Positioning, Navigation and Timing for Planetary Exploration and Colonization: to the Moon and Beyond

by Marco Lisi

Despite the coronavirus pandemic, the worldwide economic crisis and the general slow-down of space activities, the temperature is high about the NASA Artemis program, meant to land in 2024, 52 years after the last Apollo mission and 20 years of confinement in low Earth orbit, human beings on the Moon.

To justify this maintained focus, during a recent press conference, NASA Administrator Jim Bridenstine said bold aspirations are needed now more than ever, given the coronavirus pandemic: "We need to give people hope, we need to give them something that they can look up to, dream about, something that will inspire not just the nation but the entire world".

With the Artemis program, NASA plan to collaborate with commercial and international partners to establish a permanent "base camp" and a sustainable exploration of the Moon by the end of the decade. The ultimate goal is to use what will be learned on and around the Moon to take the next giant leap: sending astronauts to Mars.

Challenges ahead are numerous: as a matter of example, studies performed at ESA and NASA determined that local materials and 3D printing technologies would be the best for constructing buildings and other structures, which means no need for transporting resources from the Earth at an astronomical cost.

But the problems to be solved for the realization of a stable manned infrastructure on the Moon (a true follow-on of the International Space Station) involve much more than just building technologies. The Moon "base camp" will have to meet very stringent requirements in terms of operations, logistics, and safety of life. From an architectural viewpoint, the "Moon base" will have to be expandable and "open" to the integration with other systems, hence integrability and expandability will be key issues. But first and above all, a permanent base on the Moon will have to be affordable and sustainable, i.e., its cost will need to be assessed over its life-cycle, under a long term technical, economic, and political perspective.

The exploration of the Moon with human and robotic missions and its colonization, through the establishment of a permanent base, will require many vital supporting infrastructures, such as communication networks and positioning, navigation, and timing (PNT) systems.

All architectural approaches considered so far by NASA and ESA to develop communications and PNT infrastructures on the Moon can be divided into two main categories:

- Comprehensive, well-structured and forward-looking (but costly) architectures, based on constellations of orbiters and relay satellites;

- “ad hoc”, flexible, expandable architectures, based on a fusion of all available resources and commercial technologies.

The second approach looks like a more promising, affordable, and sustainable solution.

A Lunar Communication Network

The Moon communication infrastructure shall be able to provide several capabilities, that can be summarized in two main categories: users/applications that need low data rate and very reliable links, and those that require high data rate links. The first category includes monitoring and control of the base camp systems/payloads and essential audio, video, and file transfer among users. Links for these applications shall have high service availability (for instance 99.99%) also in case of emergencies and (lunar) disasters, regardless of Moon phases, Earth position, terrestrial weather conditions, etc. The second category instead includes HTTP surfing, high quality, Audio/Video communications, video streaming, HD television, file sharing, cloud computing, etc. These applications will be provided with a service availability lower than the first category (for instance 98%).
A pragmatic answer to these requirements might consist in a scalable network that relies on terrestrial, wireless technologies, such as 4G and 5G, intending to limit the effort of designing and developing dedicated technologies for the Moon “base camp” (fig. 1).
Consequently, the design of the lunar communication network will be mainly devoted to the definition of its cell distribution on the lunar surface. The cell distribution will strongly depend on the network (performance, functional, and operational) requirements, the lunar site location, and the selected air interface.
Starting from these inputs, a possible strategy for defining the cell distribution is summarized in Fig.2 and described as follows. The “Moon Base” requirements and the, e.g., 5G air interface definition are inputs for the definition of the link budgets, in particular for the transmitting and the receiving chains, to derive the maximum attainable path loss. At the same time, the base camp location physical and environmental properties are a starting point for the definition of a path loss model, that can be derived through analysis based on the already available information and, in the future, from testing in specific environmental conditions. Once that path loss model and link budgets are completed and consolidated, the coverage distribution of a single cell can be determined. The coverage will depend on its location (latitude, longitude, height from the surface), the adopted antennas, and the surrounding infrastructure: notice that all these parameters can be elaborated from software tools and the coverage pattern computed for several positions. This allows deriving a first iteration of the cell distribution, and thus of the lunar cellular network, by dovetailing several cells on the selected site and verifying that the total coverage meets the initial requirements.
An important component in the Moon Base communication network is the backhauling link with Earth, which allows 5G communication terminals to access all services in the terrestrial network (e.g. a Skype© call from a Lunar operator inside the habitat with its family on Earth).
The backhauling link will be designed to provide an ultra-high data rate and high-availa-

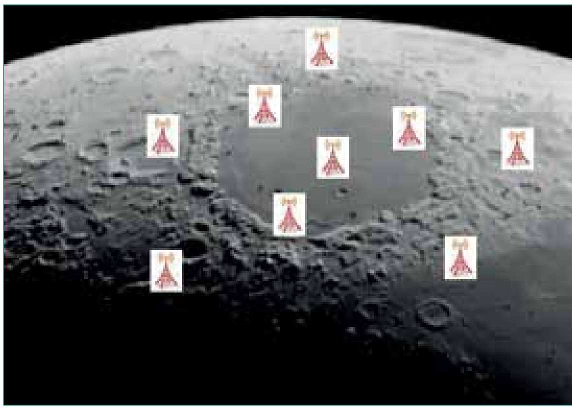

Fig. 1 - Modular, Expandable Moon Navigation & Communications Infrastructure

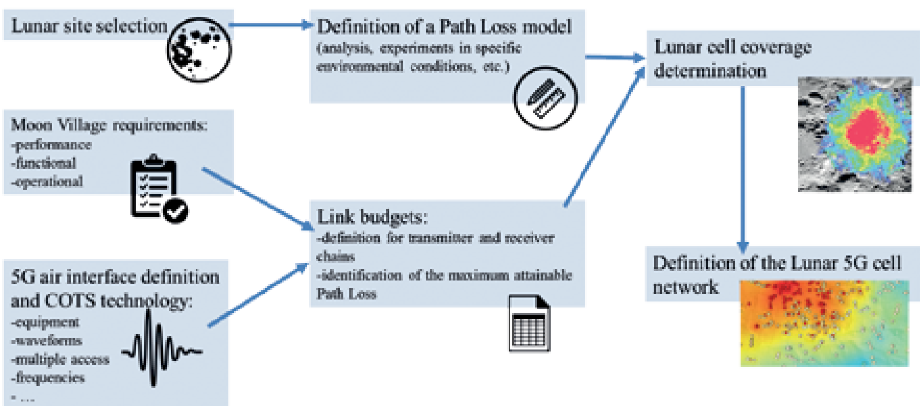

Fig. 2 - Logical steps for the design of the lunar cellular network

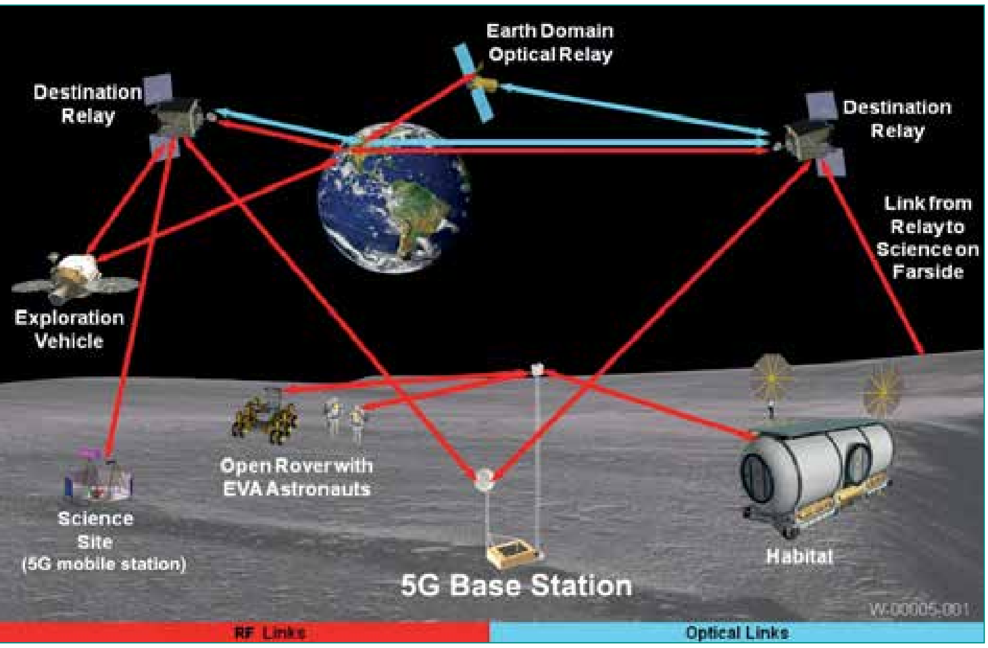

Fig. 3 - Example of possible 5G communication network with backhauling to Earth realized using Moon orbiter satellites

bility link. Candidate technologies for backhauling are both microwave and optical communications, each of them with advantages and disadvantages in terms of data rates, weather sensitivity, and pointing accuracy An example of backhauling configuration is the one shown in fig. 3 where orbiters are in stable orbits around the Moon and relay all the traffic from the Earth directly to Moon ground stations.

Alternatively, the backhauling could be realized through a direct link Moon-Earth. A possible configuration is depicted in Fig.4, where 5G stations are wired to optical backhauling stations that communicate directly with Earth.

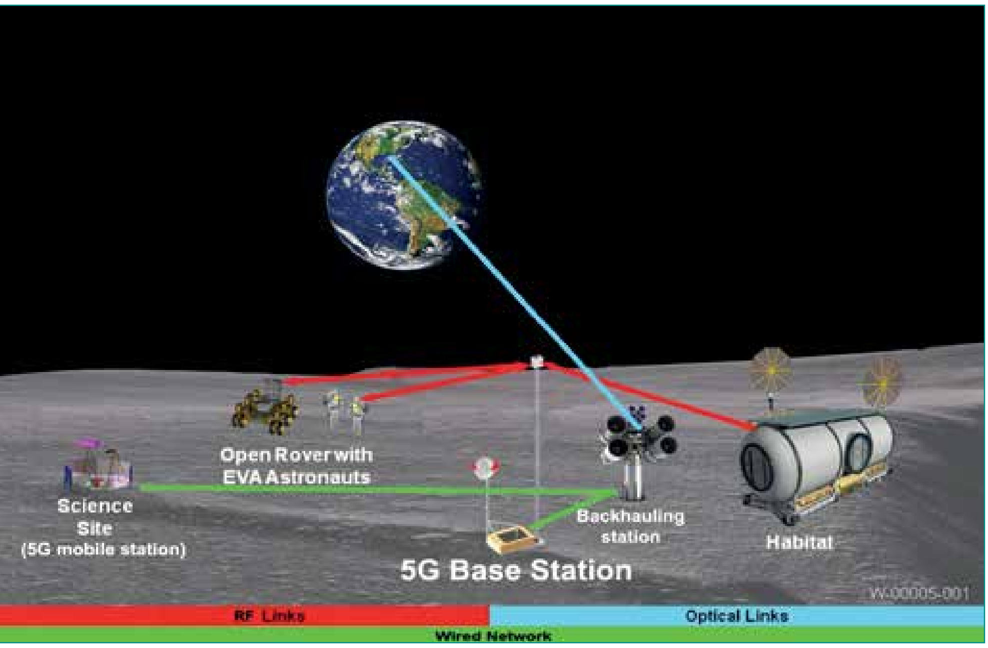

Fig. 4 - Example of possible 5G communication network with backhauling to Earth realized through direct-to-Earth optical link.

Positioning, Navigation and Timing on the Moon

Lunar positioning

Since 2001, the Aurora space exploration program has led the European activities towards the potential deployment of human bases on Mars and the Moon. Within this framework, two feasibility studies of a reduced planetary navigation and communications system were performed. Both studies concluded that COTS equipment, based on IEEE 802.16 WiMAX standard, could be used to fulfill the mission requirements for short-range activities (i.e., link distance below 8 km), but long-range activities were not foreseen to be covered only with an infrastructure on the planetary surface. Future 5G technology is expected to overcome these challenges and to provide the necessary coverage, flexibility, and performance required by a permanent base.

The 5G standard looks like a promising standard to support communication and positioning capabilities for a wide range of applications, such as massive Internet of Things (IoT), mission-critical control, and enhanced mobile broadband. For this purpose, advanced wireless technologies, such as massive MIMO antennas and wideband millimeter-wave links are foreseen. Similarly to the 4G LTE standard, 5G multicarrier waveforms will allow the flexible allocation of data, as well as dedicated pilot signals for positioning purposes. These pilot signals can be used to perform ranging measurements for time-of-arrival (ToA) location methods, and multi-antenna techniques can enable angle-of-arrival (AoA) localization.

The 5G networks for the Moon Base mission are designed according to the requirements for potential manned and robotic activities. The main design parameters are the cell site location, cell coverage, and signal bandwidth. These parameters define the achievable communication and positioning capabilities. The configuration of multiple cell sites over a certain area, i.e., the geometry of cell sites with respect to the receiver, determines the dilution of precision (DOP) of ToA and AoA methods. The cell coverage mainly depends on the height of the cell mast, transmit power, antenna pattern, and propagation conditions. For instance, on the Moon, a cell tower of 10 meters above the surface is required to achieve a line-of-sight (LoS) distance to the horizon of almost 6 km, but this distance may be limited by the irregular topography of the surface. Last, the spectrum allocation of the positioning resources (i.e., pilot signals) determines the ranging accuracy, as well as the data rate. Design procedures developed for 5G terrestrial networks could be adapted to the conditions on the Moon. In some situations, the ToA estimates will need to be combined with data from inertial measurement units. Furthermore, in mesh or ad hoc networks, such as device-to-device (D2D) communications, cooperative positioning between wireless sensors or sites may provide additional location solutions.

Precise synchronization of lunar stations

5G systems on Earth rely on GNSS signals for precise synchronization. GNSS receivers are used to provide precise timing in different parts of the 4G LTE ground network, which requires within 3 to 10 microseconds accuracy, depending on the application and the standard adopted. On Earth, such accuracies are easily achievable by a professional GNSS timing receiver, which has an accuracy in the order of tens of nanoseconds. This same approach could be adopted for Moon-based 5G gateway stations.

Clearly, on the Moon, the conditions are significantly different with respect to the Earth surface. The use of GNSS (such as GPS or Galileo) signals in the Moon environment has been studied in past ESA contracts. The major challenges to be considered are:

- Signal power: in addition to the higher free-space loss, the majority of the received signals come from the GNSS transmitter antennas' sidelobes (with considerably lower gains). Additionally, stronger signals may interfere with the correct acquisition and tracking of weaker signals (near-far effect), with a consequent impact on receiver sensitivity and robustness;
- Dynamics: high ranges for Doppler and Doppler rates hinder acquisition and impose additional stress on the tracking loops, also making it more difficult to process weak signals;
- Geometry: the geometry of the usable satellites is considerably worse than for terrestrial applications. Additionally, occultation by the Earth and Moon and receiver sensitivity (minimum C/N0 required to acquire and track GNSS signals) may also have an impact on the dilution of precision (DOP).

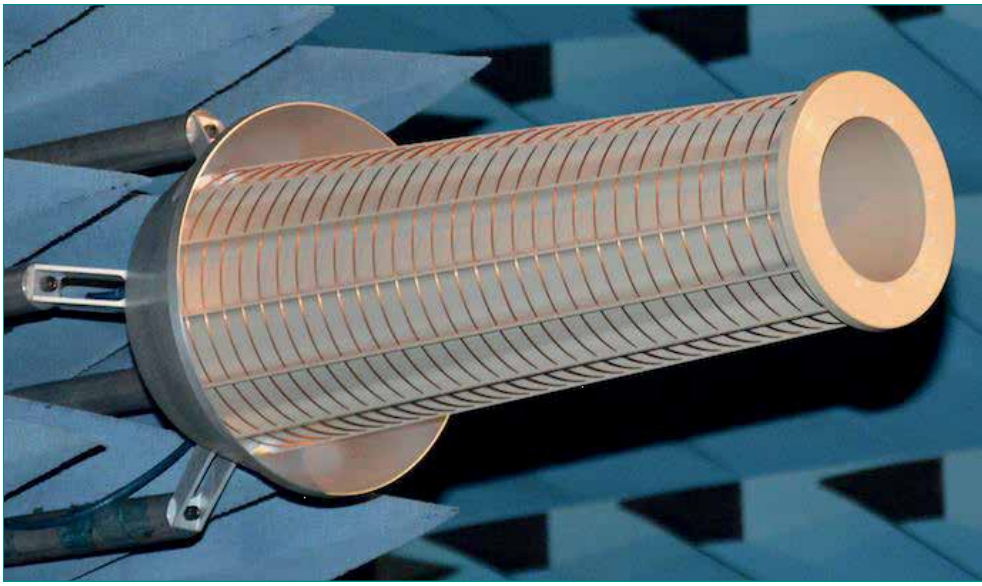

Fig. 5 - GNSS space antenna developed for GEO orbit.

The studies however showed that GNSS could be used for MTO (Moon transfer orbit), LLO (Lunar Low Orbit), D&L (Lunar Descent and Landing) and, with strong limitations, for Lunar Surface real-time positioning.

The accurate synchronization of the 5G base stations on the Moon surface can be achieved using a professional high sensitivity timing GNSS receiver equipped with a directional high gain antenna (fig. 5), kept pointing to the Earth.

The receiver will be configured in timing mode, i.e., it will compute only a precise time solution, by assuming a precise knowledge of the antenna location (better, of its phase-center), assessed at least once through non-GNSS methods. Such information can be kept in the receiver, which will then only work as a timing receiver. The need for long coherent integration and the high dynamics, as well as the need for a reliable back-up, will suggest the use of miniaturized atomic clocks to avoid degradation of the performances during the integration (COTS miniaturized atomic clocks are already available in the market and currently used in professional ground equipment).

Conclusion

The exploration of the Moon with human and robotic missions and its colonization, through the establishment of permanent bases, will require planetary communications and navigation infrastructures. An affordable, no-nonsense approach might rely on the use of COTS components, presently deployed on Earth in LTE and 5G networks, for communication and navigation on the Moon surface. This approach largely satisfies the requirements of performance, reliability, affordability, and sustainability, as based on commercial technology and being incrementally expandable over time.

ABSTRACT

With the Artemis program, NASA plans to collaborate with commercial and international partners to land in 2024 human beings on the Moon and then to establish a permanent "base camp" by the end of the decade.

Challenges ahead are numerous: the Moon "base camp" will have to meet very stringent requirements in terms of operations, logistics, and safety of life; moreover, a permanent base on the Moon will have to be affordable and sustainable, i.e., its cost will need to be assessed over its life-cycle, under a long term technical, economic, and political perspective.

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KEY WORDS

Positioning; navigation; timing; GNSS; Moon; infrastructure; network; communication; IoT; 5G

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