Manfred Memorial Moon Mission (4M): development, operations and results of a privately funded low cost lunar flyby

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ABSTRACT

The first privately funded mission to the moon, Manfred Memorial Moon Mission (4M), was developed within six months. The attractive launch opportunity itself and three mission objectives powered the development: 1) to honor and commemorate Prof. Manfred Fuchs the founder of LuxSpace's parent company OHB, 2) to demonstrate crowd-based navigation for deep space missions, 3) to measure the radiation dose on the way to the moon and back.

Following three maxims enabled success of this endeavor: a) low complexity, b) simple documentation and c) reduced launch site operations. This approach requires continuous communication and trust-based relationship between all project partners (customer, governments, launch provider, system integrator, suppliers and the public).

The 12 kg spacecraft is attached to the last stage of a Chinese Long March 3C/G2 launcher dedicated for Chang'e 5 T1, a re-entry demonstrator capsule. Housekeeping data, greeting messages and data from the radiation experiment were transmitted at 145.98 MHz. 4M started to hibernate after 438h (100h design lifetime).

More than 75 registered radioamateurs from 29 countries supported 4M with a variety of ground stations. The mission increased public awareness in moon exploration, international cooperation, and affordable space missions, which always were central concerns for Prof. Manfred Fuchs.

INTRODUCTION

At the start of 2014, as a result of a long-lasting relationship with China Great Wall Industry Corporation, LuxSpace was offered an opportunity to hitchhike with the Chang'e 5T1 moon probe at end of October. The proposed trajectory was a lunar transfer orbit, i.e. go to the moon, fly around it, and then come back. Limits for the payload's mass and volume were quite stringent, as well as the requirements on safety of the main mission.

The question was not whether to take this opportunity, but how to do it. A mournful occasion in April 2014 triggered the final decision to fund the mission with the company's own money: Professor Manfred Fuchs, founder of the OHB group, passed away in April 2014. He always had the dream of a lunar mission and considered to invest in private pioneering of the moon. In his memory, the mission was christened 4M, the Manfred Memorial Moon Mission.

Broadcasting of greeting messages (including memorial messages for Prof. Fuchs) from the Moon to the whole world was decided as one objective. To collect messages and raise awareness for the upcoming mission, a mission website and social media marketing was initiated. The radio amateur community was gained to receive those messages and acknowledge their reception.

LUXSPACE PLATFORMS

The ten years old Luxemburgish member of the OHB SE group LuxSpace has two major platform lines for microsatellites: The Triton platform for cube-shaped spacecraft that rely on the SatEdu and Vesselsat heritage above 20 kg and the Skylark platform for flat panel-shaped spacecraft below 20 kg.[1, 2]

The Triton platforms range from a controlled tumbling 30 kg spacecraft (Triton-1, examples: Vesselsat-1 and Vesselsat-2), 3-axis stabilized 80 kg spacecraft with and without propulsion (Triton-2, examples: ESAIL, LADSB) up to a 3-axis stabilized full electrically propelled spacecraft in the 350 kg class (Triton-10, example: MicroGEO).

The Skylark platforms are exemplified by the Pathfinder 2A and Pathfinder 3 spacecraft, which were attached to the last stages of Indian and Chinese rockets. Free-flying derivates of the Skylark platforms are also available.

Selecting the class from the platform lines is a process to be performed jointly with the customer. Major decision criteria are time to launch, requirements of the main passenger, financial budget, allowed risk and level of documentation.[3]

DESIGN APPROACH

LuxSpace follows an approach that has been pioneered by small companies with strong involvement of radioamateurs within the last 40 years, the microspace approach. [4, 5] Fundamental aspects of this approach are a) low complexity (Keep It Simple, Stupid), b) simple documentation and c) reduced launch site operations. Continuous communication and trust-based relationship between all project partners (customer, governments, launch provider, system integrator, suppliers and the public) is essential. Therefore this approach is also more risky for all included entities. Nevertheless, the commitment of the entities is experienced to be extraordinary high.

Classifying projects according to certain measures like program risk, cost, prestige supports LuxSpace in defining the proper methods and approach for a broad range of projects [6]. Of these four LuxSpace project classes, the 4M project was classified as a lowest cost – high risk project similar to two previous projects. The short timeframe until launch, the high safety requirement of launcher and main passenger and the cost budget in the lower six-figures range required a simple and robust architecture. Minimization of mechanisms and reduction of sources of potential failure was a primary goal. For such missions, the Skylark platform of LuxSpace is best suited. In addition to its robust architecture, the platform was already known to the Chinese launcher authorities, which eased the cooperation.

SPACECRAFT DESCRIPTION

Platform

The selected spacecraft structure was based on the proven Skylark structure, i.e. with a bare aluminium structure milled from a solid block (550 x 370 x 55 mm^3). The structure is mechanically robust, thermally stable, provides adequate radiation shielding and was already qualified for a large range of launchers. It accommodates a solar panel and shielded payload room inside. Figure 1 shows a view of the interior.

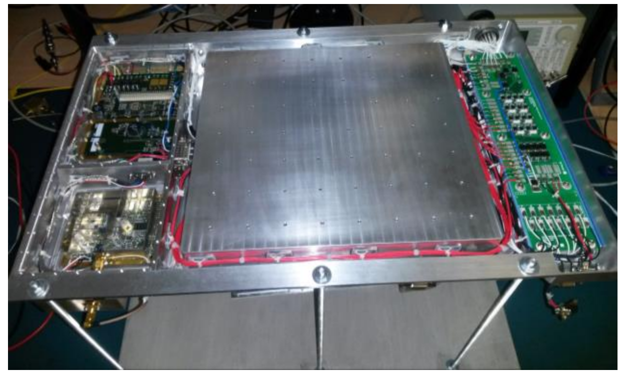

Figure 1: 4M spacecraft upside down with open bottom

To reduce complexity and increase reliability of the spacecraft, no separation from the launcher was foreseen, i.e. the free-flyer option of the Skylark platform was not chosen as baseline. The baseline design was the attached payload option of Skylark, i.e. the spacecraft remains mechanically attached to the launcher. Electrically it remains fully independent. One drawback of this option, however, is that the spacecraft would not always be illuminated, which imposes certain constraints on the thermal and power architecture. Nevertheless, this design was considered as the best compromise of time to launch, low risk on launcher and main passenger, low cost and high prestige. The goal was to reach the moon, make the flyby and come back. For this primary mission goal a minimum mission lifetime of 100h had to be guaranteed.

Spacecraft electrical power supply

The mission required a 100% duty cycle for the message transmission. Relying only on the photovoltaic array was impossible. Therefore, a pack of non-rechargeable cells, which can withstand the expected temperature range and meet the required payload power demand have been selected as primary power supply. A set of LSH20HTS cells from SAFT were used in an assembly of 7 x 4 cells in series.

As the trajectory for the remaining mission after the moon flyby was not absolutely clear (a 10% percent chance of not directly reentering Earth atmosphere was communicated in the beginning) a secondary power supply was implemented. The secondary power source comprises a photovoltaic array and rechargeable batteries. The photovoltaic array is a DB_SW_3061US from SunWare from LuxSpace stock. This panel has been qualified in previous projects and proved to work very well (>2.5 years at 900 km LEO). Overvoltage protection was provided by adding a simple circuit based on Zener diodes. A bank of 4 SAFT MPS170065 rechargeable Li-ion batteries also on stock completed this subsystem.

The non-rechargeable cell pack was connected 12 hours before launch. A cable was routed from the 4M spacecraft to an access window in the fairing and a special connector was plugged in, connecting the negative return of the cell strings to the ground. The cable also included a RS-232 diagnosis link, mainly to check the proper functioning of the pressure sensors and the clock settings. The connector included an LED, which provided a convenient and simple way of indicating the status of 4M.

The total power consumption of 4M (including experiments) was only 3.8 W for a RF output power of 1 W.

Spacecraft controller

The FM430 on-board controller (OBC) was also on stock. It is based on the MPS430 TI microprocessor and was qualified on a previous project. It was plugged into a custom-designed interface board**.**

Spacecraft Activation

One of the major challenges was the activation of the 4M spacecraft. No external command from the launcher was available, so we used a proven and qualified system based on pressure sensors and a timer.

There are two on-board pressure sensors, which are powered individually by separate point-of-load regulators. The OBC monitors both, the output voltage and the supply voltage of each sensor. It is mostly in stand-by mode and checks the pressure every 5 minutes. In this configuration, the power draw is minimal and the payload could, in principle, last for weeks prior to launch using only the battery. After launch, a timer was started when the 12 km altitude (its representative ambient pressure) threshold was detected by the pressure sensors. After 4000s, this timer then activated the spacecraft with its experiments.

Data transmission

The link budget was of concern given the distance (>400,000 km), the available power, the expected equivalent isotropic radiated power (EIRP), and the size of the average receiving station antenna. The widely used Earth-Moon-Earth (EME) mode JT65B was selected. It had the required data rate, met the link budget requirements, was proven in the field and was readily available.

Transmission Chain

The transmission chain consists of an I/Q modulator (specifically designed for this mission) followed by a power amplifier. The modulator's maximum output is 5 dBm and the power amplifier has a nominal output power of 1 W (30 dBm). The I/Q modulator is based on a MiniCircuit I/Q mixer. It is biased at the mid-supply voltage by a set of op-amps to avoid the need of a negative power supply to drive it. This was followed by an Avago Technologies gain block. The raw I/Q signals from the internal digital – to – analog converters (DACs) of the processor were filtered by a reconstruction filter based on a Sallen-Key elliptical filter with a 4 kHz cut-off. The sampling frequency is 16,384 Hz.

Demodulation Software

The JT65B sequence was followed by an analog sequence, serving as boundary indicator. This also allowed easier synchronisation as the on-board computer (OBC) clock was known to be rather unstable. For this mission, the OBC clock was set up 8 days before the launch. This ensured the JT65B sequence would start +/-1s within the UTC minute, accounting for the measured drift. Two of the internal DACs of the MSP430 microprocessor were used to generate the I/Q signals. The software generated the signals with a numerically controlled oscillator (NCO) approach, keeping the required phase continuity for JT65B sequence generation. It also handled the necessary Reed-Solomon encoding. The offsets and amplitude of the I/Q signals were handled in software. The 6 internal ADCs were used for monitoring the voltage, current, pressure, and internal temperature sensors.

Antenna

Two key design points, both related to electromagnetic interference (EMI) and electromagnetic compatibility (EMC), were of major concern. The first one was the close proximity of critical launcher equipment. We had to ensure that the EM fields of 4M do not put it at risk. This restricted the output power and the antenna. The second one was the close proximity of a 1 kW EIRP S-Band telemetry transmitter. This meant that we had to design the 4M carefully making sure that no EMI would occur, especially on the activation system. Although using 435 MHz was preferred due to lower noise at receiving stations, the location on the launcher, available space there, and available output power made the 146 MHz frequency more suitable.

Early estimates indicated an average gain of -6 dBi, while the simulation results were in the range of -10 dBi. Signals that were actually received showed around

-13 dBi average gain, with some peaks at - 1 dBi, which were expected. Nevertheless, the link budget had enough margins to cope with it, and actually made the challenge more interesting. The -13 dBi gain represents 50 mW EIRP on average.

Radiation Experiment

The chip design company IC Malaga from Spain came up with an on-board experiment based on their new dosimeter chip. Their proposal, an answer to a call for experiments, was selected as main secondary experiment. They provided a complete experiment, which was easily integrated into the 4M unit. This experiment was developed built and tested within 5 weeks and proved successful.

Data reception contest

To setup a world-wide crowd-based ground station network, radioamateurs were motivated with a data reception contest. The challenges were to submit as much received and decoded signals to the data warehouse as possible.

Electronic Qualification

All electronics were designed for the expected radiation environment, either by having been qualified through on-orbit operation or the appropriate selection of components. They also had to work at a 100% duty cycle between -40° C and +80° C. The RF-Power Amplifier engineering model was qualified at 120° C, 100% duty cycle, 150% output for 6 hours.

Test campaign

The entire 4M spacecraft underwent the following tests to show that it survives the launch without threatening the launcher and main payload as well as increasing designer's confidence in the chosen robust design:

- vibration and shock tests for all axes, in accordance with the LM-3C launcher user manual,
- thermal vacuum test, between -20° C and +50° C (Figure 2 and Figure 3),
- activation sequence test with vacuum conditions of thermal vacuum chamber,
- long-duration test burns (2 x 120 hours), of which one was conducted with a set of LSH20 cells,
- EMC/EMI tests, and
- EIRP tests.

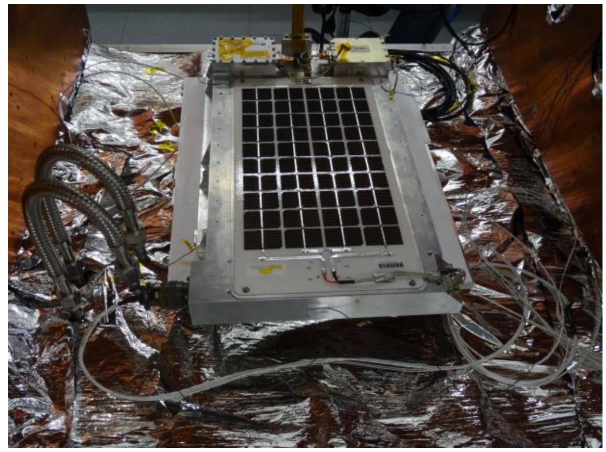

Figure 2: 4M in thermal vacuum chamber for thermal vacuum test and activation sequence test

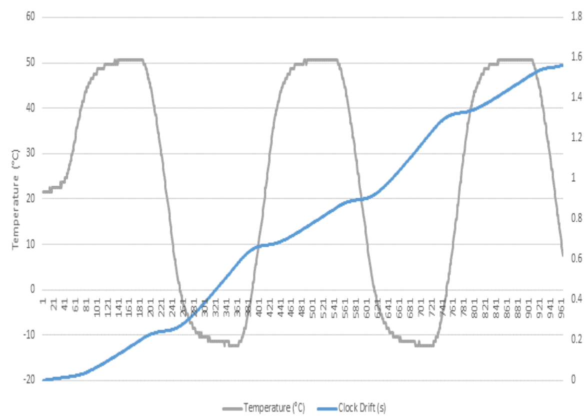

Figure 3: Temperature log of thermal vacuum test and corresponding clock drift

RESULTS

Launch and Activation

The 4M spacecraft was bolted to the main payload at the launch site (Figure 4). The launch itself took place at Xichang Satellite Launch Centre, located in Sichuan Province. It was scheduled for a narrow window and went off smoothly.

The 4M spacecraft was activated at the exact planned time of October 23, 2014 at 1918 UTC. First signals were received by two stations in Brazil, soon followed by Australia and New Zealand. Stations along the U. S Pacific coast also received signals.

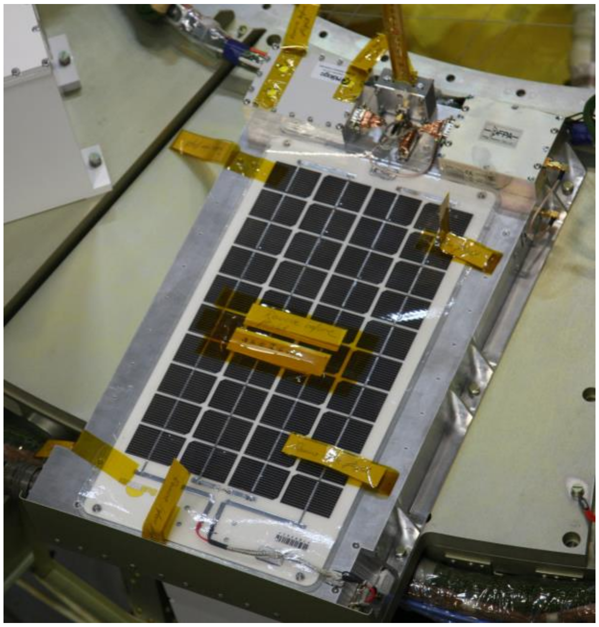

Figure 4: 4M spacecraft bolted to the launcher

Downlink

The JT65B sequence was well synchronized with the UTC minute, eliminating a time offset search. Signal levels at apogee were received consistently at levels up to -17 dB SNR (in JT65 convention) and were consistently decoded down to -160 dBm at receiver input, -24 dB SNR, showing the quality of the generated signal. There was unavoidable QSB (fading signal) due to the rotation of the last stage and the resulting uncontrolled radiation pattern.

The 4M spacecraft was visible in Europe on October 24 and its signals were readily received. Some radioamateurs went to incredible lengths with their equipment to receive those signals. For at least the first day, they succeeded with an Eggbeater antenna and a FunCube dongle without any preamplifier.

Given the trajectory and the commitment of stations, 100% of the messages were received up to the Moon flyby, which occurred in the night of October 28.

Spacecraft Trajectory

Errors can be magnified during a flyby. A slight deviation in the injection vector can lead to a wide difference between the actual final trajectory and the one that was predicted. This is what happened in our case.

The launcher's trajectory was very accurate. However, since 4M was located on the last stage, its trajectory had some uncertainties. The main reason was that it is common practice for all launchers to vent their tanks after they are depleted. This is done to avoid possible explosions and, therefore, avoid, as well, the production of debris. The remaining quantity of propellant in the tanks of the last stage introduced a margin of uncertainty, but we were provided with good estimates of the trajectory. Until the lunar encounter, the actual trajectory was barely distinguishable from the nominal one - the tracking was very good.

After the lunar flyby, a Doppler shift higher than expected was observed. This was initially attributed to the 5 ppm temperature compensated crystal oscillator (TCXO) of the modulator local oscillator as well as the decrease in temperature of the payload. It soon appeared that this was not the reason and that the return to Earth had occurred sooner than expected. Some stations received the signal purely by chance at a time when they weren't expected to. The actual orbit still needed to be determined via Doppler shift measurements.

This was made possible by the automated data collection provided by LSE Space. As more Doppler data came in, we refined our estimate. The automated data collection system made it easy to access the data (Figure 5). In this figure, the “zero Doppler” is at 355 Hz. The unexpected temperature stability of the payload became apparent through consistent measurements.

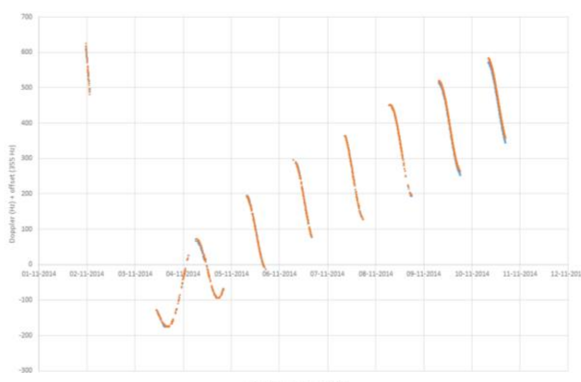

Figure 5: Doppler measurements of 4M signals

After the lunar fly-by, the orbit had an apogee of 386,000 km, a perigee of 90,000 km, and inclination of 60°. It is not likely to remain stable as each encounter with the Moon will change the orbit.

Radiation Experiment

The radiation experiment operated for 215 hours, demonstrating the quality of the dosimeter chip, as well as producing data which matched well with simulated radiation doses, particularly during the first hour

(Figure 6). The rapid rise of the doses impressively exemplifies the harsh environment encountered during the crossing of the van Allen radiation belts. The radiation experiment stopped working due to an apparent software bug, but the performance IC Malaga's device was both impressive and highly effective. A detailed presentation of the DRALUX experiment design and its results is presented in Cesari et al 2015. [7]

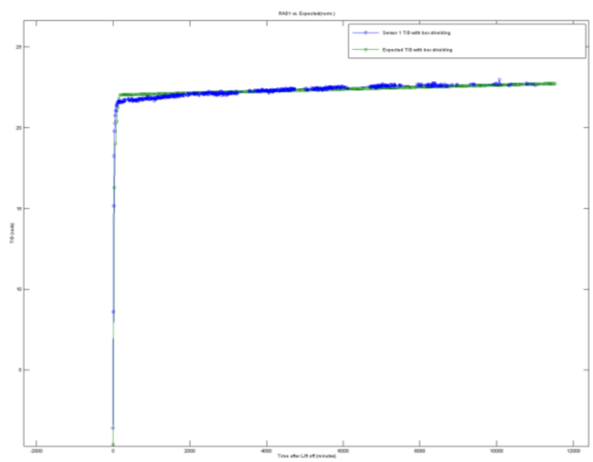

Figure 6: Measured radiation dose of DRALUX experiment

Data Reception Contest

The contest for data reception was very successful -we expected 20 stations but 75 entered. The number of greeting messages was deliberately set so that there was a cycle of about 50 hours in order to be broadcast at least twice during the minimum mission time. The contest duration was set at 151.5 hours. The maximum number of messages that could be collected during that time was 9090. The random hand-over from station to station allowed consistent reception, particularly after the moon flyby when the trajectory determination allowed the publication of good orbital elements.

Secondary Experiments

As a secondary experiment, it was initially planned to perform in time difference of arrival (TDOA) experiments. For more information on this, also known as multilateration or delta-differential one-way ranging (delta-DOR), see reference. [8]

For this, we set up the necessary routines using MATLAB. The objective was to provide a more accurate estimate of the trajectory before the fly-by. We weren't optimistic about this, since measurement accuracy shorter than 1 ms was required, and the Windows operating system is considered to have to low accuracy and precision. The result of the multilateration was even worse. If many stations used time synchronisation systems based on network time protocol (NTP), the configuration of the NTP was generally poor. However, it indicated the way to improve this. Also considered was frequency difference of arrival (FDOA), though we were not optimistic about it, either. It worked unexpectedly well. The reason was that the frequency offset of the stations was rather stable and so, also, was the frequency of 4M. The process included the minimization of a cost (i. e., objective) function that computed the difference between the measured and computed Doppler values. The stability of the frequency offset allowed it to be considered as an input variable (which had to remain fixed during the process) in that minimization.

HIBERNATION AFTER 438H

4M stopped transmitting on November 11 at around 0135 UTC, with the last messages received by Rein Smit. By that time, 4M had already passed its second apogee (Figure 7) and outperformed its design mission lifetime by more than factor 4. This success is even more noteworthy as the spacecraft average temperature was at the cold end of what was expected, i.e. the worst case cold conditions.

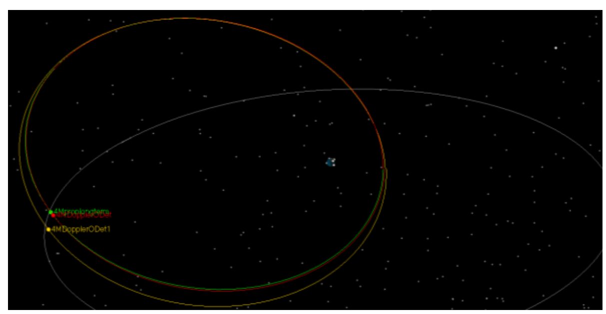

Figure 7: 4M trajectory

FUTURE PLANS

Building on the success of 4M and the Chinese Lunar Exploration Program, the next step has to be planned. Another mission to the moon is planned for 2018 and we already booked a place on it. The planned trajectory is similar to that of Chang'e 5T1, albeit much better controlled. The current plan is a scientific mission with the objective to study the far magnetosphere and magnetopause, and, possibly, the detection of near-Earth objects. Our plan right now is to use our rugged and successful extended Triton-1 platform, which presently is in commercial service on other missions. An option with electrical propulsion is depicted in Figure 8. To realize this we are welcoming partners and investors to join our endeavor.

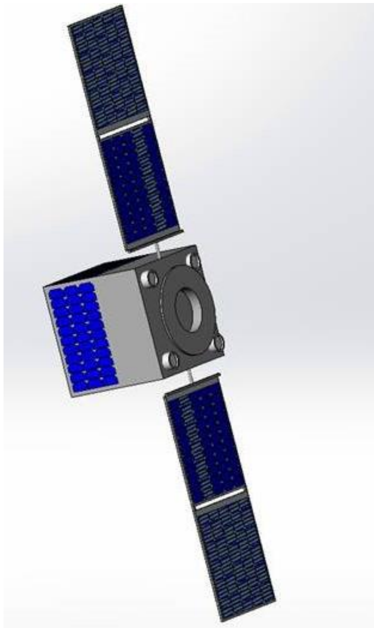

Figure 8: Model of Triton-based mission option for the next moon mission

CONCLUSION

To conclude, 4M is another example of LuxSpace's successful microsatellite platforms. It demonstrated the feasibility of low cost interplanetary space missions realized within less than half a year. Key to success is the microspace design approach that is in contrast to mission development processes directed by large entities. Before entering hibernation after 438h, 4M outperformed its design lifetime by a factor of more than 4. Public awareness was not only increased by the data reception contest for radioamateurs, but also by a social media campaign that continuously provided up to date news on the project. Finally, by raising the attention for moon exploration, forwarding international cooperation, and promoting affordable space missions, we continued the pioneering efforts of Prof. Manfred Fuchs. With the upcoming opportunity, the next step in commercial and privately funded space missions is in preparation.

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