SSC23-WII-04

Technology Challenges of SURROUND: A Constellation of Small Satellites Around the Sun for Tracking Solar Radio Bursts

Nicholas H. Crisp, Alejandro Macario Rojas, Ciara N. McGrath
School of Engineering, The University of Manchester
Oxford Road, Manchester, M13 9PL, United Kingdom
nicholas.crisp@manchester.ac.uk

Shane Maloney, L. Alberto Cañizares, Dale M. Weigt, Sophie Murray, Eoin Carley, Peter Gallagher
Astronomy and Astrophysics, Dublin Institute for Advanced Studies
10 Burlington Road, Dublin 4, D04 C932, Ireland

ABSTRACT

The SURROUND mission proposes the operational monitoring and forecasting of space weather events using a constellation of five small satellites in orbit around the Sun. This unique mission concept would enable the localisation and tracking of solar events with unprecedented accuracy. The small payload combined with high launch requirements makes this an ideal candidate mission for a distributed constellation of small spacecraft and provides an opportunity for technical development in the areas of deep space communication, propulsion, and survivability. The baseline configuration for SURROUND proposes the deployment of spacecraft to Earth-Sun Lagrange points L_1, L_4, and L_5, and two additional spacecraft in Earth leading (<1AU) and trailing (>1AU) orbits. However, the development and realisation of such a constellation in deep space presents a number of challenges, particularly when the use of small spacecraft is considered. This paper presents the conceptual design for the proposed SURROUND constellation, principally focusing on the key technical challenges of deploying the spacecraft into their desired locations around the Sun and subsequently communicating the collected data back to Earth. In addition to the key propulsion system and communications architecture trades, additional technological challenges of the mission are also considered, including attitude control, radiation hardening, and electromagnetic compatibility.

INTRODUCTION

Solar flares and coronal mass ejections (CMEs) are the most powerful eruptive events in our solar system.[1, 2] Studying these phenomena can provide a unique opportunity to better understand fundamental processes of the Sun, and critically improve our forecasting capabilities of these key space weather drivers. This cutting-edge area of research has received increasing attention in recent years due to the potential impacts space weather events can have on our technologies on Earth, and in near-Earth space and beyond. Solar eruptions can disrupt a range of vital technologies and infrastructure, including power grids, radio communication, navigation systems, and spacecraft instrumentation.[3] As society becomes ever more dependent on technology and space exploration moves further away from Earth with missions such as ESA Heracles,[4] NASA Artemis,[5] and SpaceX Interplanetary Transport System,[6] there is an increasing need to monitor the current space weather environment and improve the accuracy of space weather forecasting.

As of 2023 there are many operational forecasting centres around the world providing a mix of automated predictions as well as tailored space weather guidance. While there are a large number of ground- and space-based observations of the solar surface and lower atmosphere, and even some operational missions (e.g., the Geostationary Operational Environment Satellite (GOES)[7]), there are few such observations distributed elsewhere in the heliosphere. The only imaging observations of space weather in the heliosphere come from heliospheric imagers like those on board the Solar Terrestrial Relations Observatory (STEREO)[8] and Parker Solar Probe (PSP)[9] spacecraft. Thus while the occurrence and onset of flares and CMEs is well observed and documented, tracking their progress and thus accurately forecasting if and when the generated charged solar particles will interact with the Earth remains a challenge. Further, certain types of space weather cannot be detected with white-light or EUV observations directly, for example accelerated particles or Solar Energetic Particles (SEP) emitted from the Sun. These energetic particles do not emit or scatter enough radiation to be detected at these wavelengths.[10] However, the electrons in these SEP produce Langmuir waves[11] which can be detected with solar radio measurements. The accelerated electrons are exciters for radio emission which appear as distinct features in dynamic spectra known as Solar Radio Bursts (SRBs).

SURROUND MISSION DESCRIPTION

The SURROUND mission[12] proposes to detect radio bursts associated with two of the more hazardous space weather phenomena: (1) CMEs associated with Type-II bursts and (2) SEPs associated with Type-IIIs.

Type-II bursts are associated with shocks produced in the Sun's upper atmosphere or corona. These shocks accelerate large numbers of electrons, which are beamed along the magnetic field, which in turn produce radio waves via plasma emission. Observations have shown interplanetary Type-II bursts to be linked to CMEs. The propagation velocity of a CME can typically range from $\sim 200\,\mathrm{km\,s^{-1}}$ to $2000\,\mathrm{km\,s^{-1}}$ with the highest recorded velocity being $\sim 3500\,\mathrm{km\,s^{-1}}$.[2] This corresponds to a propagation time from the Sun to the Earth of $\sim$ 12 hours to around 9 days. Space weather monitoring spacecraft therefore need to provide warnings of incoming CMEs within these time ranges.

Type-III bursts are caused by electrons which can be accelerated by Solar flares. The high drift rates in frequency space, which in turn can be linked to high propagation velocities averaging $\sim 0.3\,c$ (or a travel time from Sun to Earth of $\sim 8\,\mathrm{min}$), means Type-III SRBs are indicative of accelerated electron beams propagating along open magnetic fields. Thus they provide the only remote sensing diagnostic to track solar particles from the Sun to the Earth. At an operational level, these bursts can be used to track the propagation of SEPs and as a means of nowcasting particle events. Further, this information can be used to forecast the arrival of heavier particles (i.e., protons) SEPs using propagation techniques or by modelling particle motion and diffusion through the heliosphere.[13] These heavier particles are the most hazardous to orbiting spacecraft with the potential to damage and blind the communications and on-board electronics.

The proposed SURROUND mission is a constellation of satellites, equipped with radio spectrometers optimised for the detection of Type-II and Type-III radio bursts in dynamic spectra. Using the known positions of each spacecraft and the arrival time of the radio emissions, at the same frequency, the source of the SRBs can be localised using multilateration (or triangulation) techniques.[12] In order to achieve these tracking capabilities, SURROUND would require spacecraft strategically located at different positions at approximately 1 au from the Sun. The nominal concept consists of five spacecraft. Three of the spacecraft would be located at the Earth-Sun Lagrange points L_1, L_4 and L_5; these are referred to throughout this article as Spacecraft 1, 2, and 3 (SC1, SC2, SC3), respectively. The quasi-static configuration of the Lagrange points, with respect to the Sun-Earth line, allows SURROUND to consistently monitor Earth directed space weather events. Two spacecraft, "Ahead" and "Behind", referred to as Spacecraft 4 and 5 (SC4, SC5) respectively, will orbit marginally closer to and farther from the Sun than the Earth such that these two spacecraft drift synchronously ahead and behind Earth's orbit. These spacecraft would support the Lagrange spacecraft and reduce uncertainties in the localisation of space weather activity. The proposed configuration is shown in Figure 1. The small mass and volume of the proposed payload suggests that small satellites, or even CubeSats, may be viable candidates for the proposed mission.

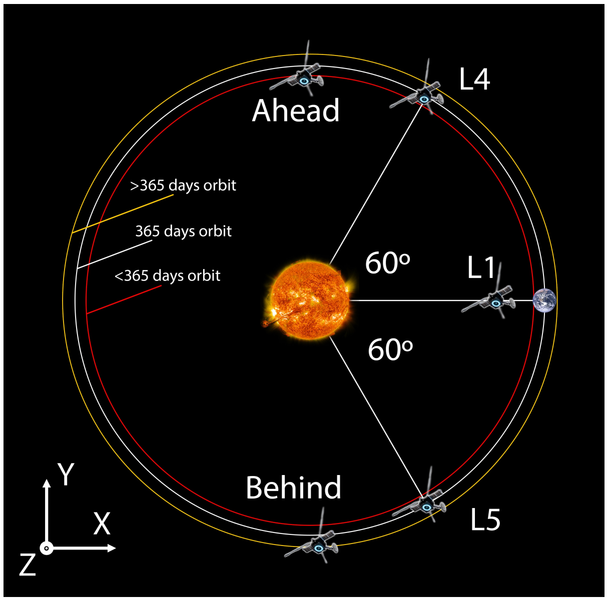

Figure 1: Diagram of the proposed configuration of the SURROUND mission.

DEEP SPACE CUBESATS

Technology miniaturisation and adoption of Commercial Off-the-Shelf (COTS) components has largely driven the increase in utility of CubeSats in Earth orbits (predominantly Low Earth Orbit). More recently, interest in, and use of, this class of spacecraft for deep space missions has been increasing, particularly as low-cost rideshare or *piggyback* launch opportunities beyond Earth are becoming more frequent and readily available. However, whilst reduced size and mass and the standardised form factor of a CubeSat can help to reduce the cost of spacecraft development and manufacture, operation in deep space presents new challenges, such as long-distance communications, long-duration transfers, and increased propulsive requirements.

To-date there have been few examples of deep space CubeSats to draw heritage and inspiration from. Mars CubeSat One (MARCO),[14,15] a pair of 6U CubeSats that were launched with the InSight mission in 2018, flew on their own trajectories to Mars and demonstrated long-distance deep space communications (over distances on the order of 300×10^6 km) and navigation technologies on a CubeSat for the first time. A 6U CubeSat, LICIACube,[16] also accompanied the DART spacecraft on a mission to the asteroid Didymos to provide remote imaging of the impact of the main spacecraft and the resulting ejecta. However, this spacecraft *piggybacked* within the main DART spacecraft and only separated 15 days before the impact. For the purposes of communications, the relative distance of this mission from Earth was also relatively small in comparison to many deep space mission requirements (11×10^6 km).

A number of further small satellite missions are being developed for use beyond Earth-orbit, for example the Milani and Juventas CubeSats (6U-XL)[17] that will be carried upon the Hera mission to the Didymos binary asteroid system. A number of spacecraft are also being developed under the ESA Lunar CubeSats for Exploration (LUCE) challenge and launched as secondary payloads on the Artemis 1 lunar mission. The Miniaturised Asteroid Remote Geophysical Observer (M-ARGO), a 12U CubeSat, is also currently being developed via ESA to be an independent deep space spacecraft for asteroid rendezvous. This concept features a highly-capable propulsion system (ion thruster) and a long-distance communications system (with reflectarray antenna) designed for payload data return to Earth.[18]

TECHNOLOGY CHALLENGES

Several key technology challenges were identified during the feasibility study for the SURROUND mission, principally communications, propulsion, attitude control, radiation hardening, and electromagnetic compatibility. While the details of the challenges are specific to the SURROUND mission requirements, the general challenges are likely to be common across many mission concepts for deep space CubeSats. These are summarised in the following sections to provide an assessment of current challenges, but also to serve as summary of opportunities for future CubeSat and small satellite technology development.

Communications

The mission concept for SURROUND presents a significant challenge in communications design, principally due to the significant distances over which data must be transmitted. The varying angle between the spacecraft and Earth throughout transfer and operation imposes additional pointing considerations, whilst the desire to use CubeSats constrains the size of deployable antennas that can be used.

SC1 has the most relaxed communications requirements as the distance between the spacecraft and Earth is relatively small (<0.1 au) and the angle between the spacecraft, Earth, and Sun will remain almost constant over the mission lifetime. In comparison, SC2 and SC3 will eventually be deployed at 1 au from Earth, and SC4 and SC5 will reach 2 au. These spacecraft will also experience a range of Sun-SC-Earth angles throughout deployment and operations, and thus will need to carefully consider the configuration and orientation of the communications antenna(s), solar arrays, and propulsion system in order to minimise losses.

Figure 2 shows the indicative gain for a reflectarray antenna for varying aperture area and carrier frequency. The parameters for the MarCO mission[19] have been marked for reference. Assuming this performance, a link budget analysis can be performed to determine the expected data rate for the spacecraft at their maximum operational distances and then to determine the time required to downlink a representative daily volume of payload data to the ground. A lower bound requirement of 5 MB/day was set.

Key parameters and trade-offs for the communications architecture include the transmitter power, pointing loss (due to antenna misalignment) and ground-segment (receiver) antenna size. A transmitter of 4 W was initially chosen to match the MarCO mission characteristics. However, higher power transmitters (up to 15 W) are also considered. Pointing losses of 3 dB are generally assumed, however with higher performing attitude determination and control and a steerable antenna this may be re-

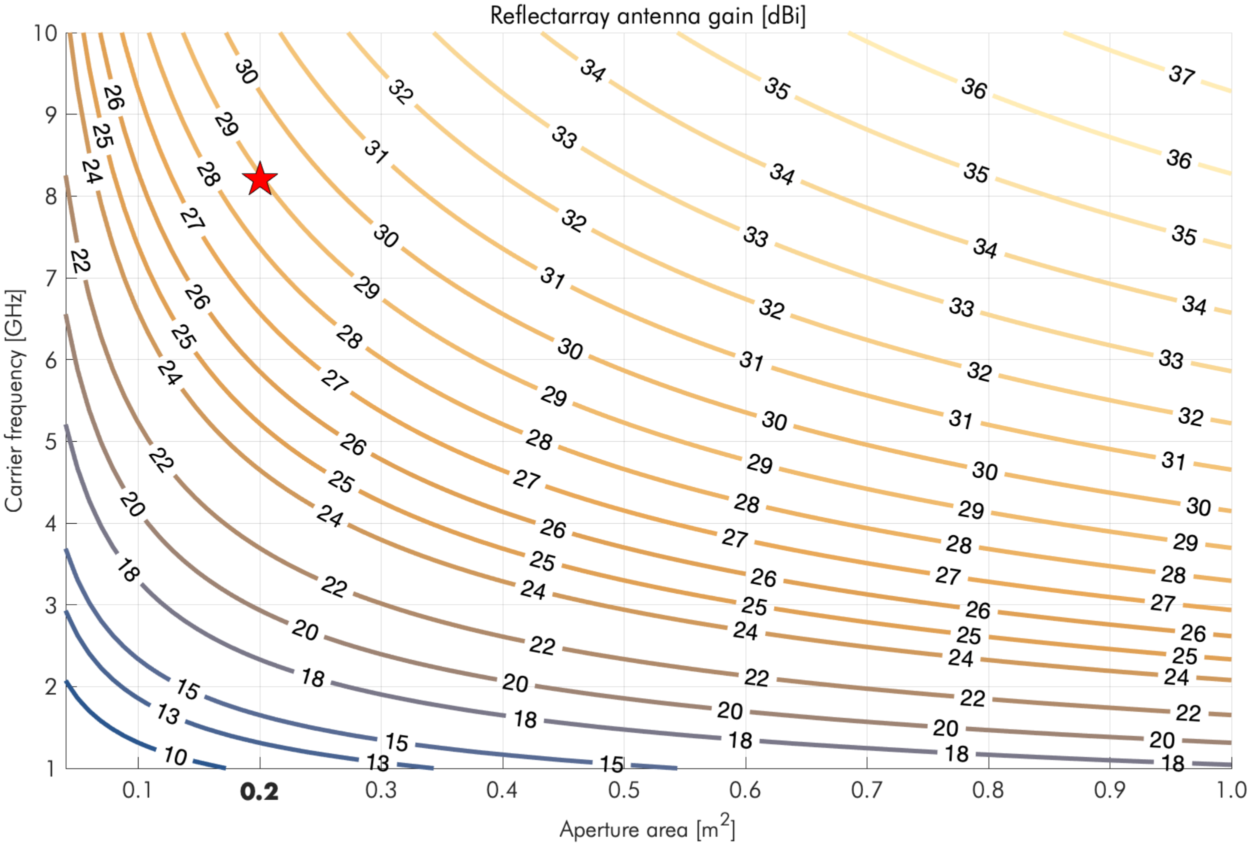

Figure 2: Reflectarray antenna (maximum) gain as a function of aperture area and carrier frequency. MarCO mission marked with a red star for context.

duced considerably. From an operational perspective, smaller and more available ground segment receivers would be preferable, for example commercial 13 m antennas. However, much larger ESTRACK or DSN alternatives may need to be considered due to the significant distances and low transmitter powers. A 50 % compression efficiency is implemented.

A summary of the link budget analysis yielding expected data rates and time to downlink the representative daily data from each spacecraft is presented in Table 1. The results clearly indicate that the combination of currently implemented transmitter power on deep space CubeSats and commercially available ground segment antennas does not provide a feasible solution for returning all data collected by each spacecraft in the constellation. Even when significantly more capable deep space ground stations are used and the transmit power is increased, the downlink times are considerable.

However, depending on the selected use case for the SURROUND mission, not all data may need to be downlinked on such a regular basis or at such a high cadence from each spacecraft. The required downlink data volume could therefore be reduced considerably. In addition to utilising the most capable technology solutions available, alternative proposals for the concept-of-operations for the system will therefore need to be considered.

Propulsion

While trajectories to the desired mission orbits are well defined, the desire to use small spacecraft for this mission places constraints on the propellant mass available for the mission. Furthermore, the significant difference in transfer and orbit maintenance requirements for each spacecraft suggest that heterogeneous spacecraft designs may be advantageous.

Based on traditional insertion trajectory and orbit maintenance design methods for Lagrange-point missions,[20] the maximum ΔV for a SURROUND spacecraft has been calculated to be less than approximately $1500\,\mathrm{m\,s^{-1}}$. This is primarily driven by the insertion requirements for SC2 and SC3 and assumes that an Earth escape launch has also been provided to reduce the ΔV that needs to be provided

Table 1: Summary of link budget analysis.

Space Segment	**Ground Segment**	**@** 1 au **(SC2, SC3)**	**@** 2 au **(SC4, SC5)**
0.2 m^2, 4 W, 3 dB loss	13 m dia.	<5 bps, 93 days	<1 bps, 463 days
0.2 m^2, 15 W, 3 dB loss	13 m dia.	∼15 bps, 31 days	∼5 bps, 93 days
0.2 m^2, 15 W, 0 dB loss	70 m dia.	∼15 kbps, 44 min	∼5 kbps, 2.2 hrs

by the spacecraft. This maximum ΔV requirement could be reduced by extending the transfer time for SC2 and SC3 (herein estimated at 15 months), though at the expense of the *fully operational* duration of the mission when the spacecraft are all in their desired locations.

Meanwhile, whilst the insertion and capture ΔV requirements for SC1 are relatively small, the station-keeping requirements around L_1 provide different challenges for the propulsion system, principally in the form of total number of on/off cycles and tight control on burn duration and thrust performance. SC4 and SC5 on the other hand are inserted into drifting orbits that lead and trail the Earth. Communications back to Earth for these spacecraft will eventually be blocked as they move behind the Sun due to solar radio interference. For a relative drift rate of approximately 17° per year, a 10-year nominal lifetime for the constellation can be achieved before these spacecraft would become incommunicable for over a year.

Assuming homogeneous spacecraft design, due to the high ΔV requirement, an electric propulsion system becomes the obvious choice. Nevertheless, for a spacecraft of 25 kg wet mass and an assumed specific impulse of 1400 s, the propellant mass fraction is over 10 %. Such propulsion systems, primarily Gridded Ion Engines (GIEs) and Hall-Effect Thrusters (HETs) also require significant power to operate (typically 100 W to 300 W) and thus, in addition to the thruster itself, may need significant power processing units, further adding to the system mass.

The use of these electric propulsion systems also presents operational concerns, for example the simultaneous use of high-power communications and interference with sensitive payload operations due to electromagnetic compatibility. Furthermore, due to challenges with long distance communications for small spacecraft (discussed hereinbefore), semi-autonomous thrust manoeuvres may need to be implemented to account for attitude errors or uncertainty in impulse.

Alternative propulsion systems for deep space missions, for example solar sails, could help to further reduce the propellant required for these transfers and could even enable deployment of spacecraft out of the ecliptic plane, further improving the loaclisation accuracy of the constellation. However, further analysis of the trajectories, transfer times, and sizing of these systems is needed.

Attitude Control

Spacecraft attitude control for CubeSats generally relies on small internal actuators such as reaction wheels and magnetorquers due to their relatively low mass and volume. However, in the deep space environment, a suitably strong external magnetic field is not available for magnetorquers to interact with to produce control torques. Meanwhile, reaction wheels used on their own would quickly reach saturation in the presence of external perturbations. Reaction control thrusters (RCTs), for example based on cold-gas propulsion, may therefore be necessary to perform attitude control and/or momentum management but would require enough stored propellant to last the 10-year mission duration.

An alternative attitude control concept could utilise the perturbing solar radiation pressure to provide control torques through the use of suitable control surfaces (e.g., louvres) and perhaps including the reflectarray antenna and solar arrays themselves. However, due to the constrained direction of the solar radiation an additional attitude control component would still be required to provide control authority and momentum management parallel to the sun vector. A gimballed main thruster could complete this configuration.

Radiation Hardening

A significant concern for the proposed SURROUND mission is the practical long-term survivability of the spacecraft. To date, CubeSats and small satellites have primarily operated in low-Earth orbits (a comparatively benign environment) and for relatively short mission duration (on the order of < 5-years). Currently available COTS may therefore be unsuitable for the proposed mission without further development and testing.

A key concern for long duration and deep space missions is exposure to radiation. Radiation sources of concern for the SURROUND mission are direct solar particles and galactic cosmic rays (GCRs). The majority of lightweight COTS components for small spacecraft can withstand a total ionising dose (TID) of $<30\,\mathrm{kRad}$,[21] whilst commercial CubeSat on-board computers are commonly in the range of $<100\,\mathrm{kRad}$.[22] NASA's Iris deep space radio, used in the INSPIRE mission, the MarCO mission to Mars, and SLS EM-1 has been tested to up to 23 kRad.[23]

Estimation of TID on electronics (typically modelled as silicon) with varying shielding thickness can be calculated using the Solar Accumulated and Peak Proton and Heavy Ion Radiation Environment (SAPPHIRE) model[24] and SHIELDOSE-2Q.[25] For a 10-year mission at L_1, a thickness of over 1 mm of aluminium is needed to reduce the dosage to under the 30 kRad threshold. Although the ability to incorporate thicker shielding adds flexibility to the design for higher radiation tolerance, it is important to bear in mind that whilst it helps in the attenuation of the primary radiation source, secondary radiation behind the shielding (Bremsstrahlung in the X-ray energy range) could be created. This phenomenon must also be analysed to reduce the susceptibility to single event effects created by the primary shielding.

Careful component selection using this information is a fundamental design step towards a successful spacecraft design. Available components range from space-grade high radiation tolerant ($>100\,\mathrm{kRad}$), through non-space-grade COTS but with some inherent radiation tolerance or intended spot shielding, to standard COTS. However, the size, mass, and cost of these components must also be traded-off for use on a CubeSat platform.

Electromagnetic Compatibility

The electromagnetic compatibility (EMC) of the SURROUND spacecraft has been identified as a critical concern for the system design and mitigation needs to be put into place to avoid electrostatic discharge (ESD) events and electromagnetic interference (EMI) effects. The measurement sensitivity ($\sim 6\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$) and signal-to-noise ratio (20 dB to 30 dB) of the payload is the most demanding requirement.

The main electromagnetic energy source relevant to a SURROUND spacecraft is the Sun and would normally be attenuated by the spacecraft external walls, which are often highly conductive and act as a Faraday cage. However, induced surface charging is an expected short-term effect, wherein surfaces in sunlight may produce differential charging due to photoemission by solar UV and X-ray photons or high-energy particles yielding strong electric fields.

Surface and internal charging may produce electrostatic discharge (ESD), that if not properly mitigated, could be catastrophic to the spacecraft. Aside from generating secondary electrons that contribute further to spacecraft charging, ESD can produce secondary or sustained arcs causing surface erosion or short circuits.

The operation of onboard equipment also contributes to the internal electromagnetic environment. Although the characteristics of the internal environment are a strong function of the spacecraft design, the overall electromagnetic dynamics and interactions remain largely stochastic. The spacecraft for the SURROUND mission will be equipped with a propulsion system for station keeping and orbit transfer and will actively modify the local plasma via emitted particles (initially charged or neutral) contributing to EMC effects. The payload antennas and satellite communications system may be particularly susceptible to performance degradation in the presence of high-density plasma.

Electromagnetic interference (EMI) is another critical design parameter, and is mostly influenced by the potential use of COTS components. Insufficient knowledge of the EMC of COTS components and their mutual interactions can contribute significantly to EMI. Techniques to ensure EMI control and suppression include filtering, grounding and shielding. Eliminating all unwanted electromagnetic signals is generally not possible and engineering the signals in such a way that they can be more easily filtered or reducing them much as possible are appropriate alternatives. Existing standards (i.e., ECSS-E-ST-20-07C) define best practice for mitigating EMI and ensuring EMC and should be followed as the design of the SURROUND spacecraft develops. However, design and development of CubeSat components with enhanced electromagnetic cleanliness may be necessary to ensure that the payload sensitivity and measurement requirements for the mission are met.

SYSTEM CONCEPT

A high-level concept for a notional SURROUND spacecraft is shown in Figure 3. This concept illustrates a possible configuration of the key external elements for the spacecraft, most critically the solar array, propulsion system, reflectarray antenna, payload antennas, and solar radiation pressure control surfaces, all of which have specific pointing or orientation requirements. Provision for a primary body-mounted external radiating surface is also provided

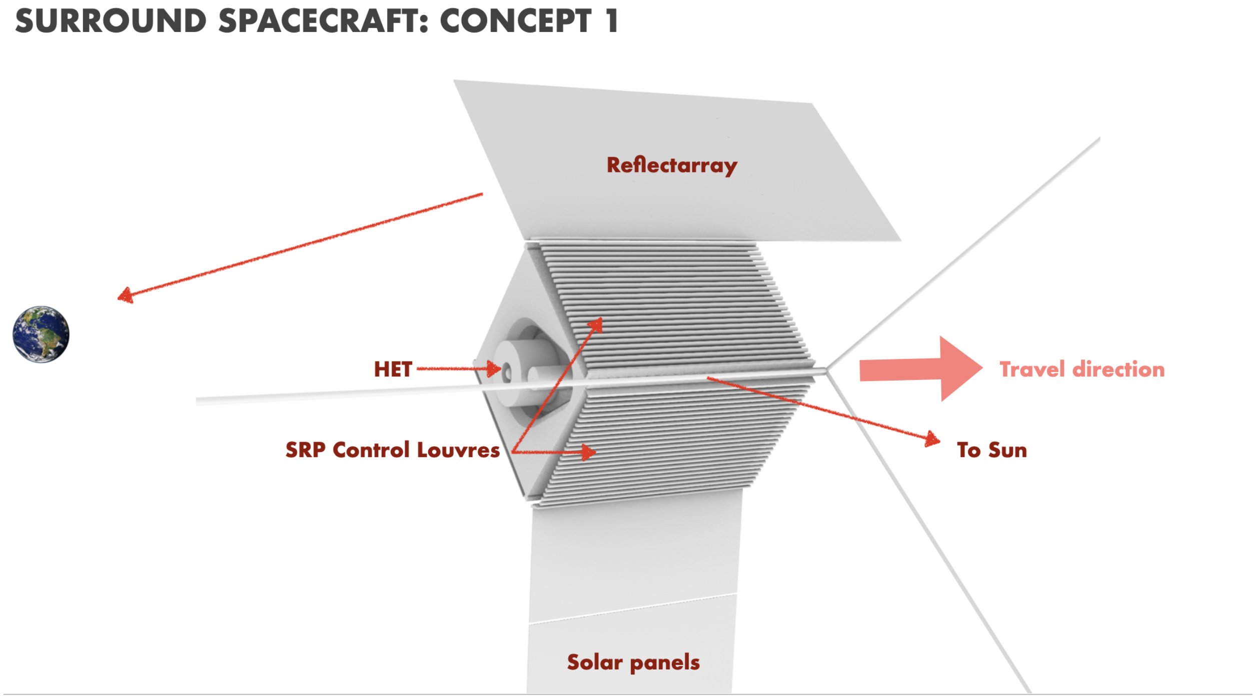

Figure 3: Notional concept for a SURROUND spacecraft.

on the opposing side of the spacecraft.

The use of the propulsion system presents the most demanding condition for the power system. A combination of solar arrays and a battery are therefore necessary to provide the necessary power whilst phased thrusting manoeuvres allow for periods of recharge. With solar arrays of effective area $0.45\,\mathrm{m}^2$ and assuming a depth of discharge of 50 %, the propulsion system (e.g., Busek BHT-200, ∼200 W) can be used for a period of ∼25 min at a time, with a corresponding recharge period on the order of 1 h. Of course, with larger solar arrays the thrusting period could be increased and the recharge time decreased respectively.

CONCLUSION

The SURROUND mission proposes the operational monitoring and forecasting of space weather events using a constellation of five small satellites in orbit around the Sun. However, the desired location of these spacecraft in deep space, far from Earth, presents a number of technological challenges which may currently hinder the realisation of this concept, particularly if the CubeSat form factor is to be used.

The long range for Earth communications means that the possible data rate and therefore total data volume that can be returned is restricted. Higher-powered communications systems for small spacecraft and novel deployable antenna technologies providing increased gain will provide improvements. However, alternative communications architectures and concept-of-operations for the constellation may also need to be considered as a result of this limitation.

The transfer of the spacecraft from Earth orbit or Earth-escape trajectories to their operational locations also presents a significant challenge for the propulsion system. An electric propulsion system seems favourable due to the high ΔV and small form factor. However this places significant demand on the power subsystem and is likely to drive the sizing of the solar arrays and any secondary power sources.

Novel methods and actuators for attitude control in deep space would also be benefit the design for small satellites in particular, reducing the necessity for reaction control thrusters and associated propellant.

Further identified challenges to the system design include the need to withstand higher doses of radiation than typically experienced in near-Earth orbits, and the necessity for small satellite components with enhanced electromagnetic compatibility to minimise interference.

Whilst these challenges have been identified and considered with the SURROUND mission in mind, they are likely to be applicable to a wide range of future small satellite and CubeSat deep space missions, particularly those with sensitive measurement objectives.

Acknowledgments

This work was supported by the European Space Agency (ESA) under contract number 4000137843/22/NL/GLC/ov.

The authors would like to thank the members of the European Space Agency Space Weather Space Segment for their support. Particularly Melanie Heil, Thomas Honig, Alberto Ruiz and Sergio Terzo.

References

[1] L. Fletcher, B. R. Dennis, H. S. Hudson, S. Krucker, K. Phillips, A. Veronig, M. Battaglia, L. Bone, A. Caspi, Q. Chen, P. Gallagher, P. T. Grigis, H. Ji, W. Liu, R. O. Milligan, and M. Temmer. An observational overview of solar flares. *Space Science Reviews*, 159(1-4):19–106, 2011.

[2] David F. Webb and Timothy A. Howard. Coronal Mass Ejections: Observations. *Living Reviews in Solar Physics*, 9(1):3, June 2012.

[3] Rainer Schwenn. Space Weather: The Solar Perspective. *Living Reviews in Solar Physics*, 3(1):2, August 2006.

[4] Harald Hiesinger, Markus Landgraf, William Carey, Yuzuru Karouji, Timothy Haltigin, Gordon Osinski, Urs Mall, and Ko Hashizume. Returning to the moon with heracles: An esa-jaxa-csa joint study. In *Geophysical Research Abstracts*, volume 21, 2019.

[5] Marshall Smith, Douglas Craig, Nicole Herrmann, Erin Mahoney, Jonathan Krezel, Nate McIntyre, and Kandyce Goodliff. The artemis program: an overview of nasa's activities to return humans to the moon. In *2020 IEEE Aerospace Conference*, pages 1–10. IEEE, 2020.

[6] Chris Palmer. Spacex starship lands on earth, but manned missions to mars will require more, 2021.

[7] Steven J. Goodman, Richard J. Blakeslee, William J. Koshak, Douglas Mach, Jeffrey Bailey, Dennis Buechler, Larry Carey, Chris Schultz, Monte Bateman, Eugene McCaul, and Geoffrey Stano. The GOES-R Geostationary Lightning Mapper (GLM). *Atmospheric Research*, 125-126:34–49, 2013.

[8] C. J. Eyles, R. A. Harrison, C. J. Davis, N. R. Waltham, B. M. Shaughnessy, H. C. A. Mapson-Menard, D. Bewsher, S. R. Crothers, J. A. Davies, G. M. Simnett, R. A. Howard, J. D. Moses, J. S. Newmark, D. G. Socker, J. P. Halain, J. M. Defise, E. Mazy, and P. Rochus. The Heliospheric Imagers Onboard the STEREO Mission. *Solar Physics*, 254(2):387–445, February 2009.

[9] N. J. Fox, M. C. Velli, S. D. Bale, R. Decker, A. Driesman, R. A. Howard, J. C. Kasper, J. Kinnison, M. Kusterer, D. Lario, M. K. Lockwood, D. J. McComas, N. E. Raouafi, and A. Szabo. The Solar Probe Plus Mission: Humanity's First Visit to Our Star. *Space Science Reviews*, 204(1-4):7–48, December 2016.

[10] Donald V. Reames. The Two Sources of Solar Energetic Particles. *Space Science Reviews*, 175(1-4):53–92, June 2013.

[11] Camille Y. Lorfing and Hamish A.S. Reid. Solar electron beam velocities that grow langmuir waves in the inner heliosphere. *Solar Physics*, 298(4):52, 2023.

[12] D. M. Weigt, L. A. Ca nizares, S. A. Maloney, S. A. Murray, E. P. Carley, P. T. Gallagher, A. Macario-Rojas, N.H. Crisp, and C. McGrath. The science behind surround: A constellation of cubesats around the sun. In *Proceedings of the 10th International Workshop on Planetary, Solar and Heliospheric Radio Emissions held in Dublin, Ireland , September 26-28, 2022*, in review.

[13] N. Agueda, D. Lario, R. Vainio, B. Sanahuja, E. Kilpua, and S. Pohjolainen. Modeling solar near-relativistic electron events. Insights into solar injection and interplanetary transport conditions. *Astronomy and Astrophysics*, 507(2):981–993, November 2009.

[14] M Kobayashi, M Shihabi, and J Taylor. Descanso design and performance summary series: Mars cube one telecommunications subsystem design. *Pasadena: NASA JPL*, 18, 2021.

[15] Richard E. Hodges, Nacer Chahat, Daniel J. Hoppe, and Joseph D. Vacchione. A deployable high-gain antenna bound for mars: Developing a new folded-panel reflectarray for the first cubesat mission to mars. *IEEE Antennas and Propagation Magazine*, 59(2):39–49, 2017.

[16] E. Dotto, V. Della Corte, M. Amoroso, I. Bertini, J.R. Brucato, A. Capannolo, B. Cotugno, G. Cremonese, V. Di Tana, I. Gai, S. Ieva, G. Impresario, S.L. Ivanovski, M. Lavagna, A. Lucchetti, E. Mazzotta Epifani, A. Meneghin, F. Miglioretti, D. Modenini, M. Pajola, P. Palumbo, D. Perna, S. Pirrotta, G. Poggiali, A. Rossi, E. Simioni, S. Simonetti, P. Tortora, M. Zannoni, G. Zanotti, A. Zinzi, A.F. Cheng, A.S. Rivkin, E.Y. Adams, E.L. Reynolds, and K. Fretz. Liciacube - the light italian cubesat for imaging of asteroids in support of the nasa dart mission towards asteroid (65803) didymos. *Planetary and Space Science*, 199:105185, 2021.

[17] Patrick Michel, Michael Küppers, Adriano Campo Bagatin, Benoit Carry, Sébastien Charnoz, Julia de Leon, Alan Fitzsimmons, Paulo Gordo, Simon F. Green, Alain Hérique, Martin Juzi, Özgür Karatekin, Tomas Kohout, Monica Lazzarin, Naomi Murdoch, Tatsuaki Okada, Ernesto Palomba, Petr Pravec, Colin Snodgrass, Paolo Tortora, Kleomenis Tsiganis, Stephan Ulamec, Jean Baptiste Vincent, Kai Wünnemann, Yun Zhang, Sabina D. Raducan, Elisabetta Dotto, Nancy Chabot, Andy F. Cheng, Andy Rivkin, Olivier Barnouin, Carolyn Ernst, Angela Stickle, Derek C. Richardson, Cristina Thomas, Masahiko Arakawa, Hirdy Miyamoto, Akiko Nakamura, Seiji Sugita, Makoto Yoshikawa, Paul Abell, Erik Asphaug, Ronald Louis Ballouz, William F. Bottke, Dante S. Lauretta, Kevin J. Walsh, Paolo Martino, and Ian Carnelli. The esa hera mission: detailed characterization of the dart impact outcome and of the binary asteroid (65803) didymos. *The Planetary Science Journal*, 3(7), July 2022.

[18] Roger Walker, David Binns, Cristina Bramanti, Massimo Casasco, Paolo Concari, Dario Izzo, Davar Feili, Pablo Fernandez, Jesus Gil Fernandez, Philipp Hager, Detlef Koschny, Vasco Pesquita, Neil Wallace, Ian Carnelli, Michael Khan, Mehdi Scoubeau, and Daniela Taubert. Deep-space CubeSats: thinking inside the box. *Astronomy & Geophysics*, 59(5):5.24–5.30, October 2018.

[19] Nacer Chahat, Emmanuel Decrossas, David Gonzalez-Ovejero, Okan Yurduseven, Matthew J. Radway, Richard E. Hodges, Polly Estabrook, John D. Baker, David J. Bell, Thomas A. Cwik, and Goutam Chattopadhyay. Advanced CubeSat Antennas for Deep Space and Earth Science Missions: A review. *IEEE Antennas and Propagation Magazine*, 61(5):37–46, October 2019.

[20] G Gómez, J Llibre, R Martínez, and C Simó. *Dynamics and Mission Design Near Libration Points*. World Scientific Monograph Series in Mathematics, 2001.

[21] Doug Sinclair and Jonathan Dyer. Radiation effects and cots parts in smallsats. In *27th Annual AIAA/USU Conference on Small Satellites*, Logan, UT, 2013.

[22] AAC CLYDE Space. SIRIUS-OBC-LEON3FT SmallSat Onboard Computer, 2020.

[23] M. Michael Kobayashi, Sarah Holmes, Anusha Yarlagadda, Fernando Aguirre, Matthew Chase, Krisjani Angkasa, Brandon Burgett, Lauren McNally, Tatyana Dobreva, and Edgar Satorius. The iris deep-space transponder for the sls em-1 secondary payloads. *IEEE Aerospace and Electronic Systems Magazine*, 34(9):34–44, 2019.

[24] Piers Jiggens, Athina Varotsou, Pete Truscott, Daniel Heynderickx, Fan Lei, Hugh Evans, and Eamonn Daly. The Solar Accumulated and Peak Proton and Heavy Ion Radiation Environment (SAPPHIRE) Model. *IEEE Transactions on Nuclear Science*, 65(2):698–711, 2018.

[25] P. Truscott. JORE^{2}M^2 Project: SHIELDOSE-2Q Software User Manual. Technical Report QINETIQ/TS/AS/SUM1003576, 2010.