SATELLITE NAVIGATION BEYOND EARTH

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CONTENTS

- SPACE EXPLORATION: NEED FOR NAVIGATION
- EARLY GNSS TRIALS IN OUTER SPACE
- PRINCIPLE OF GNSS NAVIGATION ABOVE GNSS ALTITUDE
- STUDY RESULTS AND RUNNING PROJECTS
- OTHER MEANS OF GNSS NAVIGATION IN OUTER SPACE
- CONCLUSIONS

AFTER APOLLO 11 – 1969
BACK TO THE MOON AND STAY...

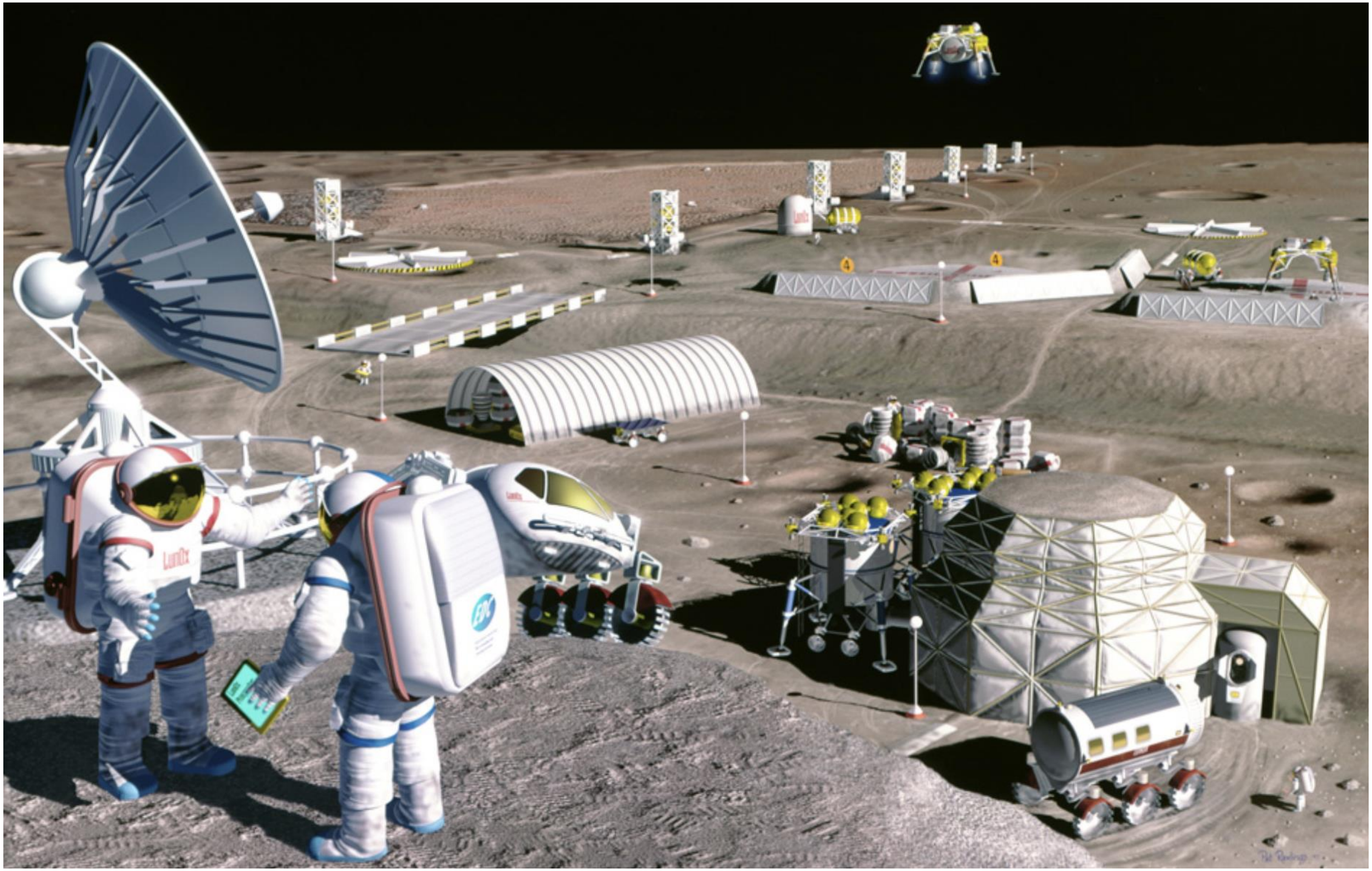


Image Credit: SAIC/Pat Rawlings

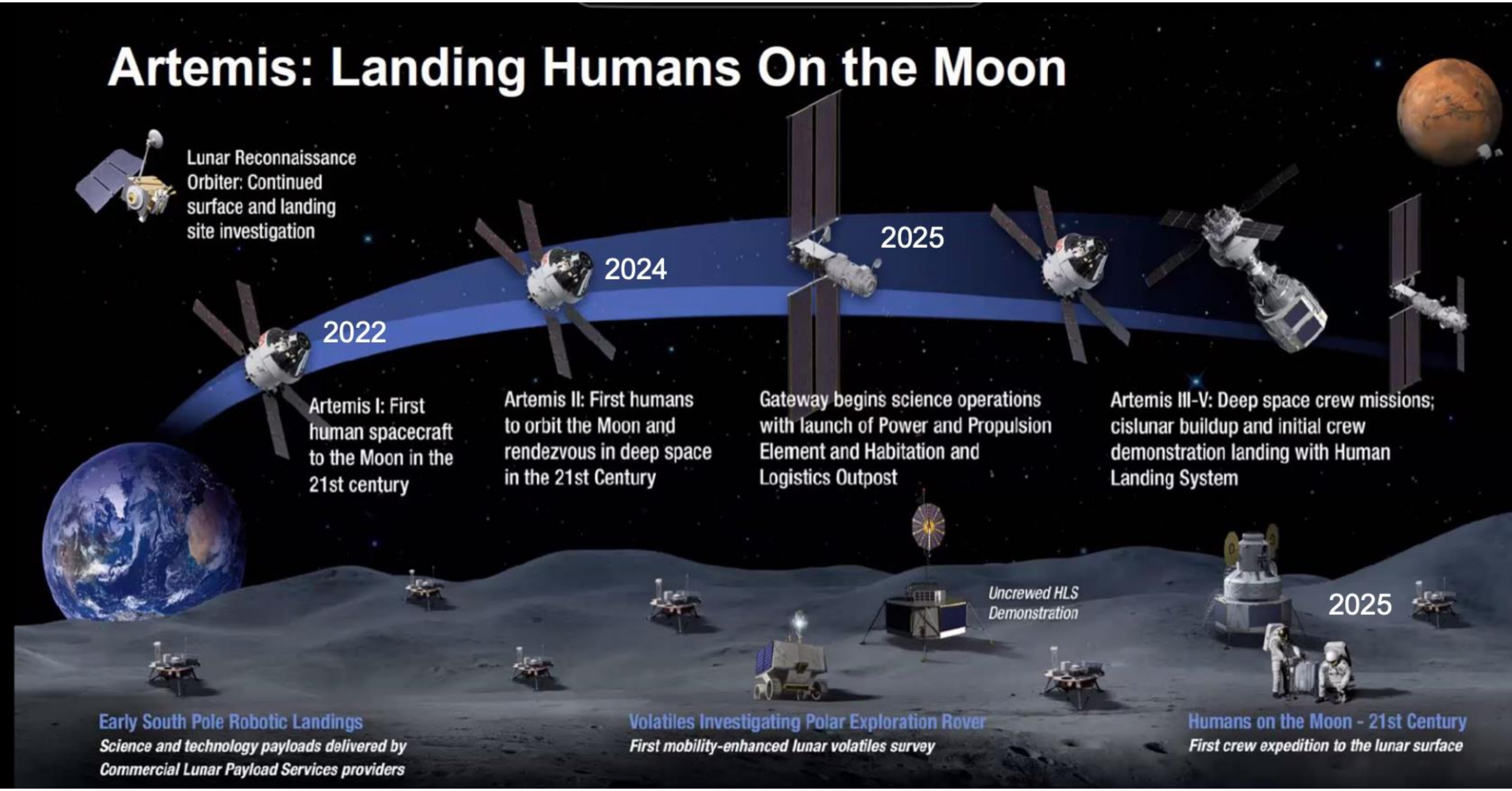
NEED FOR NAVIGATION IN SPACE

- Over 250 moon missions planned already for this decade
- **All require Com & Nav provision means !**

- Many simulation studies already carried out w/r use of GNSS

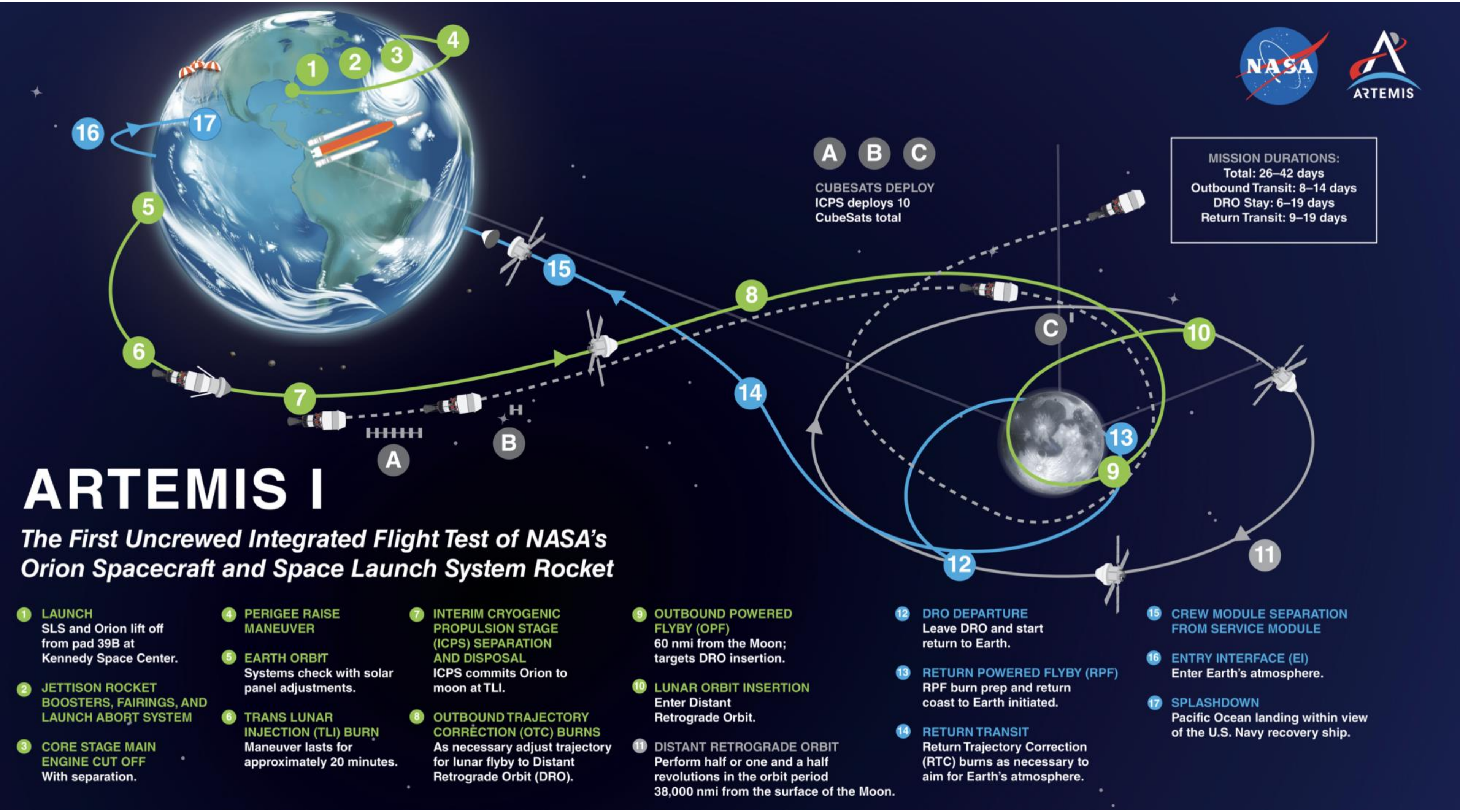
- Big projects going on:
  - NASA: **ARTEMIS**
  - ESA **Moonlight Initiative**: Lunar Communications and Navigation Services (LCNS)
  - **Chinese Lunar Exploration Program** (CLEP), also known as the **Chang'e Project**

NASA‘s ARTEMIS PROGRAM



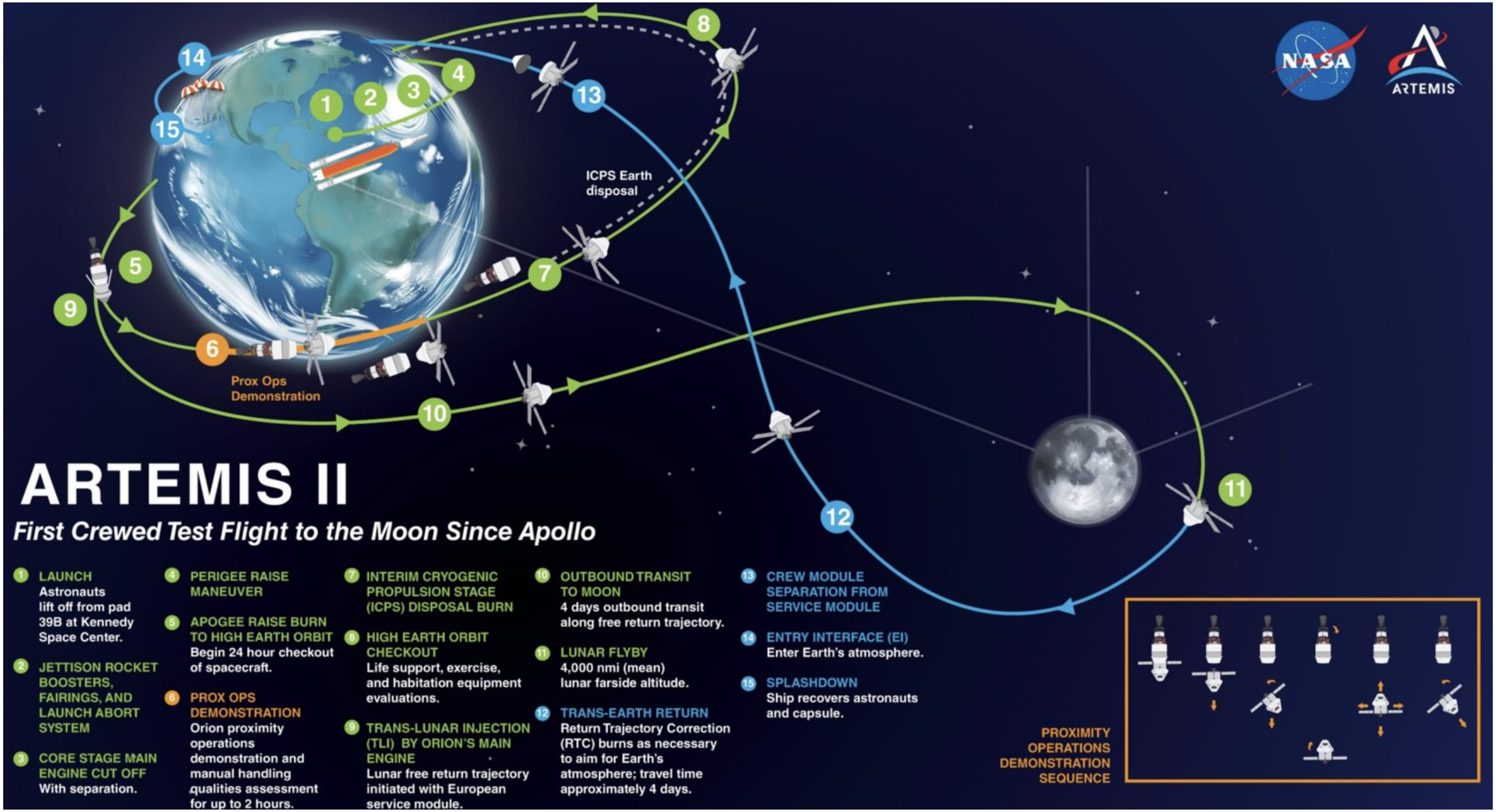
Courtesy: ESA

ARTEMIS I



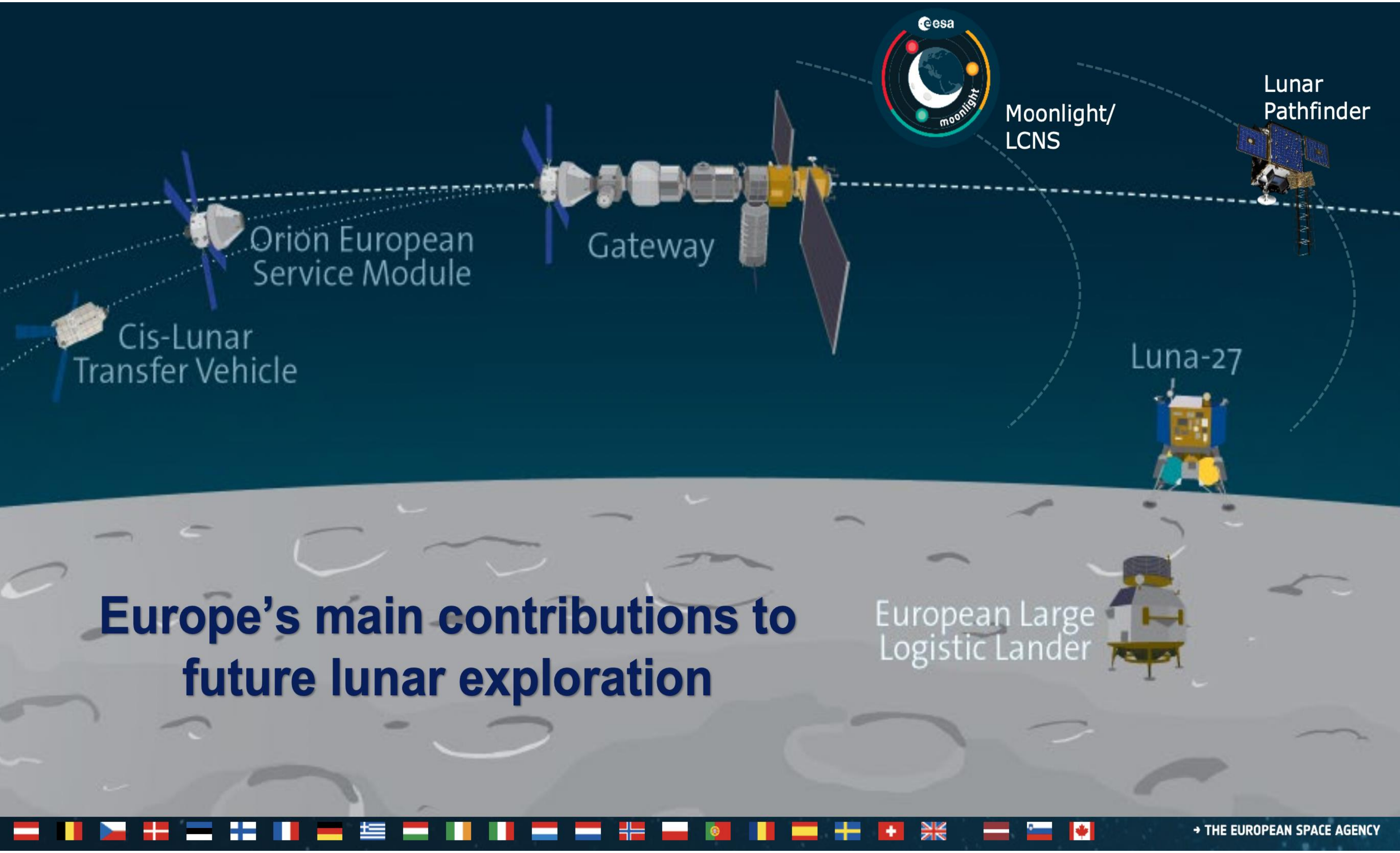
Courtesy: NASA

ARTEMIS II



Courtesy: NASA

ESA's MOONLIGHT



Recall of ESA Roadmap vision for Lunar Navigation Services

esa

Phase 1: Use of Existing GNSS Systems (2023 – 2027)	Phase 2: Moonlight NAV Initial Services (2027 – 2035)	Phase 3: Moonlight NAV enhanced services (2035 – onwards)
Preliminary Lunar PNT services Adequate for Earth-to-Moon transfer and Lunar orbit	**Moonlight Lunar PNT services** High improvement of lunar orbit PNT services Initial PNT services for lunar landing and lunar surface (South Pole coverage)	**Enhanced Moonlight Lunar PNT services** Full lunar surface coverage Improved PNT accuracy and availability services Integrity for PNT safety related applications
Earth-based GNSS (Galileo and GPS) Use of high-sensitivity GNSS space receivers with high-gain antennas **Lunar Pathfinder GNSS Payload IoD**	Earth-based GNSS (Galileo and GPS) Initial Moonlight Lunar Navigation Satellites constellation GNSS-like services **MOONLIGHT / LCNS Initial Services**	Enhanced Lunar Communication and Navigation Satellites constellation Moon surface PNT Beacons / Local PNT Moon augmentations **MOONLIGHT / LCNS: Enhanced Services**

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→ THE EUROPEAN SPACE AGENCY

ROADMAP FOR LUNAR NAVIGATION SERVICES

Phase 1: Use of Existing GNSS Systems (2022 – 2025)	Phase 2: Enhancing GNSS with Lunar Communication and Navigation System (2025–2035)	Phase 3: Towards an autonomous PNT Lunar System (2035–onwards)
Preliminary Lunar PNT services (low accuracy and availability, low lunar surface coverage, very fast time to service)	**Initial Lunar PNT services** (improved accuracy and availability, lunar surface service focused on Moon South Pole)	**Full Lunar PNT services** (final accuracy and availability targets, complete lunar surface coverage, high number of users, providing potentially integrity for safety applications)
Existing GNSS Systems (Galileo and GPS) Use of high-sensitivity GNSS space receivers with high-gain antennas	Existing GNSS Systems (Galileo and GPS) 3 to 4 Lunar Communication and Navigation Satellites and ground infrastructure (LCNS) 1 or 2 Moon surface PNT Beacons	3 to 4 Lunar Communication and Navigation Satellites and ground infrastructure (LCNS) Additional Lunar orbiting satellites Additional Moon surface PNT Beacons Optional: Existing GNSS Systems

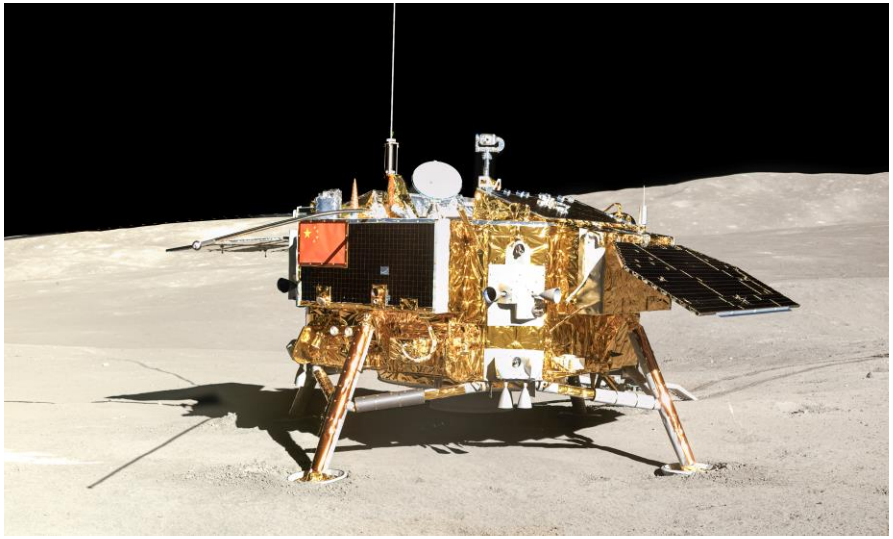
TABLE 3 Roadmap vision for lunar navigation services

CHINESE LUNAR EXPLORATION PROGRAM CHANG'S

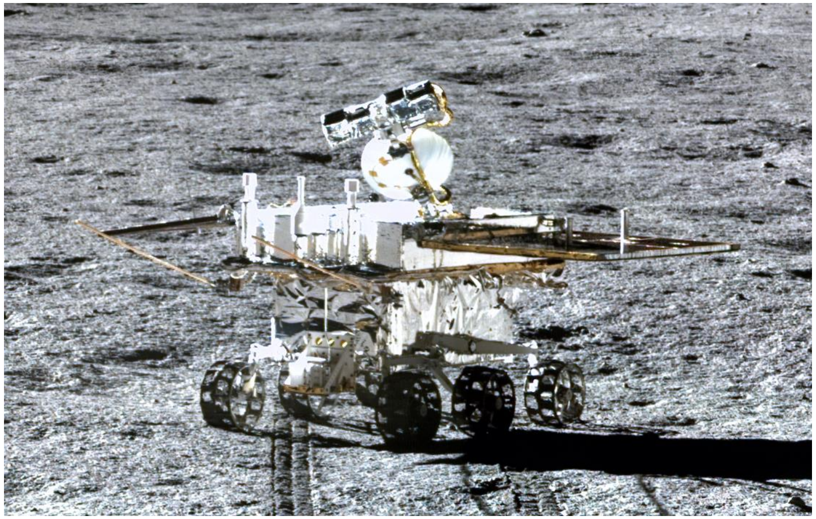
中国探月
CLEP

PHASE 1. ORBITAL MISSIONS

PHASE 2. SOFT LANDERS / ROVERS



Chang's 4 lander on the moon



Yutu-2 rover on the moon (Jan 2019)

PHASE 3. SAMPLE-RETURN

PHASE 4. LUNAR ROBOTIC RESEARCH STATION

CHINESE LUNAR EXPLORATION PROGRAM CHANG'S

Mission	Launch Date	Launch Vehicle	Orbital Insertion Date	Landing Date	Return Date	Notes	Status	
							Main Mission	Extended Mission
Phase 1								
Chang'e 1	24 Oct 2007	Long March 3A	7 Nov 2007	1 Mar 2009	-	Lunar orbiter; first Chinese lunar mission.	Success	-
Chang'e 2	1 Oct 2010	Long March 3C	6 Oct 2010	-	-	Lunar orbiter; following lunar orbit mission flew extended mission to 4179 Toutatis.	Success	Success
Phase 2								
Chang'e 3	1 Dec 2013	Long March 3B	6 Dec 2013	14 Dec 2013	-	Lunar lander and rover; first Chinese lunar landing, landed in Mare Imbrium with Yutu 1.	Success	Ongoing
Queqiao 1	20 May 2018	Long March 4C	14 Jun 2018	-	-	Relay satellite located at the Earth-Moon L_2 point in order to allow communications with Chang'e 4.	Success	Ongoing
Chang'e 4	7 Dec 2018	Long March 3B	12 Dec 2018	3 Jan 2019	-	Lunar lander and rover; first ever soft landing on the Far side of the Moon, landed in Von Karman crater with Yutu-2.	Success	Ongoing
Phase 3								
Chang'e 5-T1	23 Oct 2014	Long March 3C	10 Jan 2015	-	31 Oct 2014	Experimental test flight testing technologies ahead of first Lunar sample return; tested return capsule and lunar orbit autonomous rendezvous techniques and other maneuvers.	Success	Ongoing
Chang'e 5	23 Nov 2020	Long March 5	28 Nov 2020	1 Dec 2020	16 Dec 2020	Lunar orbiter, lander, and sample return; which landed near Mons Rümker and returned 1731g of lunar soil to Earth. The service module made a visit to Lagrange point L1 and also performed a lunar flyby in extended mission.[25]	Success	Ongoing

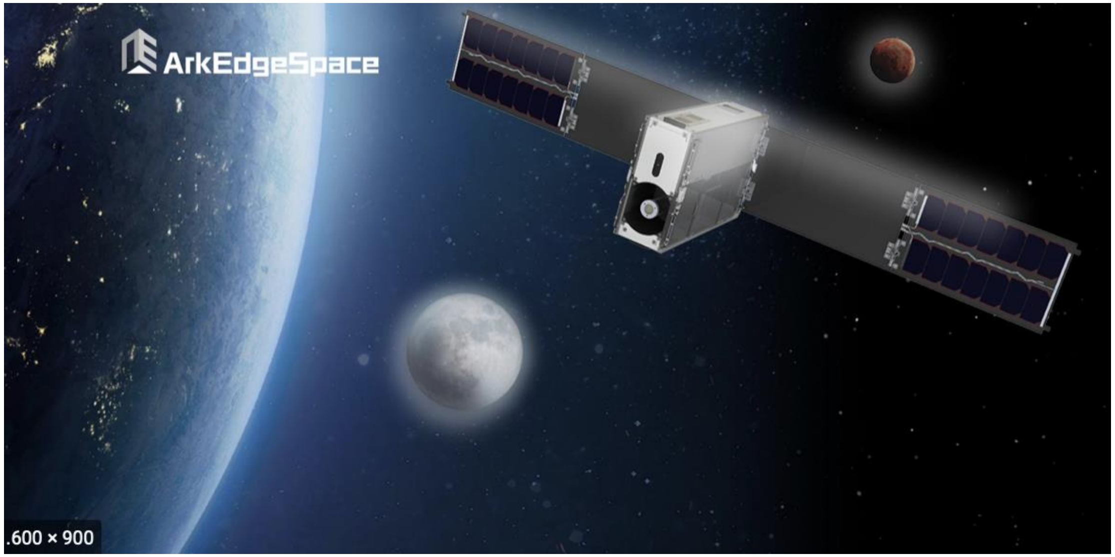
CHINESE LUNAR EXPLORATION PROGRAM CHANG'S

中国探月
CLEP

Mission	Launch Date	Launch Vehicle	Mission Type	Notes
Phase 4				
Chang'e 6	2024	Long March 5	Lunar sample return	Lunar orbiter, lander, and sample return; scheduled to land at the South Pole–Aitken basin near the lunar south pole.[16]
Chang'e 7	2024[26]	Long March 5	Lunar surface survey	Lunar orbiter, lander, rover, and mini-flying probe; expected to perform in-depth exploration of the lunar south pole to look for resources.[19]
Chang'e 8	2027	Long March 5	Lunar surface survey	Full mission details are currently unknown; may test new technologies including an ISRU system, ahead of future crewed exploration of the Moon.

JAPAN: A Study of Developing Lunar Navigation Satellite System and Lunar-Earth Communication System

- Japan Aerospace Exploration Agency (JAXA) awarded a contract to ArkEdge Space beginning of 2022
- One of the Strategic Programs for Accelerating Research, Development and Utilization of Space Technology (STARDUST R&D : "Positioning and Communication," "Construction," "Energy, "Food")



Reference:
AIThority.com

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EQUATOR-S LAUNCHED 2 DEC 1997

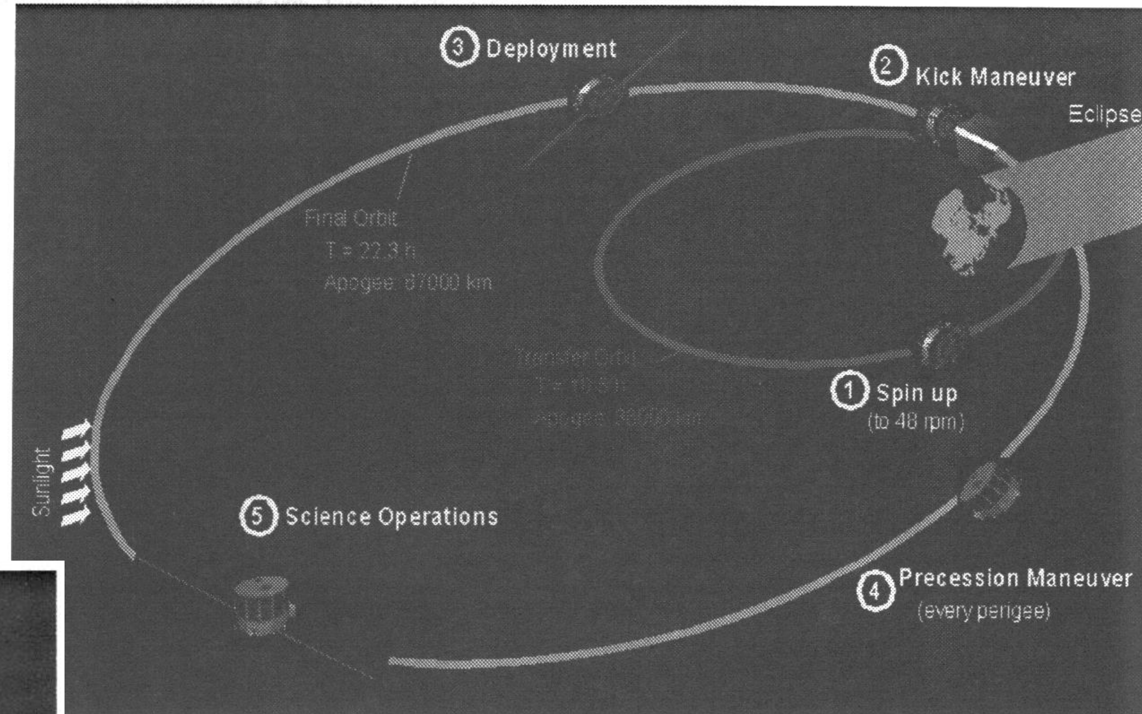

Fig. 6: Equator-S Mission Events

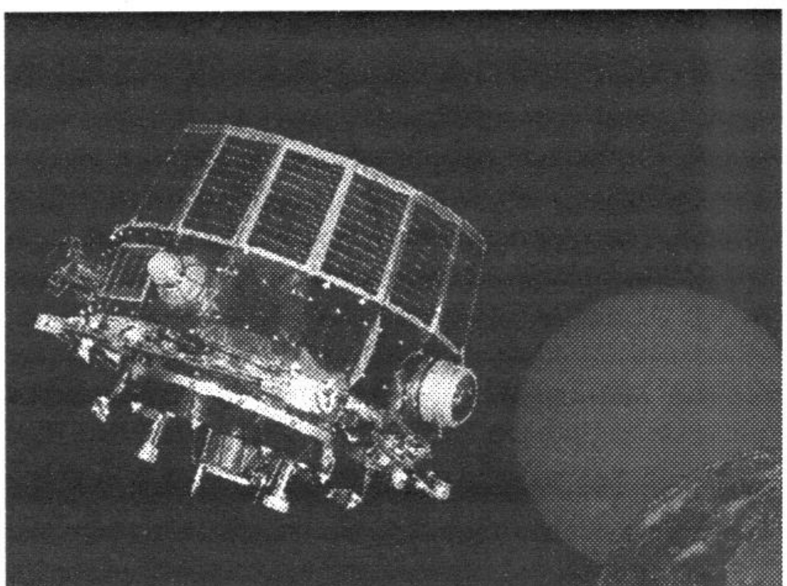

Fig. 1: German Small Satellite Equator-S

GOAL: Investigation of the Earth‘s magnetic field and interactions with the magnetic field of the Sun

EQUAROR-S TECHNO-EXPERIMENT

GOAL: Investigation of GPS data reception conditions in very high altitudes

Prime Investigator:
Institute of Geodesy and Navigation, University FAF Munich

Tracking GPS Above GPS Satellite Altitude: Results of the GPS Experiment on the HEO Mission Equator-S
Oliver Balbach, Bernd Eissfeller, Günter W. Hein, T. Zink, Werner Enderle, Michael Schmidhuber, Norbert Lemke

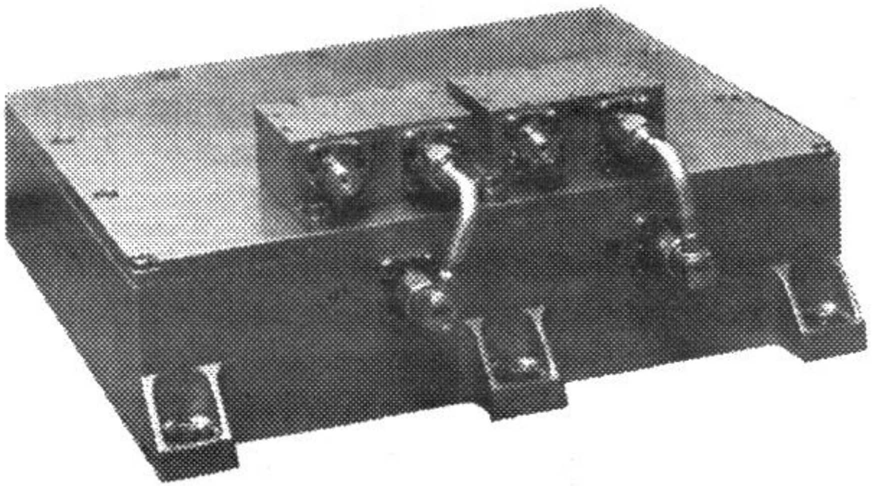

Fig. 4: Motorola Viceroy™ GPS Receiver

03-Dec-1997	PRN24: 34,000 km
03-Dec-1997	PRN5: 25,000 km
04-Dec-1997	PRN5: 34,000 km
04-Dec-1997	PRN19: 34,000 km
09-Dec-1997	PRN3: 23,000 km
11-Dec-1997	PRN3: 24,000 km
13-Dec-1997	Side Lobe Reception
19-Feb-1998	
30-Mar-1998	
31-Mar-1998	PRN22: 45,000 km
31-Mar-1998	PRN30: 61,000 km

Tab. 5: GPS Signal Tracking Altitude Results

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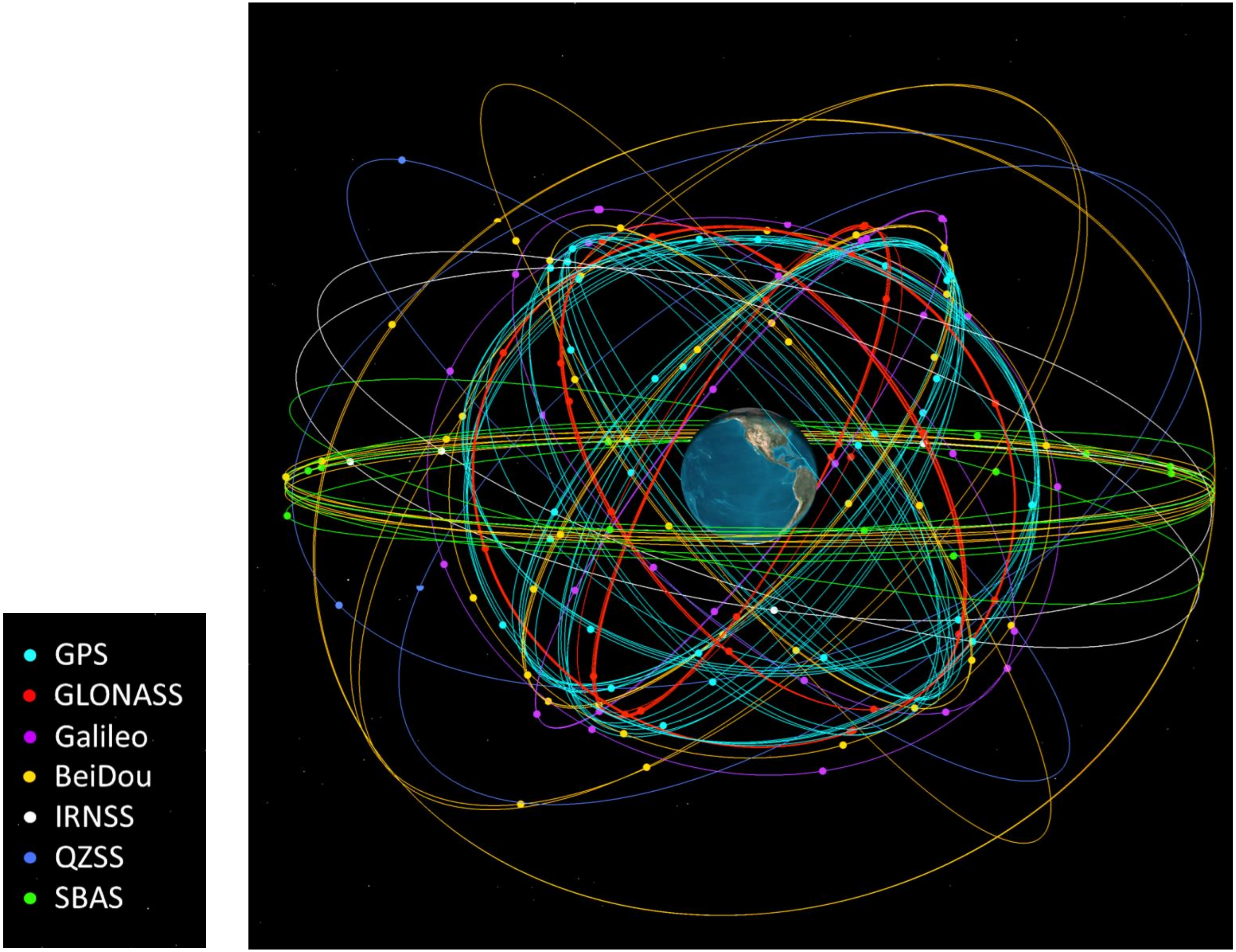
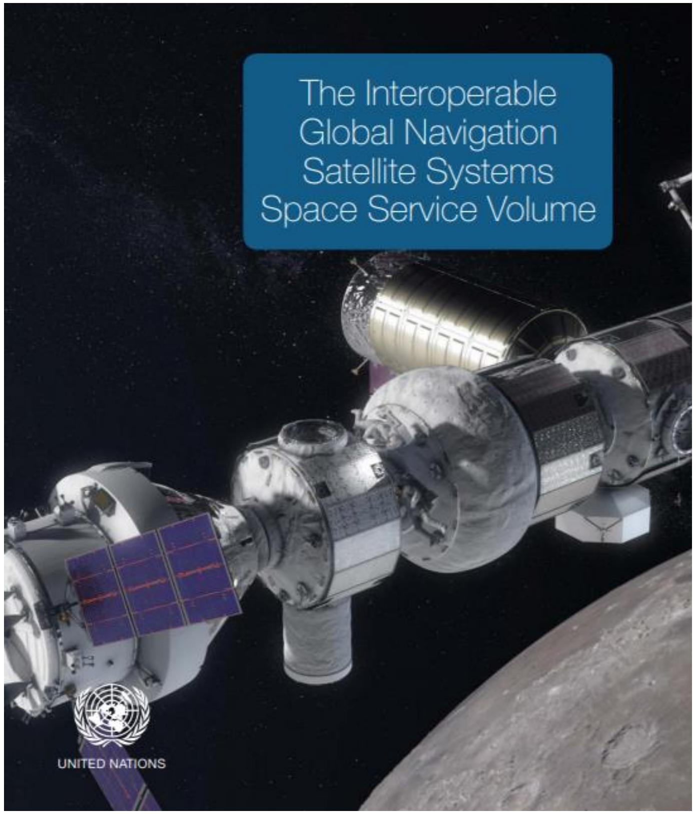
SATELLITE NAVIGATION SYSTEMS



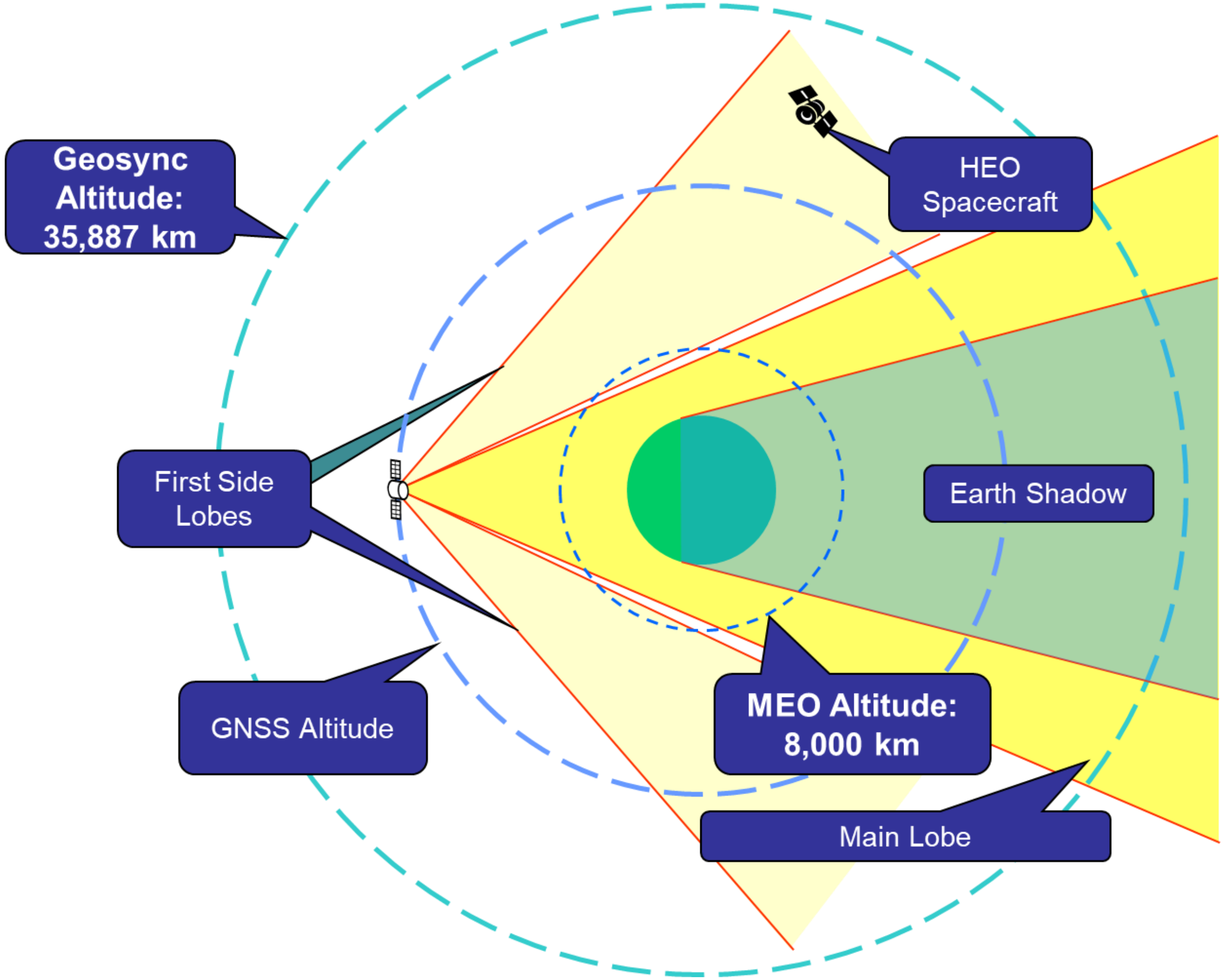
SPACE SERVICE VOLUME AT ICG

- ICG (International Committee on GNSS) established dedicated group to address the establishment of interoperable GNSS SSV among all service providers
- SSV booklet
  - Established jointly with contributions from all service providers
  - SSV template included specifying the contributions from every system
  - SSV template information can be scaled by user to specific mission needs



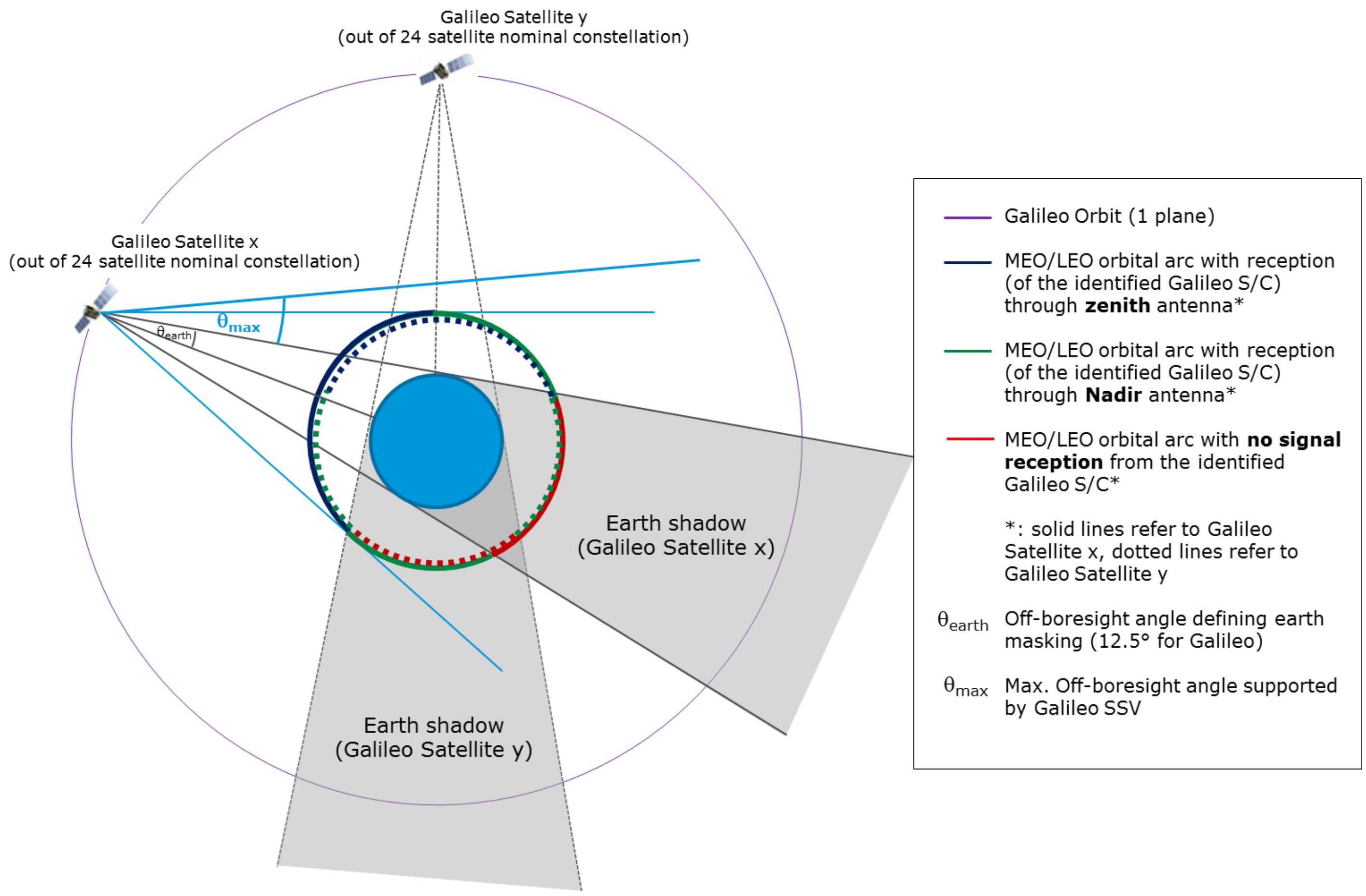
(http://www.unoosa.org/res/oosadoc/data/documents/2018/stspace/stspace75_0_html/st_space_75E.pdf)

RECEPTION GEOMETRY FOR GNSS SIGNALS IN SPACE



Courtesy: Stefan Wallner, ESA

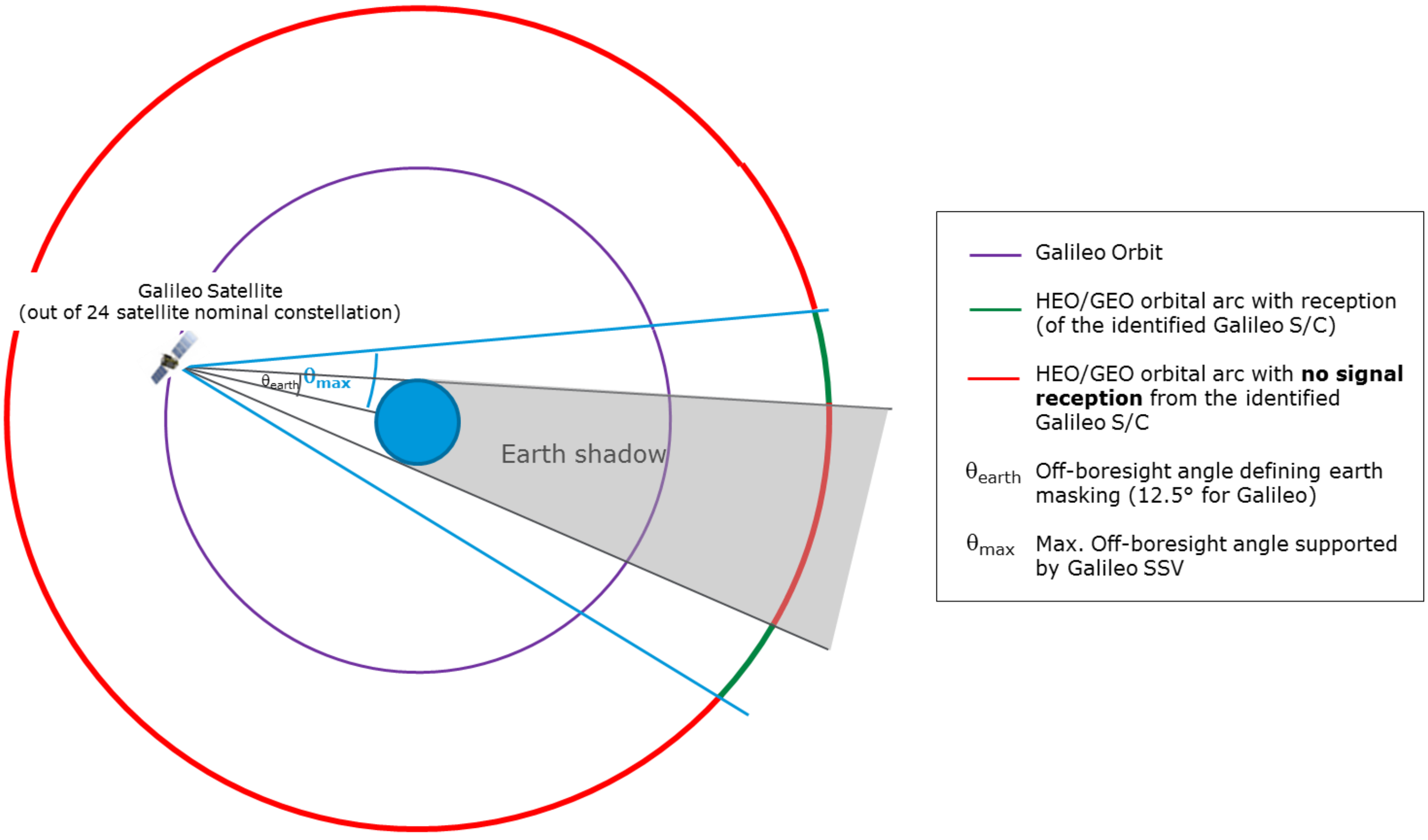
SSV GEOMETRY FOR LEO/MEO



- Important note: It is assumed that the user has capability to receive signals from
  - NADIR direction and
  - Zenith direction

Courtesy: Stefan Wallner, ESA

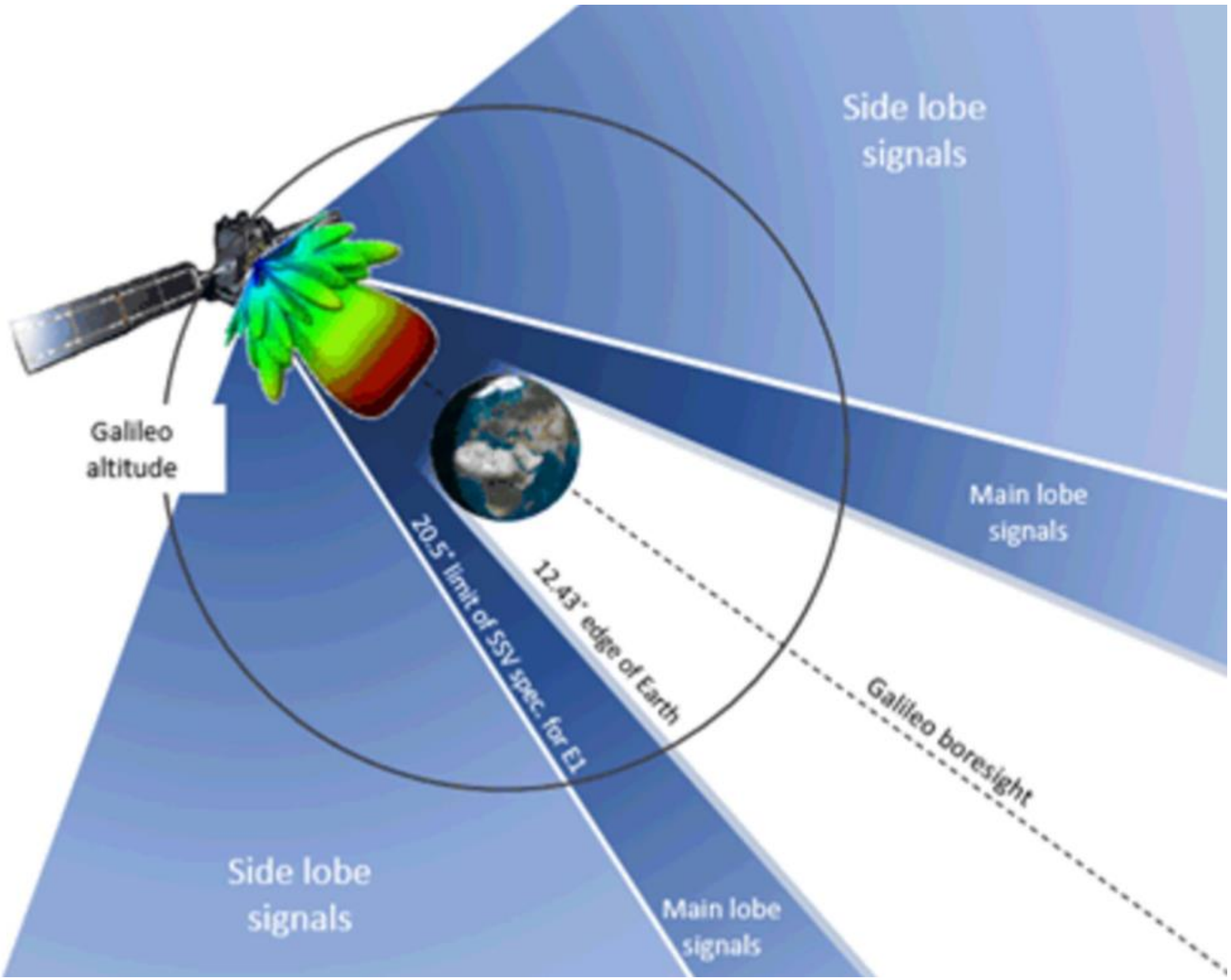
SSV GEOMETRY FOR GEO/HEO



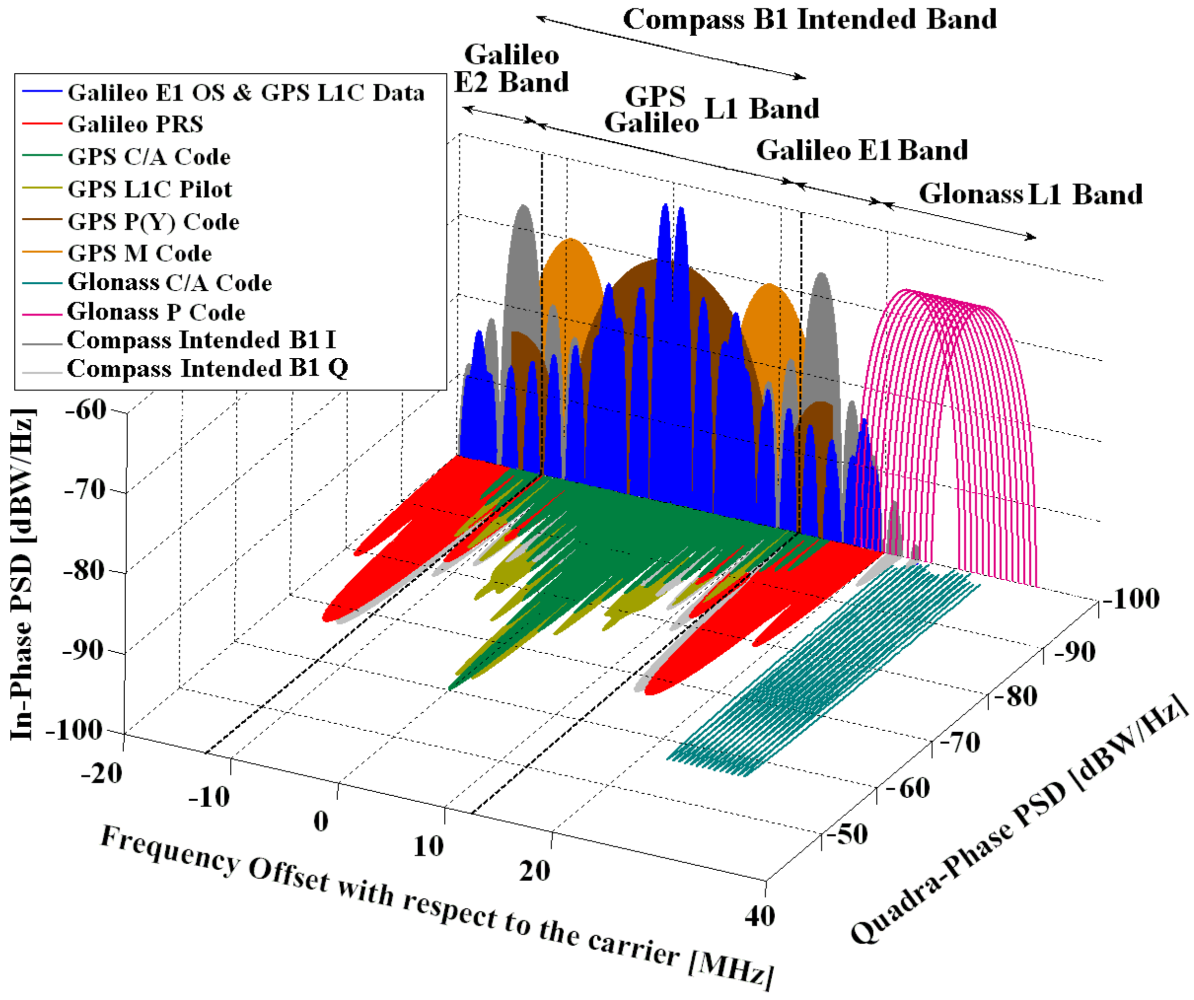
- Important note: It is assumed that the user has capability to receive signals from NADIR

Courtesy: Stefan Wallner, ESA

GNSS SIGNAL TRANSMISSION

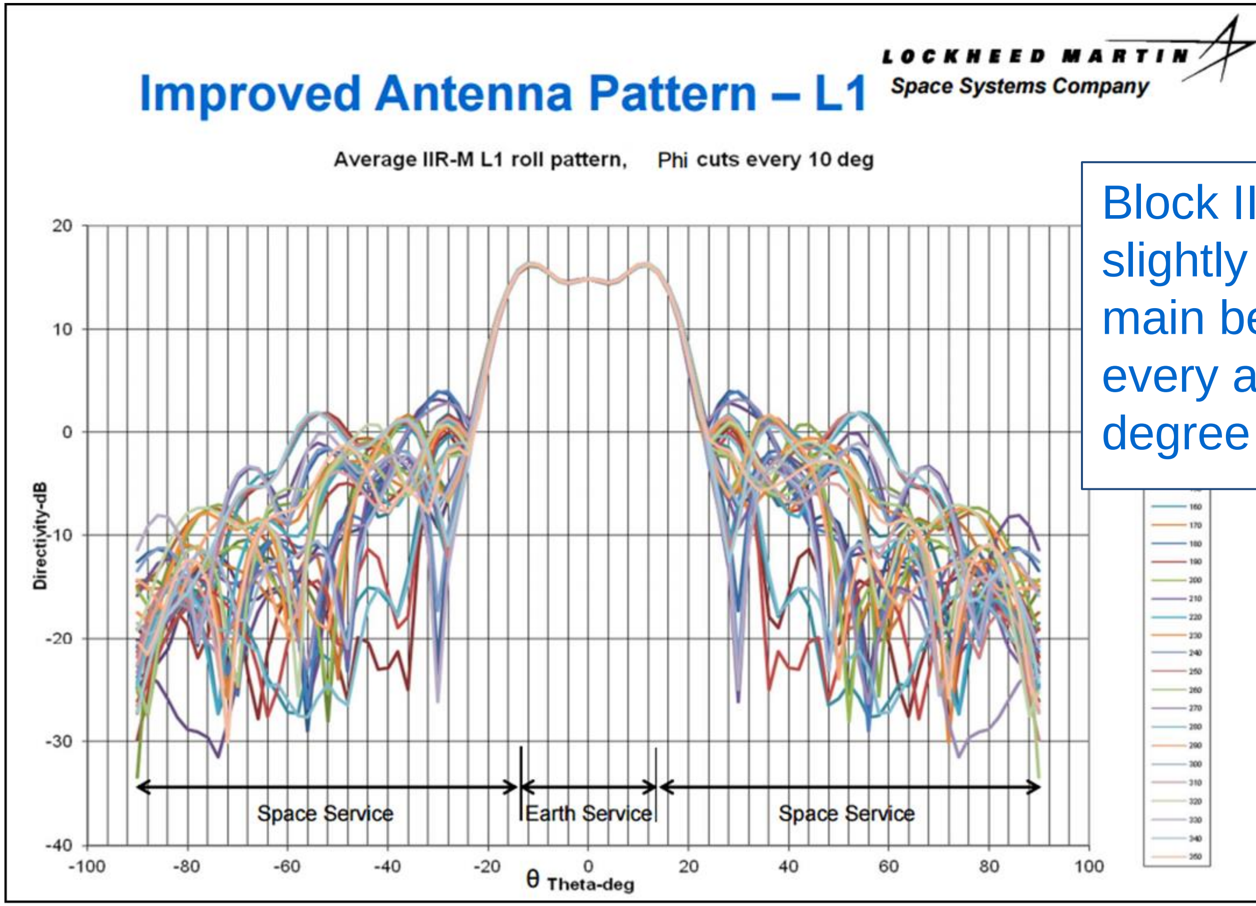


GNSS SIGNALS IN E1/L1



SATELLITE ANTENNA GAIN PATTERN

- GPS Measured Antenna Gain Pattern (Block IIR-M)



Antenna Side Lobes
High gain variation vs. azimuth

Antenna Main Beam
good control of gain vs. azimuth

Antenna Side Lobes
High gain variation vs. azimuth

Block IIR-M provides slightly wider antenna main beam (for SSV every additional degree in θ counts!)

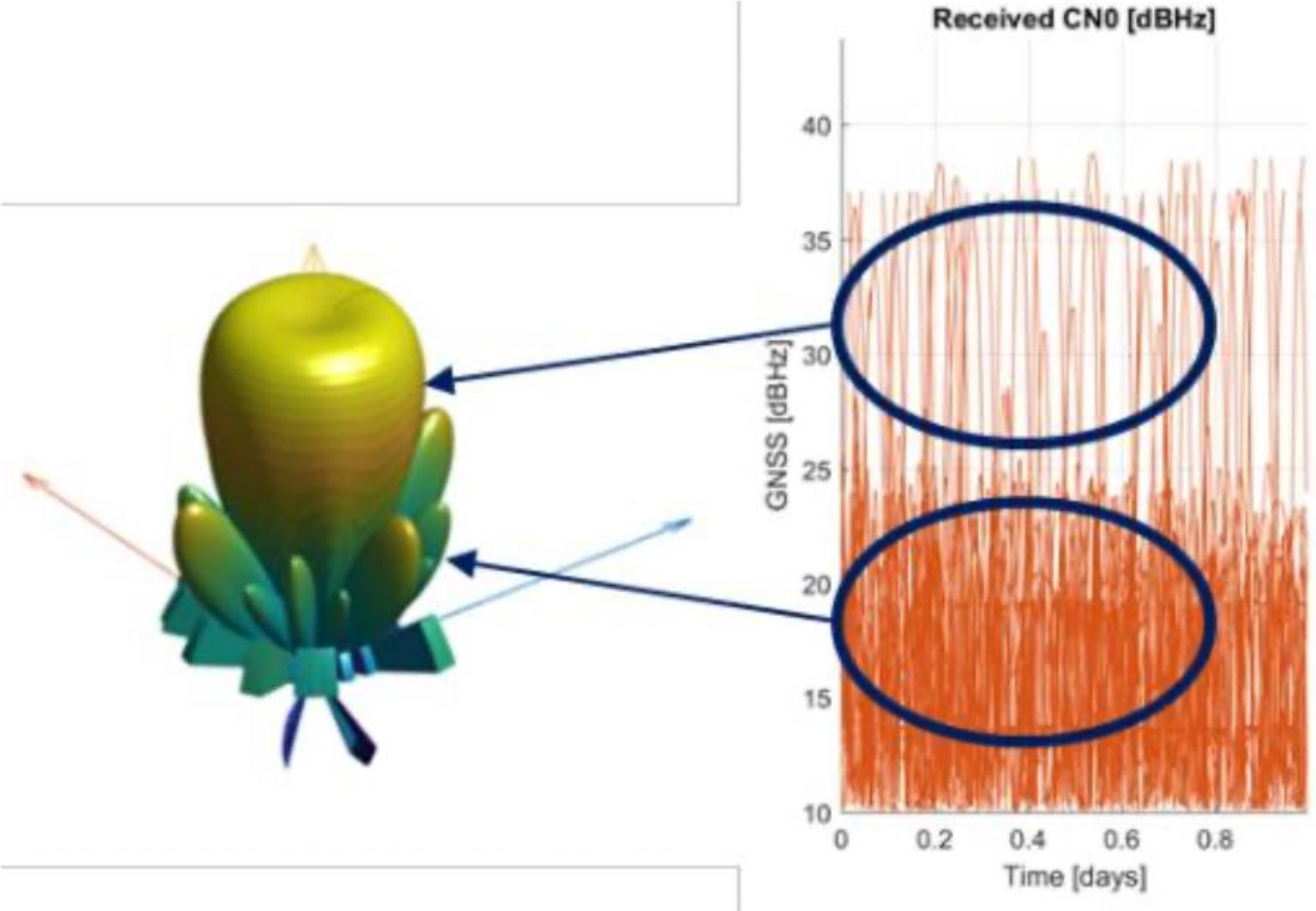
Source: http://www.lockheedmartin.com/content/dam/lockheed/data/space/documents/gps/GPS-Block-IIR-and-IIR-M-Antenna-Panel-Pattern-Marquis-Aug2015-revised.pdf

RECEIVER CHALLENGES

The GNSS receiver has to be extremely sensitive:

- Receiver acquisition and tracking threshold < 15 dB-Hz
- Demodulation of the navigation message due to low signal power challenging
  - *Periodic reception via TeleCommand link from ground*
  - *Use of long-term ephemeris and on-board orbit propagation of clock models*
- Transmit GNSS satellite antenna pattern has to be known accurately

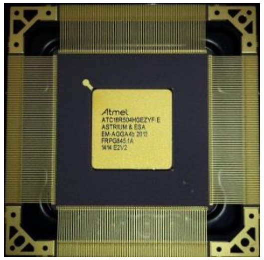
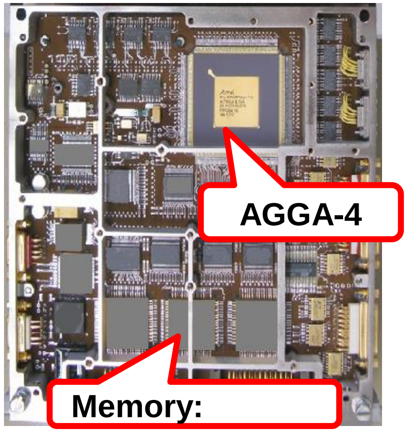
RECEIVED C/NO FROM MAIN AND SIDE LOBES



REFERENCE: Mangialardo et al (2021): The full Potential of an Autonomous GNSS Signal-based Navigation System for Moon Mission

ESA TECHNOLOGY FOR SPACE APPLICATIONS: AGGA-4 MULTI-CONSTELLATION GNSS CHIP

- AGGA-4 (Adv. Galileo/GPS ASIC) available since 2014.
  - Compatible with L1/L5/L2C, E1bc, E5a, E5b, Beidou, Glonass
- Applications
  - Navigation solution, and Precise Orbit Determination (2 cm in GOCE mission)
  - Scientific Radio Occultation (RO) for atmospheric sounding. With MetOp &Cosmic, it is ranked among top 5 sources for Numerical Weather Prediction
  - Rapidly growing interest in GEO / GTO mission: **multi-constellation is key to overcome low SNR**

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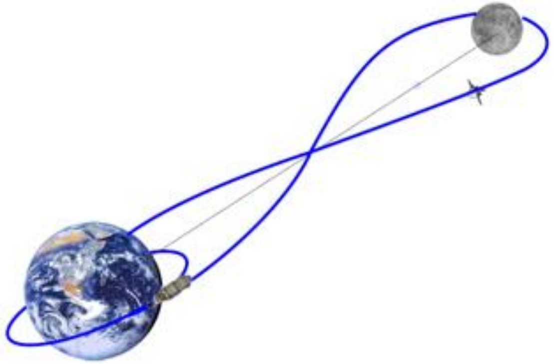
LUNAR MISSION SETUP: EXPLORATION MISSION 1 (EM-1)

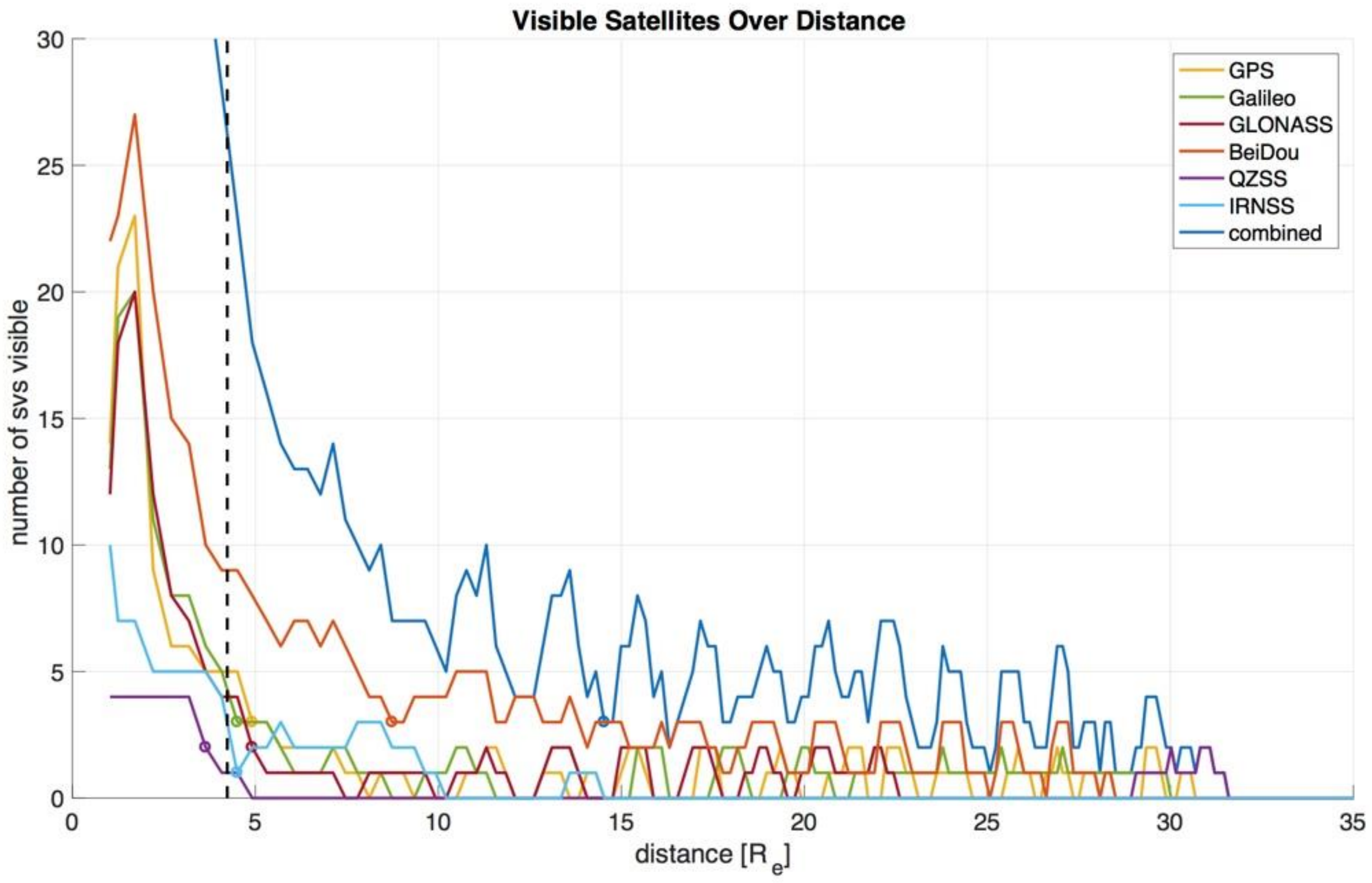
Basic Info:

Mission	Exploration Mission 1 (EM-1)
Description	Free-return lunar trajectory with optional lunar orbit phase
Perigee	391 km
Apogee	378 021 km
Inclination	28.5°
Duration	10 d
Attitude profile	TBD (simplification: nadir-pointing)
Receive antenna	High-gain



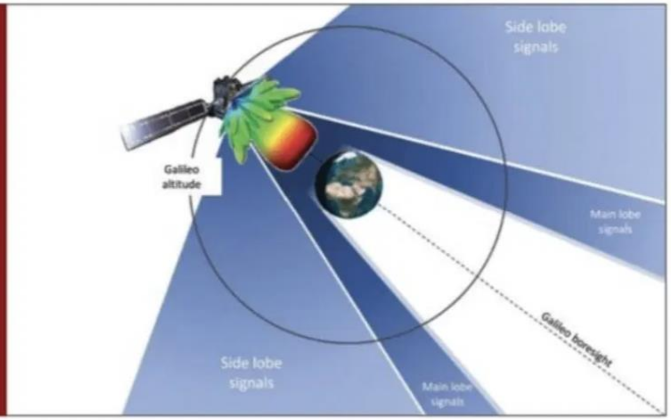
Courtesy: Stefan Wallner, ESA

LUNAR MISSION SIMULATION RESULTS



RESULTS

FIGURE 3 GNSS transmit antenna lobes and signal transmission in SSV



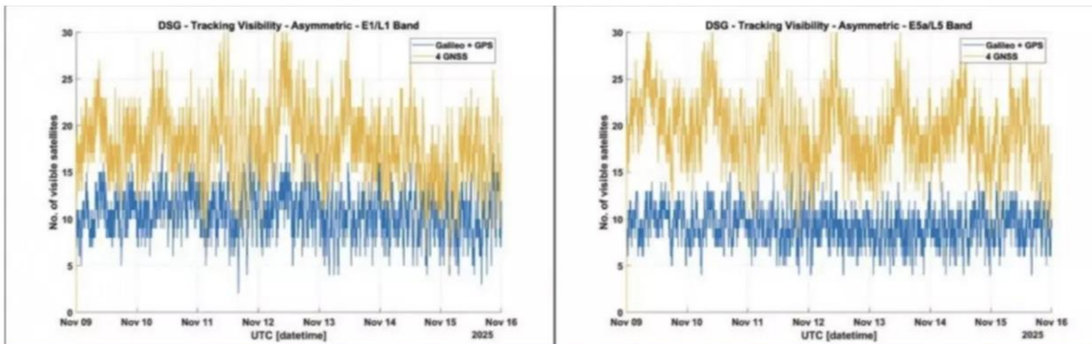


FIGURE 4 GNSS-tracked satellites at the Gateway lunar Near Rectilinear Halo Orbit [21]

Parameter	
C/N_0 threshold	15 dB-Hz
LNA gain, noise figure	30 dB, 2 dB
Antenna Temp. T_A	113 K
Antenna gain in boresight direction	14 dBi
Antenna 3dB beamwidth	12.2 °

TABLE 1 Space GNSS receiver parameters

Reference:

inside unmanned systems

SATELLITE GEOMETRY

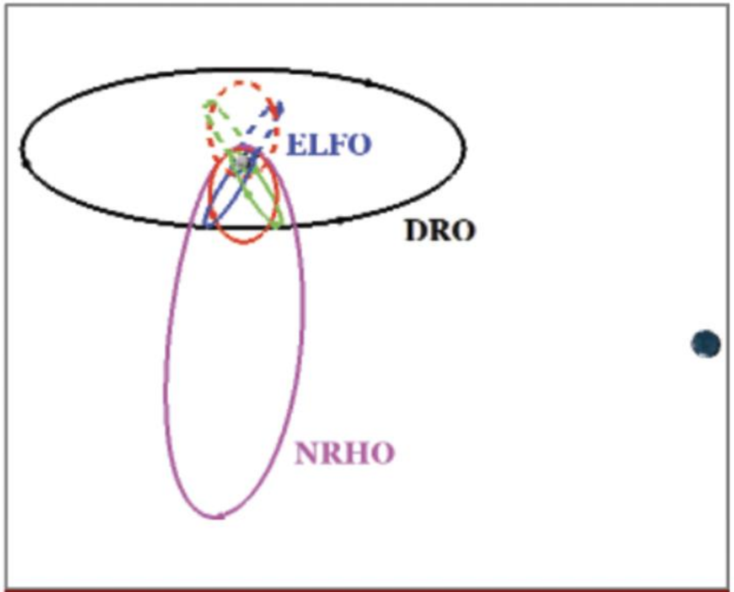


FIGURE 8 Illustration of lunar orbits ELFO, NRHO and DRO for global lunar coverage

	GNSS only	GNSS + Beacon	GNSS + ELFO	GNSS + ELFO + Beacon
Mean number of satellites	3.6	4.2	6.6	7.2
Mean PDOP	6646,0	50,3	3,6	2,5
Time PDOP < 5	0 %	0 %	100 %	100 %

TABLE 3 Statistical analysis for Lunar Lander Trajectory DL phase

GNSS AVAILABILITY ON THE MOON

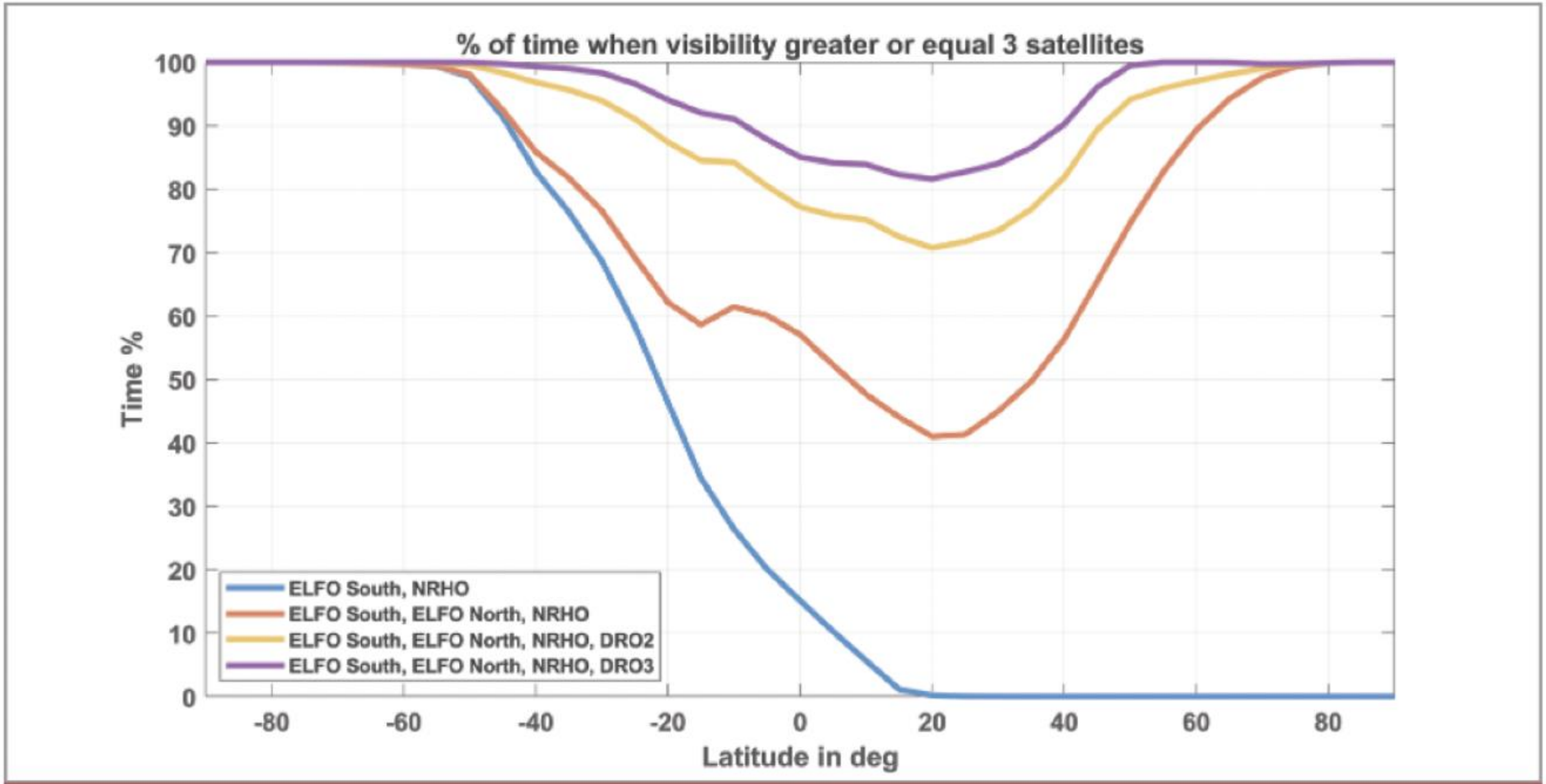


FIGURE 9 Percentage of time a certain latitude on the moon's surface is covered by at least 3 satellites (right)

AVAILABILITY & MAXIMUM OUTAGE

Signal	Constellation	Signal availability (%)		Max Outage Duration(min)	
		At least 1 signal	4 or more signals	At least 1 signal	4 or more signals
Main lobe	BD	64.93	0.33	422	1905
	GPS	57.75	0	717	2433
	Combined	83.92	4.78	717	935
Main lobe and Side lobe	BD	96.01	26.89	64	850
	GPS	83.69	0.83	106	647
	Combined	99.40	62.33	46	514

REFERENCE: Space Vehicle Orbital Determination Performance Analysis Considering GNSS Side Lobe Signals
Xisova Liu • Xingqun Zhan " • Jihong Huang • Chao Oin • Cheng Chi

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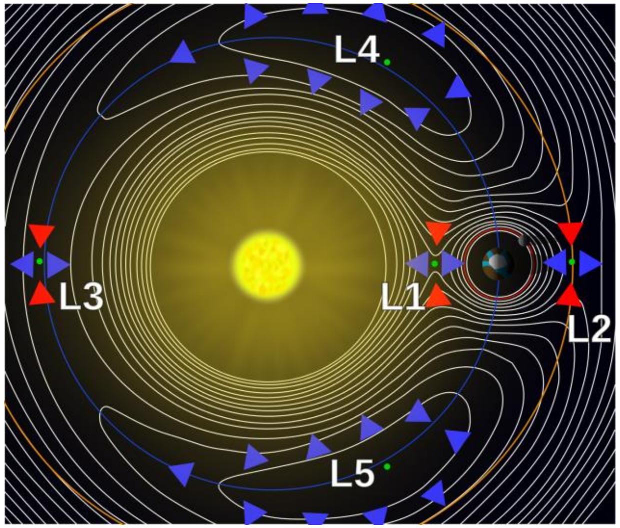
NOT (YET) EXPLORED

- **Zenith antenna on GNSS satellite**
  - ➢ Would save approx. 27 000 km in transmission range
  - ➢ Possible coupling/interference between Nadir and Zenith antennae
  - ➢ Possible problems with launch rocket dispenser
  - ➢ No investigations yet
- **GNSS Pseudolite system**
  - ➢ Moon, satellite in the Lagrange point L1
  - ➢ Perhaps in Phase 3 or later



L1 lies 1.5 million kilometres inside the Earth's orbit, partway between the Sun and the Earth. Lagrangian points are where all the gravitational forces acting between two objects cancel each other out and therefore can be used by spacecraft to 'hover'.

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CONCLUSIONS

- Many studies were/are carried out w/r to the use of GNSS navigation for the Moon missions and on the moon
- All are using the principle of the GNSS transmission from the other side of the Earth
- Simulation studies by ESA, NASA and the Chinese show gaps in the GNSS availability
- Limited Position accuracies > 50-100 m in minimum
- Are those navigation results guarantee the required safety for the Moon missions ?
- Navigation Requirements not yet fixed

THANK YOU FOR YOUR ATTENTION
&
GOOD LUCK FOR THE COMING MOON MISSIONS