A status update on Southern Hemisphere Meteoroid Measurements with SAAMER

Diego Janches(1), Juan Sebastian Bruzzone(1,2), Jose Luis Hormaechea(3,4), Robert Weryk(5), Peter Gural(6), Mark Matney(7), Joseph Minow(8), William J. Cooke(9), Robert Robinson(2)

(1) ITM Physics Laboratory, NASA Goddard Space Flight Center, Code 675, 8800 Greenbelt Rd, Greenbelt MD, 20771 USA, diego.janches@nasa.gov
(2) Department of Physics, Catholic University of America, 620 Michigan Ave., N.E. Washington, DC 20064, USA, juan.s.bruzzone@nasa.gov; Robert.m.robinson@nasa.gov
(3) Facultad de Ciencias Astronómicas y Geofísicas, Universidad Nacional de La Plata, Argentina
(4)Estacion Astronomica Rio Grande, Rio Grande, Tierra del Fuego, Argentina; jlhormaechea@gmail.com
(5) Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu HI 96822, USA, weryk@hawaii.edu
(6) Gural Software and Analysis LLC, 351 Samantha Drive, Sterling, Virginia USA 20164, pgural@gmail.com
(7) NASA Johnson Space Center, Mail Code XI5-9E, 2101 NASA Parkway, Houston, TX 77058, USA, mark.matney-1@nasa.gov

(8) NASA Engineering and Safety Center, Marshall Space Flight Center, Huntsville, AL 35812, joseph.minow@nasa.gov
(9) Meteoroid Environments Office, EV44, NASA Marshall Space Flight Center Huntsville, AL 35812, William.j.cook@nasa.gov

ABSTRACT

Hypervelocity meteoroid impacts are a risk to spacecraft operations. Mitigation of the meteoroid impact risk can be accomplished by implementing spacecraft designs that minimize the threat to critical systems, operational changes to the spacecraft orientation during mission operations, or a combination of both. Knowledge of the meteoroid threat in terms of mass-dependent flux (both rate and direction) is required in order to best implement the mitigation strategies. NASA's Meteoroid Environment Office (MEO) assesses the risk posed to space assets by naturally occurring meteoroids, either from the sporadic background or meteors showers. Historically, most models used are based on monitoring the meteoroid environment in the Northern Hemisphere and only partially the Southern Hemisphere, leaving some potential threats without means to be catalogued. To address this gap, an effort to upgrade an existing radar facility in Southern Argentina is underway in order to develop the needed capability to provide the required data from the Southern Hemisphere.

1 INTRODUCTION

The majority of the incoming meteoroid flux originating from the Zodiacal Dust Cloud (ZDC) is in the mass range of 10^{-11} to 10^{-4} g and enters the atmosphere at speeds between 11 and 72 km.s^{-1} [1,2,3,4,5,6]. The highly energetic collisions with air molecules cause the meteoroids to heat and ablate, releasing both neutral and ionized atoms from the meteoroid. These phenomena associated with a meteoroid impacting a planetary atmosphere are collectively termed a meteor and are typically observable by an assorted class of ground-based radars [7,8]. In particular, all-sky VHF meteor radars detect mainly "underdense" specular meteor trails, which are generally semi-stationary plasma columns of lower electron line density left in the wake of the meteoroid's trajectory [9]. The advantage of using such systems is that they are generally dedicated to meteor observations and over time are capable of collecting large data sets of meteoroid statistics covering various conditions, namely the seasonal and diurnal changes to the Earth's orientation and location in space, as well as to monitor for meteor shower activity and detect outbursts that can present potential danger to spacecraft [10,11].

Over the past 50 years, three meteor radar systems were used for detailed orbital surveys of both the Sporadic Meteor Complex (SMC) and from shower activity: 1) the Harvard Radio Meteor Project (HRMP; 12,13); 2) the Advanced Meteor Orbit Radar (AMOR) operated in Christchurch, New Zealand (14,15); and 3) the Canadian Meteor Orbit Radar (CMOR) in Ontario, Canada [16,17,18]. Of these, only CMOR is currently operational. The HRMP observations provided about 2×10^4 meteoroid orbits from 1968-1969 and have been used as the basis for many existing near-Earth meteoroid stream searches [19] and environment models [20]. A much larger study was conducted by AMOR, which observed approximately 5×10^5 orbits over the course of five years from 1995-1999 [14,15]. Additionally, AMOR was the only southern hemisphere radar dedicated to orbital studies, and although the radar is no longer operational, it provided the only orbital data set in this region of the sky until very recently. The still-operational CMOR system has recorded over 15 million individual meteoroid orbits for particles with mean mass near 10^{-7} kg from 2002 to date (P. Brown, personal communication, 2019) and each day ~4000-5000 orbits are added.

Meteoroids impacting spacecraft are a quantifiable risk as they can puncture pressurized volumes (i.e. space station modules, propellant tanks) or destroy components (i.e. engines, electronics). Understanding the meteoroid environment enables spacecraft designers to better protect critical components on spacecraft or avoid critical operations such as extravehicular activities during periods of higher flux such as meteor showers. Yet, no comprehensive radar meteor shower surveys in the Southern Hemisphere (SH) exists. This is crucial because unlike optical techniques, radar observations are not limited by daylight and weather observing conditions. Since 2012, the Southern Argentina Agile MEteor Radar - Orbital System (SAAMER-OS) is the latest meteor radar conducting continuous meteor orbital observations in the SH made possible by some initial system upgrades performed in August 2010. This paper describes the history of the system, the current status and future plans.

2 BACKGROUND

SAAMER-OS is hosted by the Estacion Astronómica Rio Grande (EARG), located in Rio Grande, Tierra del Fuego, Argentina. It currently consists of five distinct radar stations: the central station (SAAMER-C; 53.786º S, 67.751º W) that hosts the transmitting and interferometry-enabled receiving antenna arrays; SAAMER-N (53.682º S, 67.871º W) located approximately 13 km northwest of the central station; SAAMER-W (53.828º S, 67.842º W) located approximately 7 km southwest of the central station; SAAMER-S (53.852º S, 67.76º W) located approximately 7 km south of the central station; and SAAMER-E (53.772º S, 67.727º W) located approximately 4 km northeast of the central station (Figure 1). The radar transmits at 32.55 MHz at a peak power of 64 KW and currently uses a pulse repetition frequency of 625 Hz,

Fig. 1 SAAMER-OS operates at ideal geographical location to survey the southern sky.

SAAMER-OS has been built in stages over a decade leveraging resources from several funding programs. SAAMER-C has been in operation since May 2008 funded initially through a National Science Foundation (NSF) Aeronomy award for mesospheric dynamic studies [21]. The first two remote stations, SAAMER-N and SAAMER-W, were deployed in August 2010, funded through an NSF Astronomy award with the purpose of making SAAMER an orbit determination system [22]. When a meteor is detected at SAAMER-C, the location (i.e. range, azimuth, and zenith angle) of the specular reflection point on the meteor trail is determined using the interferometric receiving array [23.24]. In order to obtain orbits, the meteor has to also be detected, via forward scattering, by at least two receivers operating at some distance from the radar. The meteoroid absolute velocity is obtained by triangulation from the time differences of the detection at the various receivers [16,22,25,26]. SAAMER-S was deployed in January 2017 supported by the NASA Solar System Observations (SSO) program with the purpose to 1) increase the statistics in our orbital data sets; 2) increase the accuracy of the orbits for those events detected simultaneously by the three remote and the central sites and; 3) to provide contingency since at least three simultaneous detections are required and the system would stop data collection when one of the remote sites experiences technical problems.

Because these stations are in semi-remote areas, they cannot always be immediately accessed and restarted. Thus, by having a third remote receiving station, SAAMER can continue collecting data, even during those times. These objectives were met as can be observed in Figure 2. The number of orbits for the years before SAAMER-S was operational totaled 1,271,530 for a 5-year period during which a lot of gaps in the data are present. The number of determined orbits during the 2.5 years since SAAMER-S begun operation reached 4,738,730 as of the end of April 2019, with practically no data gaps. The most important result of the addition of SAAMER-S is that SAAMER-OS became a reliable system that could provide meteoroid orbital data continuously.

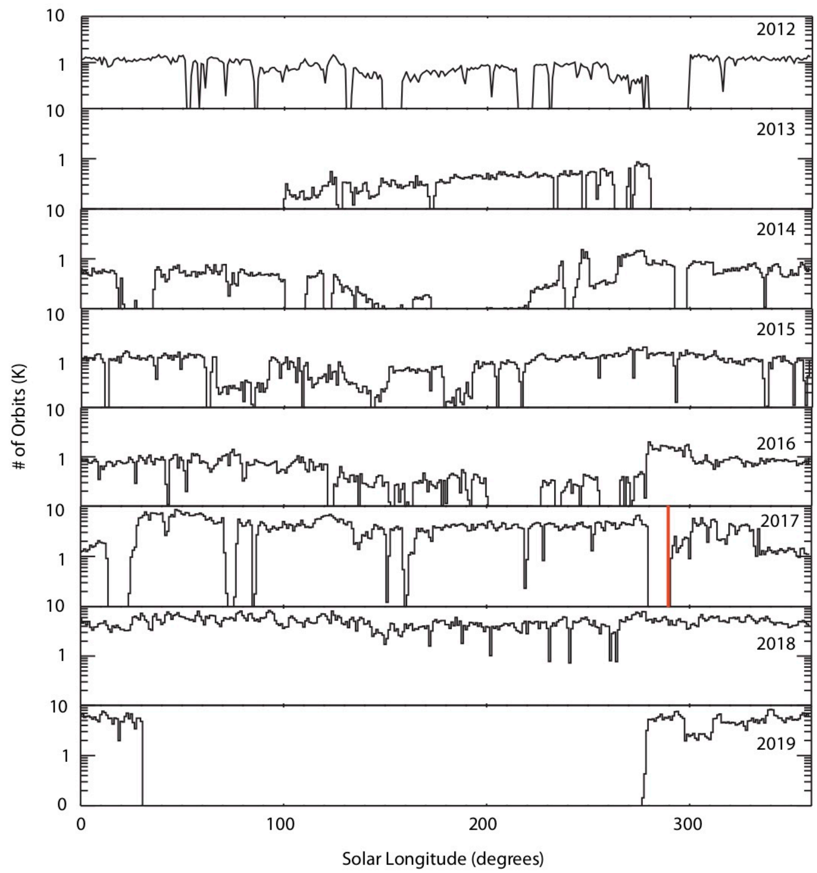

Fig. 2. SAAMER-OS orbital statistics. The red line in the 2017 panel indicates when SAAMER-S become operational. Almost no gaps have been present in the data since then and the counts increased by almost an order of magnitude. January 1st of any year corresponds to solar longitude ~280^0.

Finally, SAAMER-E, which has been cost-shared through the SSO program and an assessment funded through the NASA Engineering Safety Center (NESC) started operations in late June 2019 (See Section 3). This station not only increases our daily statistics but more importantly, it enables more accurately constrained orbital solutions among the events detected by all the stations. Key technical details of SAAMER can be found in [21] and [22].

The distribution of the observed meteoroid radiants by SAAMER-OS is shown in Figure 3, which represent the directions in the sky from where the meteoroid arrived at the Earth [27]. The radiants are displayed in ecliptic coordinates in which they are viewed from an Earth-centered frame of reference. That is, the radiants are plotted as a function of λ-λ_0, where λ is the ecliptic longitude and λ_0 is the true longitude of the Sun, effectively removing the motion of the Earth relative to the Sun, allowing the display of the position of each source fixed in ecliptic coordinates throughout the year (e.g. the Earth's apex is always at λ-$\lambda_0 = 270^o$). For reference, the locations of the six sporadic meteoroid apparent sources are also represented as ellipses in the figure [28]. These are the North and South Apex (N/SA), cause by long period comets [3,4]; the North and South Toroidal (N/ST), produced by particles originating from Halley Type comets [4] and; the Helion (H) and Antihelion (AH) caused by meteoroids originating from Jupiter Family comets [1,2].

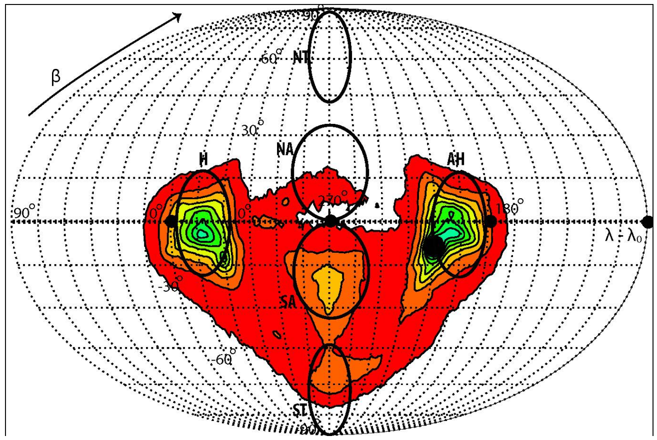

Fig. 3. SAAMER-OS enables the meteor survey of the southern hemisphere. This figure is oriented such that the center point corresponds to the Earth's Apex direction (β=0°, λ-λ_0=270°) and the Sun (β=0°, λ-λ_0=0°) is to the left of the Apex.

Contributions from the sporadic apparent sources to the radiant distribution observed by SAAMER-OS are evident in Figure 3, as well as two strong meteor showers, which appear as dense concentrated enhancements in the radiant distribution [29.30]: the Southern δ-Aquariids (SDA), a strong enhancement within the AH source; and the η-Aquariids shower (ETA), a weaker enhancement to the left of the NA. As expected, the majority of meteors observed by SAAMER-OS originate from radiant locations south of the ecliptic (i.e. the ecliptic latitude is negative), with particularly strong contributions from the SA, ST, H and AH sources, making it an ideal instrument to survey the mostly uncharted southern sky meteor showers.

3 SAAMER-OS AS A PATROL RADAR

NASA's MEO was established by the NASA Headquarters Office of Safety and Mission Assurance (OSMA) in October of 2004 as the organization responsible for meteoroid environments pertaining to spacecraft engineering and operations. The MEO's main objective is to characterize the meteoroid environment for spacecraft traveling in and beyond Earth's orbit, with its primary functions being: 1) Lead NASA technical work on the meteoroid environment; coordinate the existing meteoroid expertise at NASA centers; 2) Provide design, operational determination, and review assistance for NASA programs/projects with respect to risk mitigation; 3) Develop, maintain, and distribute a more accurate sporadic meteoroid model; and 4) Provide meteor shower forecasts to NASA spacecraft operators. Currently, MEO's mission is heavily supported by observations utilizing CMOR [17,18] together with a comprehensive suite of optical observations in the Northern Hemisphere (NH). There is almost a total lack of observations from the SH, in particular for the sub-milligram mass range commonly detected by radars. This gap in measurements of SH meteor activity effectively makes MEO "partially blind" to the particle populations impacting the Earth and represents a gap in MEO's knowledge that needs to be filled. An NESC assessment is underway to address this gap. Specifically, the assessment aims to

- Upgrade SAAMER-OS facility to provide the required data from the SH in support to MEO's mission leveraging from the existing infrastructure supported by other programs and agencies.
- Conduct a meteoroid survey in the SH, in particular during the period of the expected 2019 outburst of the Beta Taurid Meteor shower
- Deploy optical cameras sensitive enough to detect simultaneous events with the radar to compliment monitoring facilities in the NH and ultimately provide the required meteoroid fluxes and mass indices in the mass range pertinent to the MEO's mission.

The specific upgrades to SAAMER-OS required in order to fulfill the assessment's goals include: 1) hardware and software augmentations to produce a data pipeline with the accuracy required to address MEO's current observational requirements; 2) two years of continuous optical/radar meteor observations to obtain the appropriate statistics, in particular during expected outbursts from known meteor showers, for which SAAMER-OS is uniquely positioned given its geographical location; and 3) observations in conjunction with CMOR to cross calibrate the observations and produce meteoroid fluxes of both sporadic and shower meteors across the entire sky. Previous to this assessment, SAAMER's limited meteoroid orbital capabilities provided large amounts of low precision meteor data. Nevertheless, SAAMER-OS observations have resulted in the discovery and/or confirmation of approximately 30 newly-identified showers in the Southern Hemisphere (Figure 4; [30]).

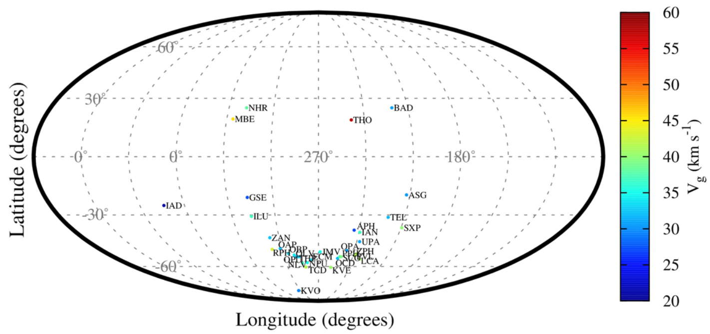

Fig. 4. Radiants of 30 newly-identified meteor showers detected by SAAMER-OS supported with data collected up to 2015 (from [30]). Note that on this map the coordinate are Sun-centered.

The continual survey of meteor showers is necessary due to the cyclic annual strength in the activity of showers. Weaker and/or minor streams require multi-year observations in order to obtain sufficient statistics to be observed above the sporadic background. Continual observations also enable the identification of expected and/or unexpected outbursts. Figure 5 shows a clear example of this, where the results of the wavelet analysis to SAAMER-OS data show the presence of the newly discovered Volantids outburst, a high southern ecliptic shower that was active only during 2015 New Year's Eve according to both optical and radar measurements [30,31,32].

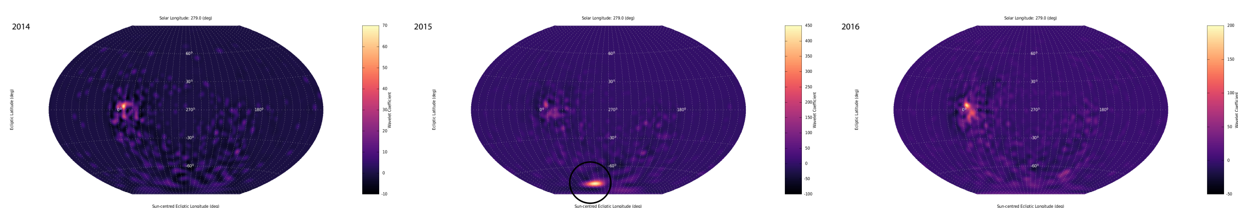

Fig.5. Results of the wavelet analysis for three consecutive years showing the strong Volantids outburst detected by SAAMER-OS during 2015's New Year's eve.

Unfortunately, the system is not calibrated to determine absolute fluxes and therefore shower mass indexes could not be provided, a crucial quantity in improving spacecraft meteor shower forecasts and spacecraft risk assessments. Our current efforts are aimed at augmenting SAAMER-OS capabilities in order to provide MEO with a comprehensive and mass calibrated survey of meteor orbital populations in the Southern Hemisphere, including observations from both sporadic and showers populations.

4 INITIAL RESULTS

To collect the appropriate continuous statistics, three specific upgrades have been implemented to SAAMER-OS. The first upgrade involves the deployment of a single new transmit (TX) antenna to detect meteors at higher zenith angles. The goal of this upgrade is to improve the detection rate, by up to a factor of 10. Since the original design of SAAMER was optimized to perform gravity wave studies, this required the detection of meteors between zenith angles of 15° and 55° (Figure 6a; [21,33]). For this, the original TX configuration is composed of eight three-element crossed yagis in a circle of diameter 27.6 m having opposite phasing of every other yagi (normal mode) designed to maximize the detection of meteors at those zenith angles. The phases can be changed for specific observation campaigns such as the detection of meteor head-echoes [34]. By concentrating the full power of SAAMER in a single (new) TX antenna, a more uniform detection pattern is achieved (Figure 6b) satisfying the original requirement but also increasing the number of events detected at larger zenith angles (Figure 6c)

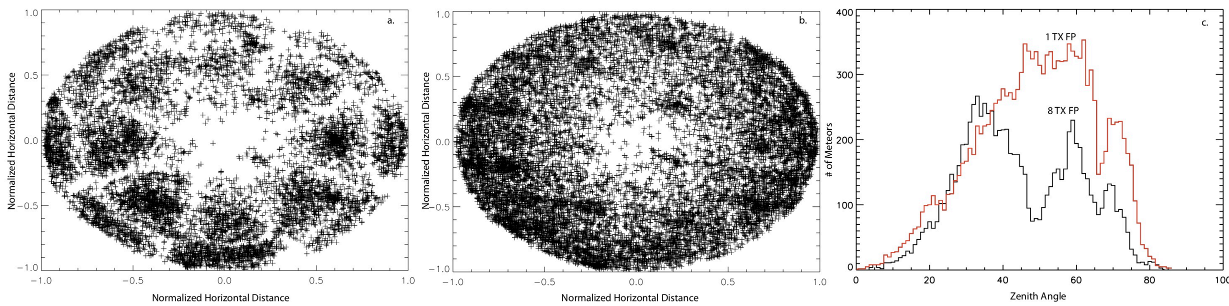

Figure 6. a) Meteor distribution using the original 8 TX antenna configuration, b) Meteor distribution with the new high-power single antenna transmitter, c) number of meteors detected per zenith distance for both transmitting antenna configuration.The data shown in these figure were collected over a 24-hr period.

The second critical upgrade entailed the optimization of the receive signal path of the existing remote receiving stations and modification of the data processing software to recognize “overdense” meteors (produced by larger and more energetic meteoroid particles), which will also improve meteor detection rates (currently only the lower-returned power “underdense” meteor echoes are detected because these events are used to estimate mesospheric wind speeds [21]). The software upgrade was achieved by implementing detection and orbital determination software that runs parallel to the standard software of the SKiYMET meteor radar systems [23]. Specifically, echoes are detected in a multi-stage process. After determining the appropriate noise thresholds for a given streamed ``dump.raw" file, the first stage identifies candidate echoes which exceed the background noise level by some set level (for SAAMER-OS, the limit is 6.0 σ). Once all echoes are found, they are analyzed by a second stage which determines the interferometry solution, the decay constant, measures the time inflection pick (corresponding to when the meteoroid reaches the specular point), and saves a record of each echo to disk. The interferometry solution, determined from the five-receiver channel typical of these systems [21,23], defines a plane which must contain the meteor trail. As well, the inflection points from all available remote receiving stations (minimum three, including the main site) are used to define a vertical plane which also contains the echo [26]. The intersection of these two planes defines the meteor trajectory, which allows for a direct measure of its state vector (ie: position and velocity at a given time; Figure 7). This is transformed into the standard keplerian elements.

Daily meteor shower reports are also currently being provided to NASA MEO and NESC (green circles in Figure 7). To search and identify showers we employ a 3D wavelet transform analysis to isolate and characterize our daily detections. This method was first applied by AMOR to identify shower structure in radar data [25,35]. This methodology has since been applied to other radar meteor surveys [17,18,30,37]. The wavelet transform is well suited to isolate radiant enhancements at various scales in the radiant coordinates and time. Meteors belonging to a specific shower naturally cluster in the radiant coordinate-speed and time domain over a characteristic scale: spread in radiant coordinates, speed and activity period. Such grouping of radiants contrast with the large-scale radiant distribution of the sparse sporadic background. Therefore, a given meteor radiant distribution can be probed with the wavelet transform to reveal enhancements at different scales. As with previous radar studies, we employ the 3D Mexican hat wavelet transform over a radiant distribution and geocentric speed.

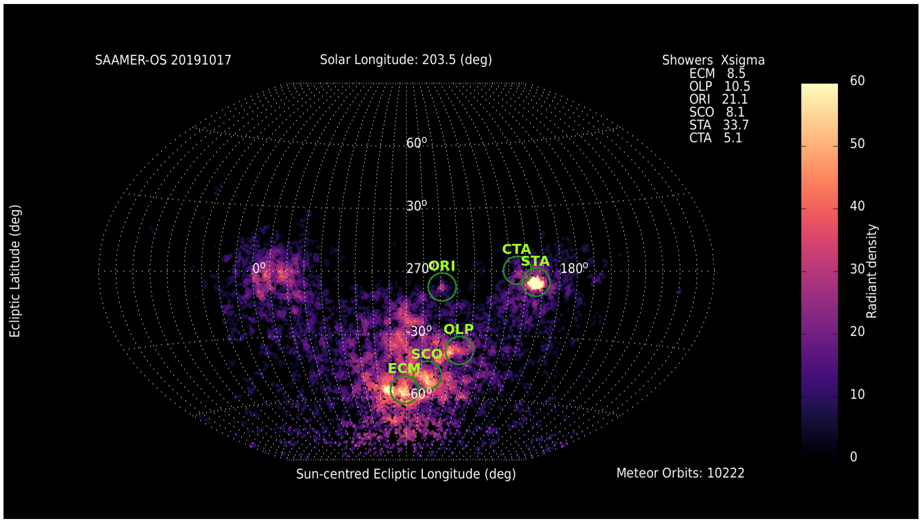

Figure 7. Sun-centered meteoroid radiants detected by the upgraded SAAMER-OS on October 17th, 2019. During this day up to 10000 orbits were recorded. On average the daily detected orbital counts varies between 6000 to 10000 as it is sensitive to changes in the daily noise environment. The green circles identify known shower radiants present in the data.

The width of the Gaussian kernel can be adjusted accordingly to resemble the true spread in angular coordinates and speed of the radiant distribution. The computation of the wavelet is achieved in Sun-centered ecliptic coordinates: λ-λ_0 and β, in degrees, and geocentric speed (V_g) in km.s^{-1} and binned by one degree in solar longitude. By choosing this reference frame, we remove the natural motion of the sun while minimizing the radiant drift with time. For our daily shower search, the wavelet is evaluated at 0.5^0 steps in spatial coordinates and 10 % steps in V_g while advancing at 1^0 steps in λ_0. This procedure returns a list of wavelet coefficients from which a yearly median and standard deviation is computed, and a 3σ rejection is applied to remove outliers. For those wavelet coefficients greater than 3σ maximum is stored and a list of wavelet maxima created. We proceed to identify a shower core radiant candidate as the radiant producing the wavelet coefficient global maxima. With the candidate shower core location identified, we cross reference it against a published list of meteor showers [30]. When the location of the candidate shower is within 3^0 and 15 % in geocentric speed of a known shower, the radiant position is labeled with the shower IAU code in the radiant map (Figure 7). We are currently adding a step that will identify new showers not listed in [30], and also flagging potential outbursts.

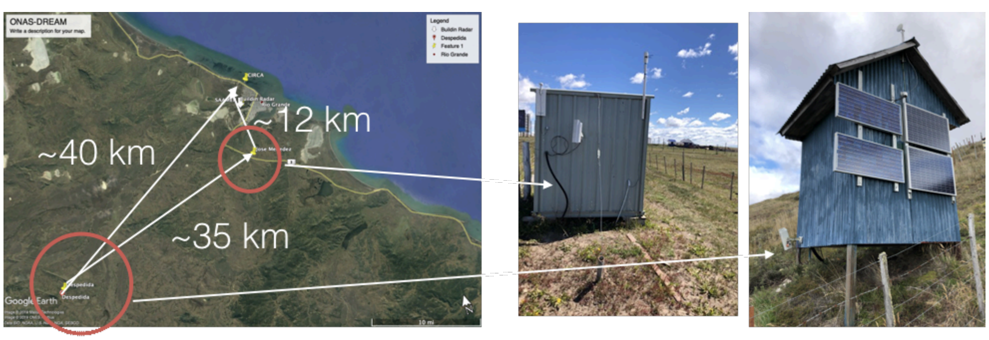

Figure 8. (left) Location of each of the cameras of ONAS-DREAM. (middle and right) pictures of the camera set up.

Finally, we have recently deployed a set of three narrow-field (16 x 21 degrees) video cameras to perform simultaneous radar and optical meteor observations. These will provide absolute mass fluxes and mass indices to the MEO, enable cross calibration with CMOR, as well as provide additional daily sporadic and shower meteor monitoring as weather conditions allow. The Optical Network At SAAMER for Detection of Radar Echoes Arising from Meteors (ONAS-DREAM) is composed of three MEO-provided Watec WAT-902H2 Ultimate cameras, equipped with a 17mm f/0.95 lens and arrayed around the SAAMER site as shown in Figure 8. The left panel of the figure shows where the cameras are deployed relative to the SAAMER transmitter with camera separations ranging from 12 to 40 kilometers. They are nominally pointed at the zenith point above the SAAMER transmitter. ONAS-DREAM's primary purpose is to overlap the main radar beam when SAAMER is operated in head echo mode [34]. However, it also captures optical meteors and provides orbits even when the radar is collecting in normal mode, albeit the optical system is in a less efficient mode due to the low zenith angle pointing of the cameras than if the cameras were pointed down in altitude angle. The optical network is sensitive to faint meteors brighter than $m_v = 7$ and detects ~10 orbits/day (Figure 9).

The integrated end-to-end image processing software for the optical system uses the standard CAMS suite of modules and applications [38]. Each site consists of a single camera deployment and thus utilizes an EzCap dongle for capturing and digitizing the NTSC video stream. The dongle then feeds the raw imagery to memory via a USB port on an Intel NUC i5 brick PC. The CAMS software provides frame capture, compression and video record archival, astrometric calibration fitting via cubic warp, photometric calibration, multi-site aggregation of tracks, and finally atmospheric trajectory and orbit estimation. One of the sites, Despidida, is extremely remote and off the electrical grid, and has been successfully outfitted with both solar and wind power charging of deep cycle batteries. When the sun does not shine, the wind blows incessantly in southern Argentina, and combining the two charging systems has made for reliable continuous operations.

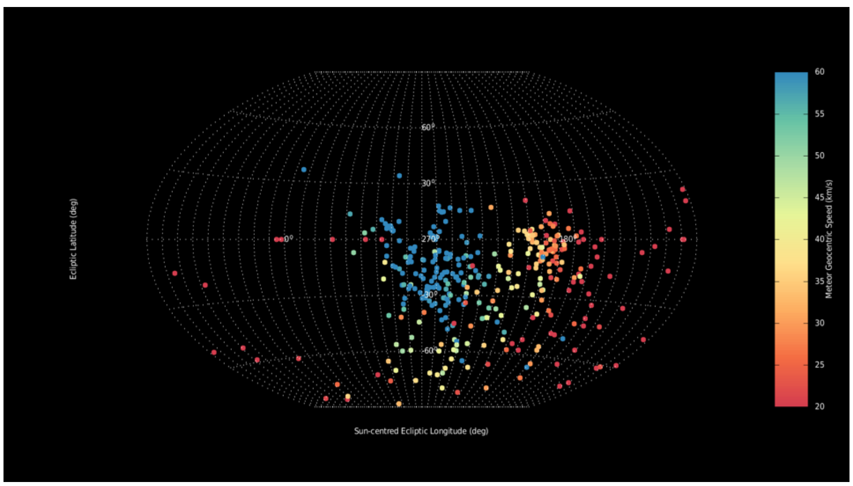

Figure 9. Sun-centered meteor radiants detected with ONAS-DREAM between February 1st and June 28th, 2019.

5 CONCLUSION

SAAMER-OS has been operational since May 2008, recording ~10 to 20 K meteor events daily. The system is ideal for the study of ST and SA sources and meteor showers in the Southern Hemisphere. To date, 30 new showers have been identified referenced elsewhere [30]. A new high-power TX antenna and a fourth remote receiving station were deployed and have been operational since October 2019. New software that utilizes "overdense" and "underdense" echoes and determines orbits using all remote sites simultaneously has been implemented, and is also currently operational. These upgrades result in the determination of ~6 to 10K independent daily orbits. In addition, wavelet software for daily shower searching has been developed, implemented, and is also operational. A data pipeline to provide reports to MEO is in progress. Currently, shower reports are sent daily, and measured speeds are are corrected for deceleration using the methodology of [39]. Daily orbital datasets are available upon request. We are currently developing a methodology to perform flux calculations, identify new showers, and monitoring for outbursts.

ACKNOWLEDGMENTS

D.J.'s work is supported by the NASA SSO Program and the NASA NESC. SAAMER's operation is supported by NASSA SSO, NESC assessment TI-17-01204, and NSF grant AGS-1647354. The authors appreciate the invaluable support of Carlos Ferrer, Gerardo Connon, and Luis Barbero with the operation of SAAMER.

6 REFERENCES

1. Nesvorný, D., P. Jenniskens, H. F. Levison, W. F. Bottke, D. Vokrouhlický, and M. Gounelle (2010, April). Cometary Origin of the Zodiacal Cloud and Carbonaceous Micrometeorites. Implications for Hot Debris Disks. *Ap. J.* 713, 816-836.
2. Nesvorný, D., D. Janches, D. Vokrouhlický, P. Pokorný, W. F. Bottke, and P. Jenniskens (2011a, December). Dynamical Model for the Zodiacal Cloud and Sporadic Meteors. *Ap. J.* 743, 129.
3. Nesvorný, D., D. Vokrouhlický, P. Pokorný, and D. Janches (2011b, December). Dynamics of Dust Particles Released from Oort Cloud Comets and Their Contribution to Radar Meteors. *Ap. J.* 743, 37
4. Pokorný, P., D. Vokrouhlický, D. Nesvorný, M. Campbell-Brown, and P. Brown (2014, July). Dynamical Model for the Toroidal Sporadic Meteors. *Ap. J.* 789, 25.
5. Carrillo-Sánchez, J. D., D. Nesvorný, P. Pokorný, D. Janches, and J. M. C. Plane (2016), Sources of cosmic dust in the Earth's atmosphere, *Geophys. Res. Lett.*, 43, 11,979–11,986, doi:10.1002/ 2016GL071697.
6. Swarnalingam, N., D. Janches, J. D. Carrillo-Sanchez, P. Pokorný, J. M. C. Plane, Z. Sternovsky, and D. Nesvorný (2019, May). Modeling the Altitude Distribution of Meteor Head Echoes Observed with HPLA Radars: Implications for the Radar Detectability of Meteoroid Populations. *A. J.* 157, 179.
7. Janches, D., M. C. Nolan, D. D. Meisel, J. D. Mathews, Q. H. Zhou, and D. E. Moser, On the geocentric micrometeor velocity distribution, *J. Geophys. Res.,* 108(A6), 1222, doi:10.1029/2002JA009789, 2003.
8. Janches, D., J. Swarnalingam, N. Carrillo-Sanchez, R. Gomez-Martin, J.C. Marshall, D. Nesvorný, J. M. C. Plane, and W. Feng (2017, July). Radar Detectability Studies of Slow and Small Zodiacal Dust Cloud Particles: III. The Role of Sodium and the Head Echo Size on the Probability of Detection. *Ap. J.* 843, 11.
9. Baggaley, W. J.: Radar observations, in: *Meteors in the Earth's Atmosphere*, Cambridge Univ. Press, 123–148, 2002.
10. Campbell-Brown, M. and P. Wiegert (2009, January). Seasonal variations in the north toroidal sporadic meteor source. *Meteoritics and Planetary Science* 44, 1837-1848.
11. Younger, P.T., I. Astin, D. J. Sandford, and N. J. Mitchel (2009). The sporadic radiant and distribution of meteors in the atmosphere as observed by VHF radar at Arctic, Antarctic and equatorial latitudes, *Ann. Geophys.*, 27, 2831–2841.
12. Brown, P. and Jones, J.: A determination of the strength of the sporadic radio meteor sources, *Earth, Moon Planets*, 68, 223–245,1995.
13. Taylor, A. D. and Elford, W. G.: Meteoroid orbital element distributions at 1AU deduced from the Harvard Radio Meteor Project, *Earth Planets Space*, 50, 569–575, 1998
14. Galligan, D. P. and Baggaley, W. J.: The orbital distribution of radar-detected meteors of the solar system dust cloud, *Mon. Not. R. Astron. Soc.*, 353, 422–449, 2004.
15. Galligan, D. P. and Baggaley, W. J.: The radiant distribution of AMOR radar meteors, *Mon. Not. R. Astron. Soc.*, 359, 551–560,2005
16. Webster, A. R., P. G. Brown, J. Jones, K. J. Ellis, and M. Campbell-Brown (2004). Canadian Meteor Orbit Radar (CMOR). *Atmospheric Chemistry & Physics Discussions* 4, 1181- 1201.
17. Brown, P., R. J. Weryk, D. K. Wong, and J. Jones (2008, June). The Canadian Meteor Orbit Radar Meteor Stream Catalogue. *Earth Moon and Planets* 102, 209-219.
18. Brown, P., D. K. Wong, R. J. Weryk, and P. Wiegert (2010, May). A meteoroid stream survey using the Canadian Meteor Orbit Radar. II: Identification of minor showers using a 3D wavelet transform. *Icarus* 207, 66-81.
19. Sekanina, Z. (1973). Statistical Model of Meteor Streams. III. Stream Search Among 19303 Radio Meteors. *Icarus* 18, 253.
20. Drolshagen, G., Dikarev, V., Landgraf, M., Krag, H., Kuiper, W. (2008). Comparison of Meteoroid Flux Models for Near Earth Space. *Earth Moon and Planets* 102, 191.
21. Fritts, D. C., D. Janches, H. Iimura, W. K. Hocking, N. J. Mitchell, R. G. Stockwell, B. Fuller, B. Vandepeer, J. Hormaechea, C. Brunini, and H. Levato (2010, September). Southern Argentina Agile Meteor Radar: System design and initial measurements of large-scale winds and tides. *Journal of Geophysical Research (Atmospheres)* 115, 18112.
22. Janches, D., S. Close, J. L. Hormaechea, N. Swarnalingam, A. Murphy, D. O'Connor, B. Vandepeer, B. Fuller, D. C. Fritts, and C. Brunini (2015, August). The Southern Argentina Agile MEteor Radar Orbital System (SAAMER-OS): An Initial Sporadic Meteoroid Orbital Survey in the Southern Sky. *Ap. J.* 809, 36.
23. Hocking, W. K., B. Fuller, and B. Vandepeer (2001). Real-time determination of meteorrelated parameters utilizing modern digital technology. *J. Atmos. Solar Terr. Phys* 63, 155-169.

24. Lau, E. M., S. K. Avery, J. P. Avery, D. Janches, S. E. Palo, R. Schafer, and N. A. Makarov (2006, July). Statistical characterization of the meteor trail distribution at the South Pole as seen by a VHF interferometric meteor radar. *Radio Science* 41, 4007-+.
25. Baggaley, W., R. Bennett, D. Steel, and A. Taylor (1994). The advance meteor orbit radar facility: Amor. Q. J. R. *Astr. Soc.* (35), 293-320.
26. Jones, J., P. Brown, K. J. Ellis, A. R. Webster, M. Campbell-Brown, Z. Krzemenski, and R. J. Weryk (2005, April). The Canadian Meteor Orbit Radar: system overview and preliminary results. *Planet Sp. Sci*. 53, 413-421.
27. Jones, J. and P. Brown (1993, December). Sporadic meteor radiant distribution: Orbital survey results. *Mon. Not. R. Astron. Soc.* 265, 524-532.
28. Fentzke, J. T. and D. Janches (2008). A semi-empirical model of the contribution from sporadic meteoroid sources on the meteor input function observed at arecibo. *Journal of Geophysical Research (Space Physics)* 113 (A03304).
29. Janches, D., J. L. Hormaechea, C. Brunini, W. Hocking, and D. C. Fritts (2013, April). An initial meteoroid stream survey in the southern hemisphere using the Southern Argentina Agile Meteor Radar (SAAMER). *Icarus* 223, 677-683.
30. Pokorný, P., D. Janches, P. G. Brown, and J. L. Hormaechea (2017, July). An orbital meteoroid stream survey using the Southern Argentina Agile MEteor Radar (SAAMER) based on a wavelet approach. *Icarus* 290, 162-182.
31. Jenniskens, P., J. Baggaley, I. Crumpton, P. Aldous, P. S. Gural, D. Samuels, J. Albers, and R. Soja (2016, April). A surprise southern hemisphere meteor shower on New-Year's Eve 2015: the Volantids (IAU#758, VOL). WGN, Journal of the International Meteor Organization 44, 35-41.
32. Younger, J., I. Reid, and D. Murphy (2016, January). Radar observations of the Volantids meteor shower. In A. Roggemans and P. Roggemans (Eds.), *International Meteor Conference* Egmond, the Netherlands, 2-5 June 2016, pp. 352-357.
33. Fritts, D. C., D. Janches, and W. K. Hocking (2010), Southern Argentina Agile Meteor Radar: Initial assessment of gravity wave momentum fluxes, *J. Geophys. Res*., 115, D19123, doi:10.1029/2010JD013891.
34. Janches, D., W. Hocking, S. Pifko, J. L. Hormaechea, D. C. Fritts, C. Brunini, R. Michell, and M. Samara (2014). Interferometric meteor head echo observations using the Southern Argentina Agile Meteor Radar.*J. Geophys. Res. Space Physics* 119.
35. Galligan, D.P., Baggaley, W.J., 2002. Wavelet enhancement for detecting shower structure in radar meteoroid data II. Application to the AMOR data. In: Green, S.F., Williams, I.P., McDonnell, J.A.M., McBride, N. (Eds.), *IAU Colloq. 181: Dust in the Solar System and Other Planetary Systems*, 15, p. 48.
36. Bruzzone, J. S., P. Brown, R. J. Weryk, and M. D. Campbell-Brown (2015, Jan). A decadal survey of the Daytime Arietid meteor shower using the Canadian Meteor Orbit Radar. *Month Not. R. Astron*. Soc. 446 (2), 1625-1640.
37. Schult, C., Brown, P., Pokorný, P., Stober, G., Chau, J.~L. (2018). A meteoroid stream survey using meteor head echo observations from the Middle Atmosphere ALOMAR Radar System (MAARSY). *Icarus* 309, 177.
38. Jenniskens P., Gural P. S., Dynneson L., Grigsby B. J., Newman K. E., Borden M., Koop M., Holman D. (2011). CAMS: Cameras for Allsky Meteor Surveillance to establish minor meteor showers". Icarus, 216, 40–61.
39. Brown, P., Jones, J., Weryk, R.~J., Campbell-Brown, M.~D. (2004). The Velocity Distribution of Meteoroids at the Earth as Measured by the Canadian Meteor Orbit Radar (CMOR). *Earth Moon and Planets* 95, 617.