The BayKoSM Project: Technologies for Swarm Missions

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Abstract: *The BayKoSM project is a cooperation of several universities and companies in Bavaria, funded by the Bavarian government. The aim of the project is the development of key technologies for swarms of mobile vehicles. These swarms consist of either pico satellites or uninhabited aerial vehicles (UAVs). The paper describes the corresponding technologies and how they are used within the scope of BayKoSM for intelligent swarm behavior.*

Keywords: *Distributed Satellite Systems, Swarms, Uninhabited Aerial Vehicles (UAVs)*

1. Introduction

The usage of swarms of vehicles instead of a single large vehicle offers a multitude of novel application sectors. Swarms of small satellites will be able to take pictures of the Earth with much higher quality compared to a single image sensor using fusion of sensor data and they might be used for deorbiting of larger satellites. Swarms of UAVs (Uninhabited Aerial Vehicles) will be able to provide ad-hoc networks in remote or isolated regions, for example disaster areas. Many advantages can be achieved by the usage of vehicle swarms. They are easily scalable concerning cost and swarm size and operations become very flexible and cost-saving in comparison to large systems. Furthermore a swarm system is able to compensate failures of single members whereby operational robustness is increased.

The ambition of this project is the development of technologies for a swarm system with advanced autonomy. Since all swarm vehicles will be relatively small, the autonomy plays a decisive role. It allows performing complex swarm tasks with a high degree of cooperation and provides functionality which cannot be realized with a single vehicle of such a size due to restricted on-board resources. In order to realize complex swarm behavior many different parts of the systems, both pico satellites and UAVs, need to be optimized and extended. Higher requirements like increased energy consumption, synchronization, accurate positioning and navigation of swarm vehicles are major challenges. BayKoSM will make contributions to technologies which are of particular interest in this area.

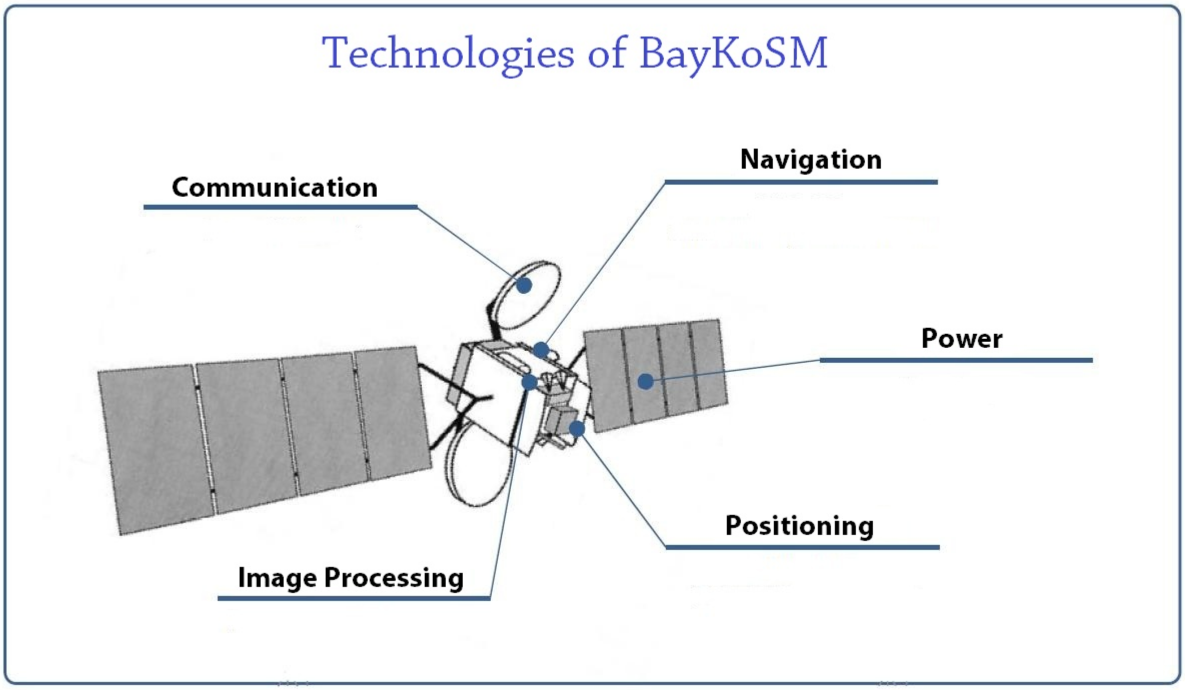

Figure 1. The five technological areas of BayKoSM

Figure 1 shows five key technologies which are handled within the scope of BayKoSM:

- Autonomous navigation of vehicles in teams
- Ad-Hoc communication for vehicles
- Power generation with temperature gradients
- Positioning via Galileo signals
- On-board Image Processing

In the following sections these technologies will be described in more detail with respect to main objectives, relevance and first results.

2. Key technologies within BayKoSM

In this section we will present the various technological areas for swarm missions to be investigated within the scope of BayKoSM.

2.1. Positioning

Carrier phase measurements from Global Navigation Satellite Systems (GNSS) can be tracked with millimeter accuracy. However, the carrier phase is periodic with a wavelength of 19.0 cm and requires an integer ambiguity resolution for each satellite. In BayKoSM, ANAVS has developed a differential carrier phase position and attitude determination system based on two low cost GPS receivers.

Low cost GPS receivers include oscillators with clock offsets in the order of milliseconds. As GNSS satellites move with a speed of 4 km/s, the satellites can move several meters within the time of the differential receiver clock offset. Therefore, a correction was required to compensate for that movement and to restore the integer property of the ambiguities. Once the correction is determined for all double difference measurements, the respective double difference ambiguities are resolved. A new Maximum a Posteriori Probability (MAP) estimator has been developed, which determines the most likely baseline and ambiguity parameters for a set of given measurements and Gaussian a priori information. The MAP solution is determined in three steps: First, a constrained float solution is determined by disregarding the integer property of ambiguities. Subsequently, a tree search is performed to find a set of integer candidates and to select the candidate of minimum MAP error norm. Finally, the fixed baseline solution is determined and coasted over time. The a priori information on the baseline length and orientation has been fully integrated into the constrained float solution, the tree search and the constrained float solution. The constraints reduce the search intervals at each node of the sequential search tree and, thereby, substantially improve the efficiency of the search. The proposed MAP estimator has also been used for cycle slip detection and correction as well as for instantaneous fixing of newly tracked satellites.

The developed position and attitude determination system enables a relative positioning accuracy of 5 mm, which corresponds to a heading accuracy of 0.5°/ baseline length [m]. The proposed algorithms have been implemented on an Intel I7 processor and tested in various car drives. A real-time heading information is provided on a Tablet with 5 Hz update rate as shown in Fig. 2-3.

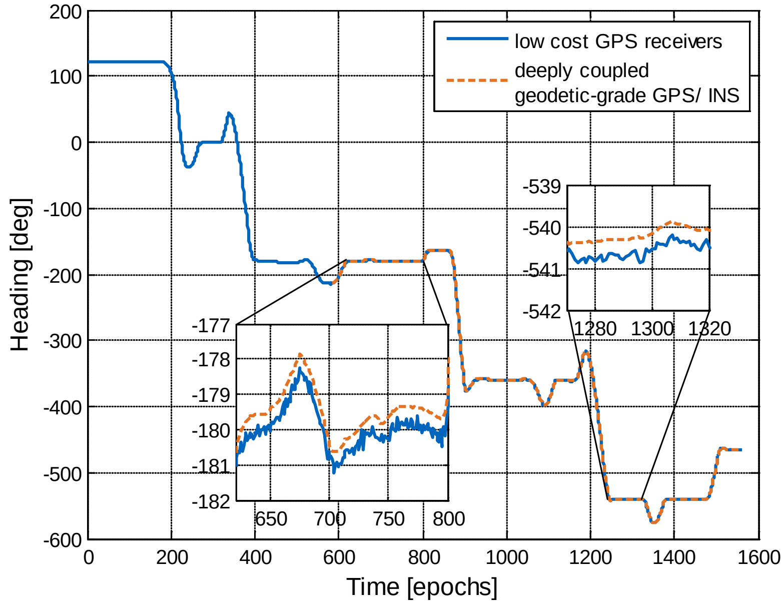

Figure 2. Heading of passenger car: Comparison of ©ANAVS solution based on two low-cost single frequency GPS receivers and a deeply coupled geodetic-grade GPS/INS for the receiver trajectory of Fig. 3. The heading is counted clockwise with 0° in northern direction. The heading of ©ANAVS solution closely follows the heading of the deeply coupled geodetic-grade GPS/INS.

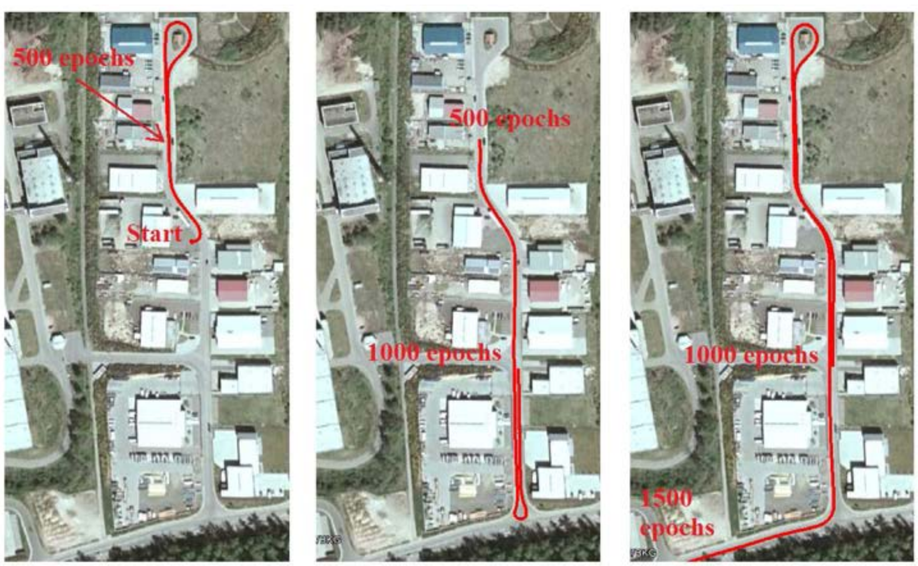

Figure 3. Track of a passenger car: The track was determined with carrier smoothing without map matching. The turn of the car in the beginning of the track can be well observed.

2.2. Communication

Formation flying missions with UAVs or small satellites will benefit from an autonomous communication network able to handle a changing topology and mobility. For this reason, the communication concepts "*Delay Tolerant Networks*" (DTN) and "*Mobile Ad-hoc NETworks"* (MANETs) are being investigated for various scenarios in the scope of BayKoSM. The reference platform for satellite technologies is the CubeSat UWE-3 [1] (Universität Würzburgs Experimentalsatellit, see Fig. 4) which has been developed by the University of Würzburg and is currently waiting for launch.

Figure 4. UWE-3: Picosatellite of the University of Würzburg

BayKoSM focuses on a transfer from terrestrial communication standards, for example IEEE 802.11 or UMTS, to formation flying missions. Various network protocols, hardware components and communication concepts have been analyzed in order to set up an efficient infrastructure for swarms of satellites or UAVs. The concept is based on defined mission requirements, for example data rate, mobility or relative distances. A bottom-up approach was chosen for the definition of all necessary communication parameters and protocols, able to fulfill the mission requirements. Starting with the physical layer, a link budget verifies the feasibility of the scenarios and requirements. It also includes a comparison of modulation techniques, coding schemes and antenna parameters.

MANETs are a type of wireless ad-hoc networks, which are capable of autonomously construct and configure themselves in a completely distributed manner. The multi-hop nature of a MANET enables to construct a fully connected topology, even in scenarios with high mobility. The advantages of a MANET refer to energy consumption and network scalability. The multi-hop capability of a MANET enables the participants to bridge huge distances by routing all information within the network. An adaptive transmitter output power, modulation technique or coding scheme are some examples which handle changing channel conditions or energy consumption. The network availability and scalability are further important advantages which increase with the number of nodes. Complex structures of partially connected nodes include various possibilities for routes between two nodes and increases with the number of nodes.

DTNs provide communication in disrupted networks with a new architectural approach to networking. Therefore an overlay communication protocol, called Bundle Protocol, is used to transfer data using a store and forward mechanism. In this approach, data is stored locally by intermediate nodes which become the custodian of data packets upon reception and forward the data once another node comes into range. The advantage of this communication approach is that data can be send towards its final destination even if the receiving node is currently not part of the reachable network and therefore no instantaneous route from sender to receiver exists. Different routing algorithms will be investigated and the efficiency of the DTN concept will be analyzed for the chosen formation scenarios and with respect to various communication parameters.

Finally selected concepts will be analyzed in different scenarios for networks of satellites and UAVs. In order to compare DTN and MANET protocols in different formation scenarios we created a simulation environment, which combines an orbit propagator and a network simulator to perform significant simulations including realistic satellite trajectory calculations. Simulations of UAV scenarios were implemented by using navigation data, described in section Navigation. Appropriate models for propagation delays and propagation loss models are utilized to increase the quality of the simulation results. Analytical and statistical evaluations will enable for conclusions concerning suitability of different communication concepts in specific scenarios.

2.3 Power generation

The increase in functionality and autonomy in satellites and satellite swarms drives the need to increase the generated power on board these systems. The two main ways to accomplish this are not very promising. A gain in efficiency of solar panels cannot be expected and the usage of radioisotope thermoelectric generators is ecologically questionable. The possibility to generate power is very limited, especially for small satellites. This is why thermoelectrical power generation is a potential key technology.

Combination of thermogenerators and solar cells

Mechanically, thermogenerators can be integrated in the satellite or between solar cells of deployable panels. Since one side of the satellite is in sunlight and the opposite side in the shade, a temperature difference is present, which makes the generation of power possible.

Integrating the thermogenerator directly behind the solar cells simplifies the construction and makes big changes in the satellite setup unnecessary.

The temperature difference that can be expected for these micro satellites lies between 20 and 50 °K. In that range, the power which can be generated is between 20 and 150 mW.

Power Management

The output voltage of thermogenerators is very low, especially for small temperature gradients. A boost converter has to be used to convert the small voltage to a higher voltage for charging the battery.

To extract a maximum amount of power from the thermogenerator a Maximum Power Point Tracker (MPPT) hast to be employed. A MPPT regulates the input power of the boost converter in a way, that the maximum available power is converted and stored in the battery.

In the scope of this project, a digitally controlled boost converter has been developed. It can start up at an input voltage as low as 70 mV using a self-oscillating circuit. Once a high enough output voltage has been reached, the digital control takes over and regulates the maximum power point.

The power consumption of the active converter with Maximum Power Point Tracking is 36 µW and the efficiency can be over 70 %, even at very small voltage and power levels.

2.4 Navigation

A New Deorbiting Concept using Small Satellites

Future space robotic systems will require a higher degree of flexibility when compared to current available solutions if they are to provide better capabilities and safer, cheaper operations. This flexibility implies a significantly higher degree of autonomy, in particular for guidance and control systems.

In the framework of the BayKoSM project a new mission concept for debris deorbiting is being developed (see Fig. 5) which offers much higher flexibility and lower costs then current deorbiting concepts. Instead of capturing the debris with a single spacecraft equipped with a robotic arm, the new deorbiting concept envisages a swarm of small satellites which act in synchronization to slow down space debris, as if they were the fingers of an (invisible) hand:

1. In a first step the formation of small satellites approaches the debris;
2. At a given instant, the deorbiting operation is activated and the small satellites move in synchronization with each other until they simultaneously touch the debris (but do not dock);

3. Upon contact with the debris, the small satellites fire their thrusters in synchronization, slowing down the debris and causing it to reenter the atmosphere;
4. The small satellites that run out of fuel will be commanded to also reenter the atmosphere while all others can be reused for further deorbiting operations.

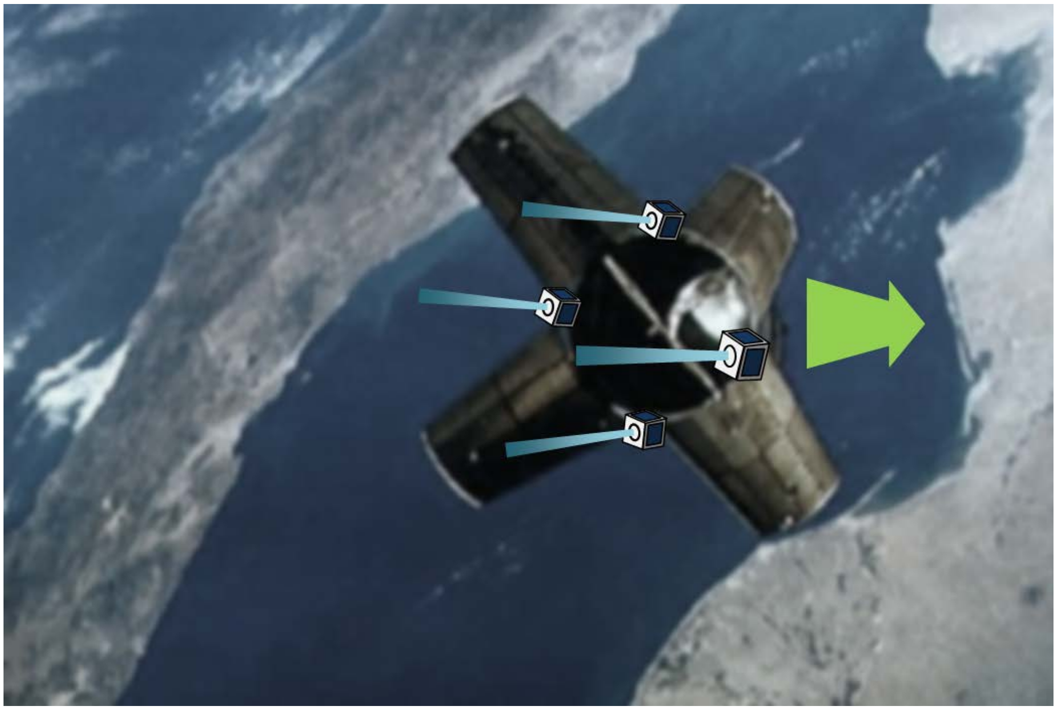

Figure 5. The deorbiting concept being evaluated in the BayKoSM project.

This level of cooperation between small satellites cannot be achieved if they simply follow pre-planned trajectories: in an environment which is dynamic, each small satellite needs to react in real-time to the status of all other satellites. To enable this capability, a new software is being developed by the company **AEVO GmbH for real-time trajectory generation and spacecraft guidance and control**. The software is being developed according to a modular architecture, and includes the following modules:

- planning/re-planning module for real time mission update
- dynamics module for calibrating the vehicle dynamics
- configuration module for setting the software parameters
- interface module that provides interfaces to sensors, actuators and other software

The software will enable the small satellites to cooperate with other, moving towards the debris in coordination while taking into account all mission objectives and constraints.

In parallel and taking advantage of the synergies generated by such a capability, the software is being adapted for autonomous guidance and control of another unmanned platform: the **UMAT, an unmanned mission avionics test helicopter of the company ESG GmbH** (see Fig. 6). Within this application several behaviors like obstacle avoidance and pursuit will be validated.

Figure 6. ESG's unmanned mission avionics test helicopter.

2.5 Image Processing

Within the scope of project BayKoSM's image processing component, two satellite mission scenarios have been established and analyzed.

In the first scenario, ANEX-1 (Autonomous Nanosatellite Experiment-1), a satellite platform for ASAP [2], a novel optical instrument for autonomous sensing of orbital phenomena like meteors, atmospheric electrical discharges, space debris etc. with onboard mission planning capabilities, has been considered. Relevant parameters for a suitable orbit as well as necessary budgets like mass, dimensions, components and their accomodation within the spacecraft, power consumption and payload data transfer have been under investigation. In order to estimate power consumption for the optical payload as system driver, power consumption measurements of various embedded microporcessors while running object detection algorithms have been performed.

The selected orbit for ANEX-1 is a circular, sun-synchronous Low Earth Orbit (LEO) with an altitude of 500 km and an inclination of i = 97°. This allows for the intended ground station location in Würzburg, Germany to be traversed up to seven times per day as well as compliance with current Space Debris Mitigation (SDM) requirements. Furthermore, lighting conditions for ASAP remain constant for any given location on the ground.

ANEX-1 is a cuboid weighing approximately 12.5 kg with measurements of 22 X 22 X 48 cm. Power is being generated by two extendable GaAs-solar panels mounted on the top as well as two body-mounted cells on the rear and the top which form together an area of 0.32 m². Electrical energy is stored in six Li-Ion batteries of the MPS cell series by Saft Batteries for reserves of up to 108 Wh supplying satellite subsystems on a 22.5

V unregulated bus. Orbit simulation shows that a typically allowed maximum DOD of 20% can be adhered to while allowing for a 60% payload duty cycle.

The satellite is three axis-stabilized by three reaction wheels and three magnetorquers for desaturation purposes. Attitude sensing is performed by two STELLA star trackers [3] and a magnetometer device. Additionally, an experimental forward-looking Earth sensor for emergency cases and six sun sensors (one on each side) are installed. Housekeepings and telecommands are being transmitted via two UHF/VHF transceivers in hot redundancy operation mode. As an additional payload, a forward-mounted SSTV camera system will send static pictures of Earth to amateur radio operators around the world in order to make up for ANEX-1's use of ham radio frequencies.

ASAP's video data is currently estimated to amount to 4 Gbyte per stored sequence (moving objects, lightning phenomena, etc.). Thus, available downlink capacity could represent a serious bottleneck. Contact times of around 35 minutes per day imply necessary transfer rates of about 15 Mbps or higher in order to download even a single sequence. A candidate device that has been considered is the experimental Ka-band transponder by the Antarctic Broadband consortium [4]. In its prototype configuration, transfer speeds of 15 Mbps can be achieved on a LEO mission while consuming less then 10 W of power. However, this rate is adjustable to up to 120 Mbps. We therefore continue to follow the progress of the development team as the transponder is likely to offer the required bandwidth while abiding the constraints of a nano satellite platform.

In the second scenario, two satellites A and B perform an undocking procedure. Initially, both are joined until ejected from the launch container, whereafter they begin to drift away from each other. While doing so, A observes its partner B with an optical instrument. Using a set of three LEDs forming an isosceles triangle pattern on B's front side, an image processing algorithm running on A's PDH system then detects the LEDs and calculates the three connecting vectors between them. This information can then be used to determine the relative orientation of both satellites and – together with known optical parameters of A's camera system – relative distance and separation speed as well. Simulating this scenario has shown promising first results. This is especially interesting in the context of a swarm mission where multiple satellites need to coordinate their activities observing minimum distance limits. Neither raw nor compressed image data would have to be transmitted between swarm members. Instead, abstract metadata about orientation, distance and speed would be sufficient. This kind of information can easily be accomodated even by inter-satellite links with limited bandwidth.

3. Conclusions

Investigations of five key technologies for swarm missions have been presented in this contribution. Though investigations will continue some interesting results have already been identified so far.

In the field of positioning a new algorithm has been developed for better accuracy of positioning, which is very important for flying in formations in particular. New methods have been developed for increasing the accuracy of positioning using GPS receivers. The developed position and attitude determination system enables a relative positioning accuracy of 5 mm.

Swarm missions will also benefit from autonomous communication networks, able to handle a changing topology and mobility. First evaluations have pointed out, that terrestrial communication standards can be adapted to space requirements. In order to provide reliable ad-hoc networks for highly mobile vehicle swarms in challenging environments, the communication concepts “*Delay Tolerant Networks*” (DTN) and “*Mobile Ad-hoc NETworks”* (MANETs) are being investigated using an open source simulation environment.

Power supply of small satellites can be improved using thermogenerators. Therefore different integration concepts have been analyzed. The generators can either be integrated in the satellite or between solar cells of deployable panels. As pointed out, the power which can be generated is between 20mW and 150mW. In spite of the lower power generation compared to solar cells, thermogenerators could be beneficial when used as secondary backup power source.

The flexibility of swarm systems implies a significantly higher degree of autonomy, in particular for guidance and control systems. In this project a novel deorbiting concept envisages a swarm of small satellites which act in synchronization to slow down space debris. A new real-time algorithm will enable the small satellites to cooperate with each other to achieve mission objectives. The same software will also be adapted for autonomous guidance and control of unmanned helicopters.

Image processing algorithms for swarms of satellites allow for a complex swarm behavior by improving determination of relative distances and attitudes and at the same time they offer novel applications for sensor data acquisition by using multiple sensors distributed in space. However investigations concerning space observations pointed out that the integration of hardware components into nano satellites is rather difficult.

In conclusion it can be pointed out that all different technologies are promising for applications in space and unmanned aerial vehicles, thus we are quite confident that swarm missions in space will become feasible in the near future.

4. Acknowledgements

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