Title: Lunar Relativistic Positioning System (LRPS) for Human Exploration

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Need

The future of human space exploration envisages the presence of permanent settlements on planetary bodies other than Earth. Long range manned and unmanned explorations will have to be conducted by means of rovers leaving from an outpost (for instance, different studies on bases at the lunar South Pole exist [1]), and covering ranges of tens, hundreds or even thousands of kilometers. When losing the line-of-sight with the planetary base, it becomes paramount to be equipped with a proper navigation system. This paper leverages nanosatellites in order to implement an innovative relativistic positioning and navigation system around the Moon, which could indeed act as a test bed for any mission of this kind. In fact, this mission would be the first of its type, both for its goal and for the navigation algorithm used. Regarding the former, LRPS will support man's return on the Moon and enhance human exploration capabilities, and later on other planets. In the far future, the final goal could be even that of supporting everyday human displacements, like GPS, GLONASS do nowadays, and Galileo, Beidou and other systems will soon do on Earth. As for the latter, the relativistic navigation strategy [2] that we use is different from that exploited by the current satellite positioning systems on Earth, but simpler to set up and more cost effective.

Mission Objectives

According to the mission need illustrated above, the following objectives are derived.

Primary objective

1) To support human exploration of the Moon by means of an innovative Relativistic Positioning System whose accuracy in its preliminary configuration is better than 50 meters (1-σ).

Secondary objectives

2) To stimulate development of Relativistic Positioning Systems making use of nanosatellites.
3) To upgrade LRPS satellites in order to host additional payloads by other space stakeholders in order to reduce the economic impact of the mission. These payloads can be of two kinds:
   a. Payloads linked to LRPS primary objective, i.e. exploiting relativistic physics in order to obtain scientific data. An example is the study of the topography of space-time around the Moon in order to characterize the Moon gravity field, like GOCE mission for Earth.
   b. Payloads unrelated to LRPS primary objective. An example could be to carry a lunar radiation detector payload in order to provide a simple but effective early-warning system in case of Solar Particle Events (SPEs).

Concept of Operations

The **space segment** consists of six nanosatellites of 2U size (see Orbit/Constellation and Space Segment sections). Each satellite emits a radar-like Radio Frequency (RF) periodical sinusoidal signal in the S band. The carrier uses pulse modulation with a pulse width equal to 10 ms and a pulse period of 25 ms, so as to emulate the signal of a pulsar [2]. In addition, Direct Sequence Spread Spectrum (DSSS) modulation is used; its purpose is twofold: to enhance robustness, thanks to the despreading gain, and to assign a unique ID to each signal, allowing to identify the transmitting satellite [3]. The proposed method for positioning [4] is based on the use of a four-dimensional grid covering the whole space-time; the grid is drawn thanks to the reception of at least four signals from a set of different sources (LRPS satellites), whose frequencies and space-time coordinates are known. The presence of a clock inside each nanosatellite assures good periodicity properties. The periodic electromagnetic signals are received by a user moving on the lunar ground (e.g. a manned or unmanned rover). Then, correlating these signals with a local replica and measuring the proper time intervals between successive correlation peaks allow to draw the grid and thus localize the user. A graphic example is provided in Figure 1 for the 2D case: the grid is built starting from signals emitted by two different sources (a, yellow, and b, black), the small ovals identify the arrival events, and the red line the user world-line (space-time trajectory).

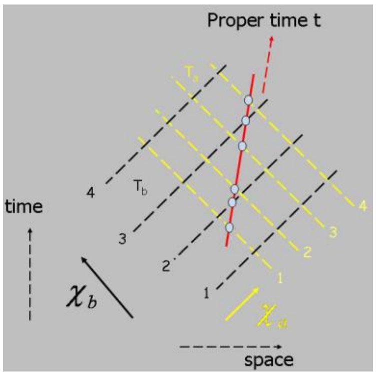

Figure 1. Bidimensional representation of the reception of successive pulses.

The Moon **ground segment** has the function to compute and update important parameters, such as ephemerides of LRPS nanosatellites (required for computing their position), clock drift and error, predicted visibility, and communicate them to the users. When in line-of-sight, the communication link would be direct; otherwise, we foresee to leverage data relay satellites primarily responding to the need of continuous communication with Earth. If no lunar base existed, then we would be compelled to measure satellites' positions from Earth and send them to the Moon. However, since the LRPS is intended especially to serve the needs of a lunar base (which could be possibly located on the rim of Shackleton crater or around Mount Malapert [5]), a laser system measuring satellites' positions placed on the Moon is not difficult to envision.

First estimates show that the user positioning can be known with a maximum error of 50 m (1-σ). The main error source is indeed represented by the difference between predicted and true ephemeris. It is expected that by increasing the ephemeris update frequency (for example exploiting the communication link with the base), this error can be reduced [6].

Concerning the **launch segment**, each nanosatellite will be loaded into a Poly-Picosatellite Orbital Deployer (P-POD), utilizing a tubular design with maximum dimensions 34 cm x 10 cm x 10 cm [7]. After separation from primary payload and launcher, P-POD packages reach the final orbit where LRPS satellites are deployed by means of a spring.

Key Performance Parameters

1) *Coverage*. At least four satellites have to be always visible from the user for algorithm [4] to be applied. However, the more satellites simultaneously cover the area of interest, the more accurate the result will be.
2) *Dilution of Precision*. The Position Dilution Of Precision (PDOP) is paramount when talking about positioning and has to be as low as possible. It depends on azimuth and elevation of all the satellites in view.
3) *Signal Power*. Power is a key design driver, since the main signal processing difficulty lies in the extraction of the pulses when buried in the noise floor. By properly integrating the incoming signal along the pulse duration, Gaussian zero mean noise is averaged and the signal correlation peak emerges.
4) *Nadir-pointing accuracy*. Due to antenna positioning within their frame, our nanosatellites shall be made Nadir-pointing. This means that the Z body axis (nominally aligned with the antenna axis, see Figure 2) shall

be kept aligned with the orbit radial axis.

Space Segment Description

Each of the six LRPS nanosatellites is a 2U, and its external dimensions are 10 cm x 10 cm x 22.7 cm, whereas its internal volume is 2 x $9.84^3 \approx 1900$ cm^3. Figure 2 shows the preliminary CAD external configuration, and Table 1 presents specifications in terms of mass, volume, and power.

Table 1. Mass, internal volume and power budget.

Subsystem	m (kg)	V (cm^3)	P (W)
ADCS	0.84	656	1.50
EPS	0.85	199	1.20
On Board Computer	0.10	107	0.40
Clock	0.01	12	1.00
Structure	0.39		0.00
Thermal Control	0.10		0.10
Communication	0.20	73	0.50
Margin	30%	30%	30%
Total	**3**	**1362**	**6**

The subsystems were chosen mostly among off the shelf components compatible with mission requirements [8, 9]. A brief description of some of them follows.

Attitude Determination and Control Subsystem and Propulsion Subsystem. LRPS nanosatellites are equipped with sun sensors and gyroscopes (3-axes) embedded in the innovative solar panels selected for this mission, thus assuring a good level of redundancy. Furthermore, a 3-axes accelerometer is used. Concerning attitude control, a propulsion system is envisaged: each satellite is equipped with a single Pulse Plasma Thruster (PPT), like the CS-MARS-PPT-01 by Clyde Space and Mars Space, with a specific impulse of about 500-600 s. The PPT enhances their capability to reach the target orbit and, ultimately, to boost orbit lifetime. Then, we envision using a couple of electrospray thrusters, like the Microfabricated Electrospray Arrays (with a specific impulse of 2500-5000 s) under development at MIT and Yale University [10] or at the University of London [11]. ADCS and Propulsion configuration arises from the following considerations: first, the actuation system capability to guide the nanosatellites from the drop-off orbit to the designed one; second, the need for de-tumbling satellites (after the P-POD release); finally, the requirement for Nadir-pointing control strategy. In this way, attitude is determined and controlled with accuracy of about 1-2°. Then, attitude actuation systems shall be able to prevent any satellite spin around its orbital axis (roll motion around X-axis) or angular momentum axis (pitch motion around Y-axis).

Electrical Power Subsystem. For power generation, four GaAs solar arrays are employed, each one producing a power of approximately 2.3 W, with dimensions 8.25 cm x 9.8 cm x 0.21 cm and mass of 60 g. Energy is stored by means of two Li-Ion batteries with capacity of approximately 40 Wh each and mass of 240 g. EPS is sized according to the study of eclipse periods. Over the 22 hour orbital period, dark periods amount to at most one hour. Only once a year, when the obstruction is caused by Earth, eclipse lasts 5 to 6 hours: in this case, the satellite enters standby mode, and all subsystems are switched off.

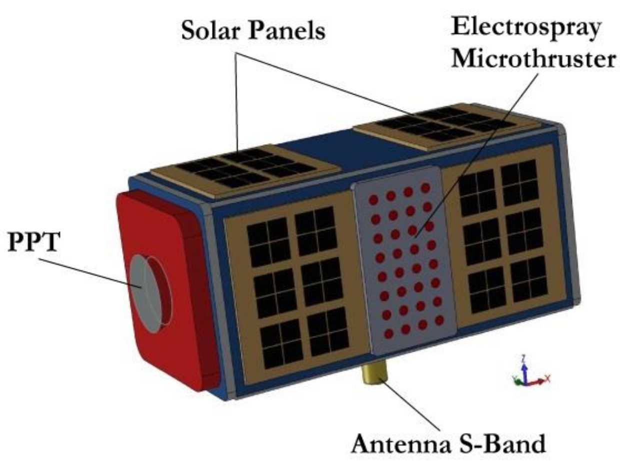

Figure 2. Preliminary CAD configuration.

Clock. Each nanosatellite is equipped with a simple but effective quartz clock, which could be considered as the only payload. Clock choice arises from the trade-off between two contrasting aims. On the one hand, the necessity of keeping clock size, required power, and cost bounded. On the other, the intention of building a plausible and robust mission scenario, able to demonstrate the real feasibility and convenience of a space mission like LRPS. Therefore, an Oven Controlled Crystal Oscillator (OCXO), like the OCXO-H by Astrium, is selected. This oscillator uses a 5^{th}-overtone SC-cut resonator with intrinsic radiation tolerance. The oscillator achieves good short-term and long-term stability. Besides, it is a low power consumption (about 1 W), very compact and low cost device.

Communication Subsystem. The signal is transmitted in S-band (2.2-2.3 GHz), using an antenna mounted on the Nadir-pointing face, with 6 dBi gain and 60° beamwidth, and a 500 mW power amplifier.

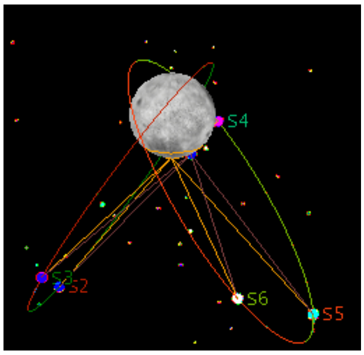

Figure 3. LRPS Constellation.

Orbit/Constellation Description

Orbit design and constellation sizing were carried out in order to fulfill coverage requirements (to provide coverage of the lunar South Pole and areas of interest with at least four nanosatellites simultaneously) and orbit stability. Following a study by Ely [12], the constellation is selected in order to provide persistent, stable coverage to the South Pole and surrounding areas. LRPS constellation is then sized as in Table 2 and Figure 3: all the orbits have eccentricity 0.6, right ascension of the ascending node RAAN=**Ω**=0°, and argument of perilune ω=90°. The orbits thus selected are like Molniya orbits around the Earth: their inclination and eccentricity assure a long permanence of the spacecraft above the lunar South Pole.

Table 2. Orbital elements for LRPS satellites. 'S': satellite. 'a': semimajor axis. 'i': inclination. 'M': mean anomaly. 'T': orbital period.

	a (km)	i (deg)	M (deg)	T (h)
S1	6541.40	56.2	0	22.16
S2	6543.98	56.2	120	22.17
S3	6537.92	56.2	240	22.14

	a (km)	i (deg)	M (deg)	T (h)
S4	6541.40	123.8	0	22.16
S5	6543.98	123.8	120	22.17
S6	6537.92	123.8	240	22.14

The choices presented in the table above are reflected in the ground coverage requirement. Analytical results show that if we travel on the lunar ground away from the South Pole up to a radius of about 1500 km, coverage from at least 4 satellites is always guaranteed. For instance, Figure 4 depicts the coverage over a circular area with radius 750 km: it can be observed that for most of the time, all six satellites have access to the area of interest.

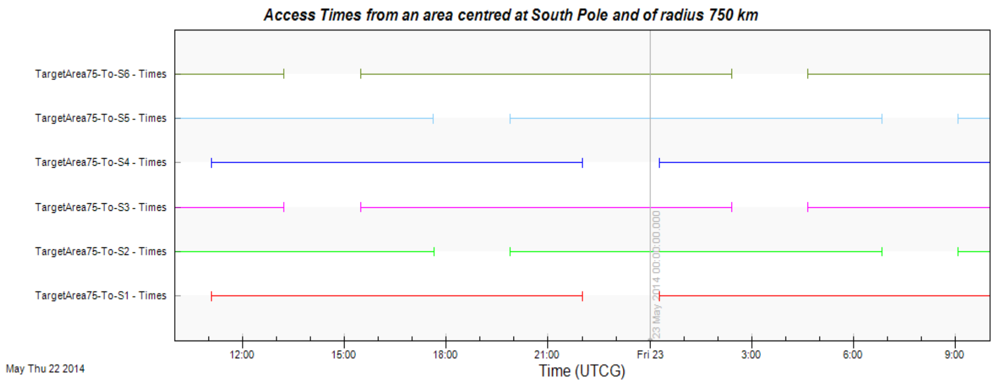

Figure 4. Coverage provided by the LRPS over a circular area centered at the South Pole with radius of 750 km.

Finally, it has to be noted that in order to increase position determination accuracy, the number of satellites should be increased. However, this lies beyond the scope of this preliminary investigation: indeed, once mission success is achieved with the present configuration, further studies will have to be conducted and a new constellation size and geometry will probably arise.

Implementation Plan

The existence of the LRPS mission is strongly related to the intention of conducting extensive lunar exploration. The main stakeholders for this kind of mission are first of all space agencies all around the world, which could tailor it to the specific architecture of the mission they are planning. The low mass and volume of LRPS nanosatellites make them highly competitive, also because only piggyback launches would be needed, where minor modifications to the launcher payload adapter configuration should be carried out.

Furthermore, each nanosatellite can be assembled mostly with off the shelf components whose cost is estimated between 100 and 150 k$. A preliminary estimate of total life cycle cost including design, development, assembly, integration, testing, launch, and operations is roughly 5 M$. Unfortunately, in this very early phase of the project it is difficult to provide both total life cycle costs and a project schedule. Anyway, following the scenario outlined in the Global Exploration Roadmap, the launch prototype would have to be ready by 2025. Before 2030, the LRPS constellation would then have to be built, and launched at the beginning of the 2030s. Concerning the design phase, as outlined in mission objectives the innovative LRPS concept is also flexible, since it can be extended to accommodate other payloads. This is why the design phase could last also more than 5 years.

Being in the very early stage of conceptual design, there is no definite organizational structure for the LRPS project. Currently, it is led by three graduate students with support from a Politecnico di Torino professor. In the future, new students and faculty members will be invited to participate: also collaboration with other universities will be sought, as well as a partnership with the European Space Agency, and/or private industry.

Finally, five top risks for LRPS mission are listed below.

1) *Uncertainty about lunar and planetary missions*. LRPS is designed for long range exploration missions on planetary bodies. Changes in the space exploration roadmap could affect LRPS negatively, but we are confident that these types of missions will not be overlooked. The Moon was chosen as case study, since it could be an effective test bed to demonstrate relativistic positioning missions.
2) *Competition with existing technologies*. The innovative character of our mission could indeed clash with proved existing positioning technologies, whose extraterrestrial utilization has already been proposed. GPS positioning on the Moon offers good results, although requiring advanced signal processing techniques, integration with inertial sensors, and showing limited availability. Nevertheless, we are positive that the low cost of our mission, the reduced complexity of our positioning system, the preferable DOP values and the better coverage will indeed capture the stakeholders' attention.
3) *Launcher separation*. At the end of this phase the uncertainty upon satellite orbit and attitude is a major issue. To counteract these effects, thrusters and attitude sensors are included in order to reach nominal values.
4) *Radiation*. Being outside the Van-Allen belts, the radiation environment to which LRPS satellites are exposed is a crucial issue; in this preliminary configuration radiation shielding is left to the structure subsystem.
5) *Maintenance*. Failure of a subsystem may result in loss of a single satellite, implying reduction in coverage. Maintenance of the LRPS constellation consists of launching new satellites, which could result in long waiting times. Thus, redundancies in constellation size should be considered.

References

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