A COMMUNICATIONS AND PNT INTEGRATED NETWORK INFRASTRUCTURE FOR THE MOON VILLAGE

Pietro Giordano[(1)], Marco Lisi[(1)], Andrea Modenini[(1)], José A. del Peral-Rosado[(2)]

[(1)]*European Space Agency - European Space Research Technology Centre (ESA-ESTEC)*
Keplerlaan 1, Noordwijk, The Netherlands
Email: { pietro.giordano, marco.lisi, andrea.modenini}@esa.int

[(2)] *Universitat Autònoma de Barcelona (UAB)*
Campus de la UAB, Bellaterra, Spain
Email: joseantonio.delperal@uab.cat

INTRODUCTION

The Director General of ESA, prof. Woerner, set forth the idea of a "Moon Village", a village on the moon built by huge 3D printers and inhabited for months at a time by teams of astronauts. The plan outlined by the ESA is that, starting from the early 2020s, robots will be sent to the Moon to begin constructing various facilities, followed a few years later by the first inhabitants.

Back in 2013, ESA teamed up with building companies to start testing out various Moon base-building technologies, and determined that local materials would be the best for constructing buildings and other structures, which means no need for transporting resources from earth at an astronomical cost. But the problems to be solved for the realization of such stable manned infrastructure on the Moon (a true follow-on of the International Space Station) involve much more than just building technologies. The Moon Village will be a large and complex system where requirements related to operations and safety of life will be of paramount importance. Moreover, from an architectural viewpoint the "village" will have to be expandable and "open" to the integration with other systems, hence integrability and expandability will be two key issues. But first and above all, the Moon Village will have to be affordable and sustainable, i.e., its cost will need to be assessed over its life-cycle. As a "Wild West" town in the old times, "Moon Village" will have to provide a number of essential infrastructures. In particular, 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.

The approach presented in this paper relies on the use of Commercial off-the-shelf (COTS) component for communication and navigation on the Moon surface. The use of LTE technology, currently deployed on Earth, and future 5G will allow communication and navigation, within the maximum throughput and the accuracy provided by the standard, assuming the implementation of all the basic pre-requisites on the Moon.

WHY 5G FOR THE MOON VILLAGE?

All architectural approaches considered so far by NASA and ESA can be divided in 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 on COTS technologies.

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

The Moon Village communication infrastructure shall be able to serve several use cases (UCs). Although not all UCs can be yet identified, at least we can define two main categories: UCs that needs a low data rate and reliable links, and those that require high data rate links. The first category includes monitoring and control of Moon Village systems/payloads and essential audio, video, and file transfer among users. Links for these UCs 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, clouding computing, etc. These UCs will have a service availability lower than the first category (for instance 98%).

While the fifth-generation (5G) of mobile technology is currently thought for terrestrial UCs, it is evident from the requirements that the eventual standard will be an excellent candidate for the design of a highly integrated and off-the-shelf Moon Village network. In addition, the selection of 5G will bring all the advantages of word-wide accepted standards (participation of a larger number of companies, cost reduction, etc.). The 5G of mobile technology promises to deliver the gigabit experience to users. Although the definition of the physical and MAC layer are still debated [1], the main requirements have been already identified by several mobile operators [2]. Some of these requirements are:

- data rate higher than 10 Mbps for tens of thousands of users in a crowded area (like a stadium), and higher than 1 Gbps for few tens of users in the same indoor environment,
- latency shall be reduced compared to LTE,
- coverage increased, especially in rural area,
- radio resource and energy consumption are minimized,
- programmability and configurability by the network,
- improved network availability (99.999%), including robustness against climatic events and guaranteed services at low energy consumption for critical infrastructures,
- network functions shall be scalable such that capacity is provided when and where needed.

A LUNAR COMMUNICATION NETWORK

The main idea here proposed is having a scalable network that relies on COTS, with the aim of limiting the process of design and development of specific technology for the Moon Village. Consequently, the design of the Lunar communication network will be mainly devoted to the definition of its cell distribution on the lunar surface. Clearly, the cell distribution will strongly depend on the network (performance, functional, and operational) requirements, the lunar site location, and what will be the 5G air interface.

Starting from these inputs, a possible strategy for defining the cell distribution is summarized in Figure 1 and described as follows. The Moon Village requirements and the 5G air interface definition shall serve as input for the definition of link budgets, in particular for the transmitting and the receiving chains, with the objective of deriving the maximum attainable path loss. At the same time, the Moon village location physical and environmental properties are a starting point for the definition of a path loss model, that can be derived by means of analysis (of the available information), testing in specific environmental conditions, etc. Once that path loss model and link budgets are completed and consolidated, the coverage distribution of a single cell can be determined. The coverage clearly will depend on its positioning (latitude, longitude, height from the surface), the kind of adopted antennas, and the surrounding infrastructure: notice that all these parameters can be elaborated from software tools (e.g. Linux/Unix software SPLAT!) and the coverage pattern computed for several positions. This allows to derive a first iteration of the cell distribution, and thus the Lunar 5G network, by dovetailing several cells on the selected site and verifying that the total coverage meets the original requirements.

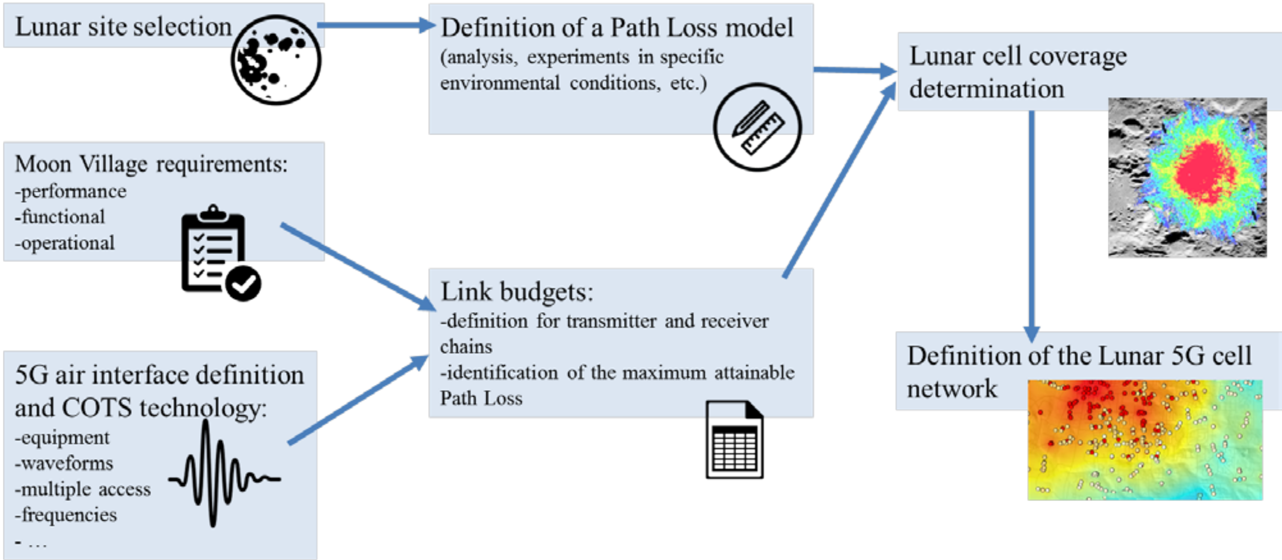

Figure 1: logical steps for the design of the Lunar 5G network

The logical steps here described could look visionary, but actually many activities are already on-going in the global research community. An example is the selection of the lunar site: the study in [3] published recently by D. Wingo, shows that Peary crater (situated in the Lunar North Pole) could be a good candidate for the Moon Village, thanks to its power availability, presence of hydrogen-based molecules, surface mobility, line-of-sight for communications, etc. In parallel, other studies for the selection of the lunar site have been carried out under the ESA contracts [4] and [5]: these studies have shown other sites of interest in the Lunar South Pole, such as between Shackleton and De Gerlache craters. Another example of on-going activity is the definition of the path loss model: some models are already existing in the literature and can be found in [6]-[8]. For instance the study in [6] introduces the use of a modified Longley-Rice irregular terrain model and digital elevation data representative of an analogue lunar site for the prediction of RF path loss over the lunar surface. Results were elaborated with SPLAT1, and validated by means of theoretical models and past Apollo studies.

Communications with Earth

An important key issue in the Moon Village network is the design of the backhauling link with Earth, that 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 shall be designed properly for having ultra-high data rate that is easily scalable for meeting initial and future capacity requests and shall have high link availability. Candidate technologies for backhauling are both RF or optical communications, since each of them has advantages and disadvantages in terms of data rates, weather sensitivity, pointing accuracy, etc., and studies that trade-off the two technologies can be found for instance in [9] and [10]. More likely, both of these technologies will be employed in the backhauling of the Lunar network whose configuration will be complex and ad-hoc designed. An example of a backhauling configuration could be the one shown Figure 2 where orbiters are in stable orbits around the Moon and relays all the traffic to Earth directly to Ground Stations or to an optical relay that could be placed in one of the fourth Earth-Moon Lagrange points EML1, EML2, EML4, and EML5.

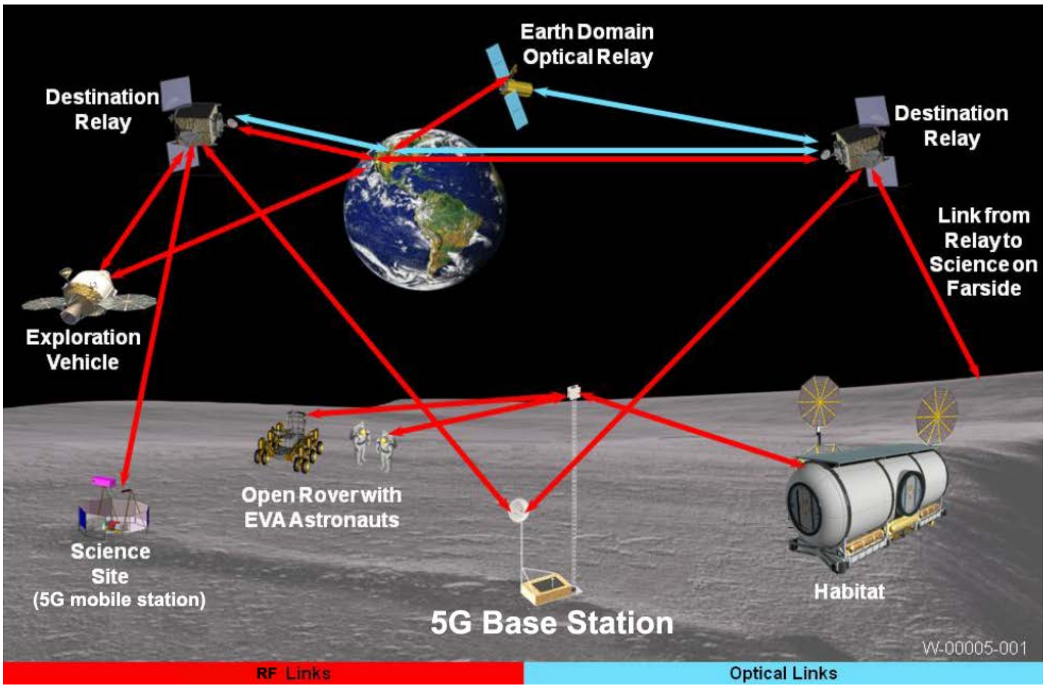

Figure 2: example of possible 5G communication network with backhauling to Earth realized by means Moon Orbiter

Clearly, the description above is just an example and many other backhauling configurations can be envisaged. However, some of the main key issues can be already identified for each link configuration. For instance, the configuration shown in Figure 2, that adopts relay orbiters, requires a constellation of satellites that are launched from Earth, injected in stable orbits around the Moon, and allow handover and continuous coverage like done by telecom satellite constellations around Earth (e.g. Iridium© and O3b© networks). Moreover, the number of stable orbits around Moon are quite limited. For instance, in low-lunar orbit there are only four circular orbits with limited perturbation due to lunar mass concentrations, namely the orbits with inclination 27, 50, 76, 86 degrees (see [11] for further details) and thus the described solution could be limited in terms of scalability.

Alternatively, the backhauling could be done by means of direct link Moon-Earth. An example of such configuration is depicted in Figure 4, 5G stations are wired to one or more optical backhauling stations that communicate directly with Earth. The backhauling station could be realized by adopting the Lunar laser ground terminals (LLGT), as shown in Figure 3, that was adopted for the optical demonstration with the Lunar Laser and Dust Environment Explorer (LADEE). This kind of backhauling configuration is probably easier to be designed and developed with respect to orbiter relays, but it could be limited by the noise temperature of the Moon: the Moon reflects sunlight at optical wavelengths and emits waves in the microwave bandwidth. Consequently, a terrestrial ground station that points directly to the Moon surface will experience an increase of noise temperature that can be several tens or hundreds of dB, either in Optical and RF bandwidths. The reader can found a detailed study of this effect in [12] for RF communications (namely, S-Band, X-Band, and Ka-Band).

Finally, a third backhauling configuration could be that 5G base stations on Moon transmit information directly to Earth. However, this last option does not look really feasible because limits the power efficiency and the location selection of the 5G base stations.

Figure 3: Lunar laser ground terminal (LLGT)

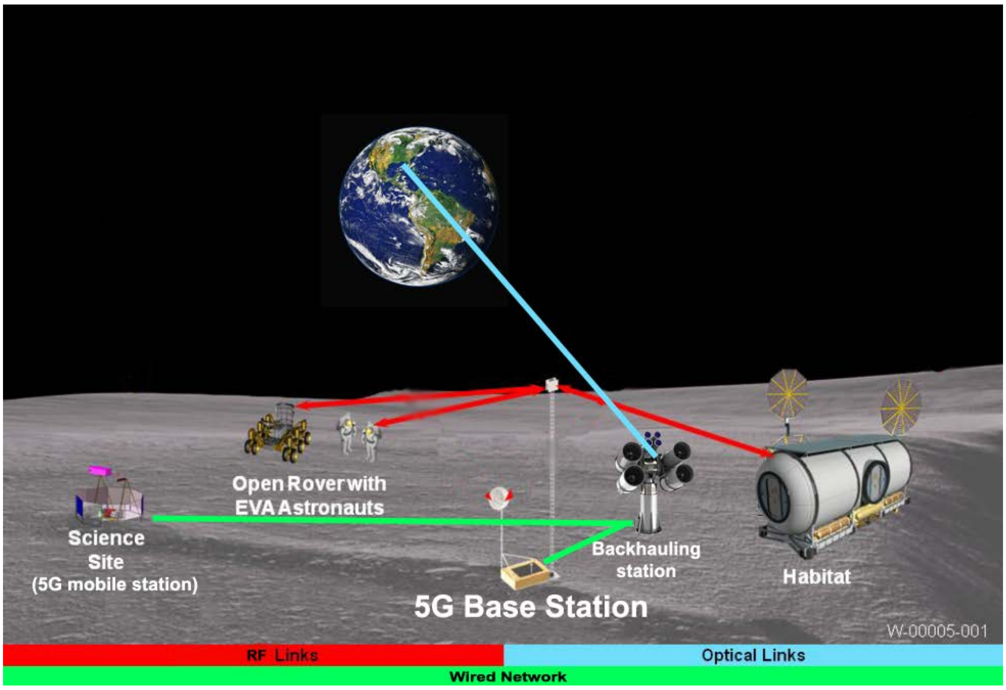

Figure 4: example of possible 5G communication network with backhauling to Earth realized by of direct-to-Earth optical link

NAVIGATION

Lunar positioning

Since 2001, the Aurora space exploration programme has led the European activities towards the potential deployment of a human base in Mars and in the Moon [13]. Within this framework, the ESA contracts [4] and [5] provided in 2008 two feasibility studies of a reduced planetary navigation and communications system. Both studies concluded that COTS equipment, based on IEEE 802.16 WiMAX standard, could be used to fulfil 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 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 the Moon village.

The 5G standard is envisaged 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, the 5G air interface is expected to be based on the combination of optimized OFDM-based waveforms and a flexible framework with advanced wireless technologies, such as massive MIMO or robust millimeter wave (mmWave). 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 Village 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., 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, in 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 [5], 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 for 5G terrestrial networks, e.g. in [14], could adapted to the conditions of the Moon.

The network topologies can also determine the selection of the primary positioning method. In short-range links, the massive MIMO techniques can enable precise AoA localization, such as in [15]. In long-range links, ranging measurements may be obtained only from one or two cell sites. Thus, the ToA estimates can be combined with inertial measurement units. In mesh or ad hoc networks, such as device-to-device (D2D) communications, cooperative positioning between wireless sensors or sites may provide an additional location solution. Considering the ToA-based methods, the cell sites should be synchronized to a certain reference time in order to achieve accurate positioning.

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 [16], depending on the application and the actual standard options implementation. On ground, such accuracies are easily achievable by a professional GNSS timing, which has an accuracy in order of tens of nanoseconds. This work proposes to adopt the same approach for Moon 5G base stations.

Clearly, on the Moon, the conditions are significantly different with respect to Earth surface. GNSS environment on the Moon has been studied in previous ESA contracts [17]-[22], showing that 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' side-lobes (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/N_0 required to acquire and track GNSS signals) may also have an impact on the dilution of precision (DOP).

Within the same studies, it was showed that GNSS could be used for MTO (Moon transfer orbit), LLO (Lunar Low Orbit), D&L (Lunar Descent and Landing) and for Lunar Surface real time positioning.

The assumption of this paper is that the signal received on the Moon surface is around 10 dBHz. This can be achieved by an antenna with noise figure around 2, active gain of 30 dB and passive gain (antenna radiating element) of maximum 10 dB. This paper assumes that the antenna will be kept pointing to the Earth and that such kind of antennas are not difficult to design and build (ESA developed an antenna for GEO orbit for GNSS and similar performances were achieved, see [23]). For such reason an antenna to track GNSS signals on the moon is assumed available at reasonable price ([23] was aiming to around 50 k€) and with expected performances (or potentially exceeding them: in [18] a beam forming antenna was proposed with passive gain up to 13 dBi) .

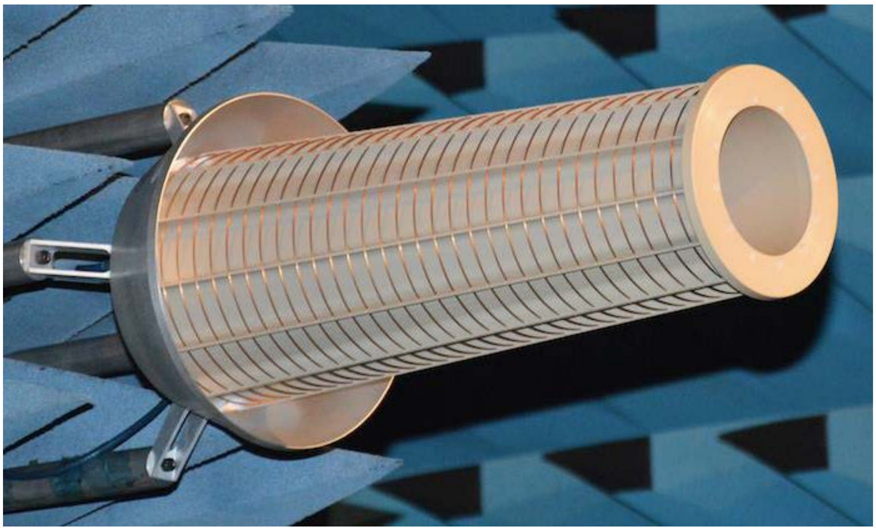

Figure 5: GNSS space antenna developed for GEO orbit [23]

Tracking of signals at such low C/N_0 is clearly very difficult, but it was proven that with coherent integration of around 500 ms (and/or with use of special techniques such as vector tracking) it is possible to produce measurements at such low signal power and compute PVT. In one of the studies showed accuracy down to 50.

The proposed approach to provide synchronization of the base stations on the Moon surface can be achieved using a professional high sensitivity timing GNSS receiver equipped with a directional high gain antenna. The receiver is configured in timing mode, i.e., it aims to compute only a precise time solution, by assuming a precise knowledge of the phase centre of its antenna. The last assumption is considered feasible assuming to have precise localization on the moon surface at least once, based on other techniques and technologies (not necessary only with GNSS). Such information can be kept in the receiver that will then only work as timing receiver. The need for long coherent integration and the high dynamics will impose 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, so they are considered valuable for this architecture, without big increase in cost.

Accuracies potentially achievable are in the order of 50-100 meters, so around 1 microsecond or less, that is good enough for synchronization of the 5G/LTE base stations. Finally, to reduce the costs induced by the non-COTS infrastructure, the lunar base might be equipped with only 1-2 timing receivers and the rest of the base stations can use COTS network base precise timing equipment.

CONCLUSION

The exploration of the Moon with human and robotic missions and its colonization, through the establishment of permanent bases, such as the Moon Village project proposed by ESA, will require planetary communications and navigation infrastructures. The approach presented in the paper relies on the use of COTS component for communication and navigation on the Moon surface. The use of LTE technology, currently deployed on Earth, and future 5G will allow communication and navigation, within the maximum throughput and the accuracy provided by the standard, assuming the implementation of all the basic pre-requisites on the Moon. The approach described largely satisfies the requirements of performance, reliability, affordability and sustainability (being based on commercial technology and incrementally expandable over time).

REFERENCES

[1] G. Wunder et al., "5GNOW: Challenging the LTE Design Paradigms of Orthogonality and Synchronicity," Vehicular Technology Conference (VTC Spring), 2013 IEEE 77th, Dresden, 2013, pp. 1-5.

[2] NGMN, “5G white paper”, available on www.ngmn.org, Feb. 2015.

[3] D. Wingo, “Site Selection for Lunar Industrialization, Economic Development, and Settlement”, New Space, Volume 4, March 2016, pp 19-39.

[4] Feasibility study for a reduced planetary navigation and communications system, PLANCOM, Final report, ESA contract, 20762/07/NL/HE.

[5] Feasibility study for a reduced planetary navigation and communications system, Final report, ESA contract, 20763/07/NL/HE.

[6] L. Foore, N. Ida, “Path loss prediction over the lunar surface utilizing a modified Longley-Rice irregular terrain model”, NASA Technical Note (TM214825), 2007.

[7] S. Hwu, M. Upanavage, and C. Sham. "Lunar Surface Propagation Modeling and Effects on Communications", 26th International Communications Satellite Systems Conference (ICSSC), International Communications Satellite Systems Conferences (ICSSC).

[8] H. Pan et al, “Path loss prediction over lunar surface with obstacle diffraction”, Proceedings of IEEE Workshop on Advanced Research and Technology in Industry Applications, Ottawa, Sept. 2014, pp. 1276-1279.

[9] V. W. S. Chan, "Optical space communications," in IEEE Journal of Selected Topics in Quantum Electronics, vol. 6, no. 6, pp. 959-975, Nov.-Dec. 2000.

[10] W. D. Williams, “RF and Optical Communications: A Comparison of High Data Rate Returns From Deep Space in the 2020 Timeframe”, NASA Technical Note (TM214825), 2007.

[11] M. Lara, Design of long-lifetime lunar orbits: A hybrid approach, Acta Astronautica, Volume 69, Issues 3, August–September 2011, Pages 186-199

[12] D. D. Morabito, “Lunar Noise-Temperature Increase Measurements at S-Band, X-Band, and Ka-Band Using a 34-Meter-Diameter Beam Waveguide Antenna”, IPN Progress Report 42-166.

[13] P. Messina, B. Gardini, D. Sacotte, S. Di Pippo, “The Aurora Programme: Europe’s Framework for Space Exploration”, ESA bulletin 126, May 2006.

[14] J. A. del Peral-Rosado, J. A. López-Salcedo, S. Kim, G. Seco-Granados, "Feasibility Study of 5G-based Localization for Assisted Driving", Proc. International Conference on Localization and GNSS (ICL-GNSS), Jun 28 2016.

[15] A. Shahmansoori, G. E. Garcia, G. Destino, G. Seco-Granados, and H. Wymeersch, “5G position and orientation estimation through millimeter wave MIMO,” in Proc. IEEE Globecom Wkshps, Dec. 2015.

[16] D. Bladsjö, M. Hogan, and S. Ruffini, “Synchronization aspects in LTE small cells,” IEEE Communications Magazine, vol. 51, pp. 70–77, September 2013.

[17] Lunar GNSS Final Report, LUNARGNSS-DME-TEC-TNO06-E, Esa Contract 4000107785/12/NL/AF

[18] Weak GNSS Signal Navigation on the Moon Final report, ESA contract . 4000107097/12/NL/AF/fk

[19] Moon-GNSS Final report, GMV-MOON-GNSS-D7,

[20] M. Manzano-Jurado, J. Alegre-Rubio, A. Pellacani, G. Seco-Granados, J. A. López-Salcedo, E. Guerrero, A. García-Rodríguez, "Use of weak GNSS signals in a mission to the moon," 2014 7th ESA Workshop on Satellite Navigation Technologies and European Workshop on GNSS Signals and Signal Processing (NAVITEC), Noordwijk, 2014, pp. 1-8.

[21] N. Witternigg, G. Obertaxer, M. Schönhuber, G.B. Palmerini, F. Rodriguez, L. Capponi, F. Soualle, J.-J. Floch, "Weak GNSS Signal Navigation for Lunar Exploration Missions," Proc. of the ION GNSS+ 2015, Tampa, Florida, September 2015, pp. 3928-3944.

[22] P.F. Silva, H.D. Lopes, T.R. Peres, J.S. Silva, J. Ospina, F. Cichocki, F. Dovis, L. Musumeci, D. Serant, T. Calmettes, L. Pessina, J.V. Perelló, "Weak GNSS Signal Navigation to the Moon," Proc. ION GNSS+ 2013, Nashville, TN, September 2013, pp. 3357-3367.

[23] Space User GNSS Antenna Final Report, SUGA-IIS-ORC-072-0600-FR.