf{z})$







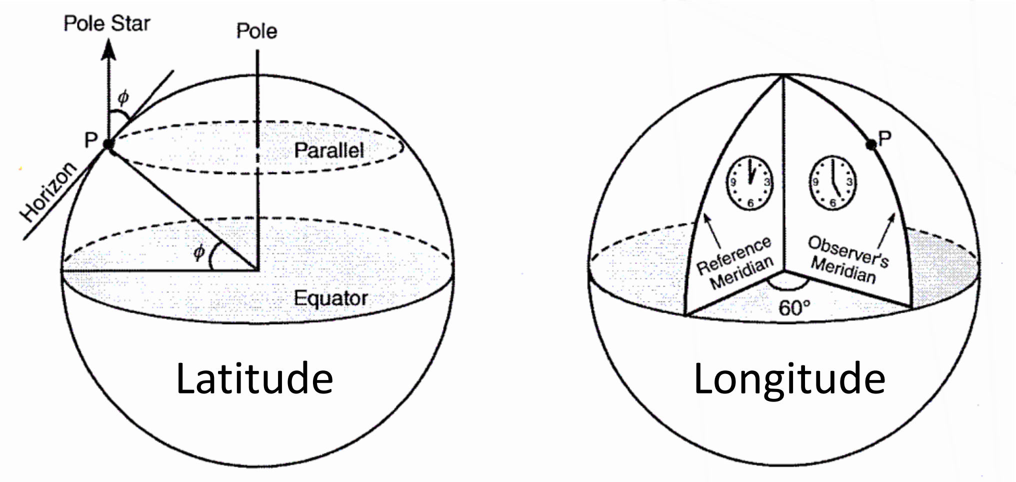
Introduction to Navigation (cont.)

Relative navigation

- Dead reckoning: monitor rate of travel and heading using a compass; prone to error, especially at sea
- Landmark bearings: angles to two known landmarks will constrain position in two dimensions

Absolute navigation: latitude and longitude (clocks vs. celestial)

- Latitude: Measure the elevation of pole star above the horizon with a sextant or astrolabe
- Longitude: Very good clock or celestial (sextant for the elevation of celestial bodies above the horizon, accurate clock to determine the time of observations, almanac to find the predicted position of the body, magnetic compass to determine azimuth and maintain course continuity between celestial observations)



Radionavigation

Measurements:

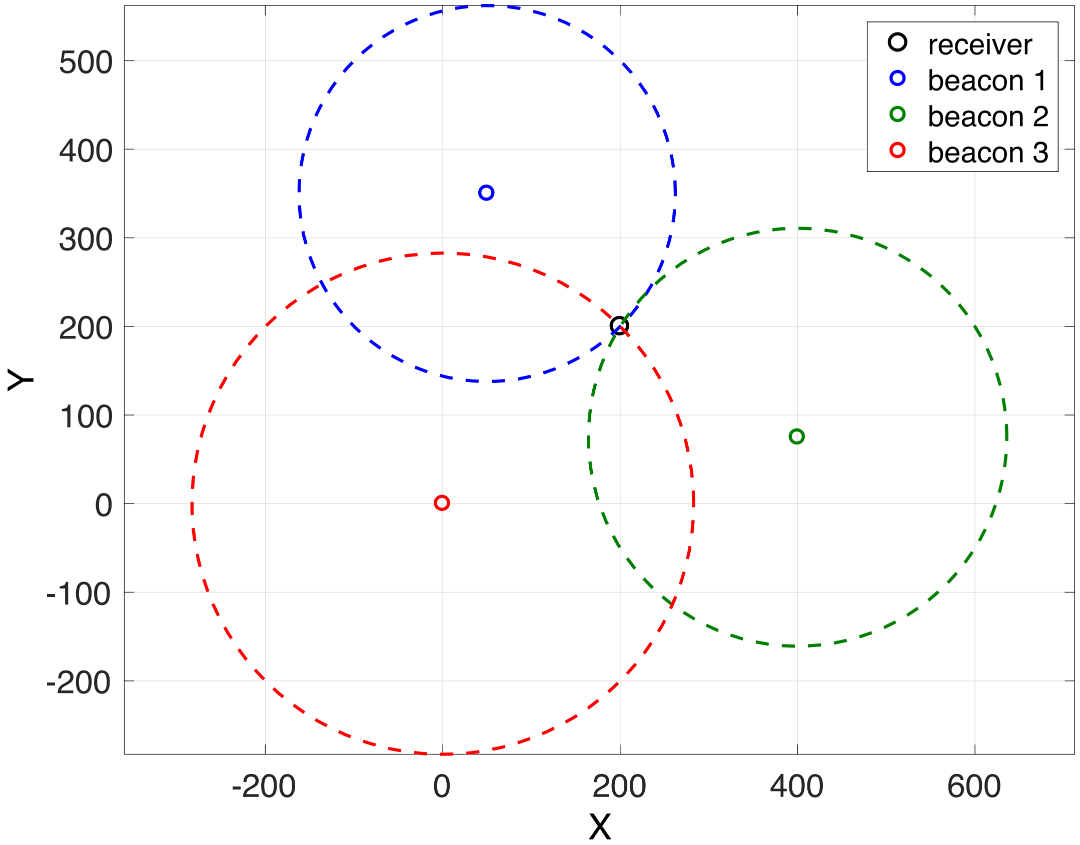
- distances from known transmitter locations via the measurement of radio frequency signal transit time

Solution to the estimation problem:

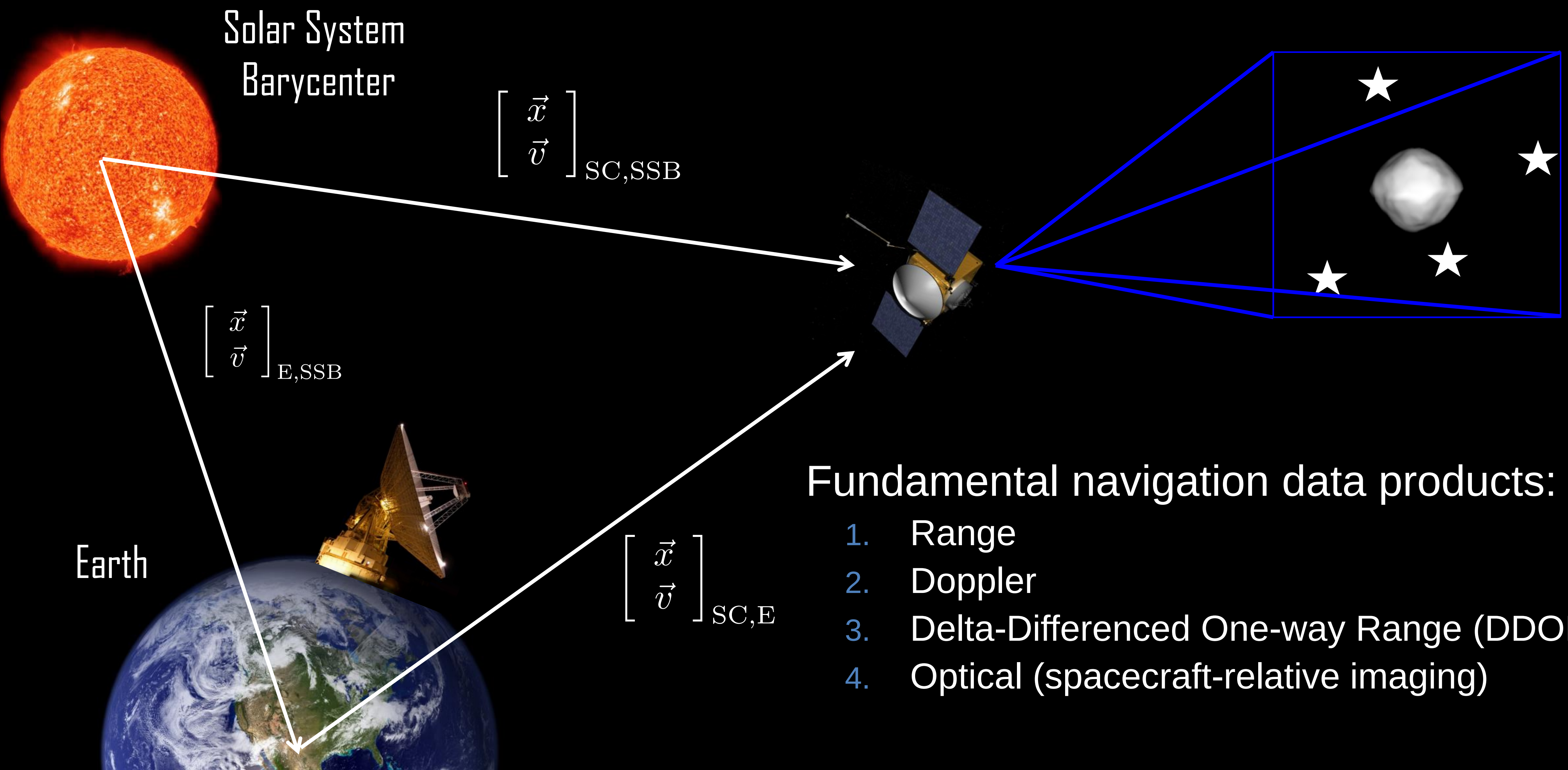
- trilateration, the determination of absolute or relative locations of points by measurement of distances using the geometry of circles, spheres, or triangles

Ground based:

- LORAN (1940s), Omega (1960s)



Navigation Example: OSIRIS-REx at Bennu



Solar System Barycenter

$$\begin{bmatrix} \vec{x} \\ \vec{v} \end{bmatrix}_{\mathrm{SC,SSB}}$$

$$\begin{bmatrix} \vec{x} \\ \vec{v} \end{bmatrix}_{\mathrm{E,SSB}}$$

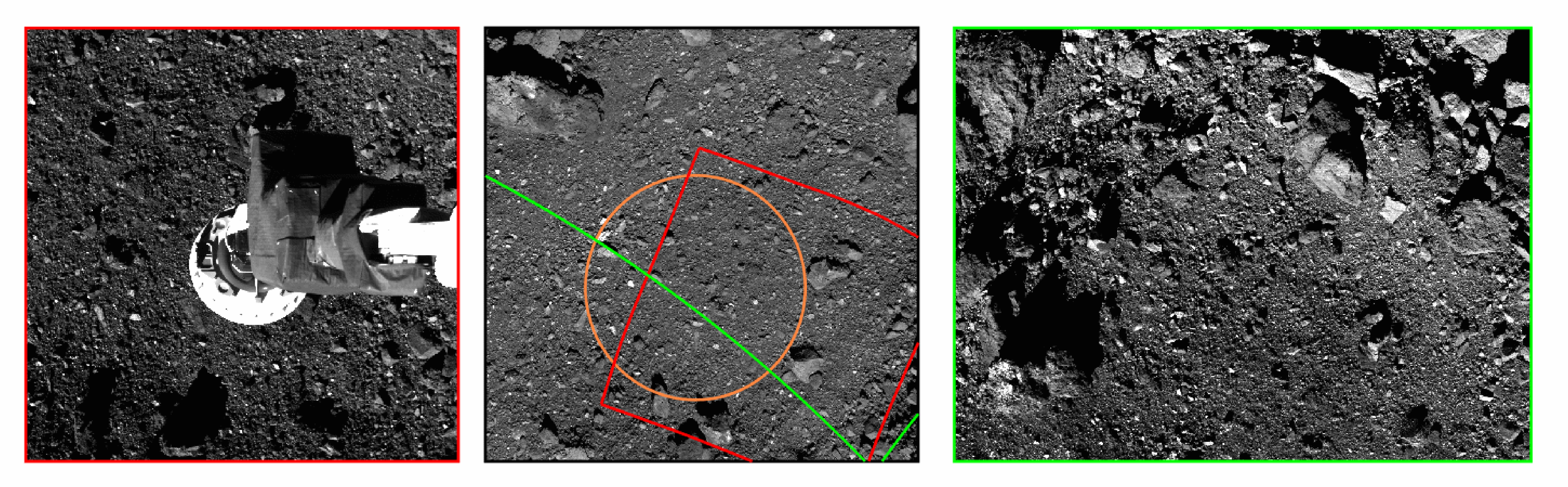
Earth

$$\begin{bmatrix} \vec{x} \\ \vec{v} \end{bmatrix}_{\mathrm{SC,E}}$$

Fundamental navigation data products:

1. Range
2. Doppler
3. Delta-Differenced One-way Range (DDOR)
4. Optical (spacecraft-relative imaging)

Navigation Example: OSIRIS-REx at Bennu



- Delivered the spacecraft to the surface **within 1 meter** of the desired TAG site
- Natural Feature Tracking (NFT): onboard landmark navigation technique processed imagery and autonomously adjusted TAG maneuvers in real time
- TAGSAM head plunged several centimeters into the surface

Radionavigation

Measurements:

- distances from known transmitter locations via the measurement of radio frequency signal transit time

Solution to the estimation problem:

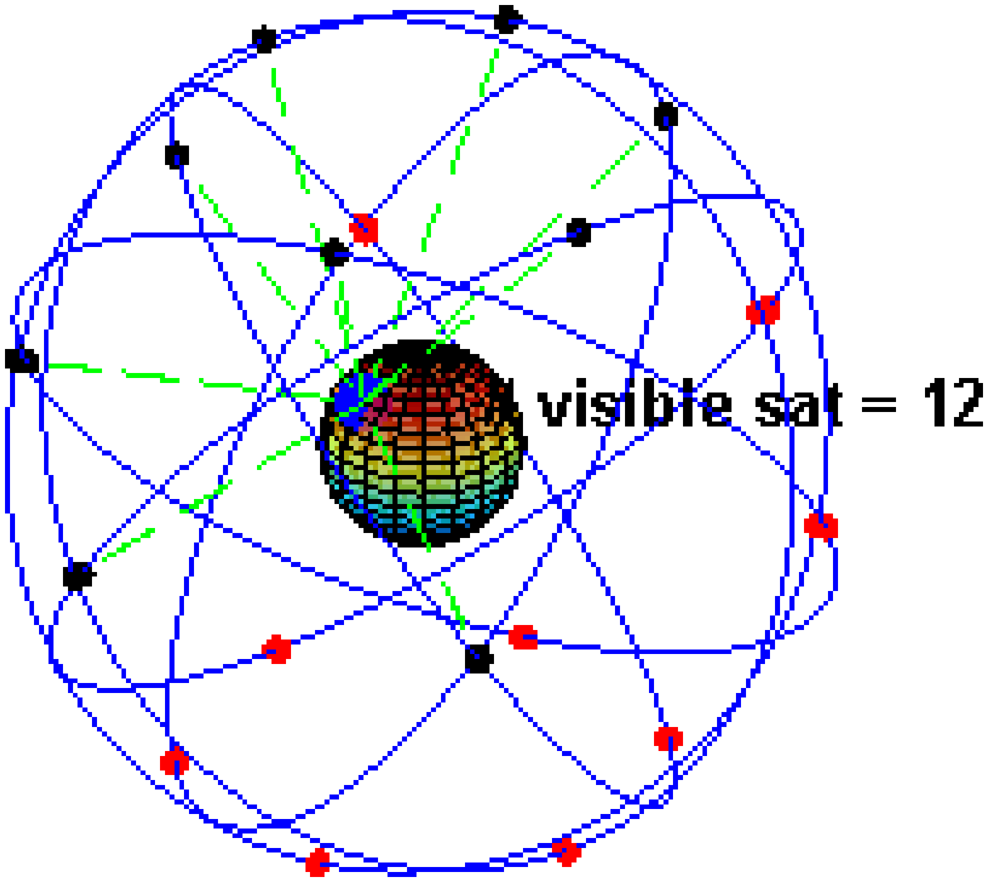
- trilateration, the determination of absolute or relative locations of points by measurement of distances using the geometry of circles, spheres, or triangles

Ground based:

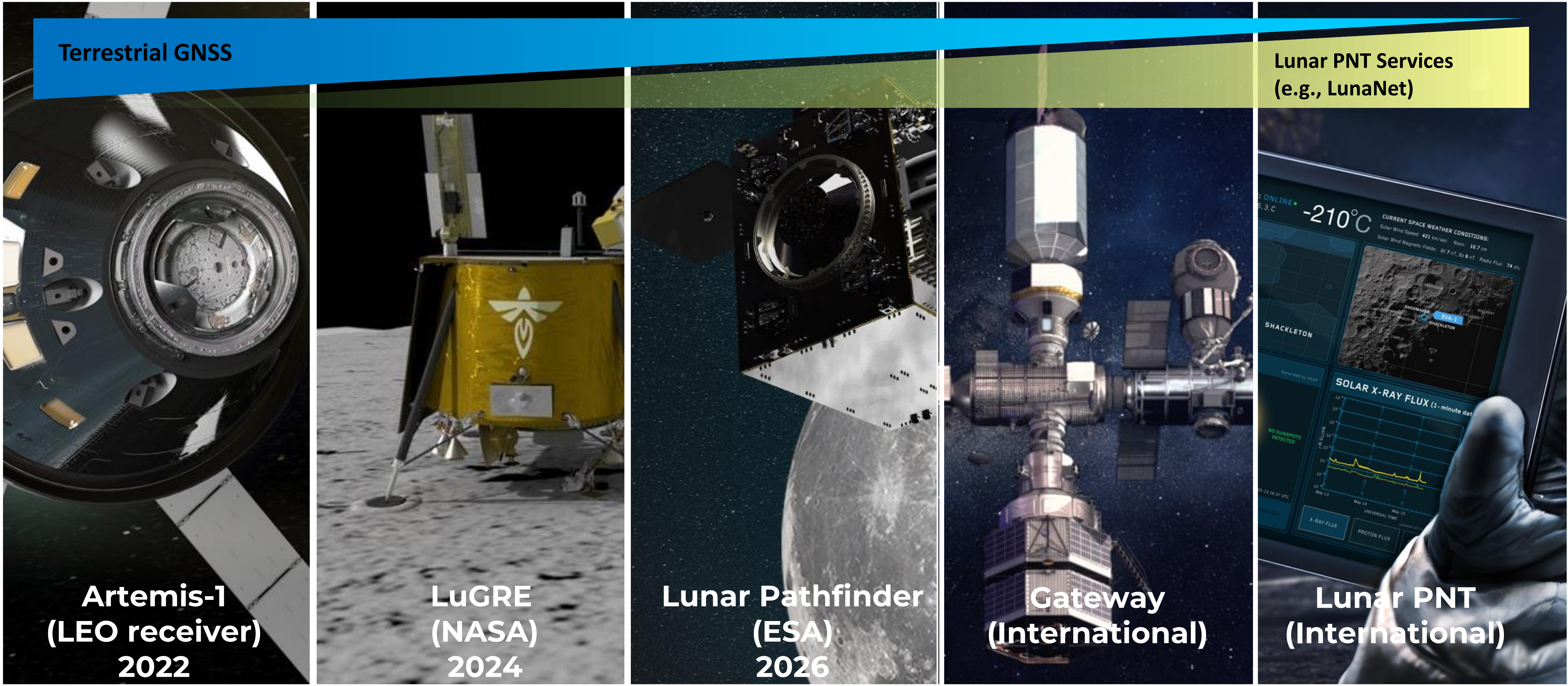
- LORAN (1940s), Omega (1960s)

Satellite-based:

- Sputnik I (1957), Parus and Tskikada, Transit, MOSAIC, and SECOR (1960s)
- Global Navigation Satellite Systems (GNSS): GPS (1995), GLONASS (2011), Galileo (TBD), BeiDou (2020)



Evolutionary Milestones in Lunar Navigation



Terrestrial GNSS

Lunar PNT Services
(e.g., LunaNet)

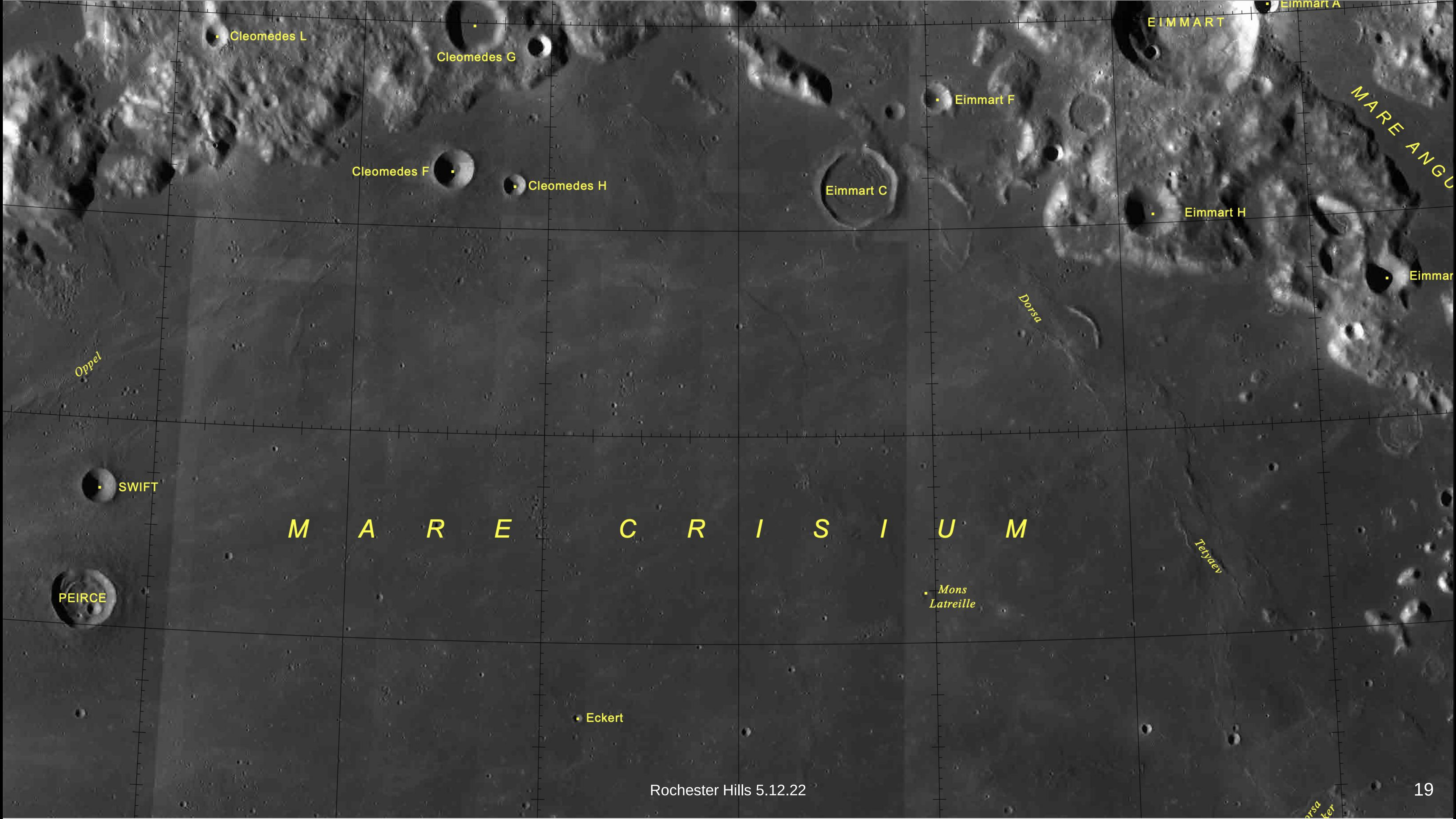
Artemis-1
(LEO receiver)
2022

LuGRE
(NASA)
2024

Lunar Pathfinder
(ESA)
2026

Gateway
(International)

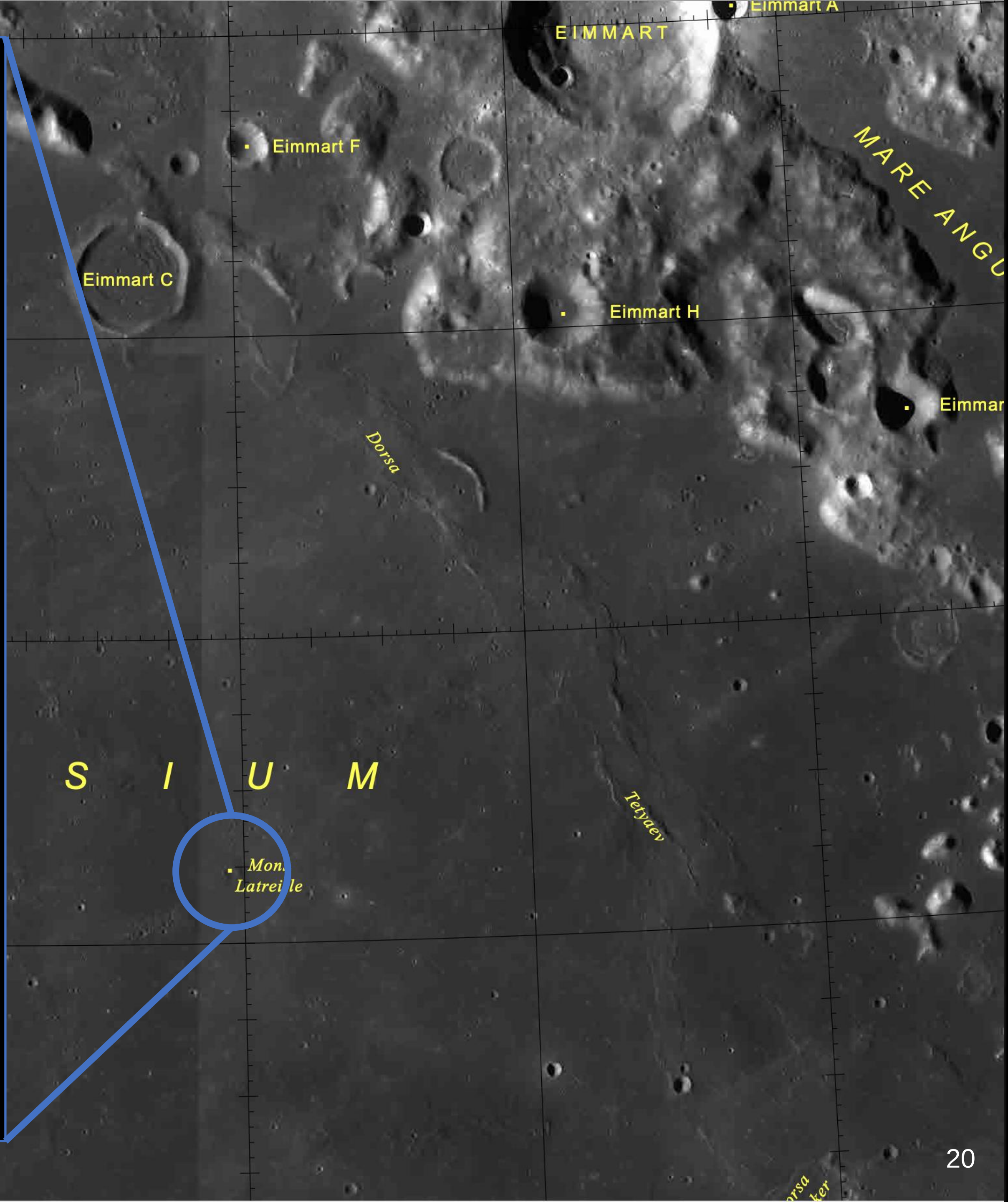
Lunar PNT
(International)


Cleomedes L
Cleomedes G
Eimmart A
EIMMART
MARE ANGU
Eimmart F
Cleomedes F
Cleomedes H
Eimmart C
Eimmart H
Eimmar
Dorsa
Oppel
SWIFT
MARE CRISIUM
Tetyaev
PEIRCE
Mons Latreille
Eckert
rsa
ker

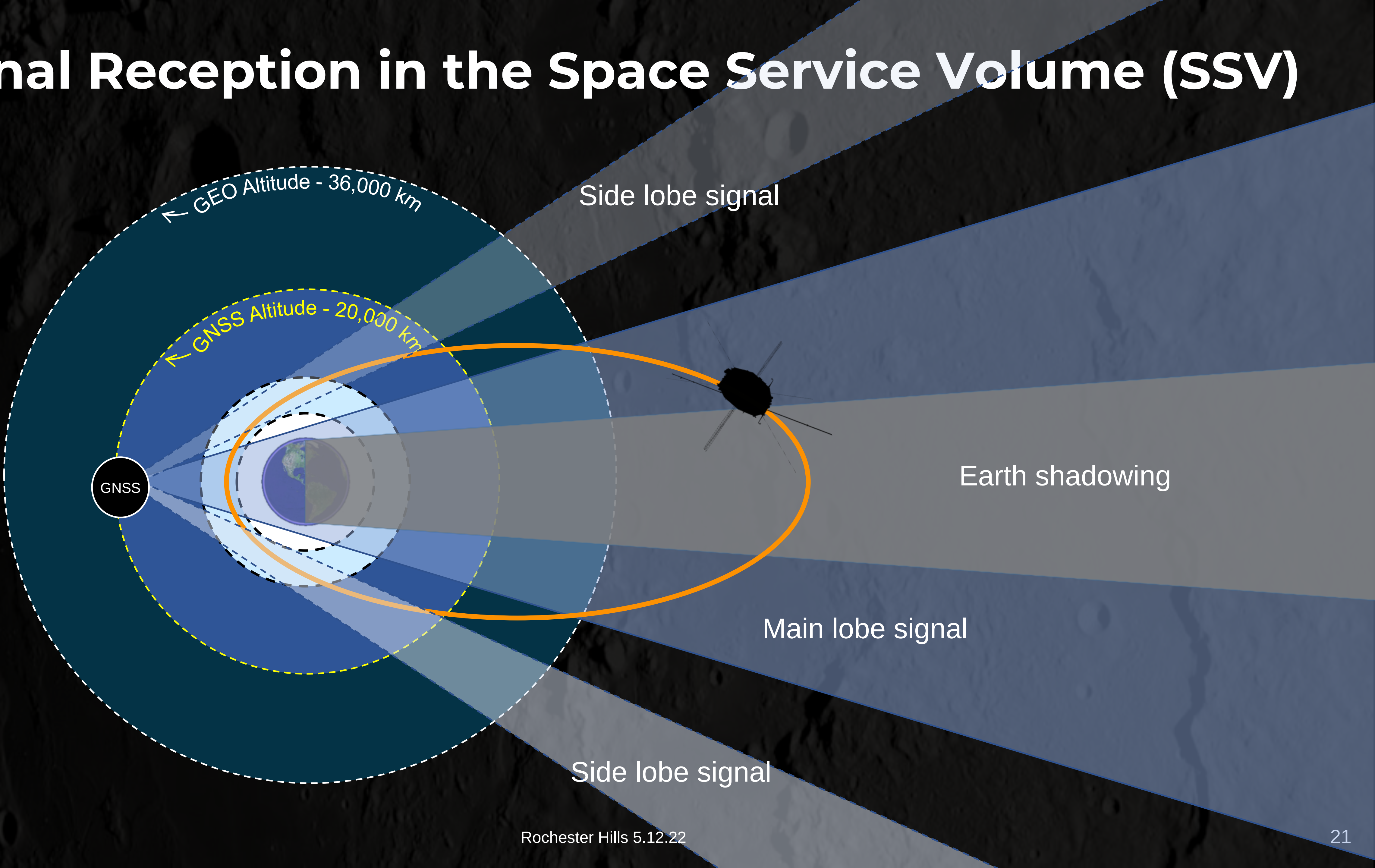
Blue Ghost 1

- Firefly Aerospace Systems awarded CLPS 19D flight in Feb. 2021
- Launching 2024 and landing in Mare Crisium near Mons Latreille
- 10 NASA payloads including the Lunar GNSS Receiver Experiment (LuGRE)
- Transit + surface observation campaign
- Surface ops one lunar day (~12 Earth days)

Entomologist Pierre André Latreille (1762-1833)



Signal Reception in the Space Service Volume (SSV)

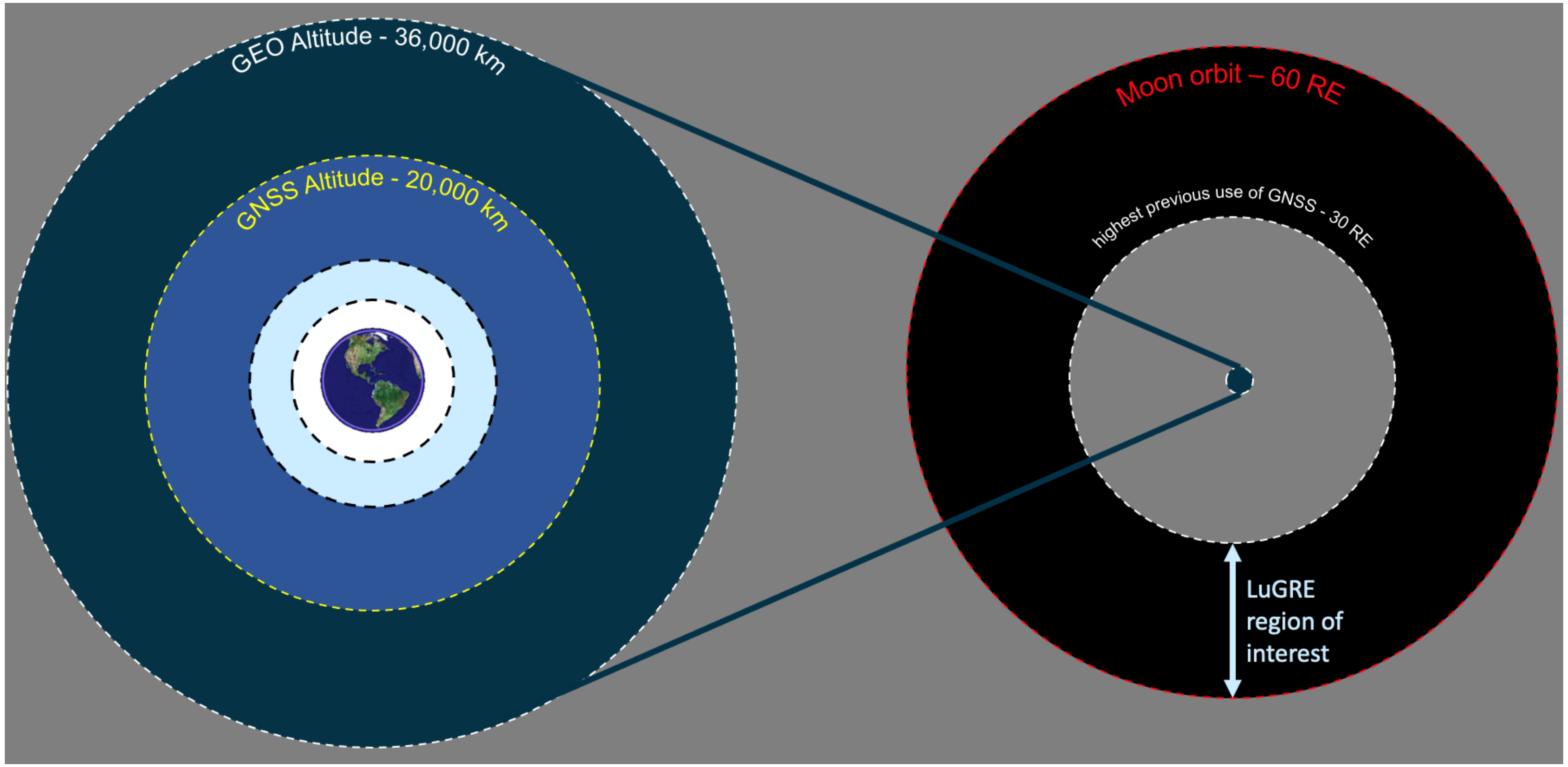


Lunar GNSS Receiver Experiment (LuGRE)

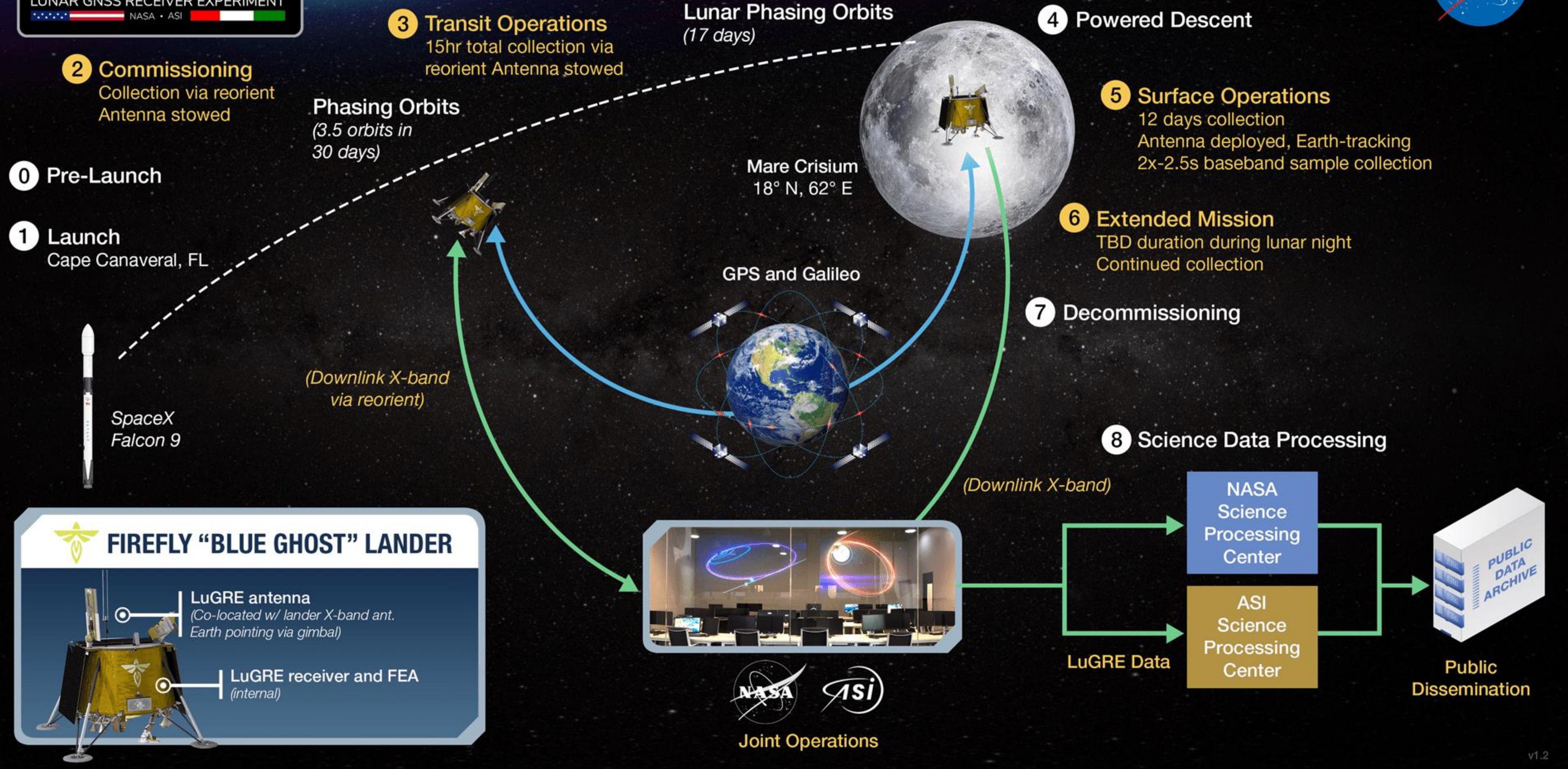
Goal: Extend GNSS-based navigation to the Moon

Objectives

1. Receive GNSS signals at the Moon. Return data and characterize the lunar GNSS signal environment.
2. Demonstrate navigation and time estimation using GNSS data collected at the Moon.
3. Utilize collected data to support development of GNSS receivers specific to lunar use.



LuGRE
LUNAR GNSS RECEIVER EXPERIMENT
NASA • ASI



⓪ **Pre-Launch**

① **Launch**
Cape Canaveral, FL

SpaceX Falcon 9

② **Commissioning**
Collection via reorient
Antenna stowed

Phasing Orbits
(3.5 orbits in 30 days)

③ **Transit Operations**
15hr total collection via
reorient Antenna stowed

Lunar Phasing Orbits
(17 days)

④ **Powered Descent**

⑤ **Surface Operations**
12 days collection
Antenna deployed, Earth-tracking
2x-2.5s baseband sample collection

⑥ **Extended Mission**
TBD duration during lunar night
Continued collection

⑦ **Decommissioning**

⑧ **Science Data Processing**

Mare Crisium
18° N, 62° E

GPS and Galileo

(Downlink X-band via reorient)

(Downlink X-band)

Joint Operations

LuGRE Data

NASA Science Processing Center

ASI Science Processing Center

Public Dissemination

FIREFLY "BLUE GHOST" LANDER

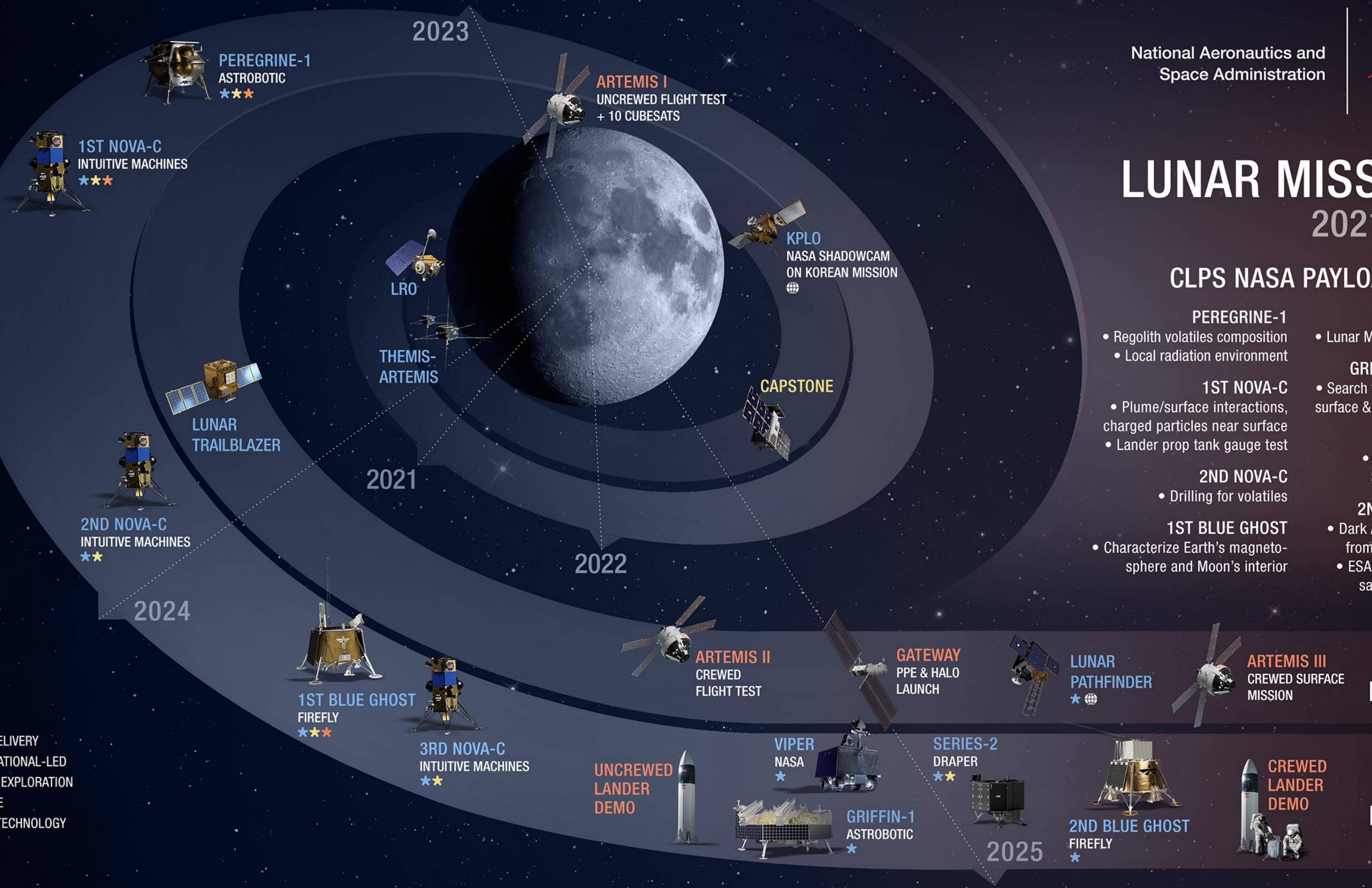
LuGRE antenna
(Co-located w/ lander X-band ant. Earth pointing via gimbal)

LuGRE receiver and FEA
(internal)

2. The Moon

National Aeronautics and
Space Administration

LUNAR MISSIONS
2021–2025



2021

2022

2023

2024

2025

LRO

THEMIS-ARTEMIS

LUNAR TRAILBLAZER

KPLO
NASA SHADOWCAM
ON KOREAN MISSION
🌐

CAPSTONE

ARTEMIS I
UNCREWED FLIGHT TEST
+ 10 CUBESATS

PEREGRINE-1
ASTROBOTIC
★★★

1ST NOVA-C
INTUITIVE MACHINES
★★★

2ND NOVA-C
INTUITIVE MACHINES
★★

1ST BLUE GHOST
FIREFLY
★★★

3RD NOVA-C
INTUITIVE MACHINES
★★

ARTEMIS II
CREWED
FLIGHT TEST

GATEWAY
PPE & HALO
LAUNCH

LUNAR PATHFINDER
★ 🌐

ARTEMIS III
CREWED SURFACE
MISSION

ORBITAL MISSIONS

UNCREWED LANDER DEMO

VIPER
NASA
★

GRIFFIN-1
ASTROBOTIC
★

SERIES-2
DRAPER
★★

2ND BLUE GHOST
FIREFLY
★

CREWED LANDER DEMO

SURFACE MISSIONS

CLPS NASA PAYLOAD GOALS

PEREGRINE-1
- Regolith volatiles composition
- Local radiation environment

1ST NOVA-C
- Plume/surface interactions, charged particles near surface
- Lander prop tank gauge test

2ND NOVA-C
- Drilling for volatiles

1ST BLUE GHOST
- Characterize Earth's magnetosphere and Moon's interior

3RD NOVA-C
- Lunar Magnetic Anomalies

GRIFFIN-1 & VIPER
- Search for volatiles, below surface & shadowed regions

SERIES-2
- Geophysics of the Schrödinger Basin

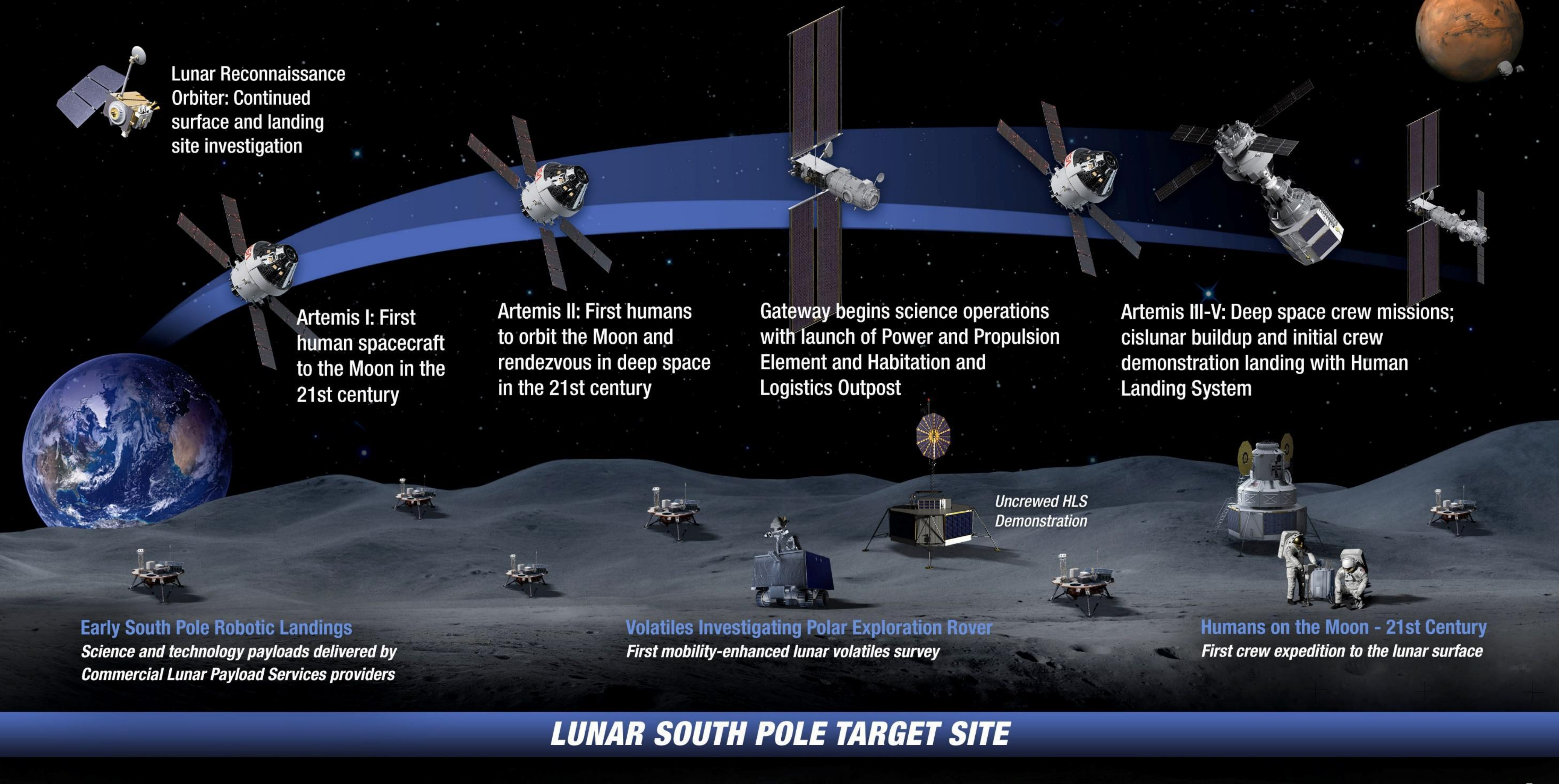
2ND BLUE GHOST
- Dark Ages observations from the lunar far side
- ESA lunar comm relay satellite deployment

KEY

★ CLPS DELIVERY
🌐 INTERNATIONAL-LED
● HUMAN EXPLORATION
● SCIENCE
● SPACE TECHNOLOGY

5.04.2023

Artemis: Landing Humans On the Moon



Lunar Reconnaissance Orbiter: Continued surface and landing site investigation

Artemis I: First human spacecraft to the Moon in the 21st century

Artemis II: First humans to orbit the Moon and rendezvous in deep space in the 21st century

Gateway begins science operations with launch of Power and Propulsion Element and Habitation and Logistics Outpost

Artemis III-V: Deep space crew missions; cislunar buildup and initial crew demonstration landing with Human Landing System

Uncrewed HLS Demonstration

Early South Pole Robotic Landings

Science and technology payloads delivered by Commercial Lunar Payload Services providers

Volatiles Investigating Polar Exploration Rover

First mobility-enhanced lunar volatiles survey

Humans on the Moon - 21st Century

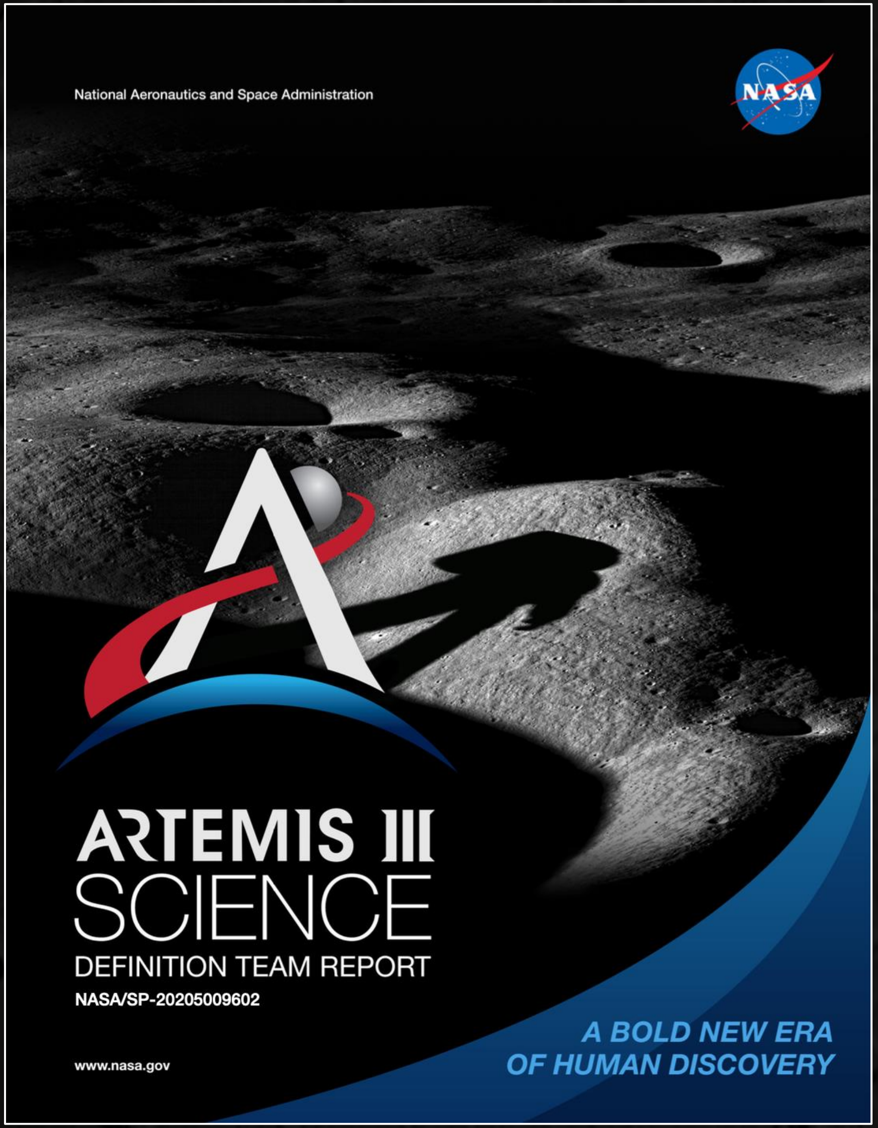
First crew expedition to the lunar surface

LUNAR SOUTH POLE TARGET SITE

Lunar Science Objectives

Seven Artemis III Science Objectives:

1. Understanding planetary processes
2. Understanding the character and origin of lunar polar volatiles
3. Interpreting the impact history of the Earth-Moon system
4. Revealing the record of the ancient sun and our astronomical environment
5. Observing the universe and the local space environment from a unique location
6. Conducting experimental science in the lunar environment
7. Investigating and mitigating exploration risks



National Aeronautics and Space Administration

ARTEMIS III
SCIENCE
DEFINITION TEAM REPORT
NASA/SP-20205009602

www.nasa.gov

A BOLD NEW ERA
OF HUMAN DISCOVERY

Lunar Science Objectives (cont.)

Seven Artemis III Science Objectives:

1. Understanding planetary processes
2. Understanding the character and origin of lunar polar volatiles
3. Interpreting the impact history of the Earth-Moon system
4. Revealing the record of the ancient sun and our astronomical environment

Moon as time capsule

5. Observing the universe and the local space environment from a unique location
6. Conducting experimental science in the lunar environment
7. Investigating and mitigating exploration risks

Moon as platform

Moon Overview

Size: Approximately ¼ the diameter of Earth and 1% Earth's mass

- Surface area ≈ continent of Africa
- 1/6 Earth's gravity
- Horizon 2.5 km away (Earth horizon ~12km)

Distance from Earth: between 356,000 km (perigee) and 407,000 km (apogee) ≈ 60 R_E

Orbit inclined 5.15° relative to ecliptic; rotational axis 1.5° relative to ecliptic

- Earth-Moon system has the greatest angular moment of all planet-satellite systems in our solar system
- Libration permits 59% of Moon to be observed from Earth over time

Lunar day = 29.5 Earth days

- Combination of orbital period, spin rate, movement of Earth in its orbit → same hemisphere always facing Earth

The Moon's gravity causes tides; tidal braking is gradually slowing Earth's rotation

- Tidal bulge is enlarging the Moon's orbit by ~4 cm/yr; 300 Mya Moon distance was ~40 R_E

Moon Overview

Regolith blankets the entire surface

- Rock ground up by continuous micrometeorite impacts

Surface is divided into two physiographic provinces: Mare and Terrae

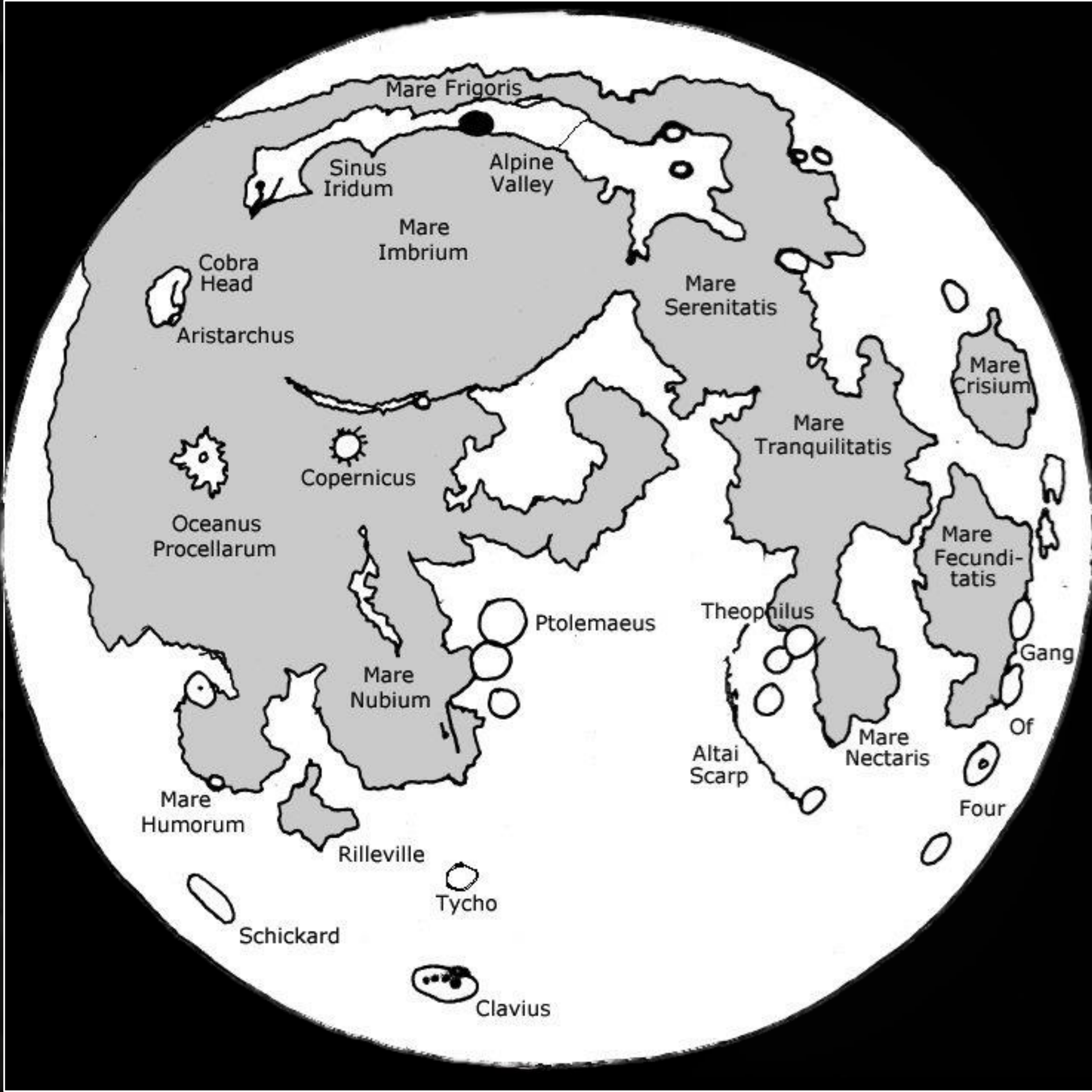
Many feature names date to a 1651 map by Italian astronomers Riccioli and Grimaldi

Mare

- Younger, dark smooth lowlands formed by lava flows
- Mean slopes = 4-5°; <100 m relief
- 16% of lunar surface (1% crust volume)
- More rocky than the highlands; regolith is less thick (<100 m) so bedrock is more easily excavated by impacts

Terrae or highlands

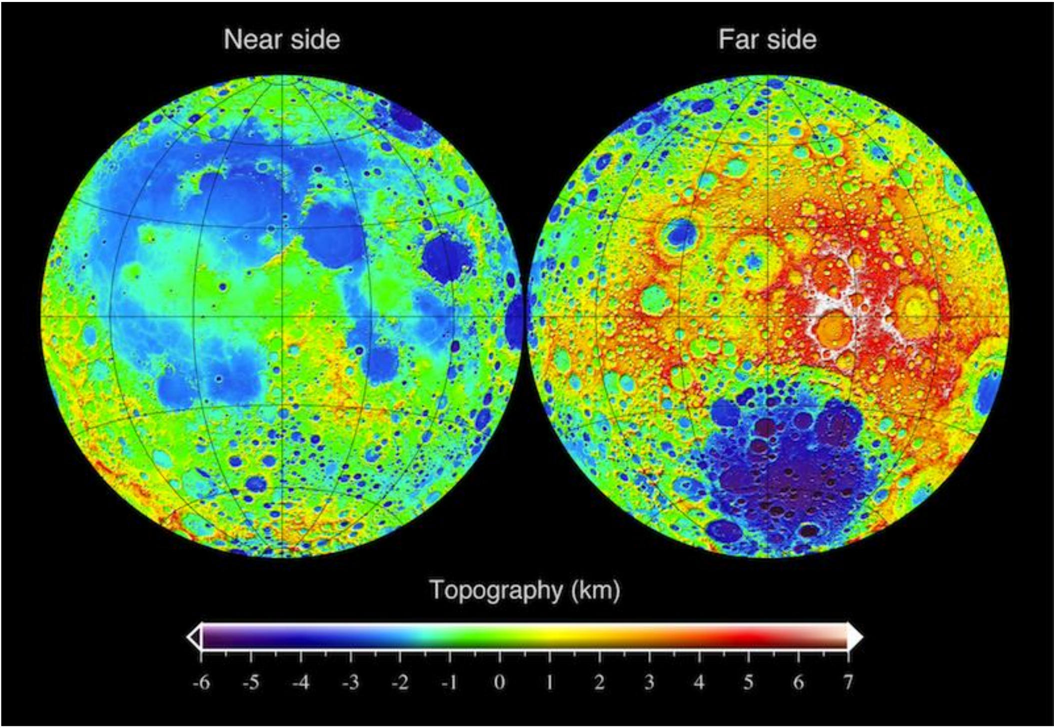
- Older, rugged uplands
- Mean slopes = 7-10°

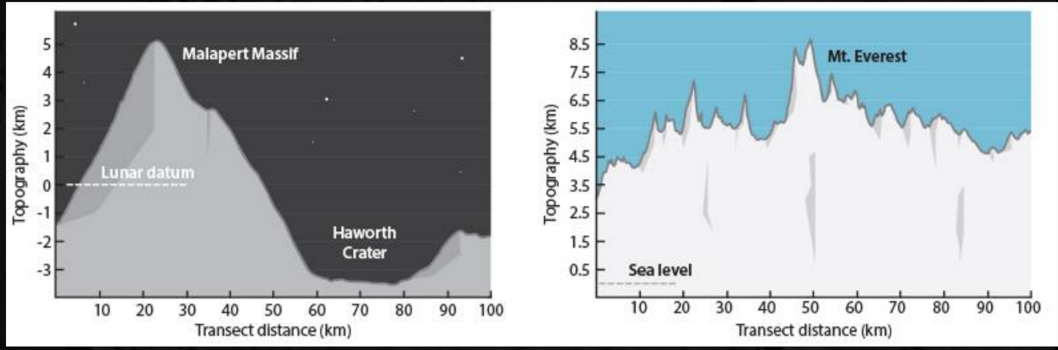


Simplified Moon map by Dave North: https://ephemeris.sjaa.net/0503/e.html

Topography

- Dynamic range of 15 km
  - Comparable to Earth range; different cause
  - Topographic variety on the Moon is almost entirely the result of large impact features
  - Some landforms arise from volcanism/tectonism (scarps, Grabens, wrinkle ridges, rilles)
- “The principal scientific product of Apollo is the recognition of impacts as a fundamental geologic process” – Moon scientist Paul Spudis
  - “The story of the Moon is the accumulation of craters on top of craters on top of craters”

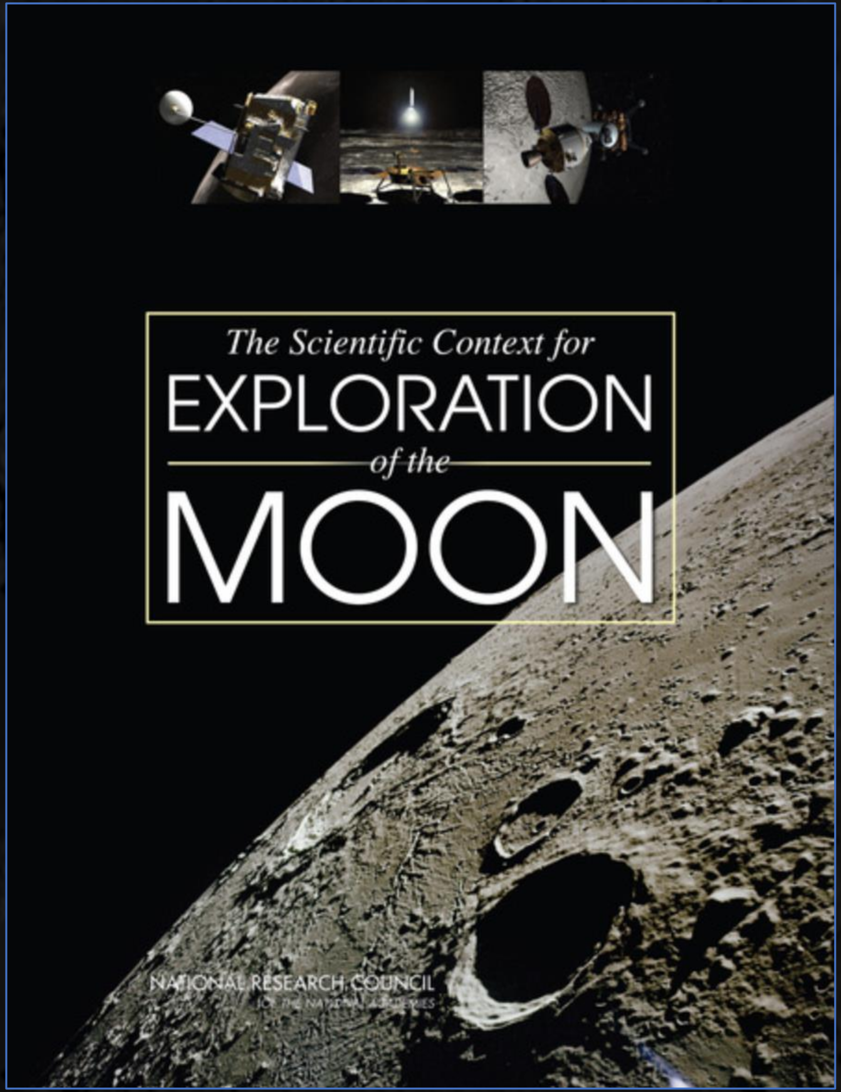




What do we want to know?

Lunar science policy example:

- Jan 14, 2004: President Bush announced the Vision for Space Exploration, a plan to extend human presence across the Solar System, starting with the Moon
- June 4, 2004: Aldridge Commission (created by EO 13326) submits final report on “Implementation of US Space Exploration Policy”
- March 13, 2006: NASA AA for Science, Mary Cleave, asks Nat’l Research Council to provide “guidance on the scientific challenges and opportunities enabled by a sustained program of human and robotic exploration of the Moon”
- 2007: Report released by the NRC (part of the National Academies) Committee on the Scientific Context for Exploration of the Moon



The Scientific Context for
EXPLORATION
of the
MOON

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

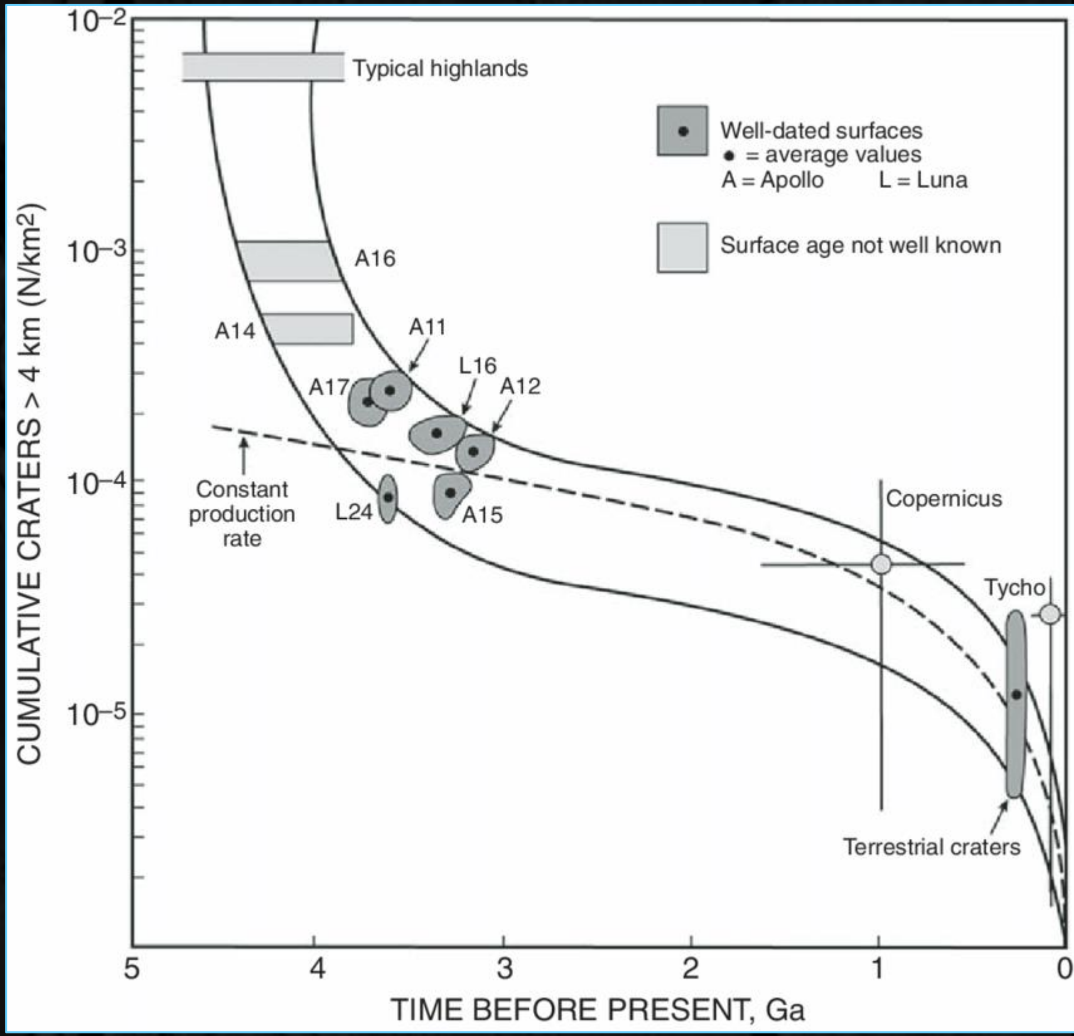
Hypotheses

1. Giant Impact Hypothesis
2. Magma Ocean Hypothesis
3. Terminal Cataclysm Hypothesis

1. Giant Impact Hypothesis (“the Big Whack”)

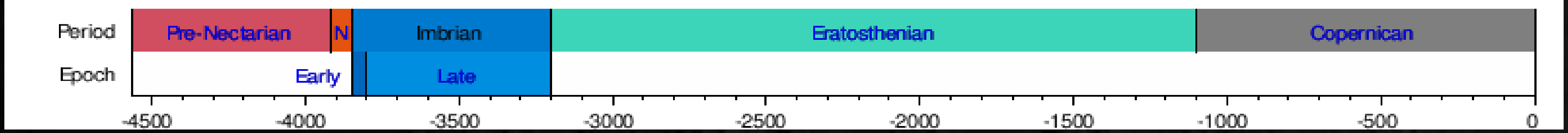
Explains the origin of the Moon as being assembled from debris after the impact of a Mars-sized object with the early Earth.

- Lunar science community arrived at consensus in 1984
- 4.5 Bya: Mars-sized proto-planet, Theia, collided with the proto-Earth, Terra
- Collision in the direction of Terra’s spin
- High concentration of siderophile elements in Earth’s upper mantle from core of Theia; Moon comprised of the remaining vaporized debris of Theia
- Similar impact process may have shaped Mercury and Venus



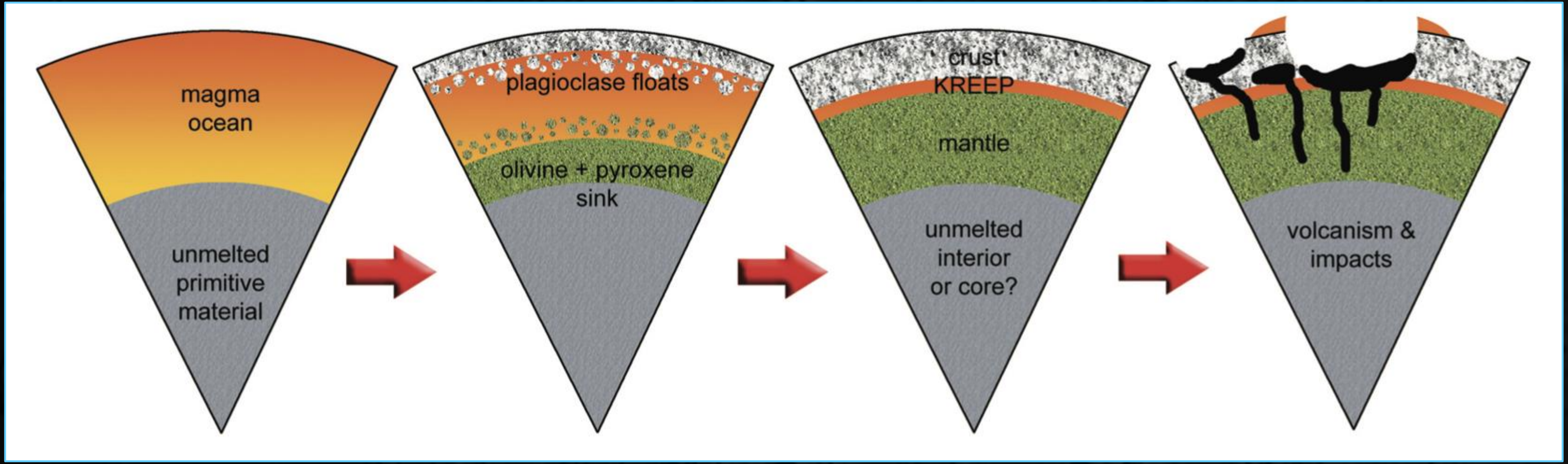
Testing the hypothesis

- Most Apollo samples date from the Imbrian period; samples are needed from the first 100 Mya



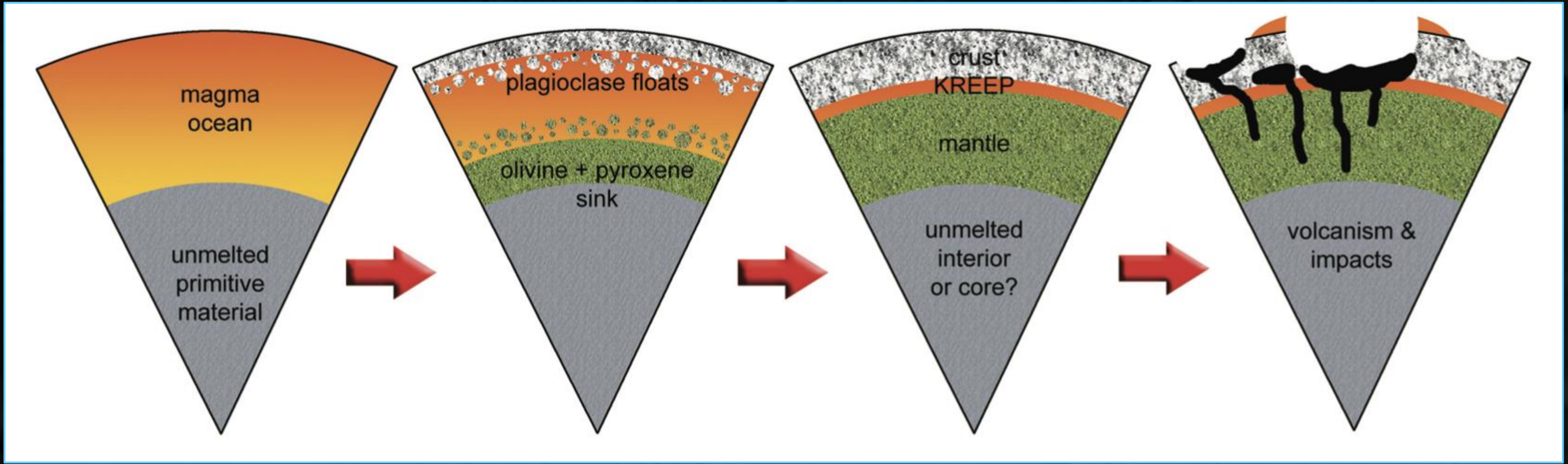
2. Magma Ocean Hypothesis

- Governs understanding of the formation of lunar rocks following lunar formation; suggests that outer hundreds of km were molten. Differentiation of the vast magma ocean resulted in the formation of the earliest crust and mantle and produced the rocks observed today.
- This is a reasonable explanation for the distribution of rocks and minerals observed by Apollo:
  1. A globe-encircling magma body cooled and minerals precipitated
  2. A lunar mantle formed from dense olivine and pyroxene
  3. A crust accumulated composed of buoyant plagioclase
  4. Elements not easily included in these minerals became enriched in the residual melt (KREEP) between the crust and mantle
  5. Basin-forming impacts and volcanism mixed these layers



2. Magma Ocean Hypothesis

- Hypothesis provides a framework for understanding the early Earth, Mars, Mercury, and differentiated asteroids such as Vesta
- Issues
  - Hemispherical asymmetry: Thorium (component of KREEP) strongly concentrated on near side
  - Wide variation in Titanium indicates a highly heterogenous mantle
- Testing the hypothesis
  - Apollo seismic network should be expanded to determine whether 500 km seismic discontinuity (presumed base of the original magma ocean) is a global feature
  - Samples from coherent lunar lithologies in craters and basins, as well as samples of the lunar bedrock would further constrain crustal formation and evolution

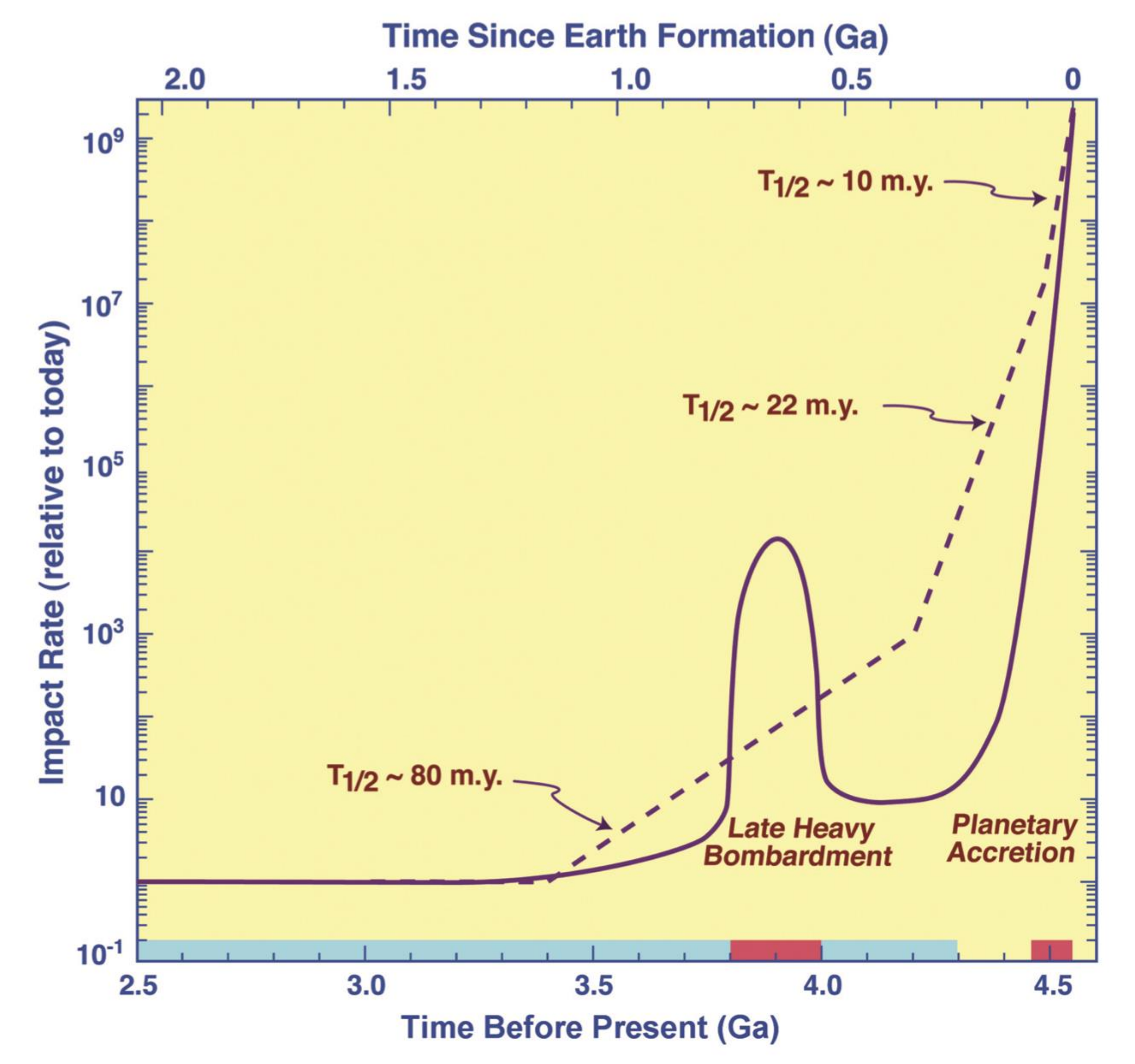


3. Terminal Cataclysm Hypothesis ("Late Heavy Bombardment")

Concerns the timing of the impact flux in the 600 million years after lunar formation

Proposes that impact basins were all formed in a brief impulse of impacts of large objects near 4 billion years ago.

- An impact on the scale of that which created the Imbrium basin would vaporize oceans and sterilize the top 100s of meters of the crust
- Hyperthermophilia of Archaea and bacteria near the base of the tree of life suggest a genetic bottleneck only survived by organisms resistant to high temp
- Impacts spanning 4.5-3.85 billion years ago would allow 10s to 100s of millions of years between impacts and the recovery of existing life
- However, a narrow pulse of a few million years at 3.85 Ga would mean all surface life originated after the cataclysm



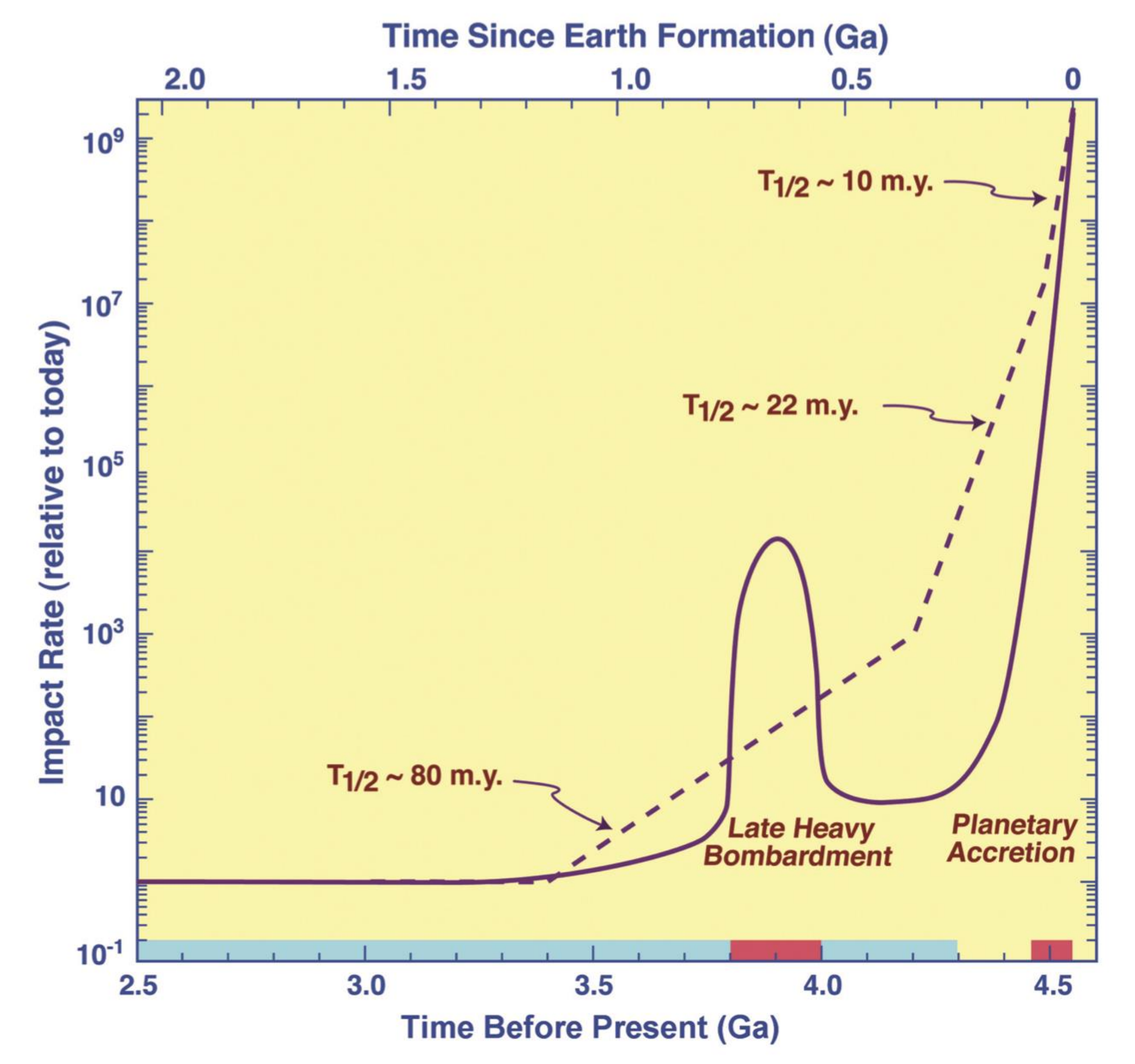
3. Terminal Cataclysm Hypothesis ("Late Heavy Bombardment")

Implications

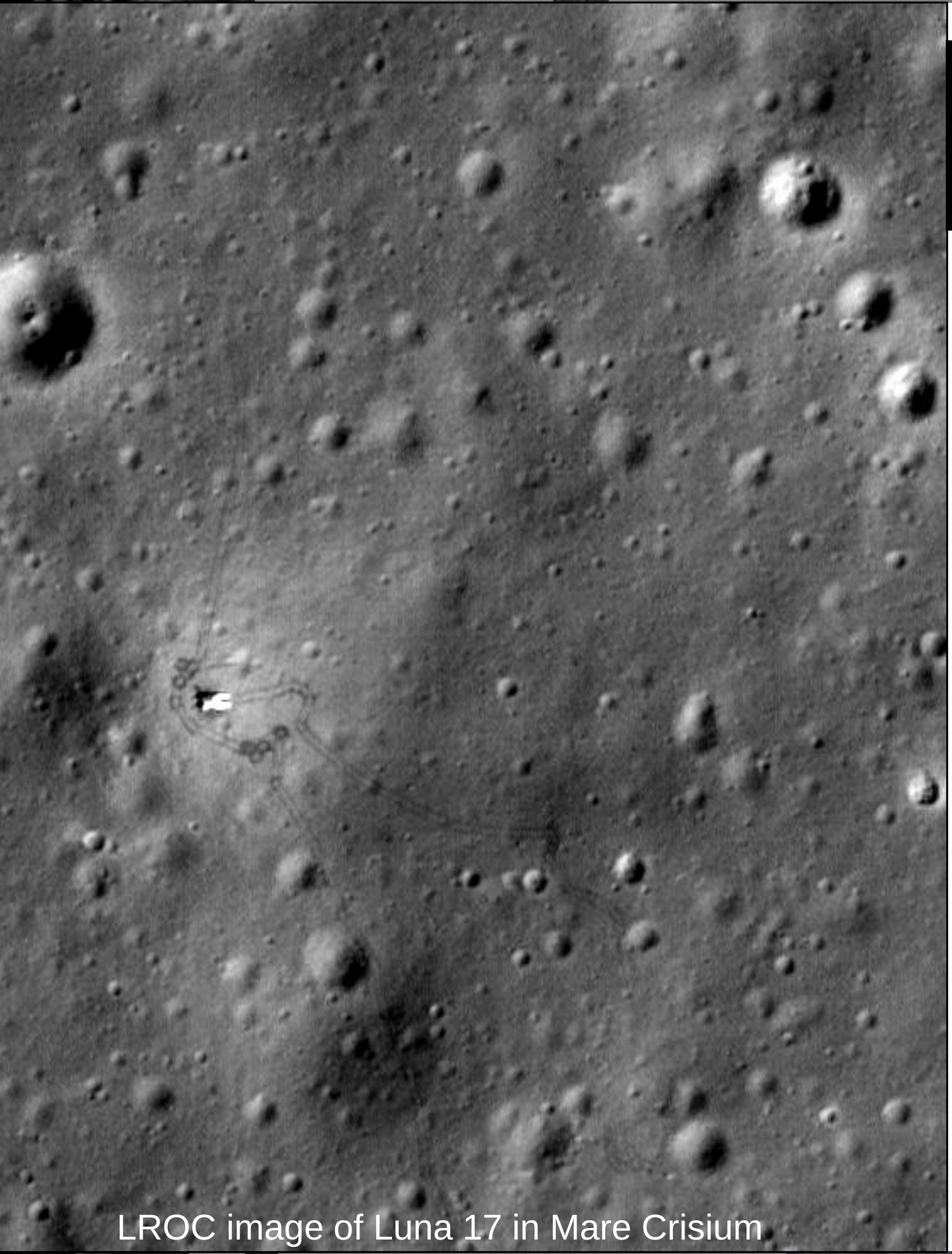
- Late heavy bombardment would allow half the time believed necessary to produce the extreme biochemical complexity observed in the Archaea and bacteria
- Would allow half the time necessary for first observed microfossils (3.5 Ga)
- If this is the case, life may have emerged more than once on Earth
- Orbits of Kuiper Belt objects are testimony to a scattering event or events that would have sprayed the inner planets with impactors

Testing the hypothesis

- The ages of large impact basins far from the Apollo sampled zone must be definitively dated; the cluster of radiometric dates near 3.8 Ga from Apollo samples may all arise from the Imbrium impact event that dominates the regions visited by Apollos



3. The Future


LROC image of Luna 17 in Mare Crisium

New Era of Lunar Exploration

The Moon is again a space exploration priority

- International Space Exploration Coordination Group (ISECG) has identified more than two dozen upcoming lunar missions globally

Motives

- Scientific research, technology development, and national prestige

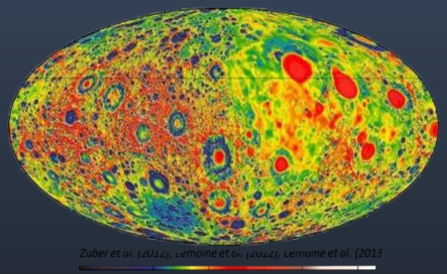
Increasingly diverse and collaborative

- More than 80 national space agencies
- Numerous private companies and partnerships

Foundational Capabilities for a Sustained Lunar Presence

Lunar Reference Frame and Time Base

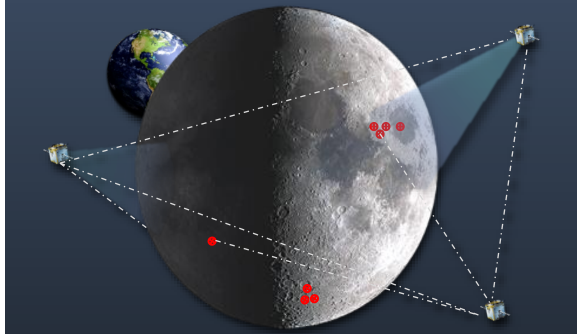
- Safe navigation requires knowledge of a frame of reference and a time base
- Ensure positioning and navigation solutions reach the same point regardless of technology used
- Central body reference frame relates to International Celestial Reference Frame; Lunar time base relates to UTC



Zuber et al. (2012), Lemoine et al. (2012), Lemoine et al. (2013

Lunar Navigation Services

- “GPS-like experience, but at the Moon”
- Support near term needs for real time navigation
- Long-term support of complex surface ops, situational awareness, prediction and avoidance
- Continue studies to define long term needs and architecture

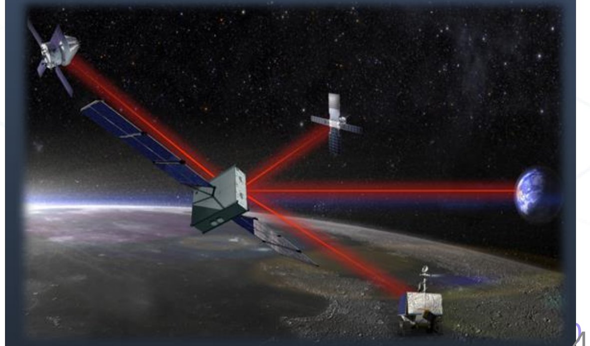


Surface Wireless Communications

- 3GPP/5G+ technology delivers a robust lunar surface network that is scalable
- Address surface and orbital link proliferation, aggregates data for backhaul via relay

Optical Communications

- Optical communications between Earth and Moon (multi-gigabit) supports high bandwidth needs and alleviates spectrum pressure
- Candidate service architecture: 1 meter class optical ground stations w/adaptive optics for Lunar trunking



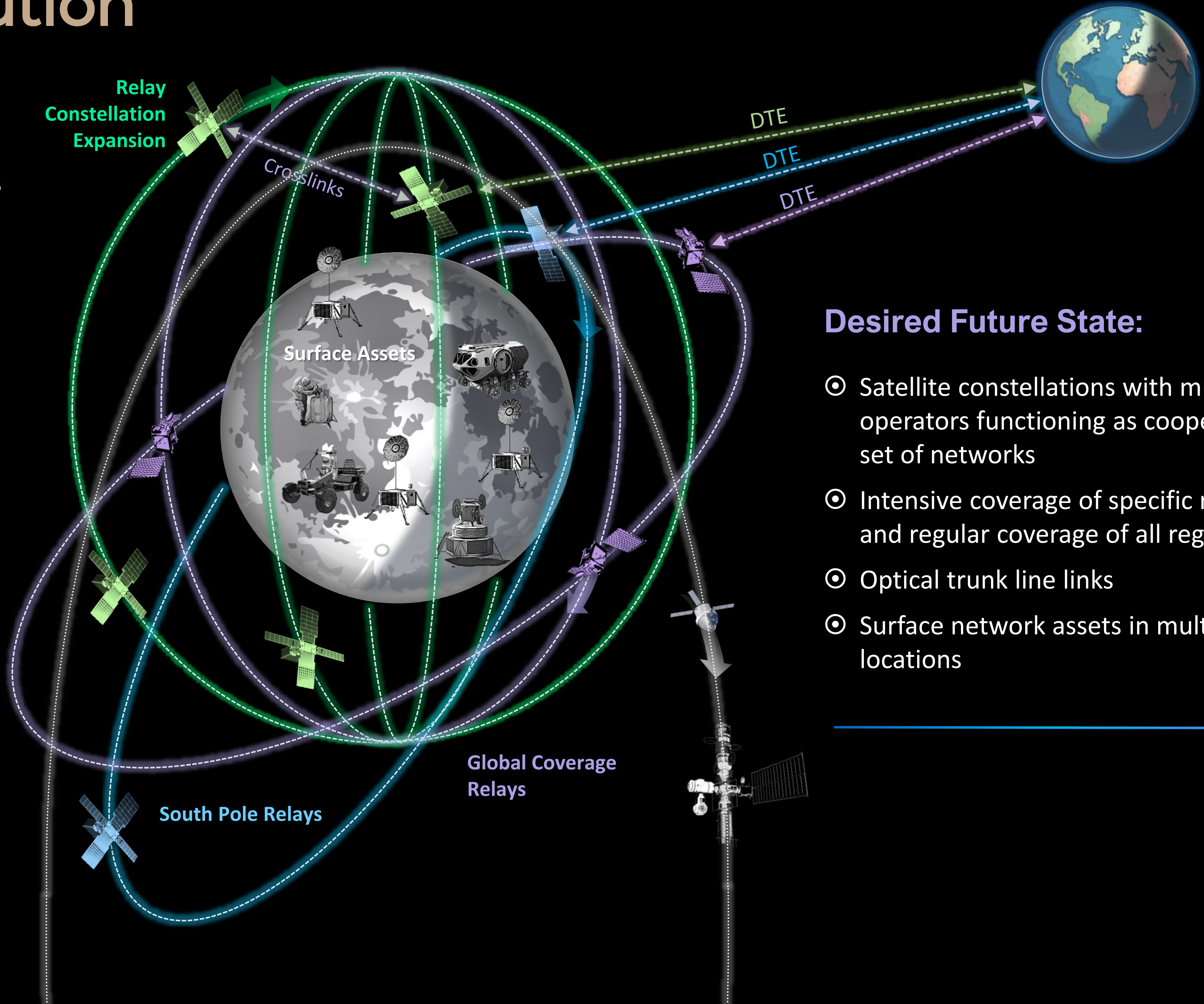
Architecture Evolution

Initial Phase: Next 5 years

- DTE service for Near Side, lunar orbiters and surface missions
- Intensive relay service for South Pole and a selected area of the Far Side
- Initial PNT service and lunar surface networks
- LunaNet interoperability established from the beginning

Growth Phase: Next 10 years

- Continued DTE service for Near Side
- Expanded relay service for South Pole and multiple Far Side regions
- Limited relay services for other globally-dispersed locations and orbiters
- Lunar Navigation Service for PNT
- Surface networking
- Introduction of optical links

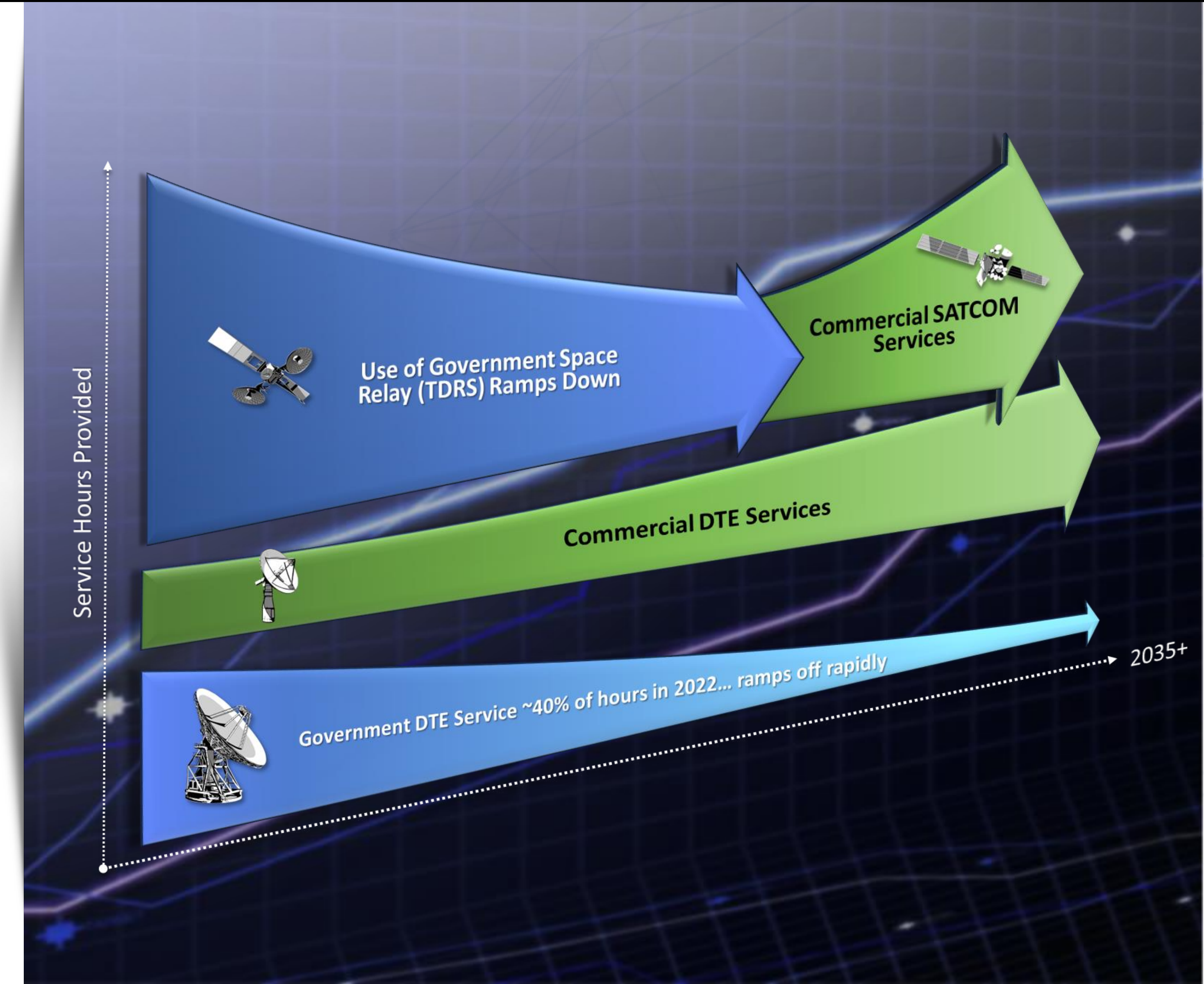


Desired Future State:

- Satellite constellations with multiple operators functioning as cooperative set of networks
- Intensive coverage of specific regions and regular coverage of all regions
- Optical trunk line links
- Surface network assets in multiple locations

Commercial Strategy

- **In 2020, SCaN defined a strategy to transition NASA's Low Earth Orbit missions to commercial services**
- **Evolution driven by National Space Policy and NASA's goal to catalyze additional commercial activity in low Earth orbit**
- **The Commercial Lunar Payload Services (CLPS) program is procuring delivery of mass to the Moon via commercially-owned and operated landers**
- **The Lunar Communications Relay and Navigation Systems (LCRNS) project is procuring communications and navigation services at the Moon from privately owned and operated relays**



International Engagement

International partnerships are essential to the United States' activities in space

Artemis Accords

- Principles for cooperation in the civil exploration and use of the Moon, Mars, comets, and asteroids for peaceful purposes
- Signed by 39 countries

National Space Council

- Focused on int'l collaboration at the Dec 2023 meeting
- Announced numerous initiatives, including U.S. Science Envoy

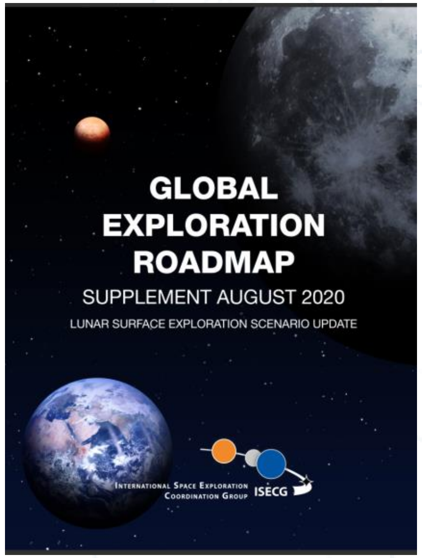
Participation in standards and coordination fora

- UN ICG, UN COPUOS, ISECG, IOAG, LNIS, etc.

Global Learning & Observation to Benefit the Environment (GLOBE) (Kuwait member since 1999)

- Uses scientific methodology to encourage global STEM engagement/enhancement and collect local data on the Earth's system

The GLOBE Program



GLOBAL EXPLORATION ROADMAP

SUPPLEMENT AUGUST 2020

LUNAR SURFACE EXPLORATION SCENARIO UPDATE

International Space Exploration Coordination Group ISECG

ARTEMIS

THE ARTEMIS ACCORDS

COPUOS

AD ASTRA PACEM HOMINUMQUE PROGRESSUM IAF

Career Path

Bachelors in Electrical Engineering, 2010

- Ohio University in Athens, Ohio

PhD in Electrical Engineering, 2016

- Purdue University in West Lafayette, Indiana
- Dissertation: *Use of GNSS Multipath for Autonomous Rendezvous and Docking of Spacecraft*

NASA Goddard Space Flight Center, 2015 - present

- TDRS-M flight dynamics lead
- OSIRIS-Rex navigation team
- LuGRE co-investigator
- LCRNS navigation lead and PNT Instrument PI

Congressional Fellowship, 2021-2022

- AAAS Science Technology and Policy Fellowship (STPF) sponsored by the Institute of Navigation
- Legislative fellow in office of Senator Brown (Ohio)

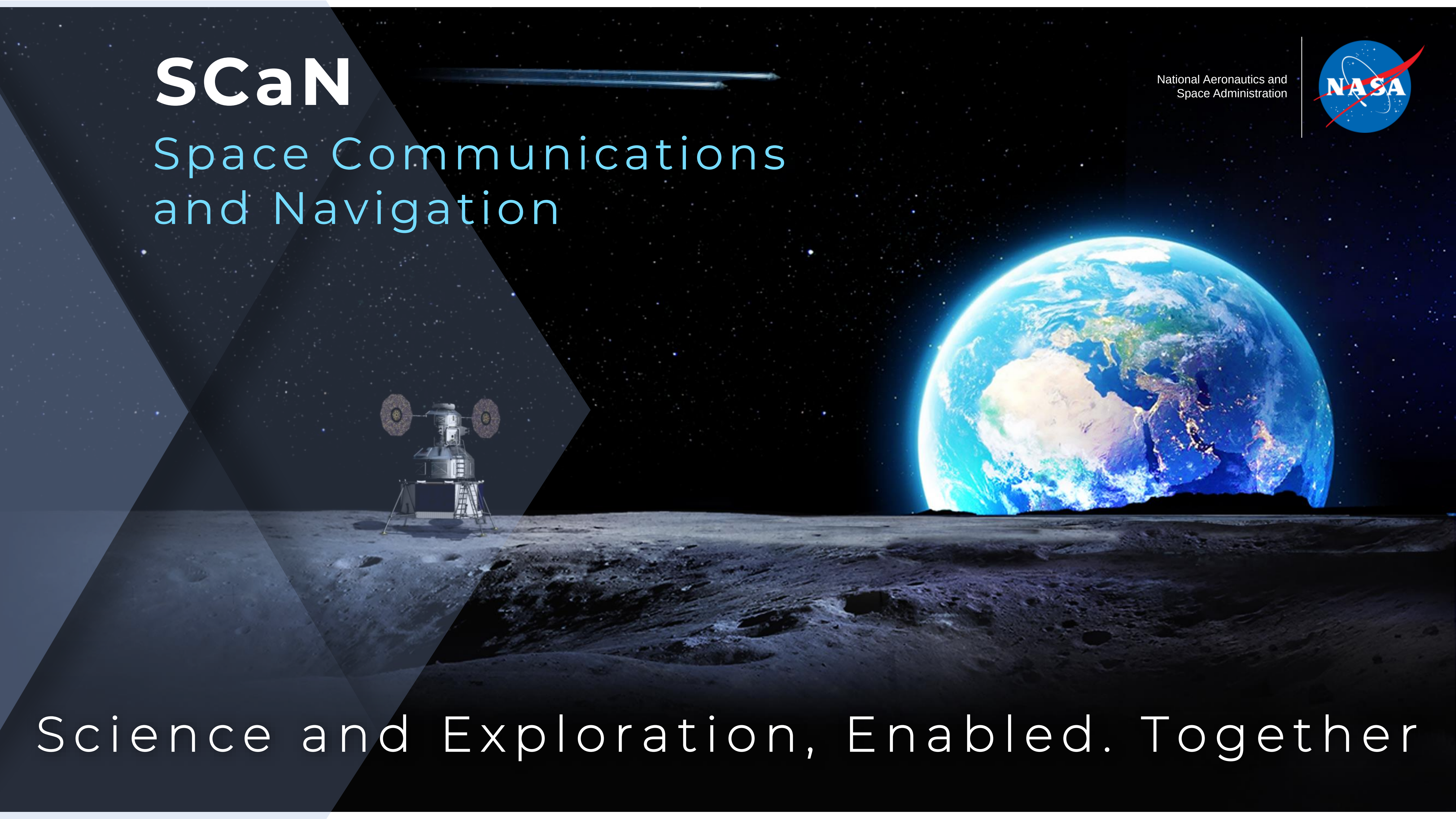
NASA Headquarters

- Technology manager for Advanced Communications and Navigation Division
- Policy support for White House initiatives around lunar time and reference frame standards

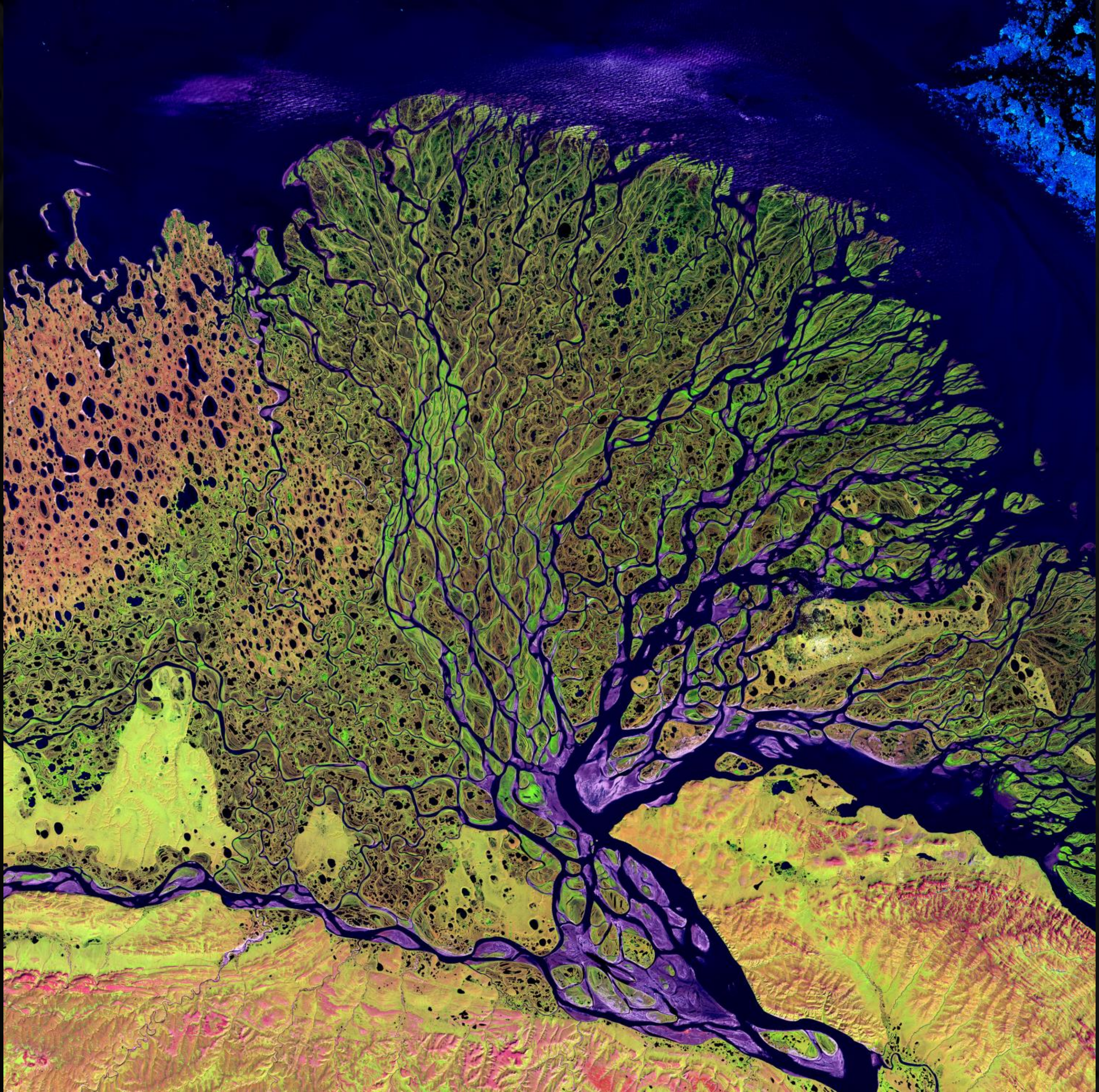
SCaN

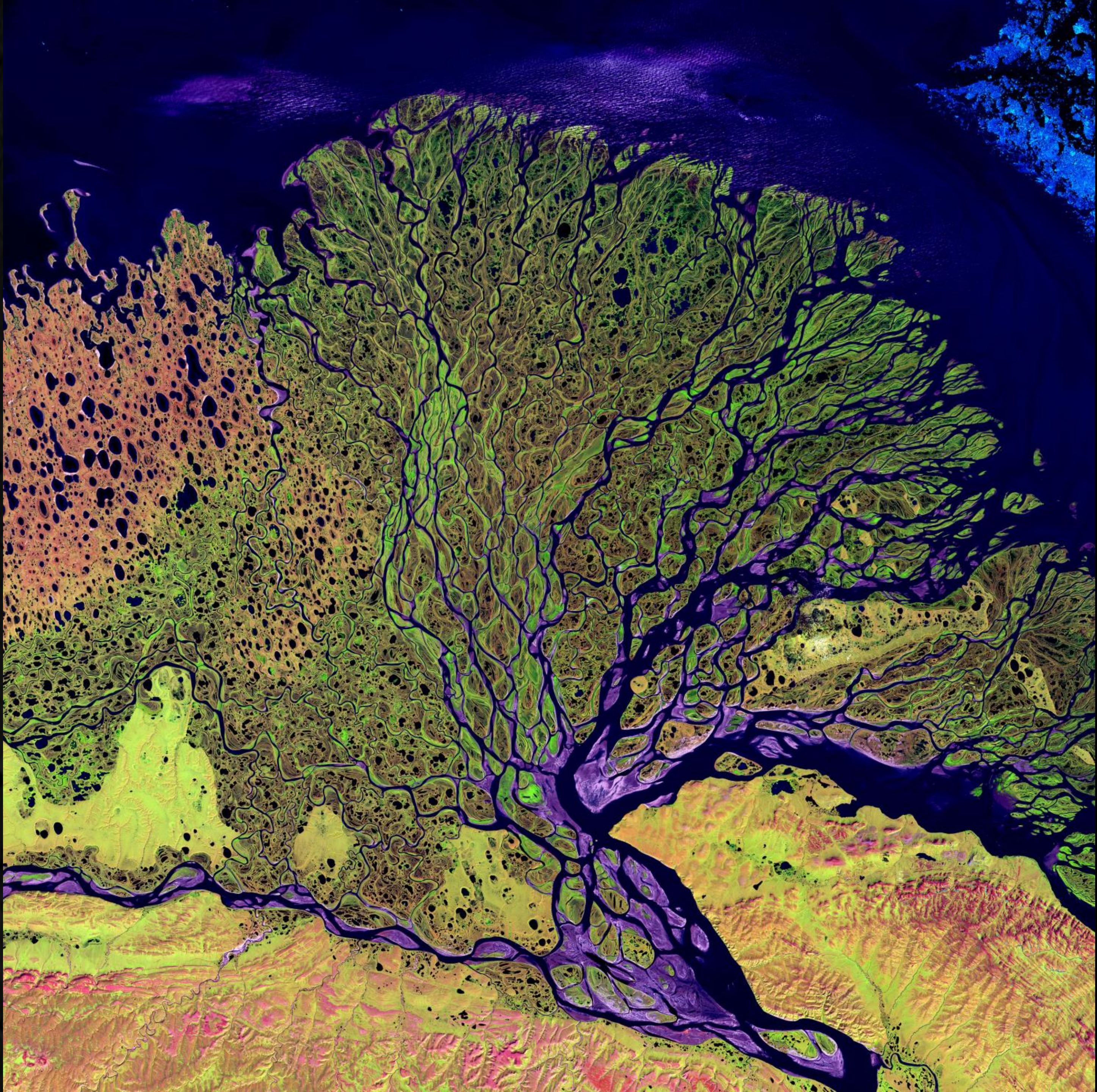
Space Communications and Navigation

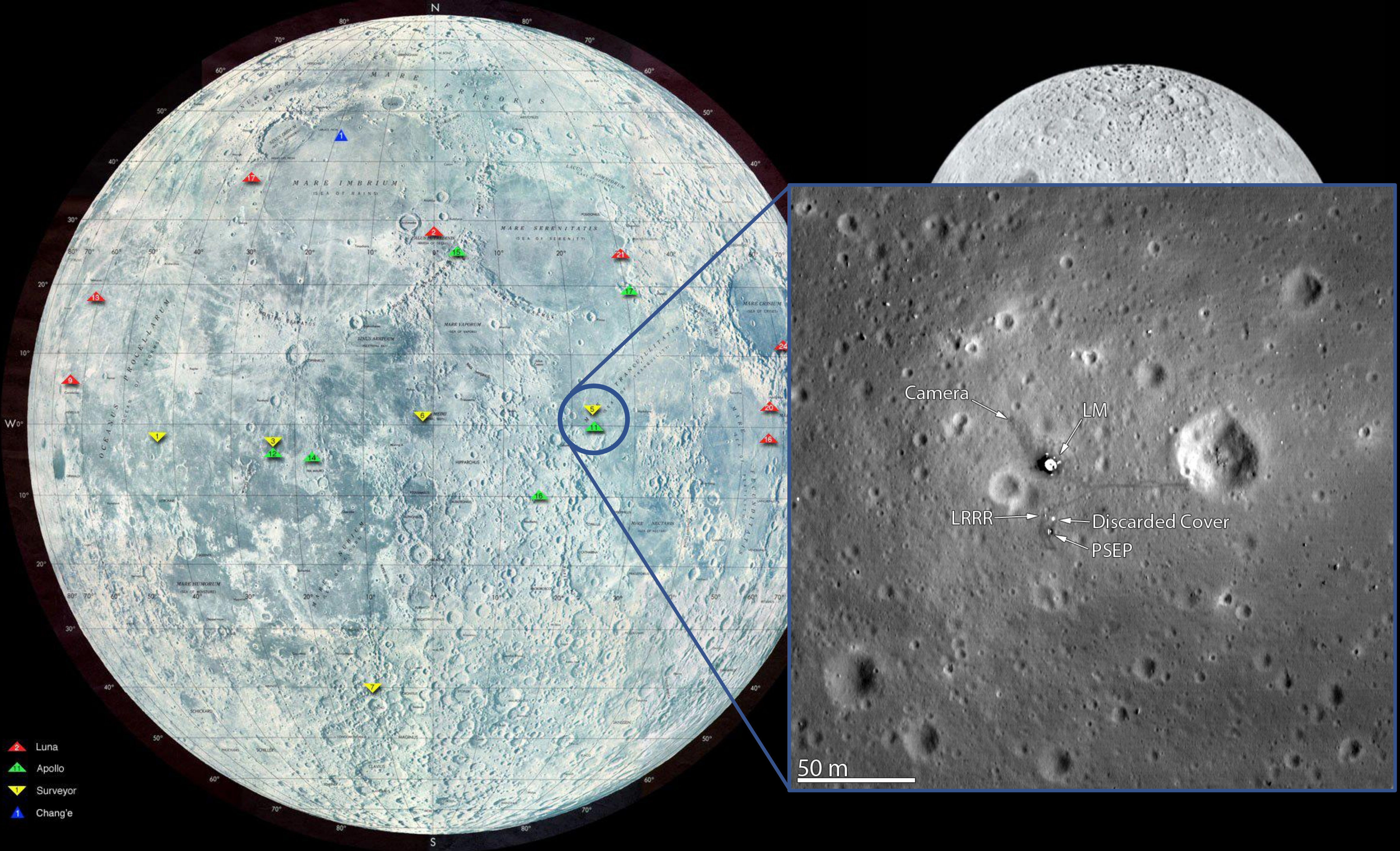
National Aeronautics and Space Administration

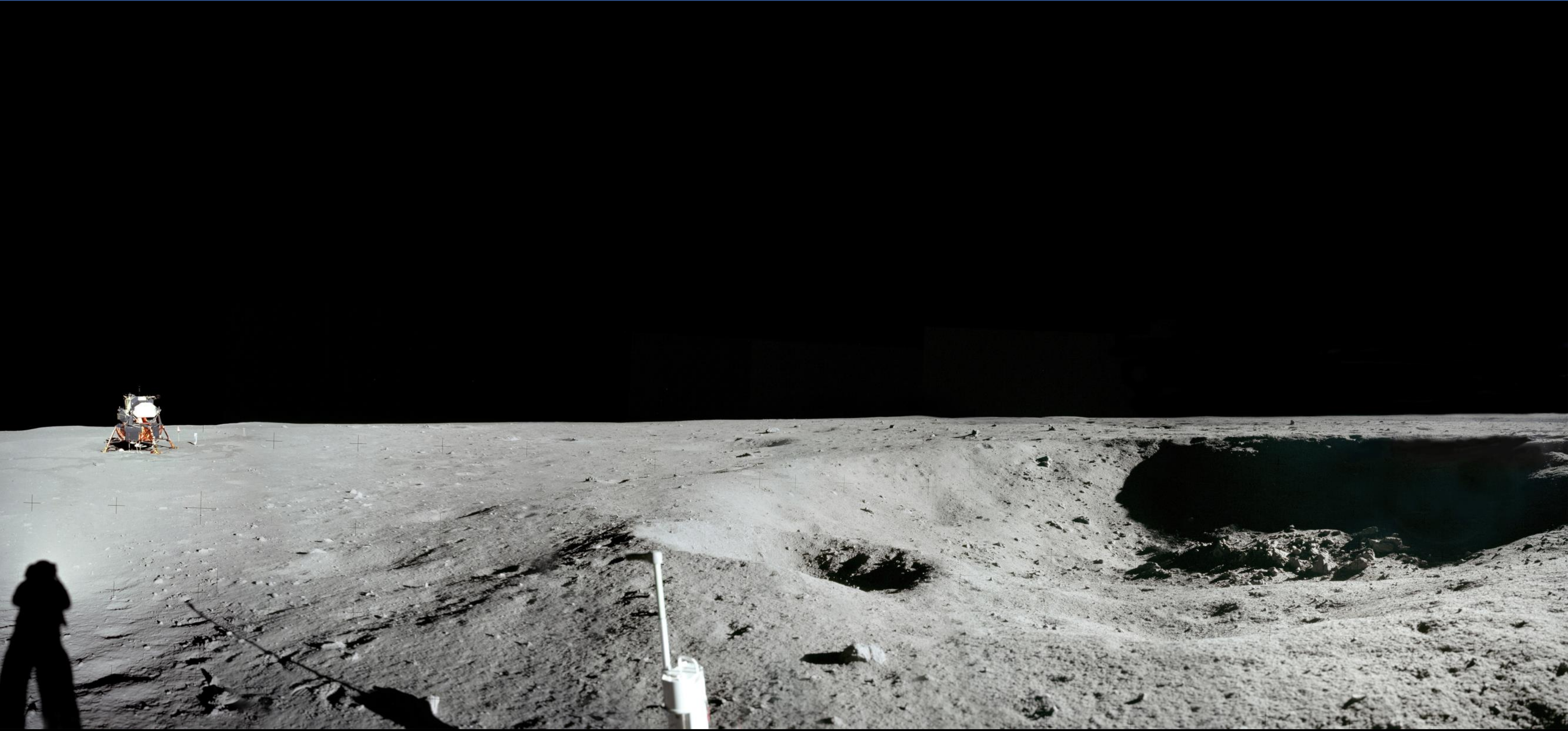


Science and Exploration, Enabled. Together





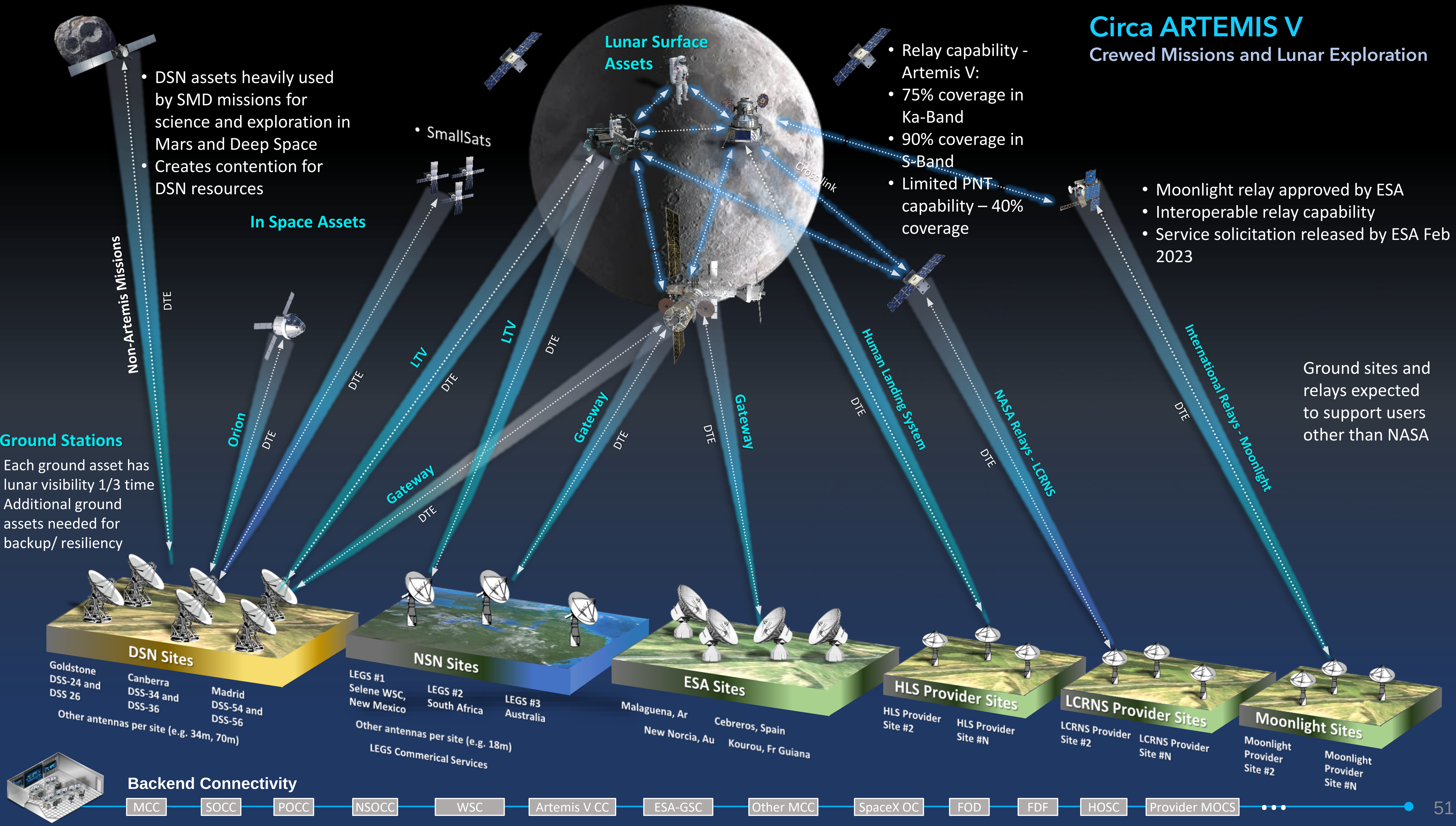

N
S
W 0°
MARE IMBRIUM
MARE SERENITATIS
MARE FRIGORIS
MARE CRISIUM
MARE VAPORUM
MARE HUMORUM
MARE NECTARIS
OCEANUS PROCELLARUM
TRANQUILLITATIS
Luna
Apollo
Surveyor
Chang'e
Camera
LM
LRRR
Discarded Cover
PSEP
50 m



Apollo 11 July 29, 1969

Circa ARTEMIS V

Crewed Missions and Lunar Exploration



- DSN assets heavily used by SMD missions for science and exploration in Mars and Deep Space
- Creates contention for DSN resources

In Space Assets

Lunar Surface Assets

- Relay capability - Artemis V:
- 75% coverage in Ka-Band
- 90% coverage in S-Band
- Limited PNT capability – 40% coverage

- Moonlight relay approved by ESA
- Interoperable relay capability
- Service solicitation released by ESA Feb 2023

Ground sites and relays expected to support users other than NASA

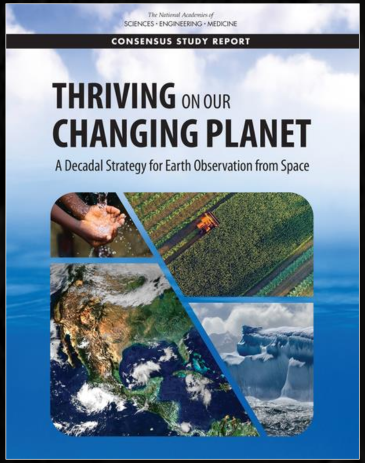
Ground Stations

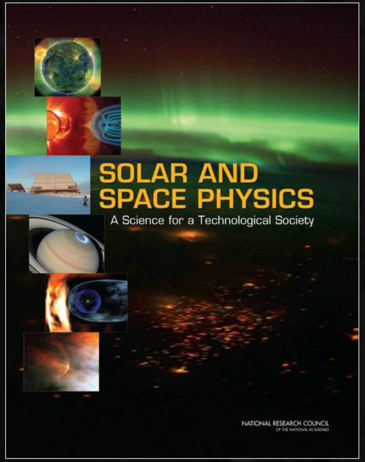
- Each ground asset has lunar visibility 1/3 time
- Additional ground assets needed for backup/ resiliency

Backend Connectivity

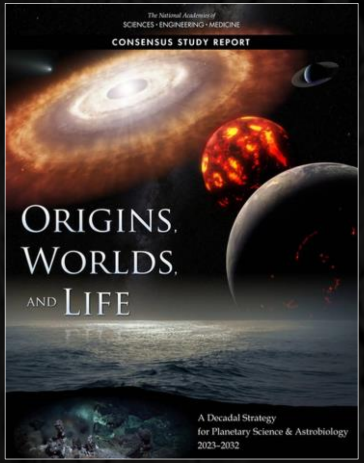
What do we want to know?

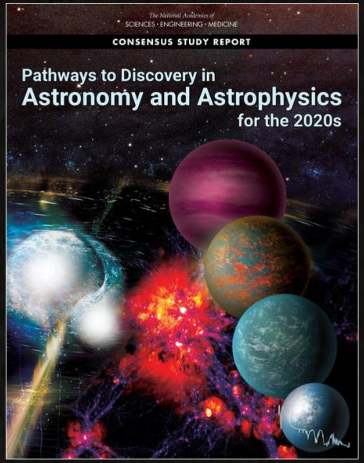
Strategic Research and Priorities from National Academies’ Decadal Surveys

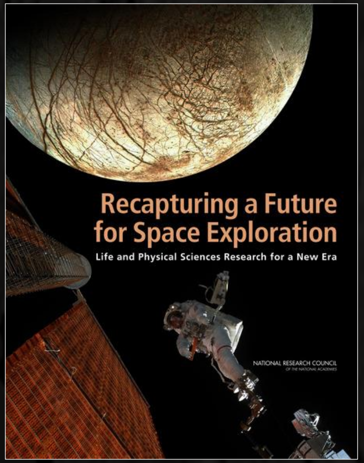

The National Academies of SCIENCES · ENGINEERING · MEDICINE
CONSENSUS STUDY REPORT
THRIVING ON OUR CHANGING PLANET
A Decadal Strategy for Earth Observation from Space


SOLAR AND SPACE PHYSICS
A Science for a Technological Society
NATIONAL RESEARCH COUNCIL OF THE NATIONAL ACADEMIES

to be updated in 2024

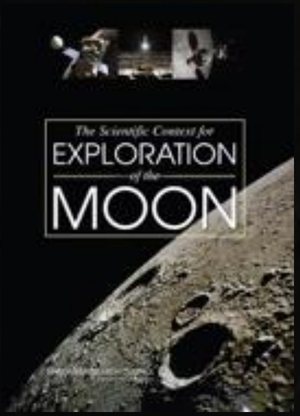

The National Academies of SCIENCES · ENGINEERING · MEDICINE
CONSENSUS STUDY REPORT
ORIGINS, WORLDS, AND LIFE
A Decadal Strategy for Planetary Science & Astrobiology 2023–2032


The National Academies of SCIENCES · ENGINEERING · MEDICINE
CONSENSUS STUDY REPORT
Pathways to Discovery in Astronomy and Astrophysics for the 2020s


Recapturing a Future for Space Exploration
Life and Physical Sciences Research for a New Era
NATIONAL RESEARCH COUNCIL OF THE NATIONAL ACADEMIES

to be updated in 2023

Planetary Science Community Reports


The Scientific Context for EXPLORATION of the MOON

2007


The United States Lunar Exploration Roadmap (version 1.3)
LEAG
LUNAR EXPLORATION ANALYSIS GROUP

2016


ADVANCING SCIENCE of the MOON
REPORT OF THE LUNAR EXPLORATION ANALYSIS GROUP SPECIAL ACTION TEAM

2017

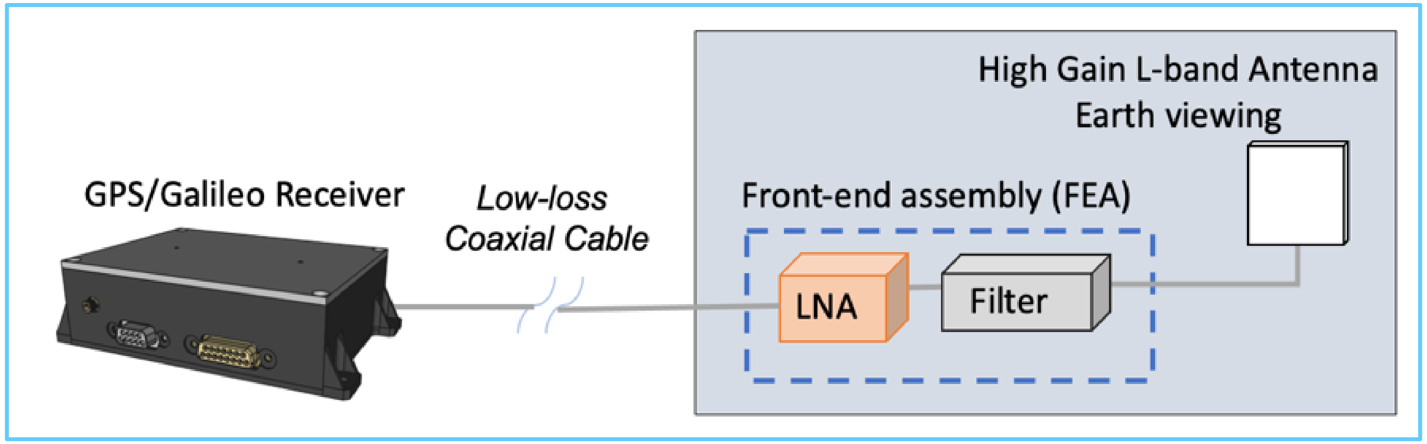
NASA reports


ARTEMIS III SCIENCE
DEFINITION TEAM REPORT

2020

LuGRE Payload

- Global Navigation Satellite System (GNSS) receiver, antenna and front end provided by the Italian Space Agency (ASI)
    - GNSS receiver designed/built for lunar applications by Qascom leveraging heritage from their QN400 space receiver
- Payload can receive and process GPS (L1 and L5) and Galileo (E1 and E5a) signals
- Data: Raw RF samples, GNSS observables (pseudoranges, Doppler, C/N0, carrier phase), and navigation measurements (position, velocity and time from the onboard filter and instantaneous point solutions)



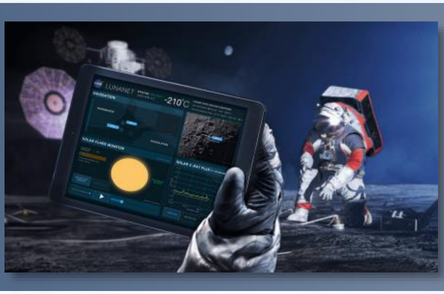
Four Point Plan to Meet Artemis Needs

DSN Upgrades

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

Lunar Exploration Ground Segment

- Alleviates user load on DSN via dedicated new set of 18-meter antennas designed to support lunar missions
- Minimum of three sites around the Earth for continuous coverage
- NASA pursuing build of LEGS sites #1-3
- Commercial services to add additional capacity as demand grows



Lunar Relay

- Removes Earth line-of-sight comm constraint & reduces user burden
- Initial relay deployment targeted at South Pole and Far-Side
- Networking and PNT services via commercial service procurement approach

International Contributions

- SCaN seeking contributions for both Earth and lunar-based assets
- Priorities:
  1. Direct-to-Earth assets that meet or exceed Lunar Exploration Ground Segment performance
  2. Lunar relay comm and PNT services
  3. Lunar surface comm and PNT capabilities

Planetary Decadal

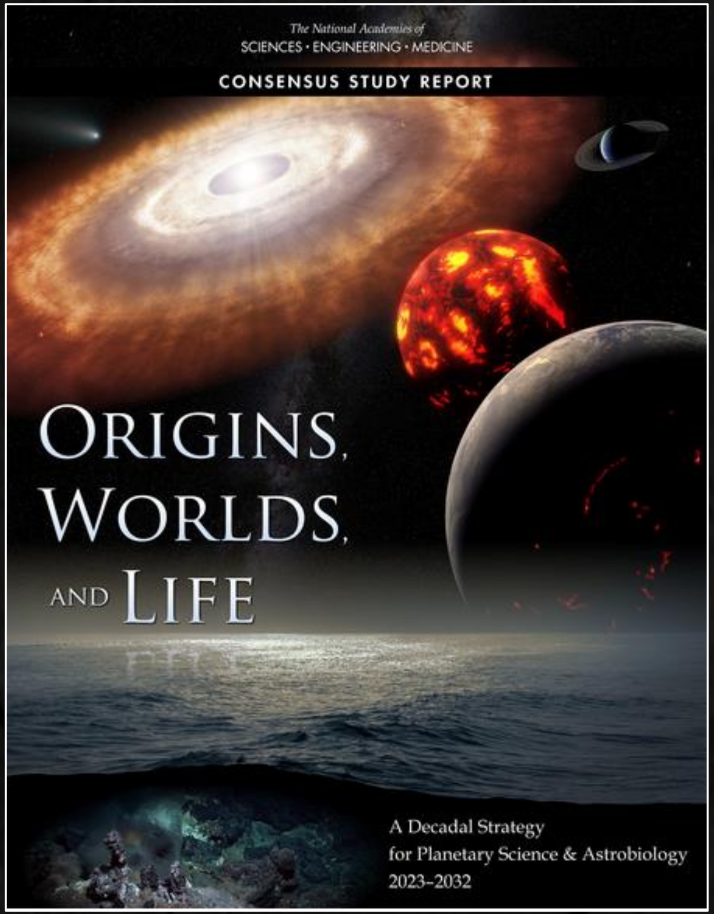
The central goal of a science-driven program of lunar discovery and exploration is to reveal the history of major events and processes that have shaped the Earth–Moon system and the solar system.

The National Academy of Sciences PSA decadal committee prioritized three overarching Science Themes:

Science Theme 1: Uncover the lunar record of solar system origin and early history. The Moon’s composition, structure, and ancient surface preserve a record of early events: from the giant impact that produced the Earth−Moon system to ongoing bombardment as life on Earth emerged and evolved.

Science Theme 2: Understand the geologic processes that shaped the early Earth that are best preserved on the Moon. The Moon retains a record of processes that set the evolutionary paths of rocky worlds, including volcanism, magnetism, tectonism, and impacts.

Science Theme 3: Reveal inner solar system volatile origin and delivery processes. The Moon hosts water and other volatiles in its interior, across its surface, and in ice deposits at its poles, providing a record that may help constrain the origins of Earth’s oceans and the building blocks for life, as well as ongoing volatile delivery processes.



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CONSENSUS STUDY REPORT

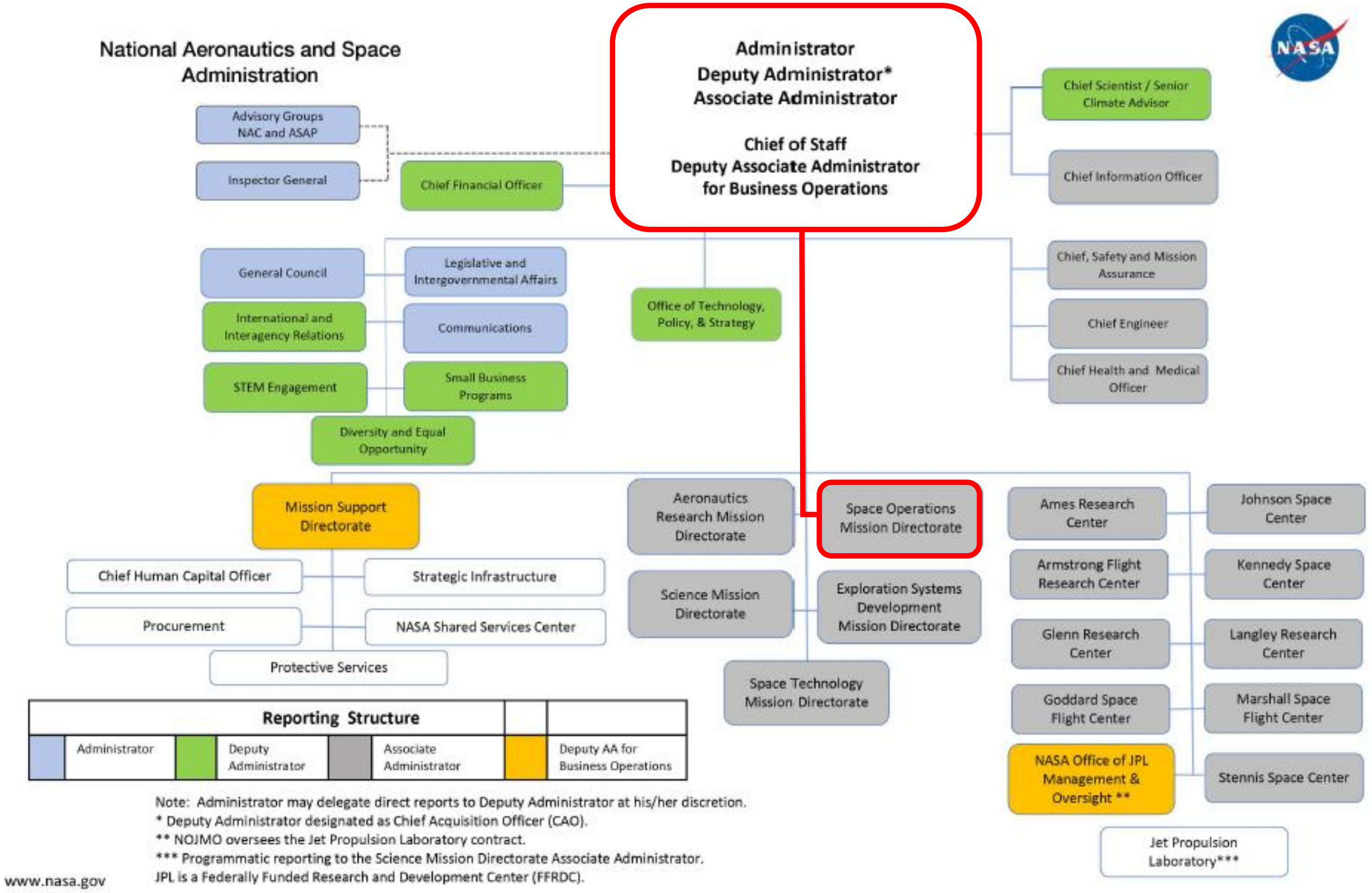
ORIGINS, WORLDS, AND LIFE

A Decadal Strategy for Planetary Science & Astrobiology 2023–2032

NASA Organization

NASA Organization

- Organized into Mission Directorates
- Space Operations Mission Directorate (SOMD) is responsible for enabling sustained exploration missions & operations
  - Manages NASA's current & future space operations in and beyond low-Earth orbit (LEO), including commercial launch services to the International Space Station (ISS)
  - Operates and maintains exploration systems, develops and operates space transportation systems, and performs broad scientific research on orbit
  - Manages space transportation services for NASA & NASA-sponsored payloads that require orbital launch, and NASA's **space communications & navigation services**



National Aeronautics and Space Administration

Administrator
Deputy Administrator*
Associate Administrator

Chief of Staff
Deputy Associate Administrator for Business Operations

Advisory Groups NAC and ASAP
Inspector General
Chief Financial Officer
Chief Scientist / Senior Climate Advisor
Chief Information Officer
General Council
Legislative and Intergovernmental Affairs
International and Interagency Relations
Communications
STEM Engagement
Small Business Programs
Diversity and Equal Opportunity
Office of Technology, Policy, & Strategy
Chief, Safety and Mission Assurance
Chief Engineer
Chief Health and Medical Officer
Mission Support Directorate
Chief Human Capital Officer
Strategic Infrastructure
Procurement
NASA Shared Services Center
Protective Services
Aeronautics Research Mission Directorate
Space Operations Mission Directorate
Science Mission Directorate
Exploration Systems Development Mission Directorate
Space Technology Mission Directorate
Ames Research Center
Johnson Space Center
Armstrong Flight Research Center
Kennedy Space Center
Glenn Research Center
Langley Research Center
Goddard Space Flight Center
Marshall Space Flight Center
NASA Office of JPL Management & Oversight **
Stennis Space Center
Jet Propulsion Laboratory***

Reporting Structure							
🟦	Administrator	🟩	Deputy Administrator	⬜	Associate Administrator	🟨	Deputy AA for Business Operations

Note: Administrator may delegate direct reports to Deputy Administrator at his/her discretion.
* Deputy Administrator designated as Chief Acquisition Officer (CAO).
** NOJMO oversees the Jet Propulsion Laboratory contract.
*** Programmatic reporting to the Science Mission Directorate Associate Administrator.
JPL is a Federally Funded Research and Development Center (FFRDC).

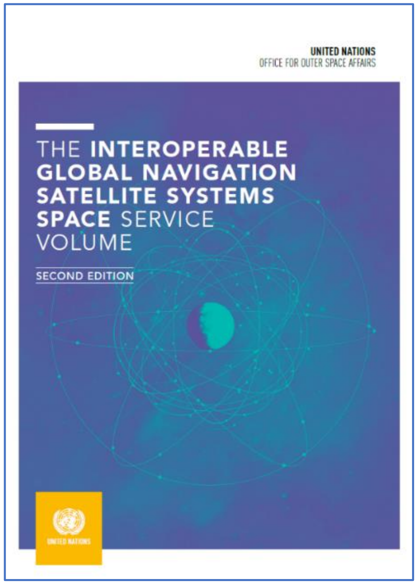
www.nasa.gov

Developing Multi-GNSS Capabilities for Space Ops & Science (2): Developing an Interoperable GNSS Space Service Volume

- **International Committee on GNSS (ICG)**
  - ICG-16 meeting held in Abu Dhabi, UAE, Oct. 9-14, 2022
  - WG-B Space Use Sub-Group (SUSG)
    - Established 2018; NASA co-chairs w/ ESA, CAST
    - Virtual meetings held monthly on rotating basis
  - SSV Booklet 2nd Edition, "The Interoperable GNSS SSV"
    - Officially released on Sep 28, 2021: https://undocs.org/ST/SPACE/75/REV.1
    - Major improvements from 1st Edition:
      - Updated BeiDou (China) & QZSS (Japan) constellation data
      - Added geometric dilution indicator
      - Added flight experiences section
  - SSV Video, "The Multi-GNSS SSV: Earth's Next Navigation Utility"
    - Released at ICG-15 alongside booklet:

https://www.youtube.com/watch?v=-1ngun6OfgQ

  - SSV Booklet 3rd Edition (in development)
    - To expand analysis to also cover Cislunar and Lunar Space


UNITED NATIONS
OFFICE FOR OUTER SPACE AFFAIRS

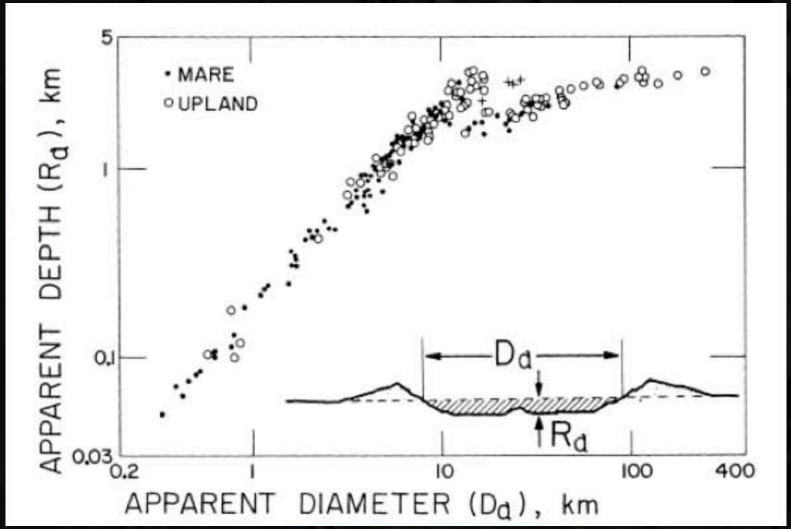
THE INTEROPERABLE GLOBAL NAVIGATION SATELLITE SYSTEMS SPACE SERVICE VOLUME

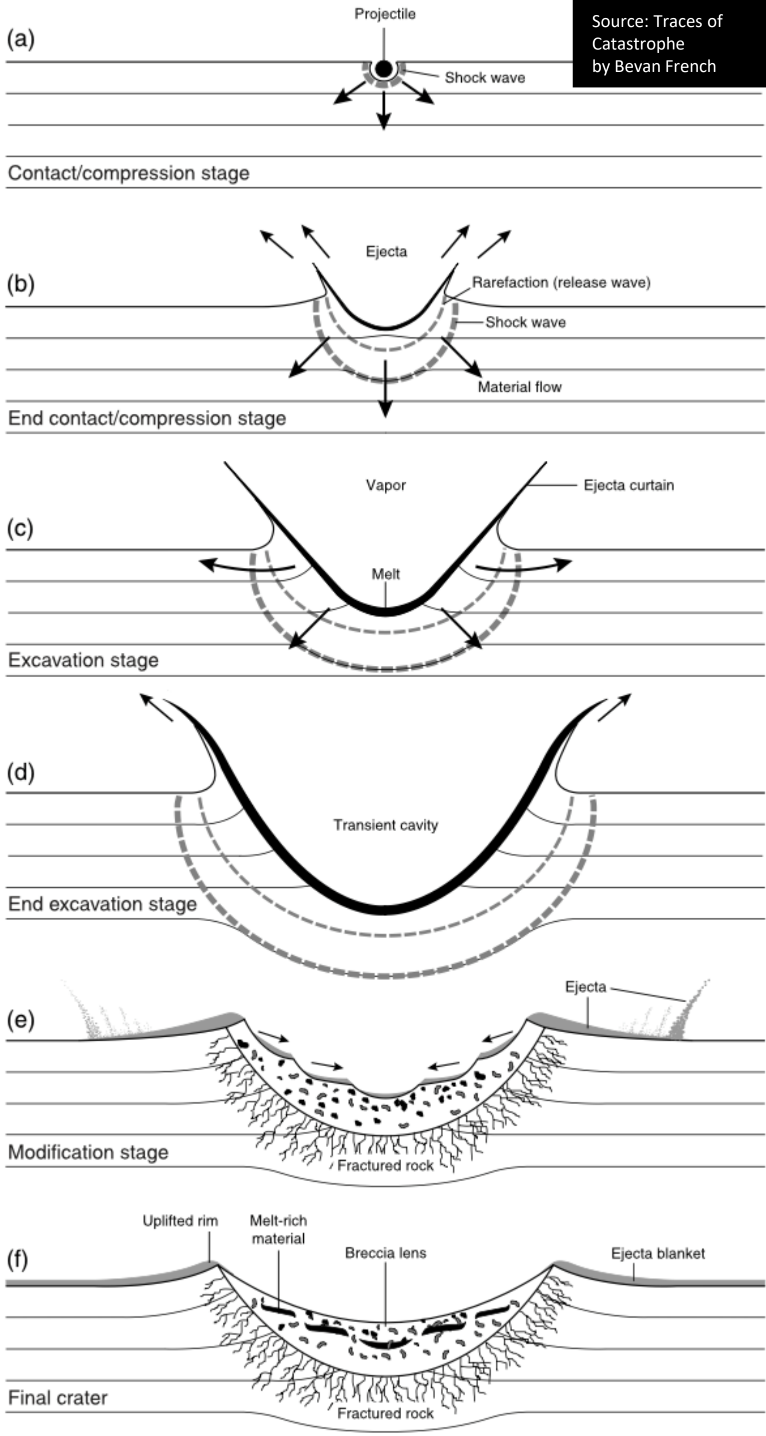
SECOND EDITION


The Multi-GNSS Space Service Volume: Earth's Next Navigation Utility

Crater Morphologies

- The impact origin of craters was debated well into the 20th century; volcanism cited as likely source
- Objects hit the Moon at cosmic speeds, on average 20 km/s (lunar escape velocity ~2.5 km/s)
  - Kinetic energy sufficient to vaporize impactor
- Crater morphology is a function of age and size
- Bowl Craters
  - D < 10 km
- Complex Craters
  - D ~ 10s of km
- Basins
  - D > 300 km





Source: Traces of Catastrophe by Bevan French

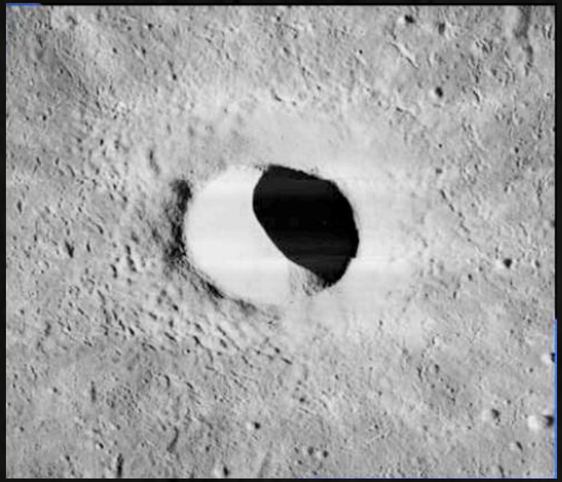
Bowl Craters

- Depth to diameter ration (d/D) ~ 1:3
- Ejecta and subsurface brecciation
- Impact melting
- Secondary impact craters

Simple to Complex Transition

- Wall slumps, floor debris
- Rim scalloping
- Incipient terracing
- Melt sheet
- Central mounds

North Ray (1km)



Mösting C (4km)

Bessel (15km)

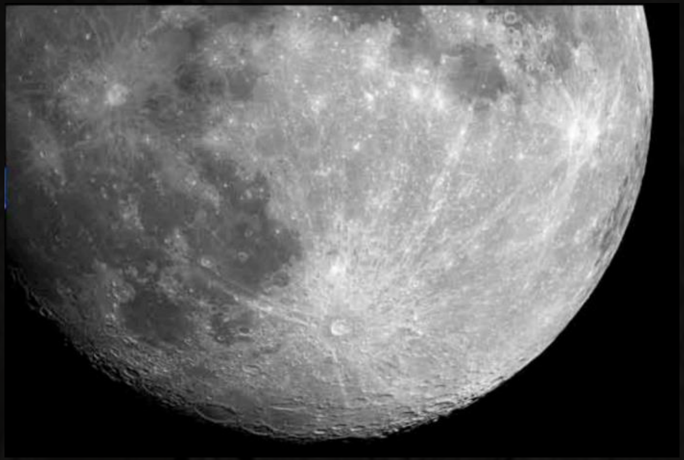
Triesnecker (26km)

Complex Craters

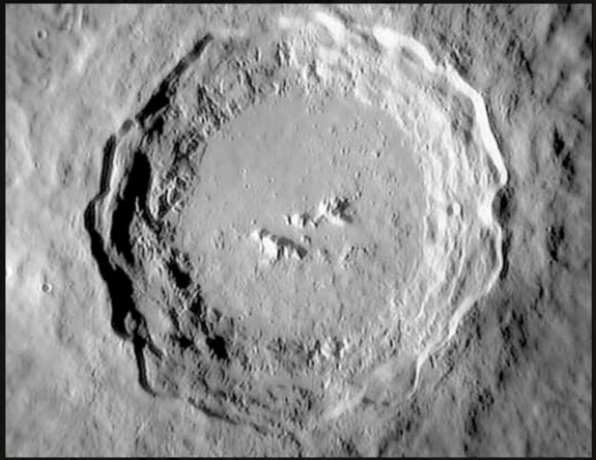
- Wall terraces
- Flat floors
- Central peaks (subsurface material?)
- Impact melt deposits
- Ejecta and secondary craters
- Rays

Crater to Basin Transition

- Central peak complexes and rings
- Peak rings
- Two-ring basins

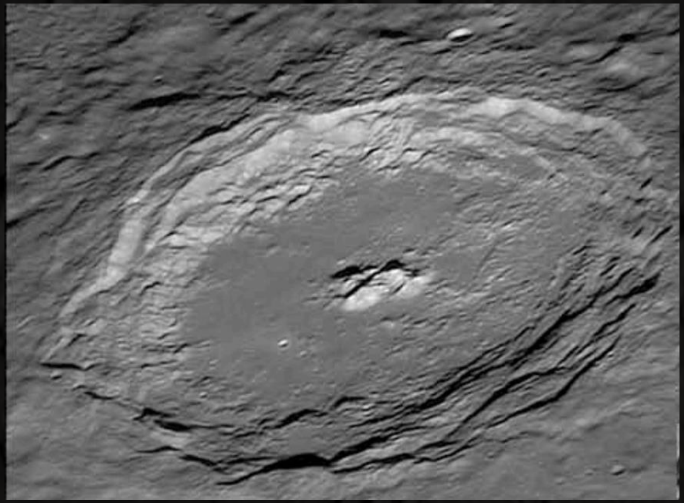


Tycho (85km)

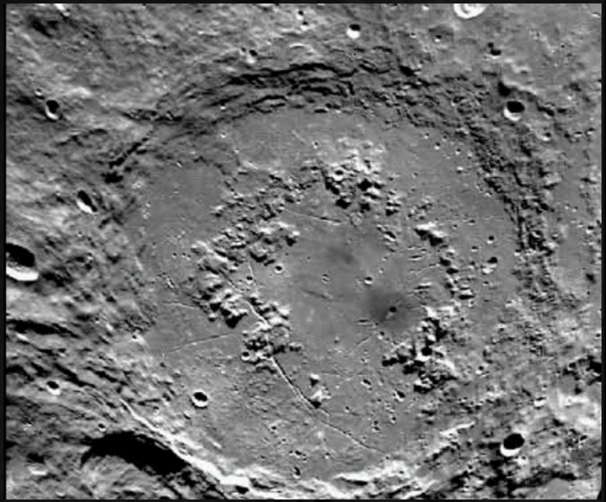


Copernicus (96km)

Langrenus (127km)



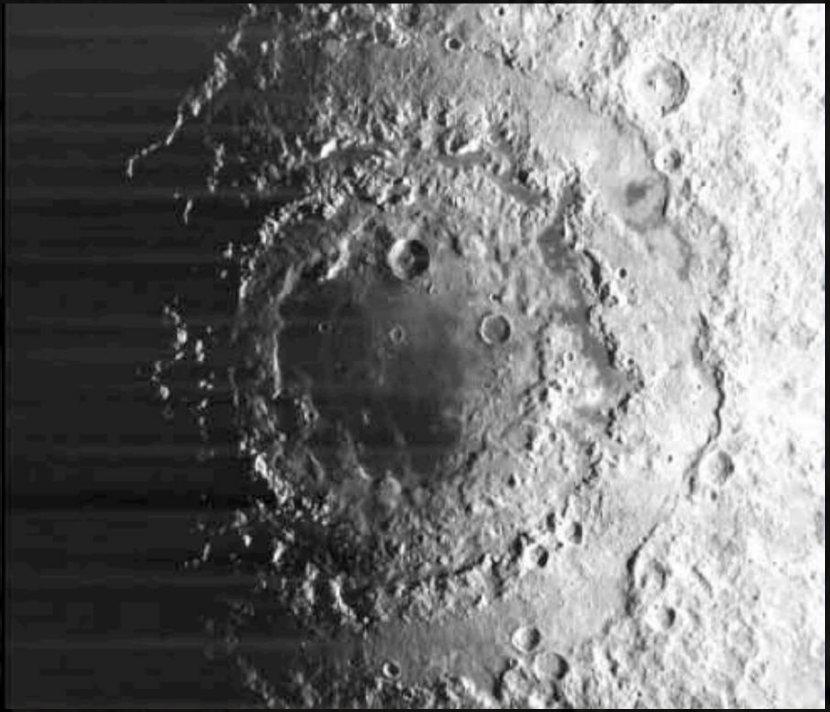
Schrödinger (320km)

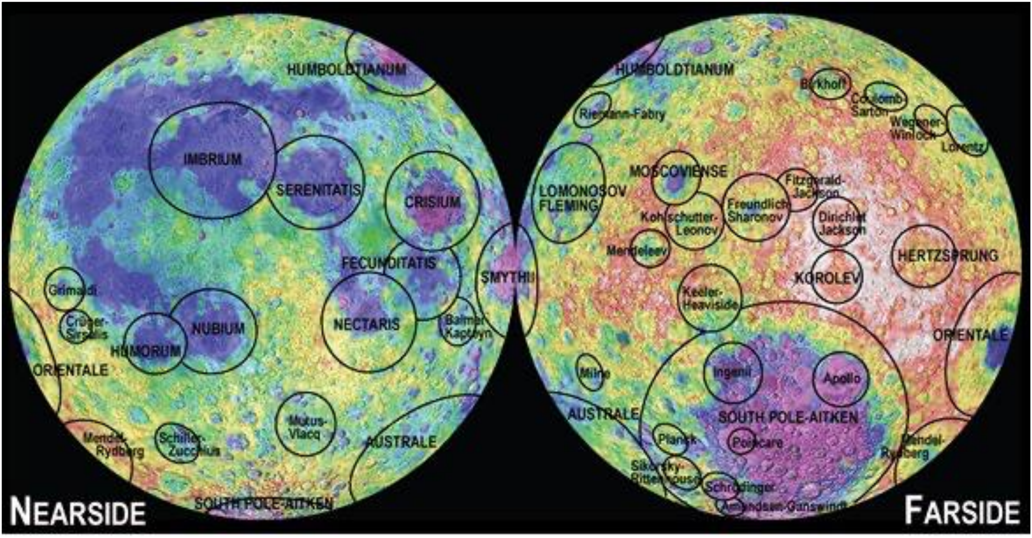


Basins (>300km)

- Multiple rings (ring composition different from surrounding material; likely from interior)
- Impact melt sheet
- Continuous ejecta facies
- Secondary craters
- Basin ejecta asymmetry and rays
- ~50 basins; uniformly distributed across lunar surface
- Basin geology fundamentally makes up the lunar crust
    - Highlands are stacks of basin ejecta subsequently gardened by smaller impacts

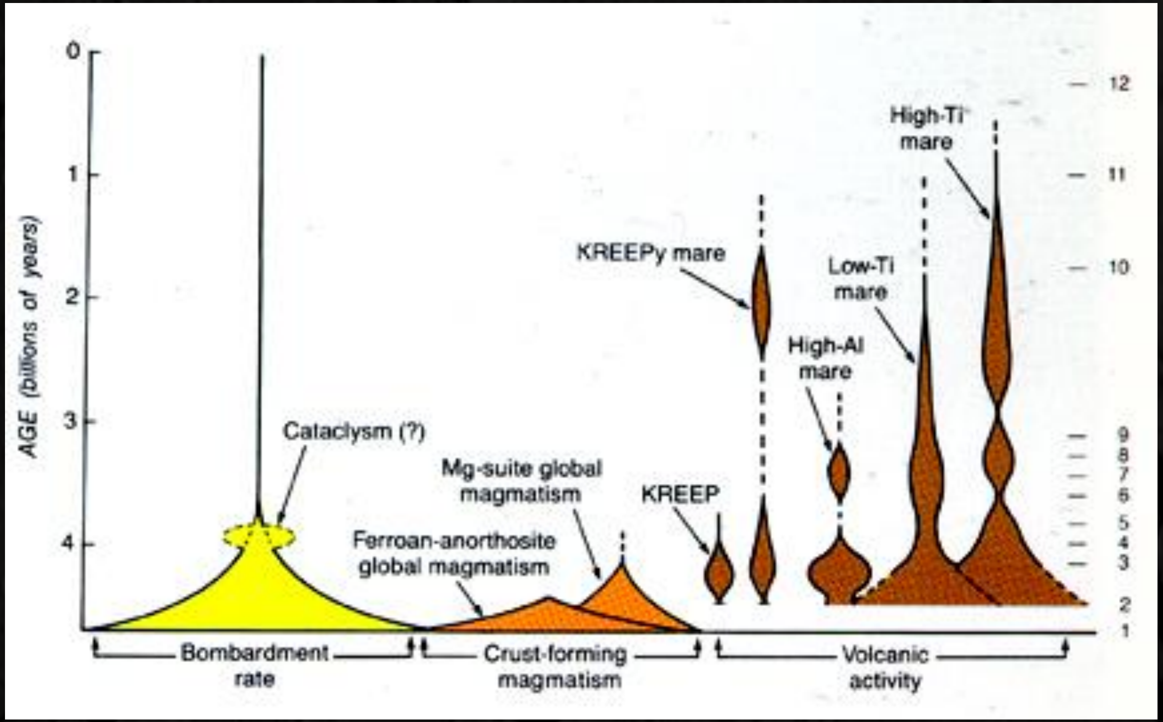
Orientale (920km)





Geology / Geochemistry

- Rock = solid aggregation of minerals
- Mineral = solid chemical compound w/ specific composition and crystal structure
- Glass = formed from rapid cooling of molten rock, lacks internal structural order of mineral
- Regolith = unconsolidated impact debris overlaying bedrock, “soil”
- Breccia = rock composed of other rock pieces and mineral fragments
- Clast = shock-altered fragment in a breccia
- Agglutinate = impact melt composed of glass, mineral, and rock fragments
- Bulk composition of Moon very similar to mantle of Earth; depleted in iron (Fe) due to absence of large iron core
- Relative to Earth: depleted in volatile, light elements (i.e., low boiling point like H, N, C); enriched in refractory elements (i.e., high boiling point like Al, Ca, Ti)



- Man on the Moon
- Tycho impact
- Lichtenberg basalts

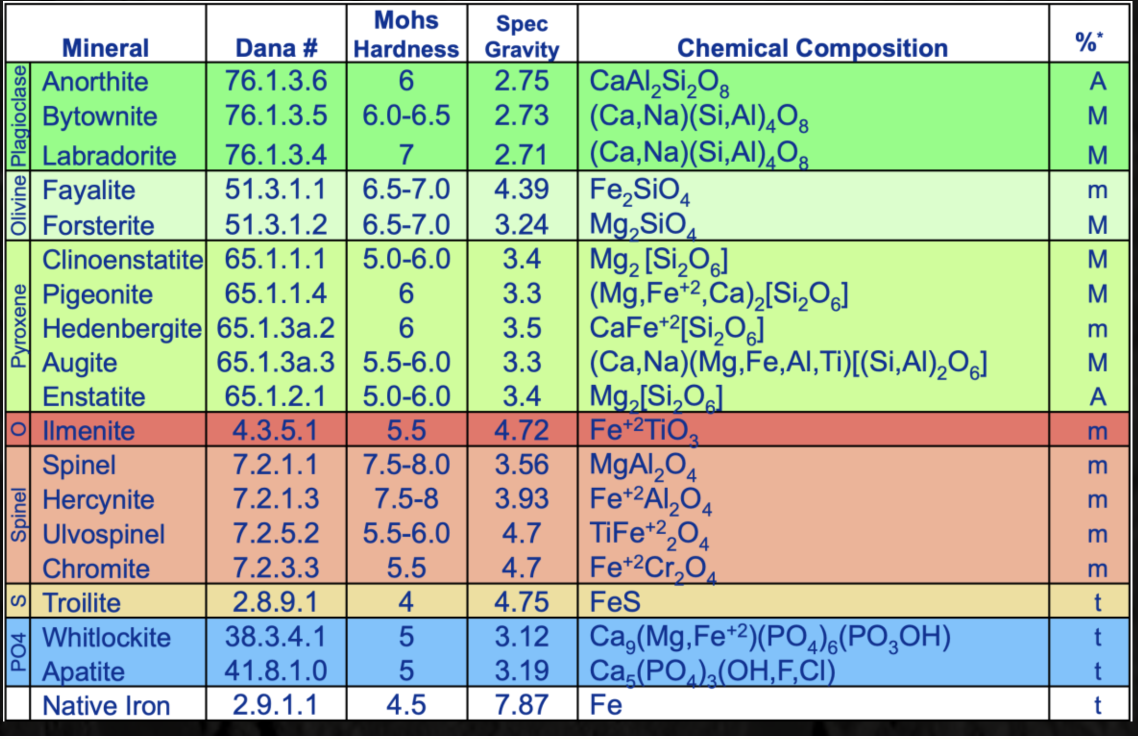
- Copernicus impact

- Imbrium basalts

- Apollo 12 basalts
- Apollo 15 basalts
- Luna 16, 24 basalts
- Apollo 11, 17 basalts
- Orientale, Imbrium form
- Magma solifies
- Moon forms

Geochemistry

- 99% of lunar mass consists of 7 elements: O, Si, Al, Ca, Fe, Mg, Ti
- Most common rocks:
  - basalts (common in the maria, relatively rich in Fe and Ti)
  - anorthosites (common in the highlands, relatively rich in Al, Ca, and Si)
- >95% of crystalline material in rocks from three mineral groups: plagioclase (Al, Ca), pyroxene (Mg, Fe), olivine (Mg, Fe)
- Significance: The mineral constituents of a rock reflect its chemical composition and thermal history.
  - E.g., KREEP = collection of “incompatible” elements left as the last parts of lunar lava to cool (acronym for ”Potassium, rare-earth elements, and phosphorus”)



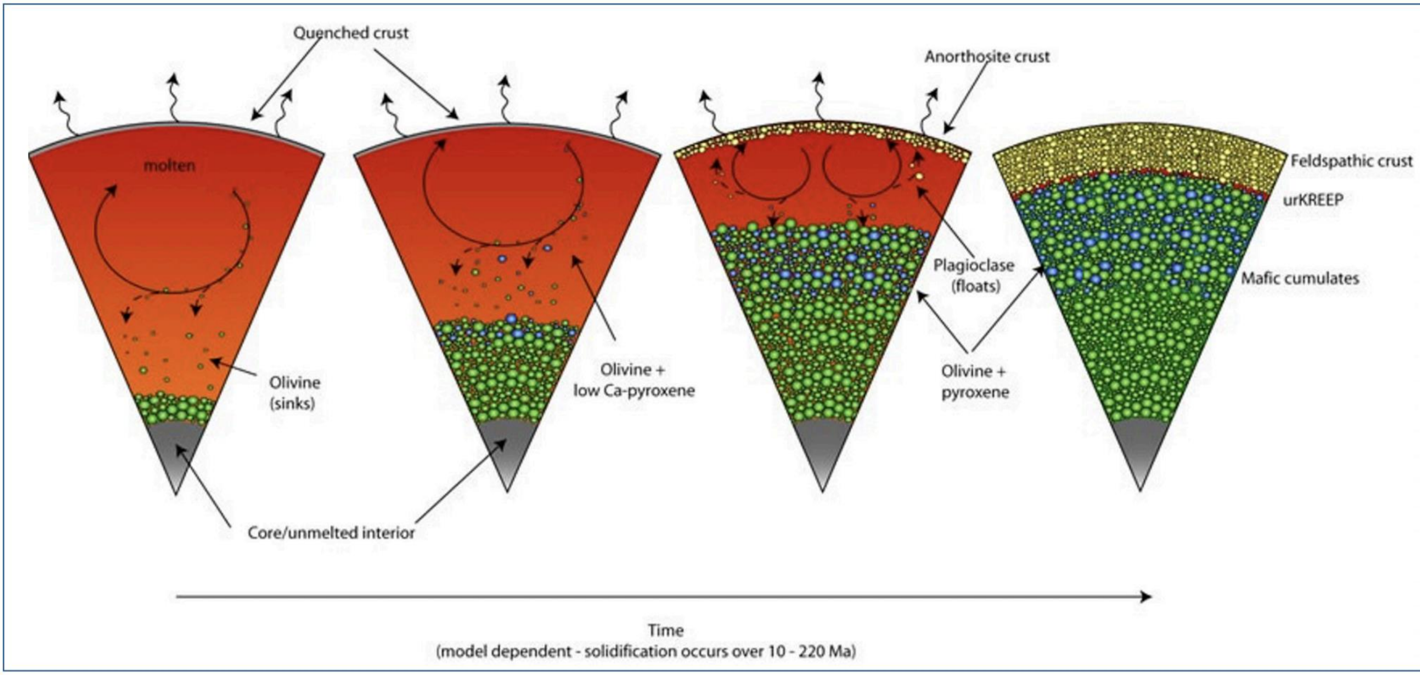
	Mineral	Dana #	Mohs Hardness	Spec Gravity	Chemical Composition	%*
Plagioclase	Anorthite	76.1.3.6	6	2.75	$CaAl_2Si_2O_8$	A
	Bytownite	76.1.3.5	6.0-6.5	2.73	$(Ca,Na)(Si,Al)_4O_8$	M
	Labradorite	76.1.3.4	7	2.71	$(Ca,Na)(Si,Al)_4O_8$	M
Olivine	Fayalite	51.3.1.1	6.5-7.0	4.39	Fe_2SiO_4	m
	Forsterite	51.3.1.2	6.5-7.0	3.24	Mg_2SiO_4	M
Pyroxene	Clinoenstatite	65.1.1.1	5.0-6.0	3.4	$Mg_2[Si_2O_6]$	M
	Pigeonite	65.1.1.4	6	3.3	$(Mg,Fe^{+2},Ca)_2[Si_2O_6]$	M
	Hedenbergite	65.1.3a.2	6	3.5	$CaFe^{+2}[Si_2O_6]$	m
	Augite	65.1.3a.3	5.5-6.0	3.3	$(Ca,Na)(Mg,Fe,Al,Ti)[(Si,Al)_2O_6]$	M
	Enstatite	65.1.2.1	5.0-6.0	3.4	$Mg_2[Si_2O_6]$	A
O	Ilmenite	4.3.5.1	5.5	4.72	$Fe^{+2}TiO_3$	m
Spinel	Spinel	7.2.1.1	7.5-8.0	3.56	$MgAl_2O_4$	m
	Hercynite	7.2.1.3	7.5-8	3.93	$Fe^{+2}Al_2O_4$	m
	Ulvospinel	7.2.5.2	5.5-6.0	4.7	$TiFe^{+2}{}_2O_4$	m
	Chromite	7.2.3.3	5.5	4.7	$Fe^{+2}Cr_2O_4$	m
S	Troilite	2.8.9.1	4	4.75	FeS	t
PO4	Whitlockite	38.3.4.1	5	3.12	$Ca_9(Mg,Fe^{+2})(PO_4)_6(PO_3OH)$	t
	Apatite	41.8.1.0	5	3.19	$Ca_5(PO_4)_3(OH,F,Cl)$	t
	Native Iron	2.9.1.1	4.5	7.87	Fe	t

33%

>5%

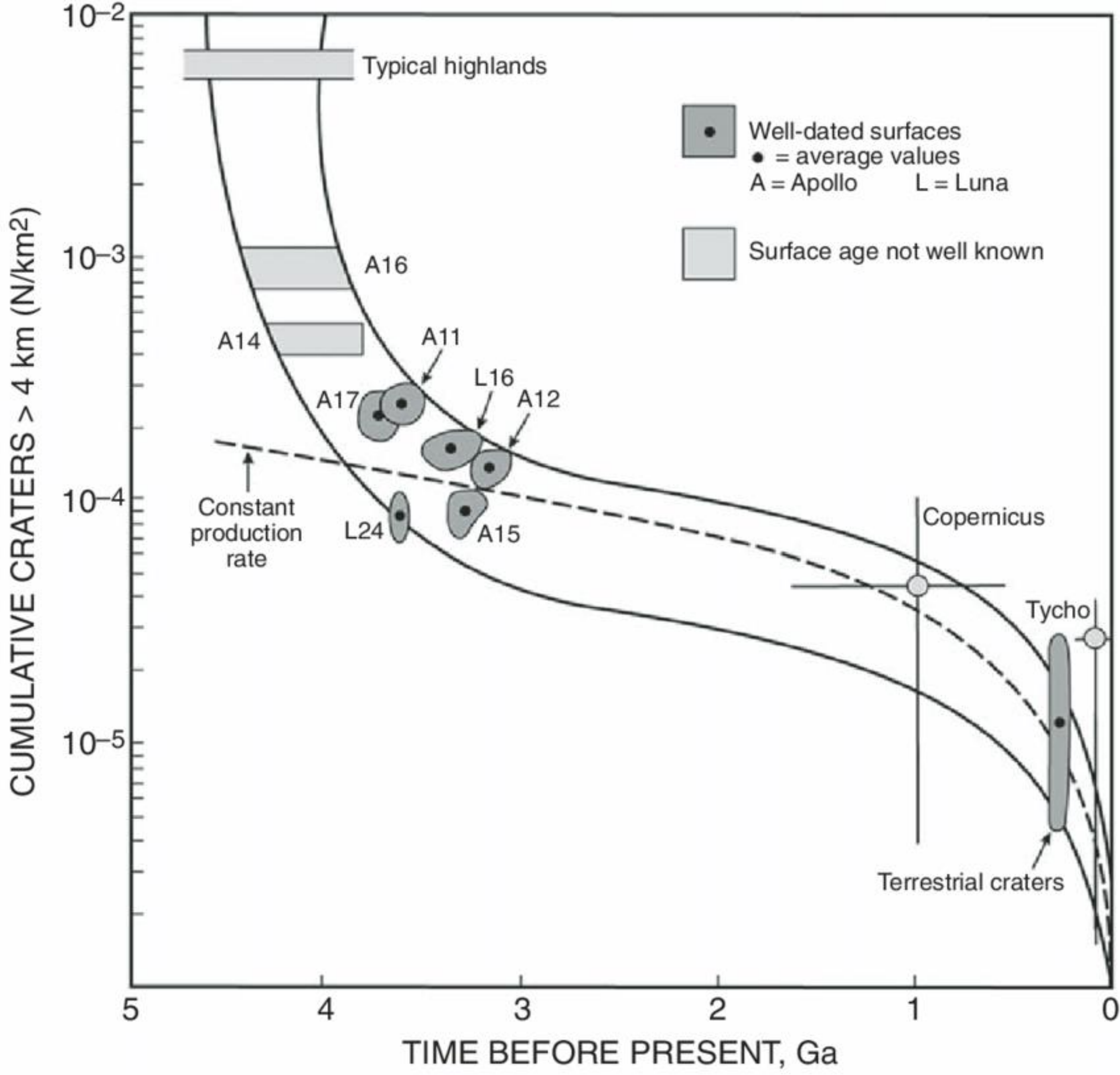
0.1-5%

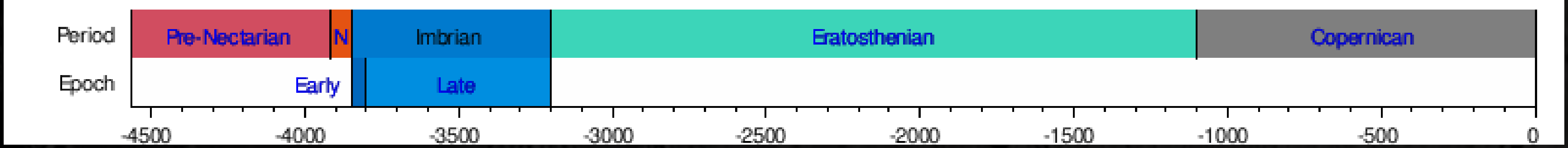
<0.1%



History of the Moon

- Geologic mapping tells us the relative ages of surface features
- Absolute ages determined from samples*
  - Many radiometric dating techniques; active research area
  - Interpretation of absolute dates relies on geologic context / stratigraphy
- Whence the Moon? Giant Impact Model
  - Lunar science community arrived at consensus in a single week in 1984
  - 4.5 Bya: Mars-sized proto-planet, Theia, collided with the proto-Earth, Terra
  - Collision in the direction of Terra's spin
  - High concentration of siderophile elements in Earth's upper mantle from core of Theia; Moon comprised of the remaining vaporized debris of Theia

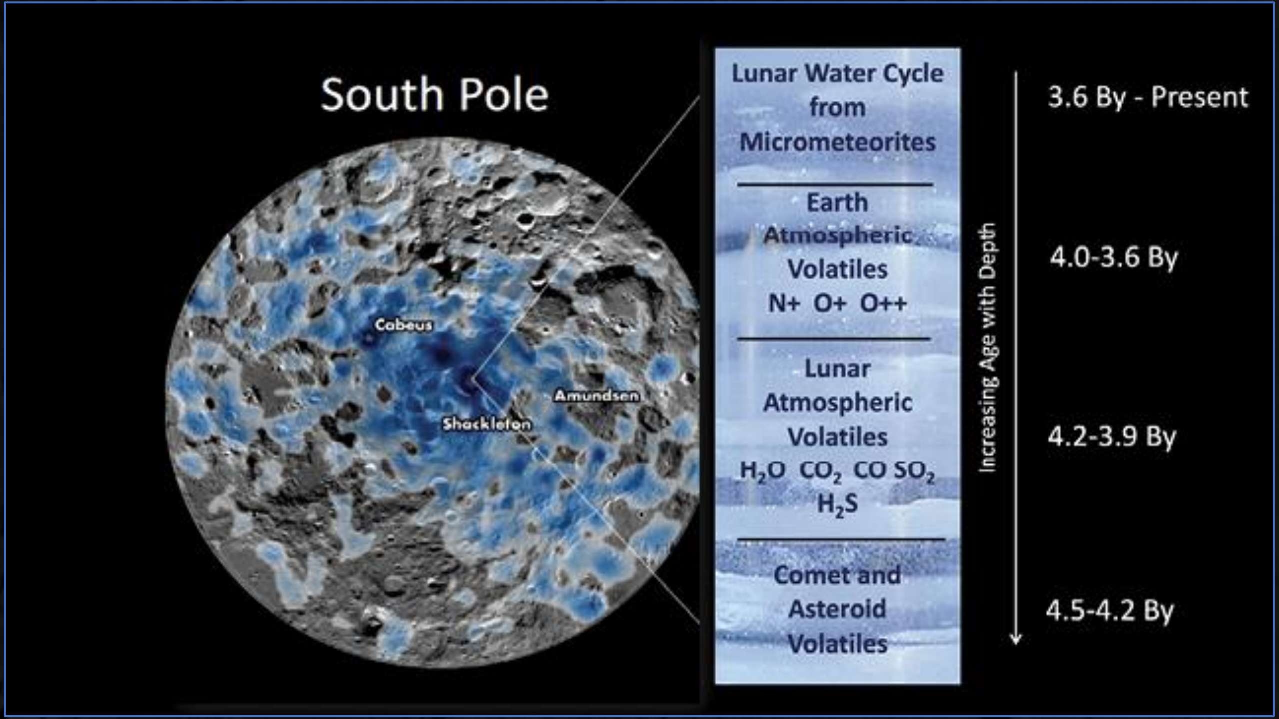




* 300 grams returned by Soviet missions, 380 kg returned by Apollo, 1000 kg lunar meteorites

Volatiles

- Volatile = element with relatively low boiling temperature
- Sources
  - Solar wind: Continual rain of particles from the Sun deposits trace amounts of gas in lunar regolith (H, He, N, Ne, Ar, Kr) (enables study of ancient Sun)
  - Carbonaceous asteroids / comets (peak 4.5-3.5 Ga)
  - Outgassing / volcanism (peak 3.7 – 3.5 Ga, rapid drop after 2 Ga)
  - Magnetic pathway to Earth?
- Permanently shadowed regions (PSRs) contain H_2O and HO
- Age of cold traps bounded by lunar axis stability (~2 Ga) and crater degradation
- Significance:
  - Drinking water
  - Hydrogen could be used for rocket fuel (estimates suggest 1km^2 x 1m thick regolith = enough hydrogen for Space Shuttle launch)
  - Helium isotope ^{3}He could be used for TBD fusion reactor



LuGRE Overview

Mission

- NASA HEOMD payload for CLPS “19D” flight
- Joint NASA/Italian Space Agency mission
- “Do No Harm” class
- Firefly Blue Ghost commercial lander
- Transit+surface observation campaign
- Expected surface duration: one lunar day (~12 Earth days)

Payload objectives

1. Receive GNSS signals at the Moon. Return data and characterize the lunar GNSS signal environment.
2. Demonstrate navigation and time estimation using GNSS data collected at the Moon.
3. Utilize collected data to support development of GNSS receivers specific to lunar use.

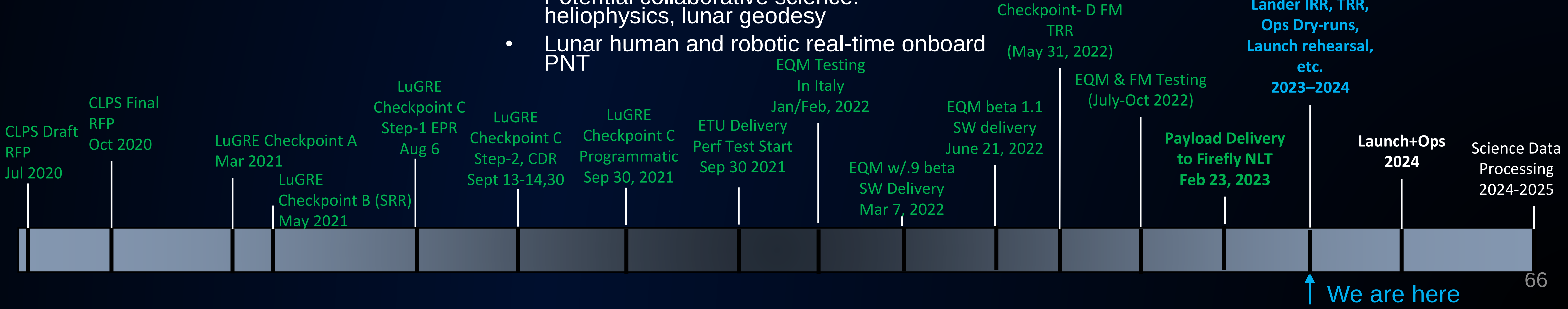
Measurements

- GPS+Galileo, L1/L5 (E1/E5)
- Onboard products: multi-GNSS point solutions, filter solutions
- Observables: pseudorange, carrier phase, raw baseband samples

Utilization

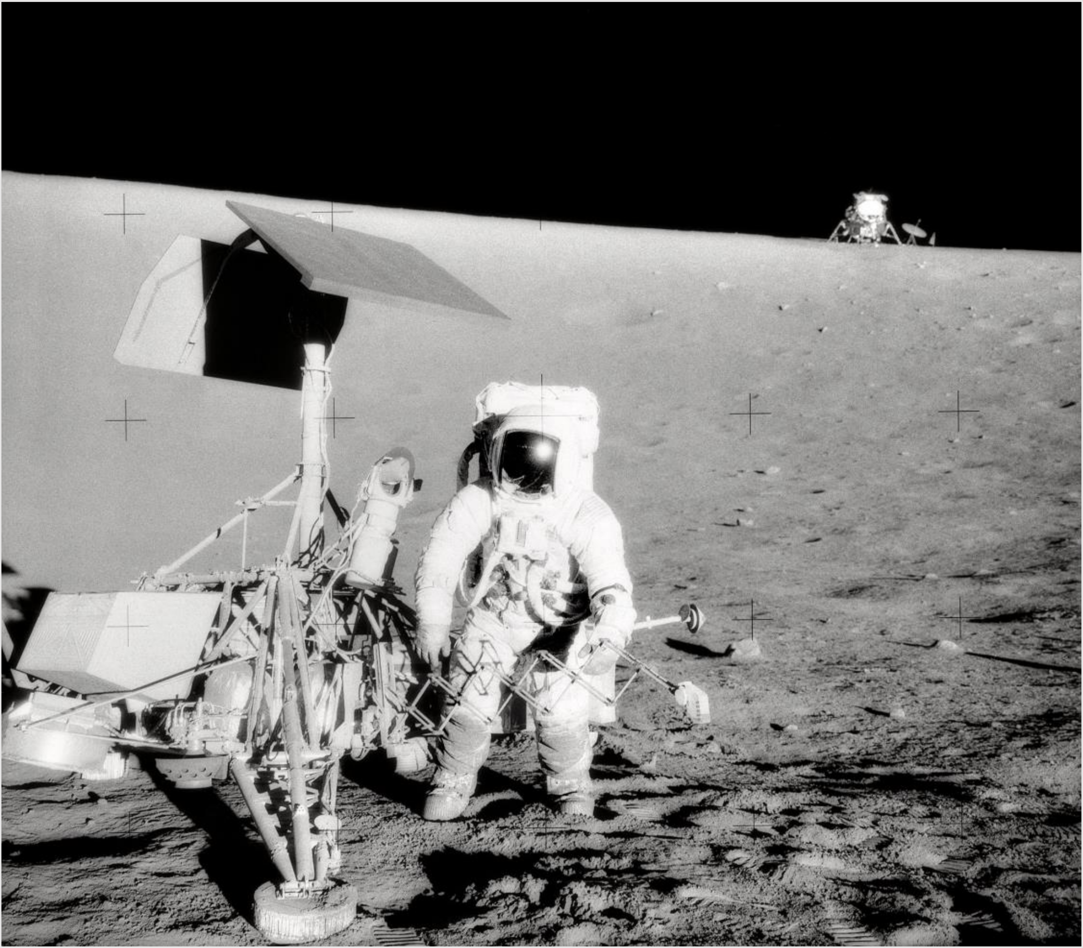
- Data + lessons learned for operational lunar receiver development
- Potential collaborative science: heliophysics, lunar geodesy
- Lunar human and robotic real-time onboard PNT

NASA
CLPS
Commercial Lunar Payload Services



Lunar Navigation

- Apollo missions relied on a global network of tracking stations and active piloting to hit landing targets
- Upcoming lunar missions:100-m performance target for precision landing



Pete Conrad examines Surveyor III spacecraft during Apollo 12