Communications of BAO, Vol. 69, Issue 2, 2022, pp. 318-323

A Modern Space Situational Awareness System

Thomas M. Jackson *[1], H. Holland †[1], G. Tuparev[1], M. Steinbatz[2], W. Promper[2], D. Weinzinger[2], and E. Doeberl[2]

[1]Tuparev AstroTech, 14 Paskal Todorov Str., Sofia 1618, Bulgaria
[2]Astro Systeme Austria, Galgenau 19, 4212 Neumarkt im Mühlkreis, Austria

Abstract

We, Tuparev AstroTech in partnership with Astro Syteme Austria, present a next-generation Space Situational Awareness (SSA) system currently being created for the tracking and characterisation of satellites and space debris in the age of big-data astronomy. Our SSA system will be based on the image processing of white-light images to detect streaks produced by satellites and space debris. These images will be obtained by a network of 20-30 custom and in-house built SSA observatory stations, which will be made operational worldwide over the coming decade. The system will use machine learning algorithms to choose the optimal part of the sky to observe at any given moment, analyse the incoming data on-site and in real-time, and deliver various standardised data packages and science-quality images to be stored on a bespoke central archive capable of storing petabytes of data. With this system, we aim to cover a greater geographical and celestial area than any previous SSA system, to create a scalable system that is both fast and efficient, and to enable access to orders of magnitude more storage capacity and information than any other system currently available, commercial or governmental.

Keywords: *Space Situational Awareness, Space Debris, All-Sky Survey, Telescope Networks, Data Archives*

1. The Current State of Space Situational Awareness

Over the next decade, more satellites are expected to be launched into Earth orbit than have been launched since Sputnik-1 in 1959. Of the current satellites in orbit, 28 percent are no longer operational (ESA, 2021), in addition to significant amounts of "space debris" (pieces from satellites which have exploded or collided). Altogether, there are ∼36500 known, uncontrolled objects with sizes greater than 10cm in orbit, with around 1 million and 130 million known pieces between 1-10cm and 1mm-1cm respectively. These pieces can collide with other objects, potentially leading to thousands more pieces of space debris being generated (e.g. Watson et al., 2021) or satellites being destroyed. This can cause a chain reaction of collisions, resulting in an exponential growth of space debris known as Kessler Syndrome (Kessler & Cour-Palais, 1978). A worst-case scenario could render the orbital space around the Earth as unusable, depriving humankind of vital services.

The detection, tracking and orbital modelling of objects, so that active satellites can be manoeuvred away from collisions, is commonly known as Space Situational Awareness (SSA). There are a number of organisations carrying out such work, both governmental and commercial, using a number of techniques in their SSA systems, all with specific advantages or disadvantages. Systems using Radar (see e.g. Apa et al., 2021, Murray et al., 2021) or Laser Ranging (e.g. Steindorfer et al., 2017, 2021) to track space debris achieve high precision in the tracking of known objects, but they are not optimal for discovering new objects. Additionally, some networks lack homogeneity and/or full geographic coverage, both of which are key to maximising the effectiveness of a system.

In the search for new objects, some organisations have turned to optical systems (e.g. Jilete et al., 2019, Park et al., 2017, Woods et al., 2012, Zhang et al., 2018), surveying the night sky using imaging data. In these images, moving satellites appear as streaks in the field of view against stars and galaxies, which are then processed using a number of techniques in order to calculate positions and orbits of satellites and space debris, including segmentation (e.g. Virtanen et al., 2016), image shifting and stacking (e.g. Yanagisawa

---

*tmjackson@tuparev.com

†hunterholland@tuparev.com, Corresponding author

doi:https://doi.org/10.52526/25792776-22.69.2-318

et al., 2005), filter matching (e.g. Cvrcek & Radim, 2021, Schildknecht et al., 2015), or transforms (e.g. Hickson, 2018, Nir et al., 2018). These techniques, however, may vary in their accuracy, the type of objects they are optimised for or can be quite computationally expensive and/or complex.

The ideal SSA system for discovering new space debris in the modern age therefore requires a number of characteristics: i) extensive geographical coverage, ii) effective and easy installation of the optical systems, iii) optimised algorithms for both observation scheduling and image analysis, and iv) efficient and extensive storage facilities and distribution methods. These are aspects we, Tuparev AstroTech and Astro Systeme Austria, aim to address in our new SSA system currently under construction.

2. SSA Stations

2.1. Test observatory

Our SSA test observatory is located near the village of Sandl, Austria, at an altitude of 880 metres above sea level. The observatory consists of a classical dome, ASA H400 telescope on an ASA direct drive mount, a Moravian C3-61000 CMOS camera, a weather station, a Windows control computer, and Mac Mini processing computer. The ASA H400 is a 40cm Newtonian telescope, with an f2.4 focal ratio, allowing for a wide field of view. The ASA mount can slew at speeds of up to 50 degrees a second, has a pointing accuracy of a few arcseconds, and sub-arcsecond tracking accuracy, ideal for both tracking and surveying SSA objects. The CMOS camera has 61 Mexapixels, a 2.15 degree by 1.43 degree field of view, a 0.807 arcsec pixel scale, relatively low dark current and read out noise, and can take immediate subsequent exposures.

The Windows control computer uses custom ASA software to control all equipment, including mount steering and camera control, with the entire system currently being robotised to enable fully automated observations and emergency shut-down procedures. Each device at the observatory is connected to—and is in constant communication with—the central system. In scenarios where one device is broken, or factors are present which could damage the systems (e.g. high winds or rainfall), the system automatically shuts down safely. These are all features which will be integrated into the fully deployable stations.

2.2. Rapidly deployable SSA stations

As classical observatories can take many months or years to plan, build, and bring into operation, we intend to use a new, custom designed system for rapid deployment. This in-house and purpose-built SSA station will take the core capabilities of our test observatory and package them up in such a way as to minimize the construction and installation times, all while decreasing overall cost.

Figure 1. An example of the envisioned, rapidly deployable SSA stations designed and built in-house by Astro Systeme Austria.

The basis for these stations, as seen in Figure 1, will be a standard shipping container, modified to include a raised dome for the telescope. A shipping container allows for easy transport worldwide, and cuts out the lengthy process of building the base, walls, and dome on-site. These shipping containers will contain 0.4 to 1 metre-class ASA telescopes and mounts, Moravian CMOS cameras, and control and analysis computers.

On delivery to the sites, these stations will allow easy connection to power and internet, and once calibrated over a few days, should be fully automated and ready to be integrated into our SSA network.

3. Software

3.1. Observation scheduling

We intend to observe the night sky in strips, starting near the zenith and moving down as close the meridian as possible, with plans to move to an optimized, Artificial Intelligence-driven system in later stages. Each vertical strip on the sky is split into 1.43 degree segments, resulting in 28 fields per strip, each of which is the subject to 10 consecutive, 1 second exposures. This strategy captures and samples Low Earth Orbit objects, which move up to a degree per second, while also sampling geostationary objects, moving at ~ 15 arcsec per second, across the field of view. In order to maximise our observing time, we take a set of 10 bias and 10 flat-field images to construct the master frames during astronomical twilight, with observations conducted during astronomical night.

As aforementioned, we are also implementing a constraint satisfaction algorithm using artificial intelligence techniques to optimise the schedules in real-time, which will take factors into consideration such as distance of the next observation field from the zenith, moon, and previous field of observation as well as any partial-sky cloud coverage to optimise the schedule. Future versions of our scheduler will also include the ability to temporarily interrupt the observations if a tracking request for a specific object is made.

3.2. Image calibration and streak detection

Once the raw exposure files are delivered to the Mac Mini for analysis, we apply bias and flat-field corrections to each of the 10 images, producing 10 calibrated science-quality images. The 10 science images are then median-stacked to produce an "average" image of the field, which we subtract from each science image to remove background objects, such as stars or galaxies. An example of this process can be seen in Figure 2.

Figure 2. Left hand panel: One of 10 raw, consecutive images of the same field taken by the 40cm Sandl telescope and CMOS camera. This image has a satellite streak in the right hand of the image. Centre panel: The median stacked science image from the 10 raw images. Right hand panel: The summed stack of the 10 calibrated and median-subtracted science images. This removes all background stars and galaxies, leaving the streak prominently in the right hand side of the image.

The subtracted images are then summed together to increase the length and signal of any streaks present (Figure 2, right-hand panel). We then calculate the background noise via sigma clipping, mask pixels below a S/N level of 3σ (with plans to go lower in later stages), and perform a Hough transform. We find any peaks in the radius and angle (Hough) phase space, and extract the likelihood of a streak, as can be seen in Figure 3. The radius and angle values of any probable streaks are then used as a secondary mask on the science images, before applying a clustering algorithm to detect and assign any pixels belonging to the streak. From the movement of the streak across the multiple images, we can determine the position and direction of the object. This can be used to generate the TDMs and will be fed into orbital models planned for future stages of our SSA system.

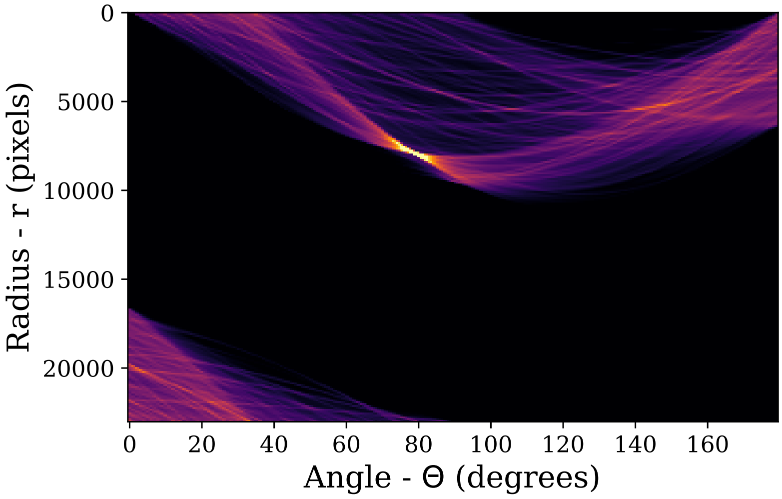

Figure 3. A heat map of the signal in radius/angle phase space (also known as "Hough space"), as run on the pure streak image (Figure 2, right hand panel). We see a definite peak at an angle of ~ 70 degrees and at ~ 7000 pixels away from the origin.

3.3. Data Transfer and Archive

After the streak extraction process is complete, the data products yielded are 10 science quality frames bundled in a 10 extension FITS file, and TDMs generated if a streak is detected. These are saved to monitored folders on the observatory's computer, and are then automatically added to a queue to be uploaded to the central server. If an upload is already taking place, the file will only be uploaded when all previously saved sequences have been uploaded. Since the file sizes are rather large, the science images will be generated faster than they can be uploaded, so the upload process will be continuous.

We expect an uncompressed image to take up around 250 megabytes storage space, with each of the FITS files containing 10 science quality images to be around 2.5 gigabytes. We expect a single observatory to be able to observe around 3000 individual fields per night, which results in approximately 7.5 terabytes of data collected per observatory, per night. We therefore expect observations by 20 observatories at this rate to produce upwards of 40 petabytes of data per year. Taking into account redundancy (an absolute necessity in such data systems), up to 100 petabytes of storage are expected to be necessary. This is currently in the initial design stages and will be created over the coming years, with increasing storage capacity as stations are integrated into our SSA system.

4. Data Products

We intend to have a number of data products from our system, each of which is outlined below. Some products will be delivered via push delivery, whereby clients will automatically receive urgent data rapidly, and other data products will be available for clients to request from the central data archive in pull requests.

4.1. Tracking Data Messages

The main data product of our system will be information on the positions of satellites or space debris at known times. This information will be formatted as what is known as a Tracking Data Message (TDM), and will be available in both push and pull systems. These TDMs will be available in both of the standard XML and KVN formats, and they will conform to the standards set out by the Consultative Committee for Space Data Systems, known as the CCSDS[1], which is commonly implemented by both governmental and commercial organisations.

TDMs contain both metadata and data sections. Metadata will include all mandatory information such as the SSA station information, coordinate and time frames and values, and information linking TDMs back to the original set of images. The data section of TDMs will include the Right Ascension, Declination and

---

[1] https://public.ccsds.org/default.aspx

doi:https://doi.org/10.52526/25792776-22.69.2-318

time values attained from our streak finding algorithms. Additionally, we intend to extract the calibrated photometry of any detected objects to provide light curves, which can then be utilised by clients to determine characteristics of the observed objects. At later stages, we intend to offer a library of light curves of known objects within our solar system.

4.2. Science Quality Images

All calibrated images will be stored on the central server, available to be pulled from the system, so that clients may run their own measurements. These images will be stored in standard FITS format, containing a top level primary HDU with information such as a unique field identifier and the number of streaks found in the images, and 10 image HDUs, one for each of the calibrated exposures of the given field. Additionally, if any streaks are found in a field, a binary table extension will be added to the FITS file that contains the unique identifiers of each of the TDMs associated with these streaks. All median stacked images of each field will also be stored on the server in a separate science server. We initially expect to make the images available for approximately 3 months before deletion, though this may increase with time and demand.

5. Scientific Potential

A data set with the size and scope as that which will be produced by our SSA system has a significant scientific potential. The all-sky coverage, homogeneity of the network, and regularity of observations are all advantageous for two particular areas: Long-term photometric catalogues and all-sky imaging.

By identifying stars and galaxies within our median stacked science images of each field of observation, we can measure the fluxes of thousands to millions of objects per night. Long-term photometric measurements can be useful for investigating astronomical objects such as variable stars and certain types of galaxies. As there is no funding time frame on this project, we have the potential to make measurements over multiple decades, which are especially suited to discovering new "changing-look" Active Galactic Nuclei (see e.g. Ross et al., 2018, Wolf et al., 2020), or previously undiscovered longer-term variable stars (see e.g. Holl et al., 2018).

We intend to take all of the median stacked images delivered to the central SSA storage server, transfer these to a science server, and continually co-add the images on top of each other (taking into account PSF effects, sky background, systematic inhomogeneities etc.). This technique has been utilised in a number of scientific surveys in recent years (e.g. Aihara et al., 2022, York et al., 2000), and can maximise the depth probed by imaging. All-sky images will then be available as in the current state (with variable depths due to different levels of stacking across the sky), or as periodically released all-sky mosaics at specific depth levels. These images could be used for characterisation of low surface brightness features (Duc et al., 2015), galaxy structure studies (e.g. Rich et al., 2017) or discovering new, faint galaxies (e.g. Greene et al., 2022).

6. Summary

In these conference proceedings, we (Tuparev Astrotech and Astro Systeme Austria) have presented an overview of our planned SSA system for tracking and characterising satellites and space debris. Our SSA system will consist of 20 to 30 custom-built stations which will be deployed worldwide over the coming decade, covering a greater geographical and celestial area than currently available commercial systems. The hardware and software systems are currently being developed and tested, with rapidly-deployable stations expected by late 2023. We aim to make our entire system fully autonomous, with automatic observation scheduling and real-time, on-site calibration, detection and extraction of satellite and space debris. The data produced from our systems will include science quality images, tracking data messages and, at later stages, orbital estimations and light curves for satellites and space debris. These data will be sent and stored on a newly-designed central data archive capable of storing multiple petabytes, and the data will be delivered either through push or pull systems according to the needs of individual clients. Altogether, we expect this system to be step above anything that has been created before, both by other private companies and by world governments, and we hope that our efforts here help to set a new standard in the world of space situational awareness for decades to come.

References

Aihara H., et al., 2022, Publ. Astron. Soc. Jpn. , 74, 247

Apa R., Bonaccorsi S., Piravano L., Armellin R., 2021, in 8th European Conference on Space Debris. https://conference.sdo.esoc.esa.int/proceedings/sdc8/paper/14/SDC8-paper14.pdf

Cvrcek V., Radim S., 2021, in 8th European Conference on Space Debris. https://conference.sdo.esoc.esa.int/proceedings/sdc8/paper/80/SDC8-paper80.pdf

Duc P.-A., et al., 2015, Mon. Not. R. Astron. Soc. , 446, 120

ESA 2021, in ESA'S Annual Space Environment Report. p. 120, https://www.sdo.esoc.esa.int/environment_report/Space_Environment_Report_latest.pdf

Greene J. E., et al., 2022, Astrophys. J. , 933, 150

Hickson P., 2018, Advances in Space Research, 62, 3078

Holl B., et al., 2018, Astron. Astrophys. , 618, A30

Jilete B., Mancas A., Flohrer T., Krag H., 2019, in Revista Mexicana de Astronomia y Astrofisica Conference Series. pp 139–143

Kessler D. J., Cour-Palais B. G., 1978, J. Geophys. Res. , 83, 2637

Murray J., Kennedy T., Miller R., Matney M., 2021, in 8th European Conference on Space Debris. https://conference.sdo.esoc.esa.int/proceedings/sdc8/paper/169/SDC8-paper169.pdf

Nir G., Zackay B., Ofek E. O., 2018, Astron. J. , 156, 229

Park J., Yim H., Choi Y., Hyun J., Moon H., Park Y., Bae Y., Park S., 2017, in 7th European Conference on Space Debris. https://conference.sdo.esoc.esa.int/proceedings/sdc7/paper/535

Rich R. M., et al., 2017, in Gil de Paz A., Knapen J. H., Lee J. C., eds, Vol. 321, Formation and Evolution of Galaxy Outskirts. pp 186–189 (arXiv:1610.02775), doi:10.1017/S1743921316011881

Ross N. P., et al., 2018, Mon. Not. R. Astron. Soc. , 480, 4468

Schildknecht T., Schild K., Vannanti A., 2015, in Advanced Maui Optical and Space Surveillance Technologies Conference. p. 36

Steindorfer M. A., Kirchner G., Koidl F., Wang P., Antón A., Fernández Sánchez J., Merz K., 2017, Advances in Space Research, 60, 1201

Steindorfer M., Wang P., Kirchner G., Koidl F., 2021, in 8th European Conference on Space Debris. https://conference.sdo.esoc.esa.int/proceedings/sdc8/paper/127/SDC8-paper127.pdf

Virtanen J., et al., 2016, Advances in Space Research, 57, 1607

Wagner G., Schramm F., Riede W., Dekorsy T., Döberl E., Weinzinger D., 2021, in 8th European Conference on Space Debris. https://conference.sdo.esoc.esa.int/proceedings/sdc8/paper/79/SDC8-paper79.pdf

Wainscoat R. J., Weryk R., 2019, in 2019 IEEE Aerospace Conference. pp 1–8, doi:10.1109/AERO.2019.8742102

Watson E., Durr N., Schimmerohn M., 2021, in 8th European Conference on Space Debris. https://conference.sdo.esoc.esa.int/proceedings/sdc8/paper/115/SDC8-paper115.pdf

Wolf C., Golding J., Hon W. J., Onken C. A., 2020, Mon. Not. R. Astron. Soc. , 499, 1005

Woods D., Shah R., Johnson J., Szabo A., Pearce E., Lambour R., Faccenda W., 2012, in Ryan S., ed., Advanced Maui Optical and Space Surveillance Technologies Conference. p. 29

Yanagisawa T., Nakajima A., Kimura T., 2005, Science and Technology Series, 109, 29

York D. G., et al., 2000, Astron. J. , 120, 1579

Zhang C., Ping Y., Zhao C., 2018, in Ryan S., ed., The Advanced Maui Optical and Space Surveillance Technologies Conference. p. 17