

IAC-21,A6,1,2,x66530

STRATHcube: The Design of a CubeSat for Space Debris Detection Using In-Orbit Passive Bistatic Radar

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Abstract

There is a growing need to detect, track and catalogue space debris in the congested Low Earth Orbit (LEO) region. A method to detect debris could be to use space-based passive bistatic radar (PBR). The STRATHcube project proposes to launch a CubeSat into LEO as a PBR technology demonstrator where a signal processing algorithm developed at the University of Strathclyde to detect space debris will be tested. The concept involves a radar receiver and antenna on-board a CubeSat orbiting at a low altitude to detect the radio signals transmitted by operational satellites orbiting at higher altitudes. These signals may have been modified by an object orbiting between the operational satellites and the CubeSat and therefore would indicate a piece of debris exists. This paper will present the integration of PBR technology onto a CubeSat as a payload on the STRATHcube mission and discuss the challenges faced due to the limitations of the small platform. The use of a custom-built 3D antenna and an off-the-shelf patch antenna are investigated as design options for the payload. A high-level design for each option was completed to evaluate their capabilities on the size of trackable debris and to determine their mass and power parameters. After an extensive trade-off analysis at a system level, carried out to narrow down the options of the PBR payload on the CubeSat platform, it was determined that the patch antenna option presented the best way of facilitating the experiment onboard the CubeSat due to its small size and mass. The completed design of the STRATHcube mission will enable an in-orbit demonstration of the PBR technology, which if successful, will provide an alternative to conventional ground-based tracking that is cheaper and more available to the space community. This method would then be proven to industry who can use this approach to implement on a larger scale in the future.

Keywords: STRATHcube, CubeSat, Space Debris, Detection, Tracking, In-orbit

Nomenclature

β	Bistatic angle
λ	Operating wavelength of operational satellite
σ_{FS}	Forward scatter radar cross section
U	Silhouette area of target object

Acronyms/Abbreviations

COTS	Commercial off-the-shelf
EISCAT	European Incoherent Scatter Scientific Association
GNSS	Global Navigation Satellite Systems
GRAVES	Grand Réseau Adapt la Veille Spatiale
LEO	Low Earth Orbit
PBR	Passive bistatic radar
RCS	Radar cross section
RF	Radio frequency
SSA	Space Situational Awareness

1. Introduction

Due to the rapidly growing space industry, there is an increasing number of man-made debris orbiting around the Earth [1]. These debris endanger the success of operational satellites as the high orbital velocity means that even debris millimetres in diameter can cause substantial damage and result in mission failure. In recent years, there have been two key satellite collision events that have doubled the amount of fragmentation pieces in Low Earth Orbit (LEO). The first recorded in-orbit satellite collision happened between the Iridium 33 and defunct Cosmos 2251 satellites in 2009, creating thousands of new debris in the process [2]. The second collision event was a deliberate strike on the old Feng-Yun 1C weather satellite by the Chinese to test their anti-satellite capabilities. This resulted in the creation of the single largest debris cloud in history with an estimated 150,000 fragmentation pieces [3, 4].

It is widely accepted that without a plan to mitigate debris, the use of space could quickly be limited. One possible result of the debris problem is known as “Kessler’s Syndrome” which predicts that once a critical number of objects in orbit is reached, one collision would

start a chain reaction and leave a cloud of debris around Earth, which would jeopardise all future missions into space [5]. This has caused concern in the space community and as a result, there has been a push to increase knowledge in space situational awareness (SSA), an initiative set up for space debris mitigation.

Part of SSA is the detection, tracking and cataloguing of debris in orbit. Debris catalogues provide a basis to propagate the orbital trajectory of debris with the aim to forecast collisions between operational satellites. This allows evasive manoeuvres to be carried out to avoid collisions, halting further debris [4]. Due to the uncertainty in the propagation models, there is a need to accurately detect and characterise new debris and continue to update the location of known debris to improve the accuracy of the model predictions. This however is difficult due to the vast number of man-made objects and cost of detection systems [6].

For current detection systems, it becomes increasingly difficult to detect debris as they reduce in size. This is not only due to limitations in current technology but also the large amount of power required and huge financial costs associated with system set-up and maintenance. The threshold for ground-based space surveillance systems is widely regarded as being 10cm or greater in LEO [7, 8] meaning that millions of smaller pieces go undetected. This limit is due to compromises in system complexity, cost and performance which mean that the larger and more dangerous objects are prioritised for monitoring because of the greater risk they present in the event of a collision. In radar tracking methods, the wavelength of the detector is ideally close in length to the diameter of the target object. As most radar systems operate using wavelengths of larger than 10cm, or smaller operating frequencies than 3GHz, it means that smaller debris particles are increasingly difficult to detect as their apparent diameter decreases according to Rayleigh's Scattering Law, providing a reason why the general limitation on size is approximately 10 cm [9]. Additionally, if shorter wavelengths were to be used, the atmospheric attenuation of the signals would become much greater and would give inaccurate readings.

Since the launch of the first satellite, space surveillance networks have relied on radar and optical methods to detect and track debris. Today, the United States has the largest resources for space surveillance on Earth and monitors more than 22,000 objects. Another system, operated by the French Air Force, is a bistatic radar system called Grand Réseau Adapt la Veille Spatiale (GRAVES) which catalogues 2,500-3,000 objects. Both Russia and the European Space Agency also have significant resources for space surveillance [9].

Space-based surveillance satellites are much more uncommon due to the high cost and complexity required when launching systems into space. The only recorded

in-orbit debris tracking instrument currently in operation is the American surveillance satellite named SBV [10].

There have been other instances of in-orbit debris sensors such as the GORID and DEBIE satellites. However, the aim of these sensors was to detect collisions and not detect or track debris [7], therefore, these do not contribute to debris population cataloguing to improve SSA.

In-orbit debris detection and tracking offer a promising solution to better observe and catalogue the space debris population compared to ground-based measurements. One such method is to use a space-based passive bistatic radar (PBR) system onboard a nanosatellite. Housing the PBR detection system on a nanosatellite in-orbit removes the need for a conventional costly and power intensive ground station, making debris detection and tracking more available to the space community. Additionally, there would be no need for any atmosphere compensation techniques.

Researchers at the University of Strathclyde have already successfully investigated the feasibility of a space based PBR system onboard a CubeSat and proved that it could work [11]. Current work involves a signal processing algorithm that will characterise the debris [12]. As a result of this work, the STRATHcube mission was set up. This mission, designed by students at the University of Strathclyde [13] [14], aims to contribute to ongoing SSA research by launching the first student-led Scottish CubeSat into LEO.

This paper will present the integration of PBR technology for space debris detection onto a CubeSat as a payload on the STRATHcube mission. This is the primary experiment on STRATHcube and will act as a technology demonstrator to test the debris detecting algorithm being developed at the University. If successful, this mission would demonstrate the benefits of in-orbit detection to the wider industry, allowing it to be implemented on a larger, scale in the future.

In this paper an overview of space-borne CubeSat passive bistatic radar is provided in Section 2 followed by an introduction of illuminators of opportunities essential for this work in Section 3. In Section 4, the challenges faced in developing this experiment for a CubeSat platform will be discussed.

2. Space-Borne CubeSat Passive Bistatic Radar

PBR is a radar system where the transmitter and receiver are separated from each other in different places which forms the bistatic part of the radar and makes use of non-cooperative, third party, radar signals – the passive section of the system. PBR is already used in many ground-based radar tracking applications, for example, in the French GRAVES system [9]. The concept of CubeSat based PBR involves a radar receiver and an on-board antenna on a CubeSat, orbiting at a low altitude to detect the variations in radio signals

transmitted by operational satellites, known as illuminators of opportunity, orbiting at higher altitudes shown in Fig 1. In this case the bistatic angle, β , is 180° . If a piece of debris crosses the baseline of the illuminator and the CubeSat it will leave an imprint on the transmitted signal, which will be detected on the CubeSat. Through measuring the variations in the received radar, signal processing algorithms can be used to interpret the size and shape of the object that passed between the CubeSat and the illuminator of opportunity.

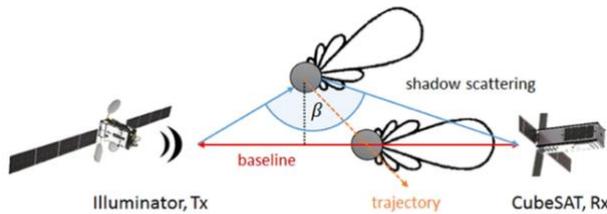


Figure 1. The concept of a CubeSat based PBR system

As outlined by Persico et al. in [11], there are three key benefits to a space-based debris detection system that allow for more accurate detection and tracking of debris:

1. There is a reduced distance between the transmitter and receiver.
2. The relative velocities between the transmitter and receiver are lower if their orbits are synchronised and at the same inclination.
3. Earth's atmosphere can be avoided and so the associated errors and losses are removed.

The size of the object can be measured more accurately when the bistatic angle β , shown in Figure 1, is close to 180° creating an effect known as “forward scattering” which can be used to determine the radar cross section (RCS) of a target using the following equation [15]:

$$\sigma_{FS} = \frac{4\pi U}{\lambda^2} \quad (1)$$

Equation 1 shows that the smaller the wavelength, and therefore higher frequency, of the received radar signals from the illuminator of opportunity, the larger the RCS which makes detecting debris easier. Implementation of a space borne PBR system would therefore allow higher frequencies to be used as the signal losses from the atmosphere and path distance between transmitter and receiver would be less, resulting in more accurate debris detection of smaller objects.

3. Illuminator of Opportunity Selection

The illuminator of opportunity selection has an important role in the PBR system and is a driving factor

in the payload's design as the antenna chosen for the experiment must be able to receive at the operational frequency of the illuminator. As outlined earlier, it is desirable that the illuminator of opportunity has a relatively high operating frequency, compared to traditional radar systems, to be able to detect smaller debris or to not be so constrained by the power limits and additionally belongs to a large constellation to increase link availability.

SpaceX's Starlink constellation is a favourable illuminator of opportunity given its large size. However, the constellation primarily operates in the Ku-band (12-18 GHz) of the radio frequency. Specifically, the radar signals Starlink uses to communicate with Earth and that must be detected by a CubeSat antenna for a PBR experiment are in the range 10.7 – 11.7 GHz. Currently, there is not a suitable COTS patch antenna that can operate at these frequencies, and therefore, the Starlink constellation – despite it providing excellent illuminators of opportunity – was discounted for the STRATHcube PBR experiment.

Present and upcoming global broadband constellations like the OneWeb and TeleSat networks were also considered as potential illuminators of opportunity. However, much like Starlink these constellations operate at frequencies in the Ku- and Ka-bands of the RF spectrum. Global Navigation Satellite Systems (GNSS) constellations were also discounted due to their limited size, with no more than 50 satellites in each constellation and located in Medium Earth Orbit.

Given these findings, older communications constellations such as Iridium and Globalstar, which operate on lower frequencies were deemed more suitable. There are only 24 operational satellites in the Globastar constellation compared to Iridium's 75 [16]. Therefore, the Iridium constellation was selected as the illuminator of opportunity for the STRATHcube PBR experiment. Iridium operates in the L-band frequency range between 1616 and 1626.5 MHz. Its 75 operational satellites will provide sufficient coverage for the primary payload experiment to take place and the constellation is also situated in LEO, providing a short distance to the receiver on the CubeSat. It should be noted that even though this constellation is not ideal, since the purpose of STRATHcube is to launch a CubeSat for testing the functionality of the PBR and not testing the limits of the technology, it is suitable for the time being.

4. Payload Design

The overarching goal of this study was to develop a viable CubeSat payload for STRATHcube with a clear design from this conceptual idea. This involved defining technical requirements, considering trade-offs at a system and subsystem levels and carrying out component selection.

4.1 Project Structure

The PBR experiment for STRATHcube was developed over two academic semesters, which would be part of the preliminary design of the project to determine the best configuration for the PBR payload and the mission itself. In the first semester, a high-level system trade-off was undertaken to narrow down the multiple forms of the CubeSat bus and mission itself. The result of the high-level trade off would be two candidate options which would be taken over to the next phase of the project (Fig 2). For the PBR payload, this consisted of a configuration for both the patch antenna and custom phase array antenna design options. During the second semester, a more detailed subsystem-level trade-off was carried out to make an informed decision on the best configuration to be taken forward for the STRATHcube mission in which a final design option for the PBR payload was selected. The project used a concurrent and iterative design process based on systems engineering principles to develop the payloads and subsystems concurrently.

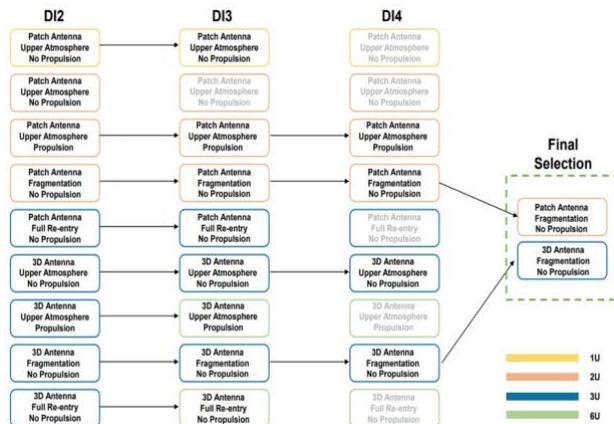


Figure 2. Summary of high-level trade-off analysis

4.2 Payload Architecture

The proposed PBR payload architecture is shown in Fig 3 and consists of an antenna to capture the signals from the illuminator of opportunity, a receiver to convert the received analogue signal into a digital signal and an on-board processor where the algorithm will interpret the signals. The work throughout both trade-offs was focused specifically on finding a suitable antenna to use in conjunction with an illuminator of opportunity. Therefore, to facilitate the PBR payload on STRATHcube, two different antenna design options were explored concurrently:

1. A novel 3D phase array antenna.
2. A commercial-off-the-shelf (COTS) patch antenna.

The 3D phase array antenna is currently being developed by a PhD researcher at the University of Strathclyde in conjunction with an external enterprise for use on STRATHcube and occupies 1U of volume in the CubeSat. The patch antenna option on the other hand will be procured from a commercially available source. Patch antennas have a low profile that can be mounted to a flat surface and are ideal in situations where a protruding antenna cannot be used due to its form – such as on a small spacecraft like a CubeSat.

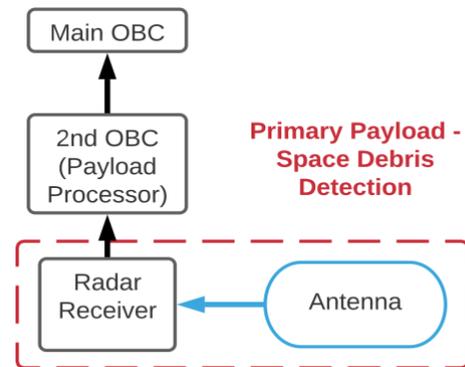


Figure 3. PBR Payload architecture

In line with the STRATHcube project structure, a high-level design for both the 3D and patch antenna options was first completed to evaluate their scientific capabilities on the size of trackable debris and to determine their mass, power, and volume parameters. These payload characteristics were then transferred into requirements for the supporting subsystems which would investigate their feasibility and allow the whole spacecraft design to be matured concurrently. An extensive high-level trade-off analysis at a system level was then carried out to narrow down the PBR payload on STRATHcube to two candidate options to be carried over into the next phase of the design. These antenna options were then developed further during the second semester sub-system trade-off.

4.3 3D Phased Array Antenna

The 3D phased array antenna was regarded as the more ambitious option as it is still in the development phase. This antenna is fundamentally different to a standard COTS solution, given it is being developed solely for its potential use on STRATHcube. Therefore, its properties can be modified, and the operating frequency tuned to the chosen illuminator of opportunity. Through regular communication with the researcher responsible for the development of the antenna, the technical and quantitative characteristics of the 3D antenna were defined to form the payload requirements.

Similar to all phased array antennas, the 3D antenna is made up of multiple elements, shown in Fig 4. In the case of the PBR, each antenna element has its own radar

receiver. In general, a major benefit of the many elements on the phased array antenna is its ability to electronically change the main beam of the antenna and therefore, it can electronically or digitally scan the environment. An exclusive feature of the 3D phased array antenna is the ability to use multiple beams to scan the environment. This opens the possibility of tracking as well as detecting debris. However, because of these more advanced capabilities the antenna is larger, heavier and consumes more power which makes the integration onto the CubeSat platform more challenging. The increased mass and power required to accommodate the large number of receiver elements in the phase array antenna has a consequence on STRATHcube’s supporting subsystems. The intense power draw caused difficulties for the power subsystem as the batteries and solar panels required to accommodate the power became too expensive and too heavy to include on the CubeSat platform. Research into more realistic power systems showed that the duty cycle of the payload would be limited because of the power required and therefore reduce its effectiveness as a scientific experiment.

Due to these constraints, three candidate configurations were put forward for the 3D phase array antenna based on the number of receiver elements, each with different values of mass and power: an Advanced, Standard, and Basic option. The key parameters of each are shown in Table 1.

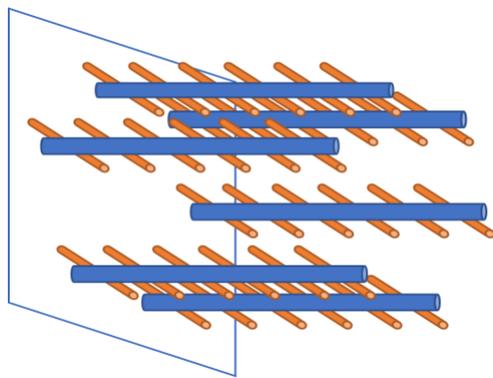


Figure 4. The design of the custom phase array antenna

Table 1. PBR Payload 3D antenna characteristics

3D Antenna Option	Number of Elements	Mass (kg)	Power (W)	Minimum Detectable Size of Debris (cm)
Advanced	42	3.69	26.210	267.4
Standard	30	2.63	18.720	356.5
Basic	16	1.404	9.984	533.4

As the number of elements decreased, the options became lighter and less power intensive, which made their inclusion on a CubeSat more viable. However, this

reduced the scientific gain of the experiment as the minimum detectable debris size increased. From Table 1 the power consumption and mass of the Advanced and Standard antennas are extremely over the budget available for the PBR Payload, with the Advanced option’s mass exceeding that of the total allowable mass of a 2U CubeSat. Although the Advanced option could detect a minimum size of debris about half that of the Basic option, the increased mass and power made it completely unfeasible. Consequently, moving into STRATHcube’s sub-system level trade-off during semester 2, only the Basic 3D antenna option was taken forward and developed.

4.4 Commercial Off-The-Shelf Patch Antenna

The primary focus when developing the design of this option was the identification and selection of a suitable COTS patch antenna. The ability to use a readily available, COTS components for STRATHcube’s primary payload rather than the 3D antenna is particularly attractive given that standardised components are typically favoured on CubeSat platforms. Therefore, the patch antenna design option simplifies the PBR payload experiment, reducing design development time.

Research was initially carried out to source a patch antenna that was suitable for the original illuminator of opportunity selected, Starlink, with an operating frequency of approximately 11 GHz. As mentioned previously in Section 3, there are no available COTS solutions that operate at the required frequency. As a result, Endurosat, a leading CubeSat component manufacturer, was contacted to explore the option of a custom-built patch antenna which would be built to meet the frequency requirement and operate at the frequency of the target Starlink constellation. Given the lack of available patch antennas this was found to be the best option. The cost of the custom-built patch antenna was quoted at €14,900. Due to the self-funded and student-led nature of this project this represented a significant cost, which at the time accounted for about 25% of the mission cost budget. Although the custom antenna offered by Endurosat met mission requirements, its cost meant that it was not feasible. This is ultimately the decision for changing the illuminator of opportunity to one that operates at a lower frequency.

Given the Iridium Constellation was selected as the illuminator of opportunity, there were increased COTS options during the detailed design carried out in Semester 2. Iridium has been operational for over 20 years and because of this there are a plethora of COTS patch antennas available for purchase at a low price. The PulseLARSEN W3227 ceramic patch antenna (Fig 5) was selected as a candidate, the main characteristics of which are shown below in Table 2. This component is specifically designed to communicate with the Iridium

constellation and is available from many online electronic providers for around £5.

There were concerns that the PulseLARSEN antenna would not be able to operate in space given its low price and non-space grade status. However, the MiniCarb mission [17] successfully demonstrated that a cheap, ceramic patch antenna could be used in LEO to communicate with the Iridium constellation. The antenna used in the MiniCarb mission is also shown in Table 2.

0.48W due to the radar receiver component when carrying out the experiment.

4.5 Data collection

The size of the data packets generated by the debris experiment is the same no matter which antenna design option is used and has been estimated at 27kbps when operational. Due to data processing that must be carried out on board the CubeSat before the data can be

Table 2. Patch antenna options and their properties

Antenna	Mass (g)	Dimensions (mm)	Operating Temperature (°C)	Material	Minimum detectable size of debris (cm)	Cost
PulseLARSEN W3227 [18]	35.8	40 x 40 x 6.6	-40 to +105	Ceramic	671.6	~£5
Taoglas IP.1621.25.4.A.02. [19]	10	25.1 x 25.1 x 4	-40 to +85	Ceramic	671.6	~£5
ISIS ISIS-GAPA-DSH-0001 [20]	18	70 x 70 x 15	-30 to +70	Ceramic	671.6	£1,500

This justifies the selection of the cheap off the shelf ceramic antenna for use on STRATHcube. Should the W3227 fail radiation or vibration tests, a more conservative option was selected and detailed. The GNSS Active Patch Antenna by ISIS was chosen to provide a robust, but more costly, option that would not be detrimentally affected by the space environment. The ISIS antenna properties are also shown in Table 2. In the future, the selected ceramic patch antenna should undergo tests to be verified for use in space and the use of a radiation protective coating on the ceramic patch antenna should be explored to further protect it from the radiation in space in order to reduce the risk of the component failing.



Figure 5. PulseLARSSEN ceramic patch antenna (credit PulseLARSSEN)

Due to the affordable cost, the PulseLARSSEN patch antenna provides an inexpensive opportunity to purchase a component to gain hands on experience in the lab to test STRATHcube's primary experiment before launch. For all the patch antenna options, the minimum detectable size of debris is 671.6cm and will have a power draw of

transmitted back to the user on Earth, a capable processor must be used. It was decided that the second processor of the on-board computer, the OBC-P3 from Space Inventor, would be used to handle data processing for the PBR payload.

Knowing the size of the data packets was important to determine the required on-board memory storage and the data rate needed to be downlinked to the ground station. The STRATHcube mission is proposed to launch from the International Space Station and as such, will have similar orbital characteristics. This resulted in limited pass durations and long revisit times with the ground station based at Strathclyde University in Glasgow, Scotland. Due to these limitations and the volume of data generated from the PBR experiment while operational, the duty cycle of the experiment was restricted to 12%. This had important consequences when it came to the power draw required by the PBR payload and highlighted an essential area of future work where the exact timing of when the PBR payload is operational would need to be determined to gain a better picture of how the power system must perform.

5. Payload Development Results

The PulseLARSSEN and the Basic 3D antenna were compared during the final subsystem trade-off to choose a final configuration of the PBR payload for the STRATHcube mission. The COTS patch antenna clearly showed that it was the better option due to its lower size, mass, power, and development cost. Despite its design evolution, the Basic 3D antenna consistently exceeded the mass budget throughout. In comparison, the COTS

patch antenna was found to contribute 1.89% in mass, whereas the 3D antenna contributed 35.1% to the final mass budget from the subsystem trade-off, ultimately pushing the mass over budget. Furthermore, the small change in minimum detectable debris size between the Basic 3D phased array antenna and the patch antenna compared to the reduction in other key parameters make it more favourable for inclusion on a small platform such as a CubeSat.

Detecting smaller debris size was one of the only benefits of the 3D phased array antenna. However, as the scientific goal of this experiment is to demonstrate the capabilities of space based PBR technology, the actual size of debris detected is not a driving factor when trading off between the two design options. The goal of STRATHcube is to confirm that PBR can be used on a CubeSat to detect objects in space and although detecting smaller debris would not immediately contribute to global SSA knowledge, simply proving that this technology works will give a strong indication into its use for future debris detection and tracking missions.

Therefore, based on physical quantities that would integrate onto a CubeSat in a more practical manner, the PulseLARSEN patch antenna was chosen as the antenna option for the PBR Payload with a backup option of the ISIS patch antenna – in the case that the antenna must be more radiation resistant. The PulseLARSEN patch antenna provides an affordable and lightweight solution with minimal power draw and has a comparable capability in the size of detectable objects. This decision shapes the STRATHcube mission, allowing a 2U CubeSat to be used, reducing mission cost and complexity.

6. Conclusions

The PBR payload on the STRATHcube mission aims to demonstrate that the passive bistatic radar method of space debris detection can be successful when carried out in space. This paper investigated the two design options of the antenna component of the payload that were developed throughout the course of the STRATHcube preliminary design. The first option was a custom developed 3D phased array antenna and the second was a COTS patch antenna. Payload requirements and design were developed concurrently using an iterative process which allowed for progress through trading off key parameters such as: mass, power, cost, and size. As a result of these trade-offs, it was determined that the 3D antenna option was not feasible due to being over the system mass budget and the very high power draw it demanded. Therefore, the PulseLARSEN patch antenna was chosen as the antenna component for the PBR payload. Its low cost, similar debris detection capability and superior physical characteristics being the reasons for its selection.

The algorithm underpinning the PBR payload continues to be developed by a PhD researcher at the University of Strathclyde and, as the design develops, future work on this payload will be focused on better defining its duty cycle. This would involve extensive modelling of the CubeSat's translational and rotational position throughout the mission to determine the visibility of the Iridium constellation as the illuminator of opportunity. Moreover, the probability of debris detection should also be investigated as this will give a better indication of the volume of data that will be generated by the payload. Better definition of the duty cycle and data volume will give a more complete picture of the data required to be transmitted back to the ground station and therefore alleviate some of the stress on the communications requirements given the short duration of pass windows. Future work should also aim to communicate closely with the PhD student to gain fuller understanding of the radar receiver component necessary to the PBR payload, to provide more accuracy to system-level technical budgets and to design and produce the communications system for the CubeSat.

The development of this payload has been encouraging and will ensure that if the PBR technology demonstration is successful, it will provide an alternative to conventional ground-based space debris tracking that is cheaper and more available to the space community.

Acknowledgements

The work carried out in this paper was supported by the University of Strathclyde Alumni Fund, the Institute of Mechanical Engineers and the Royal Aeronautical Society through funding to the STRATHcube project. A special mention must be made to the other members of the STRATHcube 20/21 Masters group project: Sam Kirk, Douglas McGarrity and Gary Stewart for their support and hard work throughout the year and finally, to Rory Hope for his many valuable contributions to the project.

References

- [1] ESA Space Debris Office, "ESA's Annual Space Environment Report," 2020.
- [2] J. R. Shell, "Optimizing orbital debris monitoring with optical telescopes," US Air Force, Space Innovation and Development Center, Schriever, 2010.
- [3] Celestrak, "Chinese ASAT Test," 22 06 2012. [Online]. Available: <https://celestrak.com/events/asat.php>. [Accessed 25 03 2021].
- [4] J. A. Kennewell and B.-N. Vo, "An Overview of Space Situational Awareness," in *16th*

- International Conference on Information Fusion*, Istanbul, 2013.
- [5] D. J. Kessler and B. G. Cour-Palais, "Collision frequency of artificial satellites: The creation of a debris belt," *Journal of Geophysical Research: Space Physics*, vol. vol. 83, no. A6, pp. 2637-2646, 1978.
- [6] C. R. Benson, "Enhancing space situational awareness using passive radar from space based emitters of opportunity," in *Military Communications and Information Systems Conference (MilCIS)*, Canberra, 2014.
- [7] ESA, "SAFETY & SECURITY Scanning and observing," 2021. [Online]. Available: https://www.esa.int/Safety_Security/Space_Debris/Scanning_and_observing. [Accessed 20 03 2021].
- [8] NASA Handbook, 8719.14, Handbook for Limiting Orbital Debris, approved July 30th, 2008.
- [9] J. Ender, L. Leushacke, A. Brenner and H. Wilden, "Radar techniques for space situational awareness," *In Proc. 12th Int. Radar Symp.*, pp. 21-26, 2011.
- [10] A. F. Pensa and R. Sridharana, "U.S. Space Surveillance Network Capabilities," in *SPIE Conference on Characteristics and Consequences of Space Debris and Near-Earth Objects*, San Diego, California, 1998.
- [11] A. R. Persico, P. Kirkland, C. Clemente, J. J. Soraghan and M. Vasile, "CubeSat-Based Passive Bistatic Radar for Space Situational Awareness: A Feasibility Study," *IEEE TRANSACTIONS ON AEROSPACE AND ELECTRONIC SYSTEMS*, vol. 55, no. 1, pp. 476-485, 2018.
- [12] I. Theodorou, C. Ilioudis, C. Clemente and M. Vasile, "SISAR Imaging for Space Debris based on Nanosatellites," *IET Radar, Sonar & Navigation*, vol. 14, no. 8, pp. 1192-1201, 2020.
- [13] C. Jenkins, R. Hope, A. R. Wilson and A. Berquand, "STRATHcube: The Design of a Student CubeSat Using Concurrent Engineering Methods," in *9th International Systems & Concurrent Engineering for Space Applications Conference*, Virtual, 2020.
- [14] A. Wilson and A. Berquand, "Concurrent Engineering and Social Distancing 101: Lessons Learned During a Global Pandemic," in *9th International Systems & Concurrent Engineering for Space Applications Conference*, Virtual, 2020.
- [15] I. Theodorou, C. Ilioudis, C. Clemente and M. Vasile, "SISAR Imaging for Space Debris based on Nanosatellites," *IET Radar, Sonar & Navigation*, vol. 14, no. 8, pp. 1192-1201, 2020.
- [16] Z. Tan, H. Qin, L. Cong and C. Zhao, "Positioning Using IRIDIUM Satellite Signals of Opportunity in Weak Signal Environment.," *Electronics*, vol. 9, no. 37, 2020.
- [17] V. J. Riot, L. M. Simms and D. Carter, "Lessons Learned Using Iridium to Communicate with a CubeSat in Low Earth Orbit," *JoSS*, vol. 10, no. 1, pp. 995-1006, 2021.
- [18] Mouser Electronics , "W3227," 2021. [Online]. Available: [https://eu.mouser.com/ProductDetail/PulseLarsen - Antennas/W3227?qs=BZBei1rCqCB8EAI5BE1LyA==](https://eu.mouser.com/ProductDetail/PulseLarsen-Antennas/W3227?qs=BZBei1rCqCB8EAI5BE1LyA==). [Accessed 25 03 2021].
- [19] Mouser Electronics, "IP.1621.25.4.A.02," 2021. [Online]. Available: https://www.mouser.co.uk/ProductDetail/Taoglas/IP1621254A02?qs=WUa1z%2FNv9%252B1n1qguBUkAVA==&gclid=Cj0KCQjw9YWDBhDyARIsADt6sGaypGcA2UVZBZAsgKOPRqELtygU9QPd-6clPK1TaY7ZwkJ6ltStl_saAnI8EALw_wcB. [Accessed 25 03 2021].
- [20] ISISpace, "GNSS Patch Antenna," 2021. [Online]. Available: <https://www.isispace.nl/product/gnss-patch-antenna/>. [Accessed 25 03 2021].