The Global Network On Sustainability In Space (GNOSIS): Activities, Initiatives, and Future Endeavours

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ABSTRACT

The Global Network On Sustainability In Space (GNOSIS) is a community-driven network supported by the UK Research and Innovation (UKRI) Science and Technology Facilities Council (STFC) through their 21st Century Challenges scheme. Founded in 2019, the Network has facilitated a variety of workshops, sandpit discussions, and multi-day conferences to bring academic researchers into contact with industry, government, and defence, with a shared aim of identifying, understanding, and solving problems pertaining to space sustainability. Despite operating in a predominantly virtual capacity due to the COVID-19 pandemic, the Network has amassed nearly four hundred members from the international space domain awareness (SDA) community.

We present an overview of GNOSIS activities and discuss key findings from the sandpit discussions that have taken place, covering a wide range of subject matter, from novel observation techniques to space-based SDA solutions, space weather effects, and SDA data management, security, and ethics. A key output from these discussions has been the identification of a series of capability gaps in current SDA knowledge and technologies, which has inspired further discourse through a recent SDA study commissioned by the UK Space Agency, with support from CGI, GNOSIS and UKspace. The study aims to understand the developments needed to progress the UK's SDA capability, by soliciting the views of academic and industrial actors.

In addition to supporting community engagement, GNOSIS also provides seed funding for short-term scoping and proof-of-concept studies, alongside part-funding for PhD studentships. Moreover, a series of "technical challenges" has been released, aimed at deriving key performance parameters, a system CONOPS, and initial implementation cost estimates for future SDA technologies; either pre-defined by the GNOSIS management team, or proposed by members of the Network. The primary aim of the GNOSIS funding stream is to foster collaboration between the academic and commercial SDA communities, by applying science, technology, and/or expertise from the STFC and other relevant UKRI-funded programmes to problems associated with orbital debris and space traffic management. We provide examples of ongoing projects supported by GNOSIS funding, including a PhD studentship developing space dust and debris detectors, making use of the University of Kent's hypervelocity impact facility, and a proof-of-concept study led by the University of Warwick, investigating multispectral signatures of geostationary satellites by repurposing the SuperWASP-North observatory on La Palma, Canary Islands.

We conclude with a look ahead to upcoming events in the GNOSIS programme, and a discussion of the Network's key goals for the future.

1. INTRODUCTION

The Global Network On Sustainability In Space (GNOSIS) was founded in 2019 with support from the UK Research and Innovation (UKRI) Science and Technology Facilities Council (STFC), through their 21st Century Challenges

Table 1: Number of registrants for GNOSIS workshops, sandpits, and conferences.

Date	Event	Topic	Registrants
Dec 2019	Workshop	*Space Weather Effects on Satellite Operations*	40
Apr 2020	Sandpit	*Space Weather*	35
Jul 2020	Workshop	*Precision SDA*	75
Nov 2020	Workshop	*SDA Data Management*	52
Apr 2021	Sandpit	*SDA Data Management, Security and Ethics*	58
Jul 2021	Workshop	*Novel/Non-traditional Observation Techniques*	72
Sep 2021	Conference	*GNOSIS21: First Annual Conference*	390
Oct 2021	Workshop	*Space Sustainability and Sustainability Development Goals*	48
Dec 2021	Sandpit	*Novel/Non-traditional Observational Techniques*	59
Jan 2022	Workshop	*Space-based SDA*	63
Mar 2022	Sandpit	*Precision SDA*	166
May 2022	Workshop	*SDA in Astronomy*	62
June 2022	Sandpit	*Space-based SDA*	41
Oct 2022	Workshop	*Black Swan Events*	*Pending*
Nov 2022	Conference	*GNOSIS22: Space Sustainability for the Next Decade (and Beyond)*	*Pending*

scheme. The primary aim of the Network is to support the STFC scientific community in tackling fundamental problems associated with space sustainability, space domain awareness (SDA), and space surveillance and tracking (SST), building from existing skills and capabilities.

Through a multidisciplinary approach, GNOSIS works with teams of scientists, exposing them to problems faced by the space sector at workshop-, sandpit-, and conference-style events, and helping them apply their knowledge to explore potential solutions. The events are designed to facilitate interactions between researchers, policy makers, and other stakeholders across academia, industry, government, and defence.

As the Network's membership has grown and evolved, so too has the scope of its programme, expanding from a predominantly technical focus in the early stages to bring elements of law, policy, and the social sciences under discussion. Furthermore, the Network is beginning to extend its global reach, frequently generating interest across an array of time zones.

The GNOSIS programme has been delivered fully virtually since the start of the COVID-19 pandemic, and this has helped to boost engagement from/with the international SDA community. That said, the virtual format has nevertheless made it extremely challenging to drive the informal sandpit discussions that often prelude the forging of new partnerships and collaborative ideas. In November 2022, proceedings will be switching to a hybrid format for the Network's second conference, *GNOSIS22: Space Sustainability for the Next Decade (and Beyond)*.

In a field that is rapidly evolving, GNOSIS aims to strengthen the SDA community by providing a platform for the sharing of knowledge, understanding, and ideas, bringing those new to the area with highly relevant skillsets into contact with established experts. This paper will review the activities conducted by GNOSIS to date, summarise key projects and initiatitives that have been sparked or supported by the Network, and conclude with plans for the future programme.

2. ACTIVITIES

The Network launched in November 2019 with video-linked events held at the British Interplanetary Society in London (UK) and the Royal Observatory, Edinburgh (UK). An in-person workshop on *Space Weather Effects on Satellite Operations* followed soonafter in December 2019, hosted at the Leicester Innovation Hub (UK), in collaboration with the Space Weather Innovation, Measurement, Modelling and Risk (SWIMMR) programme, though all subsequent events have taken place virtually due to the COVID-19 restrictions and associated logistical uncertainties. The second

GNOSIS Conference will mark the return of an in-person element to the programme; this hybrid event will be hosted by the University of Warwick (UK) from 30th November to 1st December 2022.

A comprehensive list of GNOSIS-organised workshops, sandpits, and conferences is given in Table 1. The Network's programme has enabled a diverse pool of research to be shared and disseminated among members of the GNOSIS and wider SDA communities. Below, a selection of case studies are provided, summarising key thoughts and findings from particular events.

2.1 Case study: Precision SDA

The July 2020 workshop on *Precision SDA* showcased a variety of research from the astrodynamics, observational, and modelling communities, featuring contributions from as far afield as the Netherlands, Slovakia, and New Zealand, supplementing those from a range of UK-based universities and organisations.

Representatives from the Defence Science and Technology Laboratory (Dstl, UK), University of Glasgow (UK), and University College London (UCL, UK), placed emphasis on the need to improve the fidelity of force models feeding into propagation and tracking algorithms. Northrup Grumman's first Mission Extension Vehicle served as a key example, proving difficult to track during its electric propulsion orbit-raising phase, owing to the non-Keplerian dynamics at play and the sparse coverage achievable with single-site observations. Astrodynamicists from the Universities of Auckland (NZ), Liverpool (UK), and Strathclyde (UK), presented work on the data association problem with too short arcs, the importance of being precise with uncertainty in orbital parameters, and a tool for autonomous conjunction classification under imprecise measurements, respectively.

A second contribution from UCL outlined the potential of Microwave Kinetic Inductance Detectors (MKIDs), detailing prelimary efforts to exploit their single photon, spectral, and time sensitivities to uniquely identify observed debris via its temporal spectral signature. Multiple presentations focused on object characterisation using precise light curve measurements across different wavelength regimes: robotic systems built and operated by the University of Warwick have been used to observe, calibrate, and extract high-cadence light curves for low Earth orbit (LEO) and geosynchronous (GEO) objects; and a brief from the University of Edinburgh highlighted the potential applicability of techniques used in the near-Earth asteroid community to perform 3D shape reconstruction from light curve information.

The workshop was rounded off by GNOSIS Programme Manager, Stuart Eves (SJE Space, UK), who posited a range of novel capabilities for civil and military applications that could be enabled or enhanced by transparent, precision SDA, such as: using companion satellites to monitor potential hostile activity in LEO; monitoring GNSS satellite transmissions using multiple GEO satellites for high precision orbit determination, jammer detection, and orbital drag estimation; and supplementing onboard navigation during rendezvous and proximity operations for servicing and removal concepts.

2.2 Case study: SDA Data Management, Standards, and Ethics

The April 2021 sandpit on *SDA Data Management, Standards, and Ethics* explored the ways in which SDA data have historically been collected, stored, validated, analysed, and distributed, before addressing the need to move beyond the often quoted sentiment of "always done it that way". The sandpit generated some lively discussion on the topic of existing infrastructures and best practices, in particular highlighting the community's reliance on the US Space Surveillance Network (SSN).

Attendees agreed on the importance of supporting the SSN's efforts with bespoke sensors that are optimised to meet modern SDA requirements, and to improve the depth, precision, and timeliness, of available catalogue information. To this end, the idea of a civil-commercial catalogue was discussed, as opposed to the existing military-centric approach, that could instead cater to the needs of the community with SDA at the forefront of its priorities. Two architectures for improved data management were introduced by representatives from L3Harris (US) and the US Department of Commerce: the former opting for a decentralised approach, making use of blockchain technology to support a consensus view of SDA data derived from multiple sources; the latter providing an overview of the centralised Open Architecture Data Repository.

The topics of data sharing, curation, and fusion, were discussed at length, unearthing several recommendations: avoid the assumption that all actors are doing things correctly or as expected (awareness is only as good as the last available data point); more precise and timely information is needed to reduce the frequency of non-actionable conjunction messages and boost the value proposition for operators sharing data; and address high-level disagreements between different sources/datasets before entrusting a fusion engine to assess source validity and enforce agreed upon standards.

On the subject of standards and best practices, it was recognised that significant improvements are needed in light of the rapidly evolving situation in LEO: coordination of conjunction assessment and mitigation, moving beyond email notifications; standards for covariance realism; and with reference to constellations, the development of best practices for on-orbit co-location deconfliction and ascent/descent management. With regards to ethics, the need for a broad inclusion of management concepts was highlighted, to satisfy the differing requirements of the wide range of stakeholders involved.

2.3 Case study: Space-based SDA

The January 2022 workshop on *Space-based SDA* featured a cross-disciplinary, cross-sector programme, beginning with an overview of efforts by GEOST (US) to develop on-orbit electro-optical/infrared sensors that are affordable, small-size, low-weight, and low-power, alongside the associated processing and ground-based infrastructure. A key take-away was the need to move beyond "Either...Or" and switch to a "Yes, and..." approach in order to develop a comprehensive and effective space surveillance network.

Representatives from Astroscale (UK) and ExoAnalytic (US) outlined some of the opportunities and obstacles associated with in situ SDA. Advantages of space-based surveillance include: observations are independent of weather and (most) other atmospheric phenomena; no geopolitical boundaries restricting the sensors; close proximity to target objects; new sensing opportunities (thermal, hyper-spectral, resolved imaging); improved duty cycle for LEO observations; and reduced solar exclusion for GEO coverage. Disadvantages, on the other hand, include: expensive to build, operate, maintain, and dispose of sensors; additional constraints on the system design due to mass, power, and downlink budgets; higher complexity; and the use of spacecraft to host sensors adds further risk for other space operators. With these considerations in mind, Astroscale are developing a Flexible Sensor Payload that can perform proximate inspection of client satellites, but also carry out surveillance, tracking, and characterisation activities.

A contribution from Dstl addressed a very data-poor area of research, calling for the inclusion of space environment sensors aboard future space-based SDA payloads. Severe space weather storms can cause unexpected changes in altitude and result in substantial positional errors; a drop in 1 km will advance a LEO satellite by roughly 150 km per day, rendering catalogue information useless for conjunction analysis. More reliable forecasting of geomagnetic storms will require real-time precise orbit determination from GNSS-equipped satellites, alongside advanced, non-hydrostatic, data assimilative models of thermospheric neutral density, taking into account ionospheric variation. Better forecasting will tighten error ellipsoids, and thus reduce the number of conjunction warnings that need to be issued.

Other speakers from the European Space Agency, University of Birmingham (UK), and Privateer (US), introduced a selection of proposed space-based SDA missions, respectively: the SBOC mission to observe and characterise small-sized LEO debris, in an attempt to tackle the current data gap for objects a few millimetres in size; the SubTerIS mission, which aims to utilise a long-range sub-THz Inverse Synthetic Aperture Radar (ISAR) to image objects at a range of 100 km, in all lighting conditions, with a pixel size of a few centimetres; the Pono 1 mission, comprising a 3U chassis with 12 optical cameras and 30 non-optical sensors, including photon counters, continuous wave and passive radars, and nanoscale Fourier Transform InfraRed (FTIR) spectrometers.

2.4 Capability gaps

The GNOSIS programme has helped to identify a series of critical gaps in the current capabilities of the global SDA community. Created and curated by Stuart Eves, the following list of 13 capability gaps is largely representative of the sentiments that have featured frequently in discussions at GNOSIS events:

1. Limited ability to track debris down to 1 cm and below - estimates for the number of such objects in orbit still vary considerably.
2. Insufficient system capacity (and rate of update) to maintain custody of a catalogue comprising hundreds of thousands of objects - all-on-all conjunction analyses get progressively more expensive.

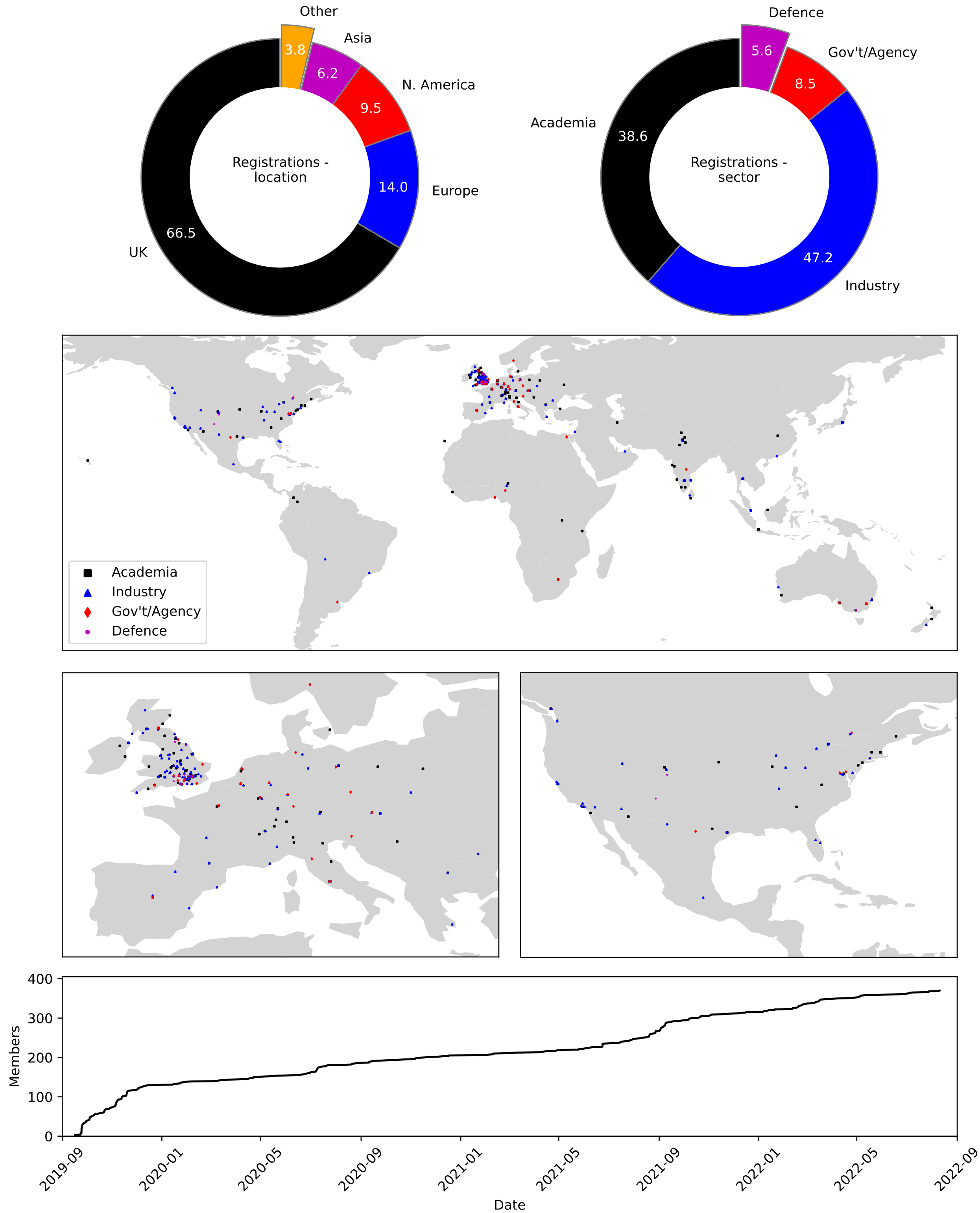

Fig. 1: Registration analytics for GNOSIS workshops, sandpits, and conferences from the period July 2020 to August 2022. Registrants lacking institutional information have been excluded from the analysis. Top row) Location (left) and sector (right) classifications. Second row) Map of institutions represented at GNOSIS events, categorised by sector. Third row) Zoomed-in panels showing European (left) and North American (right) institutions. Bottom row) Evolution of the GNOSIS membership since its launch in late 2019.

3. Lack of geographical diversity to track objects more frequently around the globe - tracking capability in the Southern hemisphere is sparse, and the military find it difficult to share tracking data.
4. Insufficient orbit measurement and propagation accuracy to support conjunction warning services - miss distance estimates are often smaller than the error bars on the positional measurements, while the poor representation of drag and other subtle perturbations in propagation models severely limits forward prediction.
5. Inability to identify targets unambiguously - maintaining custody of objects is challenging with sparse tracking; need reliable measurements of size, shape, mass, albedo, and ballistic coefficient.
6. Limited ability to monitor object orientation and motion, (spin, tumble, etc.) - time variant nature of optical and radar signatures makes correlation with previous observations (and size estimation) a complex task.
7. Limited ability to track certain classes of object during daytime - maintaining custody is once again a challenge, in particular when targets are manoeuvring.
8. Very limited ability to determine the material composition of debris objects - important for estimating lifetime, and for the planning of future removal missions.
9. Insufficient custody to reliably track objects conducting manoeuvres - orbits can become significantly inaccurate almost as soon as they are measured by external sensors, especially for targets utilising low-thrust electric propulsion.
10. Limited capability to determine operational status unambiguously - difficult to establish if a satellite is active, dormant, or dead, and therefore whether it can manoeuvre in the event of a potential conjunction with another object.
11. Sparse measurement of space weather effects - crucial to monitor and forecast events for more extensive forward prediction of satellite orbits.
12. Partial understanding of micrometeorite/asteroid flux and its effects on satellites - difficult to differentiate between natural and artificial impactors, and better forecasting needed.
13. Limited ability to monitor satellite transmissions - external monitoring networks exist, but only a limited subset of them are commercial, unclassified, and available.

In July 2021, James Blake (GNOSIS Secretary) and John Zarnecki (GNOSIS Steering Board) organised a session on SDA at the Royal Astronomical Society's National Astronomy Meeting (NAM, UK). The above list of capability gaps formed an integral part of the session, highlighting the ways in which tools, techniques, and understanding from the astronomy, solar physics, and Magnetosphere Ionosphere and Solar-Terrestrial (MIST) communities might be applicable to current SDA challenges.

Since the NAM session, GNOSIS has continued to engage with astronomers across the UK and beyond, following up with a review article on space sustainability in *Astronomy & Geophysics* [1], running a workshop on *SDA in Astronomy*, and organising another SDA session at NAM 2022. The identified capability gaps have also contributed to a recent study commissioned by the UK Space Agency into the requirements and opportunities for SDA in the UK (see Section 3.4).

2.5 Registration analytics

During the period July 2020 to June 2022, GNOSIS events drew in 1086 registrants, from 328 institutions and organisations, spanning 44 countries and 6 continents. A selection of registration analytics is provided in Figure 1. While the virtual nature of the programme has enabled the Network to reach a widespread audience across the globe, 66.5% of registrants have been from the UK. It is interesting to note, however, that only 46.8% of registered institutions are UK-based; as event timings favour the UK working day, this increases the likelihood of seeing multiple registrants from the same institution, or indeed the same registrant attending multiple events. Nevertheless, a key aim for future GNOSIS activities is to boost participation from the global SDA community. For clarity, a higher resolution map of UK registrations is provided in Appendix A.

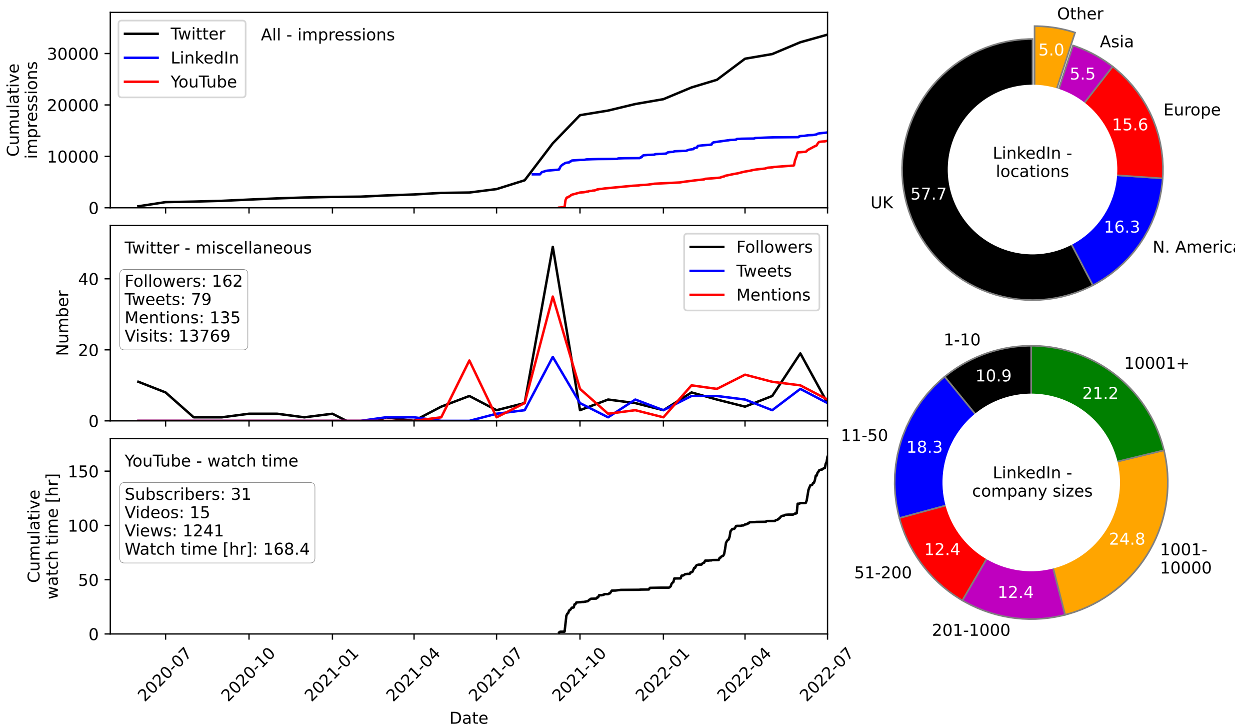

Fig. 2: Analytics for the GNOSIS social media channels, as of August 2022. Top left) Cumulative impressions (displayed content) for Twitter, LinkedIn, and YouTube. Middle left) Monthly followers, tweets, and mentions on Twitter. Bottom left) Cumulative watch time on YouTube. Right) Location (top) and company size (bottom) classifications for page visitors on LinkedIn. Note that LinkedIn analytics are for the past year only.

Owing to the Network's primary objective of bringing STFC researchers into contact with established experts, attendance has been dominated by academia and industry, together accounting for over 85% of total GNOSIS registrations. The Network's membership has grown steadily to over 370 people, as of August 2022, with surges surrounding the launch event (November 2019) and the first GNOSIS Conference (September 2021). Members are automatically signed up to receive updates via monthly GNOSIS newsletters, and can take advantage of a variety of funding opportunities (see Section 3).

2.6 Social media analytics

In addition to the monthly GNOSIS newsletters, the Network posts regular updates about upcoming events and opportunities on Twitter (@gnosis_space) and LinkedIn. Moreover, since the conference in 2021, all GNOSIS events have been recorded and made publicly available via the Network's YouTube channel. Links to the social media channels can be found on the home page of the GNOSIS website [2].

All of the channels saw a surge in activity during the months surrounding the first GNOSIS Conference, which attracted 390 registrants and featured a combination of plenary talks, parallel sessions and panel discussions, prefaced by a prerecorded interview with the UK's Astronomer Royal, Lord Rees.

The GNOSIS LinkedIn page has accrued 274 followers, as of August 2022, and the geographical breakdown for page traffic is very similar to that of the event registrations discussed in Section 2.5. Interestingly, visitors to the LinkedIn page span the full range of institution sizes fairly evenly, suggesting that the Network has reached a wide range of start-ups, SMEs, universities, agencies, and large enterprises.

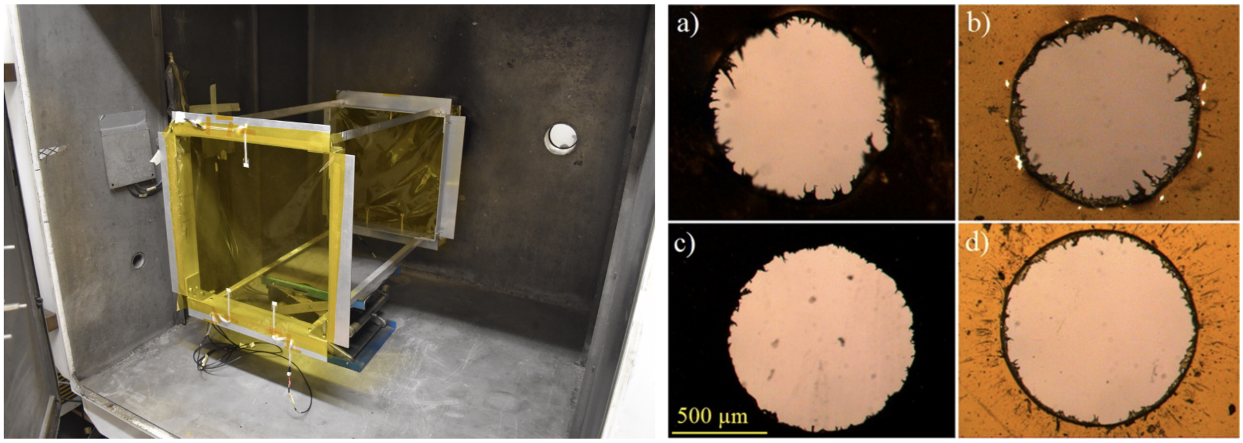

Fig. 3: Left) The prototype Kapton film, time of flight detector in the target chamber of the University of Kent's Light Gas Gun facility. Each yellow Kapton film is 40×40 cm. Right) Optical images of penetration holes viewed from the incident direction of 1 mm stainless steel projectiles, following impacts at $\sim 2\,\mathrm{kms}^{-1}$ (a, b) and $\sim 4\,\mathrm{kms}^{-1}$ (c, d). The first films are blackened by the deposition of gunpowder/soot generated by the first stage of the gun. Sourced from [3], included with the author's permission.

3. INITIATIVES

The Network addresses its overriding goals by supporting an integrated set of activities comprising events and small-scale research projects of various types. Thematic workshops instigate the intended workflow, which are followed up with more detailed sandpit discussions to identify research problems and seed ideas for GNOSIS-funded scoping and proof-of-concept studies, alongside part-funded PhD studentships.

While the sandpits have generated some lively debate, the online format has not been optimal for facilitating the informal, small-group discussions likely to yield collaborative proposals for GNOSIS funding. In July 2021, a list of "technical challenges" was created to exemplify the kinds of projects that could receive support via the GNOSIS funding stream, and stimulate the development of further ideas. The suggested challenges were designed to seed initial studies into possible future SDA technologies, such as space-based infrared/ultraviolet sensing and high-speed blind image stacking, aiming to derive high-level estimates of key performance parameters, a preliminary system CONOPS and costing structure for implementation.

Sections 3.1 to 3.3 give examples of ongoing GNOSIS-funded projects.

3.1 Part-funded PhD: Development of a new space dust and debris detector

The first GNOSIS part-funded PhD studentship was awarded to the University of Kent (UK) in 2020, for a project on developing in situ impact detectors for future space missions.

> [Project description] With the growing threat of space debris, SDA is becoming more important than ever. It is crucial to know what is in orbit and where it is, to allow active spacecraft to perform manoeuvers to avoid large debris that would cause catastrophic damage. As well as large debris, there is smaller debris that cannot be tracked; with average impact speeds of $7 - 14\,\mathrm{kms}^{-1}$, even millimetre-sized debris can cause fatal damage, and requires shielding against. To inform effective spacecraft shielding and improve sustainability in space, in situ detectors are required to measure and characterise the small particle environment in Earth orbit.
>
> The main focus of this research is the development of in situ debris detectors, such as time of flight (TOF) detectors, which have excellent speed and trajectory determination capabilities. TOF designs based on the penetration of thin films to determine impactor speed are a current area of research, with detectors based on Kapton films under development by NASA and JAXA. The project's recent study on the capabilities and accuracies of Kapton-based TOF debris detectors [3] using the prototype in Figure 3, showed that they are capable of determining impactor speed to a high degree of accuracy.

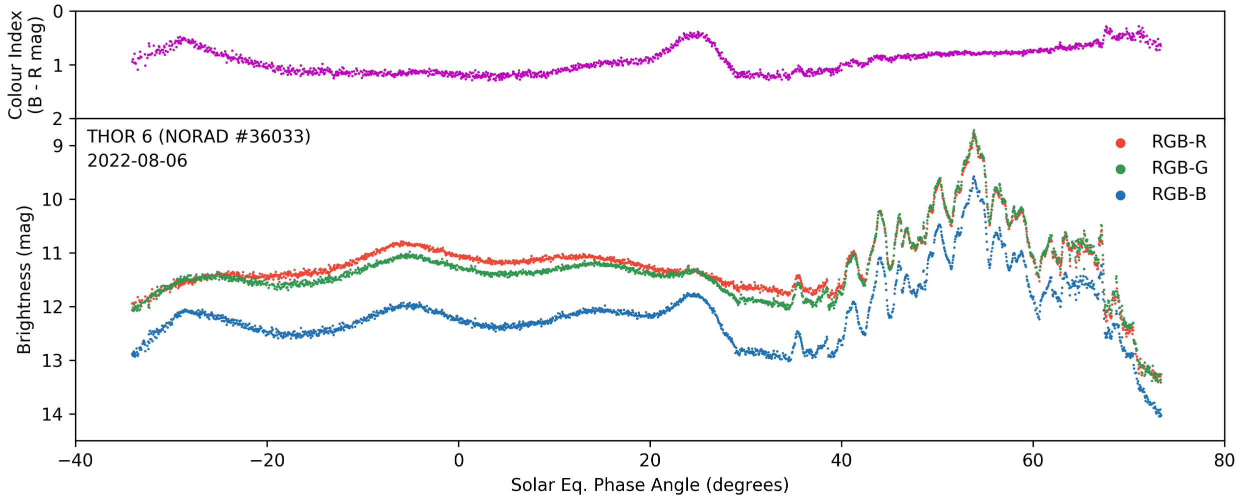

Fig. 4: A light curve of the THOR 6 geostationary satellite produced from the upgraded SuperWASP instrument demonstrates the utility of high-cadence simultaneous colour measurements. The broad glints around $\pm 25°$ phase angle are seen to feature a strong blue colour tint, while the sharp glint structures between $40° - 70°$ phase angles are entirely uniform in colour. These colour constraints provide additional information that can be applied towards source characterisation. Sourced from, and included with the permission of, Paul Chote (PI, Warwick).

Previous investigations have shown that at larger film thickness to impactor diameter ratios, impactors are decelerated and/or disrupted. Future research aims to determine and calibrate the velocity loss for smaller impactors, as well as carrying out debris environment modeling to inform on the detector area required to obtain meaningful statistical data.

3.2 Proof-of-concept: Multispectral colour signatures of geostationary satellites

In 2021, a GNOSIS proof-of-concept grant was awarded to the University of Warwick, to help fund an upgrade of the SuperWASP facility at the Roque de los Muchachos Observatory, La Palma. Formerly a wide-field exoplanet survey, the repurposed instrument will possess a capability to obtain simultaneous, multi-colour photometry, enabling a study of the multispectral signatures of GEO satellites.

> [Project description] Optical light curves have become an essential tool for classifying and characterising the properties of resident space objects. In particular, light curves of three-axis stabilised GEO satellites generally have stable signatures that encode information about their size, shape, and operational characteristics (such as solar panel bias angles). For uncontrolled debris, high-cadence light curves provide information about the size, shape, and tumble periods, the latter of which is essential knowledge for any future servicing or debris mitigation missions. Single-colour light curves of GEO objects are routinely collected for both research [4, 5] and operational uses. Research topics include studies to characterise or model the reflection geometry, and SDA providers match light curve signatures to reduce cross-tagging of measurements, which can lead to incorrect orbital fits. These uses typically integrate over a broad optical bandpass, ignoring the information available in the spectral (colour) dimension. Spectral data encodes details about the properties of the surfaces that are reflecting sunlight, which change over time due to ageing effects that remain poorly understood. This project aims to demonstrate the utility of combining spectral information with high-cadence light curves to characterise the entire population of active GEO satellites visible from the Canary Islands.

The project requested funding to purchase new detectors to upgrade the existing SuperWASP instrument, with the goal of carrying out a high-precision, simultaneous, four-colour light curve survey of the GEO region. As of August 2022, the hardware upgrades have been successfully integrated, and on-sky testing and commissioning is underway in preparation for a full robotic survey. Figure 4 shows an example light curve produced by the upgraded system.

3.3 Part-funded PhD: Towards a quantitative understanding of RSO light curves

The University of Warwick have recently been awarded a GNOSIS part-funded studentship, for a project aiming to develop quantitative techniques for light curve characterisation and classification.

> [Project description] Optical light curves have the potential to become an essential tool for classifying and characterising the properties of resident space objects (RSOs). However, our ability to exploit these data are still relatively crude: limited to qualitative feature recognition or the extraction of simple physical quantities like relative brightness or tumble periods. This project will work towards developing quantitative techniques that are able to extract additional information from the observational data such as light curve modelling through 3D ray tracing, studying the spectral and polarization characteristics, and the application of machine learning to infer properties that are not immediately obvious to the human eye in an automated and systematic way.

A student has been recruited for an October 2022 start.

3.4 UK Space Agency SDA Study

In early 2022, the UK Space Agency (UKSA) commissioned CGI to carry out a study [6] into the requirements and opportunities for SDA in the UK, with support from GNOSIS and UKspace. Over 100 experts from more than 40 academic and commercial entities within the UK space sector contributed to the study, which provides an overview of the UK's current SDA capabilities and landscape, and proposes a roadmap for future development.

The study identifies three key areas of opportunities for the development of SDA in the UK:

1. Sovereign sensors - The provision of new sensing capabilities to take advantage of UK and overseas territories, improve existing sensors and/or fill capability gaps. The UK should aim to provide more sovereign data to commercial and non-military users, and focus on contributing unique, supplementary, and/or higher quality data to support the global SST capability.

2. Non-sovereign sensors - The enhancement or expansion of datasets through agreements and relationships. In particular, the study finds a clear consensus that the UK should seek immediate re-entry into the EUSST programme, if the opportunity were to arise.

3. Analytics - The production of reliable, assured, and potentially bespoke products to enable decision making.

To tackle the existing capability gaps (see Section 2.4) and take full advantage of the above opportunities, the UK will need to leverage the strengths of its space industry, namely a world-renowned academic sector engaged in research activities spanning all areas of the SDA spectrum, and a commercial sector with proven experience in delivering capability into a wide range of national and international missions.

The study concludes with eight key recommendations, grouped into four separate themes:

NSpOC recommendations

- Space Service Desk - A national space operations centre (NSpOC), bringing together the civil, military, and commercial sectors would allow for the collection, consolidation, and exploitation of SST data to produce high quality analytical products for a range of users.

- SDA Advisory Group - Establish an advisory group for SDA to advise and guide on developing UK SDA capability. The group should include members from across academia, industry, as well as civil and military space.

- Collaboration Marketplace - A collaboration marketplace should be established to facilitate the matching of academic research with industrial demand, increasing visibility of activities and paving the way for more efficient sponsoring of research.

Sensor recommendations

- Data Accuracy Study - A study should be commissioned to assess the cost/benefit of increasing data accuracy to identify the point of diminishing returns. This study should conclude with a set of target figures for accuracy improvement over time to 2030 that can inform a plan for sensor enhancement.
- R&D for Sensor Improvements - The UK should invest in the procurement of more sovereign sensors to improve its sensing capability and international credibility, as well as contributing to closing gaps in global capability.

R&D recommendations

- SDA Strategy - A cross-Government SDA strategy and vision is required to cohere academic, industrial, civil and military entities and provide clarity on intended aims for the UK in SDA.
- National Space Sustainability Research Institute - A National Space Sustainability Research Institute should be considered to simplify and coordinate funding for research and innovation activities.

Collaboration recommendations

- Maintaining International Collaboration - The UK should attempt to maintain the strongest possible international ties, including with ESA, Five Eyes and CSpO partners, and other nations.

4. FUTURE PROGRAMME

The next GNOSIS workshop will take place virtually on 5^{th} October 2022, with a focus on "Black Swan Scenarios", exploring the potential ramifications of low probability/high impact events for future space operations. Specifically, the workshop will consider six scenarios that have thus far received relatively little coverage, at least in terms of their long-term impact on the space domain: a major collision between two large rocket bodies, potentially seeding a Kessler-like cascade; a major space weather event and its likely effects on satellites, the Earth's atmosphere, and infrastructures on the ground; a significant terrestrial environmental disaster; an undetected asteroid hitting the Earth; a massive meteor shower; and a magnetic reversal event. Further information is provided in the workshop's corresponding entry in the Network's blog series, which can be found on the GNOSIS website [2].

The Network's second conference, *GNOSIS22: Space Sustainability for the Next Decade (and Beyond)*, will be delivered in a hybrid format, with the in-person component to be held at the University of Warwick (UK) from 30^{th} November to 1^{st} December 2022. The conference will explore five key themes: fostering international collaboration for space sustainability; embedding sustainability in space law, policy, and regulation; addressing environmental issues, of space and from space; exploring the intersection between space security and sustainability; and inspiring the next generation.

Free registration is available for both upcoming events via the calendar on the GNOSIS website [2].

5. SUMMARY

The Global Network On Sustainability In Space (GNOSIS) aims to strengthen the SDA community by providing a platform for the sharing of knowledge, understanding, and ideas. Through its multidisciplinary programme of workshop-, sandpit-, and conference-style events, GNOSIS facilitates interactions between researchers, policy makers, and other stakeholders across academia, industry, government, and defence. As of August 2022, GNOSIS events have drawn in representatives from over three hundred institutions and organisations, spanning more than forty countries across six continents.

The Network's intended workflow stems from a series of thematic workshops, which are followed up with more detailed sandpit discussions to identify research problems and seed ideas for GNOSIS-funded scoping and proof-of-concept studies, alongside part-funded PhD studentships. This paper has provided an overview of key findings from GNOSIS activities to date, alongside projects and initiatives that have been sparked or supported by the Network.

Upcoming events include a virtual workshop on "Black Swan Scenarios" at the start of October 2022, and the second GNOSIS Conference, taking place in hybrid format from 30th November to 1st December 2022, to be hosted by the University of Warwick (UK). By visiting the GNOSIS website [2], the interested reader can: register for these (and other) events; sign up to receive monthly newsletters; explore the Network's range of funding opportunities; read or contribute to the GNOSIS blog series; watch recordings from past events via the GNOSIS YouTube channel; and follow the Network on Twitter and/or LinkedIn for regular updates about all of the above.

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Fig. 5: Zoomed-in view of UK institutions represented at GNOSIS events during the period July 2020 to August 2022.

A. UK REGISTRATIONS

The map in Figure 5 gives a zoomed-in view of UK-based institutions represented at GNOSIS workshops, sandpits, and/or conferences. When considering only UK registrations, 37.4% of registrants have come from academia, 49.1% from industry, 6.3% from government/agencies, and 7.2% from defence. Promisingly for the Network's goals, only 29.6% of the registered UK-based institutions are academic, suggesting that it has been common for (i) multiple academics to register from the same institution, and (ii) academics to register for multiple events.