Enhanced Standard Data Format for Reporting Electro-Optical Data Products for Space Domain Awareness

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ABSTRACT

With the increase in the number of Electro-Optical (EO) sensors collecting photometric, radiometric, and spectroscopic data on man-made Resident Space Objects (RSOs) for Space Domain Awareness (SDA) purposes, the EO SDA community of interest and stakeholders in SDA required a file format protocol for reporting the extracted information used for SSA from these datasets. In 2014, the major stakeholders in SDA EO products, collected their requirements and developed a sensor-independent file format standard to meet current and evolving needs to ingest EO datasets and produce timely and responsive analysis products. This file format for EO data products is called Electro-Optical Space Situational Awareness (EOSSA).

There are various sensors producing photometric data products of various types from various missions. As such, a format needs to be consistent, contain required information archiving the data pedigree, capture observing conditions, and yet remains flexible. For example, a space-based sensor might have data products from different collection modes: 1) multiple photometric brightness measurements extracted from metric tracklets; 2) minutes-long, high-temporally-sampled photometry measurements; and 3) multispectral measurements. However, a ground-based sensor might collect only a few photometric measurements in its metric mode. Other operational sensors, contributing sensors, and non-traditional sensors collect differently as well; therefore, the EO observations vary both in size and type depending on the sensor and/or collection mode. Thus, a standardized and extensible format is required to handle the variability. The EOSSA format was developed to accommodate all of these varieties and more. With a standardized format that includes all the relevant information on RSO collections, such as time, sensor location, target location, and calibrations, as well as the EO measurements themselves, automated analysis tools can be more readily developed and tested for RSO characterization with reduced cost.

In 2014, the EOSSA file specification format was published in the AMOS conference proceedings as a resource for the SDA community. Recently, the EOSSA File Format Description Document (FFDD) was revised and enhanced using feedback received from the EO data providers and data users, and from the authors' own experience using the FFDD for six years. The modifications to EOSSA will be presented and the new file description document will be available to the community.

We will present Release 4 of the FFDD for EOSSA version 3.1.1 that includes updated descriptions to increase clarity and correct typographical errors and an updated EOSSA example. Several sections were added in this release to help the data providers: standardization of the order of reporting spectral filters, notes column to the tables, an appendix with equations to calculate various angles, an appendix that describes how to generate EOSSA files of simulated EO data, and an appendix describing how to generate EOSSA files of LWIR radiometry data with and without images. Adding images or thumbnails of focal plane data is elementary because EOSSA utilizes the NASA FITS format. Data providers can find the public release version of EOSSA Release 4 FFDD on the AMOS conference website.

1. INTRODUCTION

There are various sensors producing photometric data products of various types from various purposes. As such, a format that is consistent, contains a pedigree of the data reduction and calibration processes, captures the in-situ observing conditions, and yet remains flexible, is required. For example, a space-based sensor might have data products from different collection modes: 1) six photometric brightness measurements extracted from metric tracklets; 2) minutes-long, high-temporally-sampled photometry measurements; and 3) color photometry measurements. However, a ground-based sensor might collect only three photometric measurements in its metric mode. Other operational sensors, contributing sensors, and non-traditional sensors collect metrics differently as well as may produce different photometric products and in different spectral regions. Therefore, the electro-optical (EO) data products vary both in size and type depending on the sensor and/or collection mode and a standardized and extensible format must be able to handle the variability. The EOSSA format was developed to accommodate all of these varieties including imagery. With a standardized format that includes all the relevant information on Resident Space Objects (RSO) collections, such as time, sensor location, target location, and calibrations, as well as the EO measurements themselves, automated analysis tools can be developed more efficiently and tested for RSO characterization with reduced cost.

The EOSSA version 3.1.1 document provides a foundation to enable data providers to format their processed data into EOSSA. The objective of this format is to handle a variety of photometric measurements from multiple sensors and provide standardized fields for specific parameters containing crucial data about the object, the sensor, the collection, and the processing. These parameters are essential for applying the EO phenomenology to identify and classify RSOs, detect and resolve anomalies, and detect and track RSO status changes.

2. BACKGROUND

The chosen format, Flexible Image Transport System (FITS), is maintained by the International Astronomical Union and NASA/GSFC [1]. FITS is the standard data format used in astronomy and has extensions and features that make it easy to transport and archive large scientific data sets. There are types of FITS files for multi-dimensional arrays, such as images or hyperspectral image cubes, tables for data extracted from the images, tables for spectroscopy, and headers for descriptive information about the data and sensor. The FITS binary table extension is the most efficient data structure to use for our purposes, both with respect to ease of programming, computational speed, and storage space [1]. The EOSSA format has two required parts. The first is the FITS primary header. The second part is the FITS binary table extension. The binary table extension itself has two sections. The first section is the binary table header. The second is the binary data table. Additional binary table extensions can be appended to the file but are not required per se.

The Hierarchical Data Format (HDF) has many of these features (e.g., HDF5). However, its biggest drawback for our purpose is that the files are large and require a lot of storage space. Secondly, no standardized HDF file structure has been developed or is supported by a U.S. government entity. Finally, there is no high-level Application Programming Interface (API). Therefore, the FITS standard was chosen to use as the basis of an EO data format for Space Situational Awareness (SSA) for the Space Domain Awareness (SDA) community.

EOSSA is a considerable leap in the formatting of SSA data and can, at first glance, be overwhelming. Therefore, it is important to appreciate the necessity of the request for all of the additional information along with the extracted radiometry. Many factors contribute to the extraction process, including events during the collection itself, condition of the sensor system, calibration data, calibration procedures, and the measurement of the pertinent illumination angles and observation angles along with their errors. After all, the true quest is to have information intrinsic to the RSO itself, and without knowledge of the other parameters that affect that information, it is a difficult if not impossible task to obtain the intrinsic features of interest.

One major problem with some formats is the lack of descriptive information about the extracted radiometry/photometry. Besides target and sensor identifiers and location information provided in these formats, information on the calibrations, measurement uncertainties, version number of the processing code, and other metadata are needed for in-depth analysis to be performed with the brightness data, metrics data, or other measured information. The archiving of such details is also important in establishing RSO patterns of life.

In order to understand what the brightness information is telling us, the ability to rapidly decide if the data is bad or unreliable is required. Without information on how the data was processed, the only recourse is to repeat the observations. With the fields in EOSSA populated, we will more easily know for example, if the data was saturated, the uncertainties are large, or some other anomaly is present. If none of these problems exist, repeating observations an inefficient use of the sensor and wastes valuable time. EOSSA allows us to make an informed decision on how to request data from a sensor for complementary data or for smarter follow-on tasking.

The extracted radiometry/photometry is a measure of the observed flux from the RSO. However, the goal is to achieve the intrinsic flux from the RSO. The role of reductions and calibrations is to perform this transformation. The observed flux is a function of the intrinsic flux as it is transmitted through the Earth's atmosphere, the efficiency and spectral response of the telescope-detector system (including filters), noise inherent in the detector and its electronics, and other factors pertaining to how the measurement is performed. Space-based sensors can eliminate the need to remove the effects of transmission through the atmosphere but not the other factors.

In addition, all these factors are a function of time as atmospheric conditions change and telescope-detector systems degrade. In practice, the optical system must be calibrated by measuring its response to a source whose absolute energy output is known with accuracy and precision. This process and the conversion from detected flux to standard exo-atmospheric magnitude is summarized in the EOSSA File Format Description Document (FFDD). With the production of well-calibrated data from any sensor, based either in space or on the ground, magnitudes or other radiometric quantities from this system can be compared with respect to one another. This allows for multi-sensor data fusion, trending patterns of life, and facilitates object characterization and change detection with the goal of increasing our confidence in the knowledge of RSO health and status.

3. EOSSA VERSION 3.1.1 RELEASE 4 IMPROVEMENTS

In the FFDD, there is a short description of FITS. We have also previously published a paper about EOSSA [2]. For complete and thorough documentation one should visit http://fits/gsfc.nasa.gov. There is the FITS standard document and a user's guide.

Release 4 contains all the information that is in Release 3. We have collected feedback from various data providers over the intervening years along with our own usage of the FFDD and have made various corrections and removed seeming inconsistencies to the existing documentation, and elaborated on keywords or table columns that have puzzled the data providers. We have addressed readability by moving several sections originally in the main body of the document to appendices, specifically, "Required Keywords for Ground-based Sensors" and "Required Keywords for Space-based Sensors". We also updated the text version of EOSSA that serves as an example file in an appendix.

New material that is in Release 4 covers several areas that can be found in new appendices of the FFDD.

3.1 SIMULATED OBSERVATIONS

First, we describe how to report simulated radiometry in an EOSSA file. The EOSSA format is intended to include all information relevant to EO observations collected for the purposes of SDA. While such relevant information has been identified and incorporated into the EOSSA format for real data, simulated data poses other problems. There are numerous simulation software programs that may be used to produce simulated observations. Different simulation programs will have widely varying parameters, and there is no realistic way to provide a suitable list of keywords ahead of time that are applicable for any and all simulated data. However, capturing simulated data in EOSSA necessitates keywords be added to the binary table extension header in order to document the simulation parameters used.

The additional keywords should reflect the relevant simulation parameters used to generate the data and the version of the simulation code that was used. Just as the standard EOSSA fields for real data track pertinent information, keywords for the simulated data should track any and all of the important settings or files used to create the simulated data. A single simulation parameter can have significant effects on the results, so a user studying the data later may need to know the values of the relevant parameters that were used to generate the data. For example, there may be two sets of simulated data for a single target on a single night but generated using different target configuration parameters. Without tracking the configuration parameters of the target model that affect the simulation results, the data sets may conflict with each other with no distinguishable cause as there is an unknown difference in how the simulations were generated. Logging all relevant simulation parameters also allows for the reproducibility of the data. Using the same simulation software with the parameters specified in the EOSSA file should produce identical results. The standard for modeling simulated data in EOSSA is that the simulations used to generate the data be well-documented and reproducible. This allows for the data to be more meaningful and adds to its usefulness. An example of how simulated data should be reported in EOSSA is included in Release 4. This example outlines the standards and considerations for using the EOSSA format to capture simulated data.

3.2 ANGLES GOVERNING REFLECTANCE FUNCTIONS AND PROJECTED AREA

Second, we provide definitions of the various angles that have been found to be useful when analyzing RSO brightness variations. These angles have been reported in various articles published in the past by a variety of authors too numerous to mention. In this appendix of Release 4, the pertinent information that is needed to compute these angles, all of which is available in a valid EOSSA file, is described along with the reference frames. The assumptions such as right-handed coordinate system are presented as well. While there are various mathematical formalisms to calculate angles, we present the vector calculus method. The angles defined and shown how to calculate are: solar phase angle, longitudinal phase angle, latitudinal phase angle, orbit angle, and the solar phase angle bisector vector. If a data provider would choose to include these angles as optional table columns, the nomenclature for these columns and their recommended position in the binary table are included.

3.3 LONG-WAVE INFRARED (LWIR) RADIOMETRY AND IMAGERY

Release 4 FFDD contains the keywords and binary table columns for reporting multi-filter LWIR radiometry. Similar to the visible regime of the electromagnetic spectrum, LWIR radiometric measurements can be collected on RSOs in any orbit regime. Objects that are large enough and/or close enough for the telescope-sensor system can be imaged in any regime of the electromagnetic spectrum. This new appendix provides the unique EOSSA keywords and formatting for reporting LWIR measurements when the RSO is spatially unresolved, e.g., an object in Deep Space (DS), and when the object is spatially resolved. The unresolved case is treated separately; however, data on resolved objects regardless of orbit regime are also formatted using these keywords. These keywords may be sensor-specific but the data provider should be able to infer what corresponding value they should report. We describe the EOSSA keywords unique to LWIR. We also describe how to include a sequence of resolved imagery in an EOSSA file. Due to the nature of an image sequence, keywords are defined to describe the parameters of the images.

When a data provider wants to include images in the EOSSA file (a 2 x 2 array), another Header Data Unit (HDU) is created that contains a header and an image or an image cube (2 x 2 x n array of n images). We include a list of the image header keywords. Multiple images can be appended to an EOSSA file either as an image cube with the same header or separate HDUs with unique headers for each image. The image sizes do not all have to be the same in any dimension. If a sensor has multiple focal planes, the images from each should be identified by a keyword in the header. These images could be simultaneous or sequential with time tags regardless. The mechanics of how to include images is presented in the same appendix with the instructions for LWIR but can be generalized to visible or near IR images but changing the relative keywords. Note that any images can be part of an EOSSA file, raw, reduced, and processed by image reconstruction software.

3.4 ORDER OF SPECTRAL FILTER NAMES

Release 3 of EOSSA did not explicitly describe conventions for reporting multi-spectral filter data. We began addressing standardization in reporting filter data in Release 4. Radiometry (and its special case, photometry) through different spectral filters is collected in order to derive color indices of an RSO. A color index is the difference between the brightness magnitudes of two spectral filters, e.g., B-V, in the photometric system of Johnson-Cousins. It can be shown that the color index is equivalent to the ratio of fluxes for the two spectral filters. Color indices are created according to a convention, the spectral filter with a shorter wavelength minus the spectral filter with a longer wavelength. This convention implies a color index that is less than zero is bluer, i.e., there is more flux in the shorter wavelength filter than the longer wavelength filter. While a color index greater than zero is redder, i.e., there is more flux in the longer wavelength filter than the shorter wavelength filter. In order to follow this convention and be consistent in the creation of a color index, the spectral filters need to be reported in order of increasing wavelength.

The 'SPFNAMn' keyword is required to be listed in order of increasing wavelength of the filter. In general, if there were four spectral filters (SPFNUM = 4), then 'SFPNAM1' is the filter with the shortest wavelength, 'SPFNAM2' is the filter with the second shortest wavelength, 'SFPNAM3' is the filter with the third shortest wavelength, and finally 'SPFNAM4' is the filter with the longest wavelength.

As an example, an EOSSA file that collected data using four Johnsons-Cousins filters (B, V, R, and I) would contain:

- SPFNAM1 = ‘B’
- SPFNAM2 = ‘V’
- SPFNAM3 = ‘R’
- SPFNAM4 = ‘I’

The ‘B’ filter has the shortest wavelength, the ‘V’ filter the second shortest wavelength, the ‘R’ filter has the third shortest wavelength, and the ‘I’ filter has the longest wavelength.

4. FUTURE ENHANCEMENTS

Work has already begun on Release 5. A complete standardization of reporting spectral filter radiometry/photometry in a given photometric system was not accomplished in Release 4. Work is continuing to incorporate the standard astronomical filter naming conventions in addition to how to report SSA filters and a standard way of reporting “open” filter data, i.e., when there is no filter in the telescope-sensor-detector system, and thus that system acts as a unique “filter”.

Another phenomenology for which standardization is needed is spectroscopy. We are working with spectrometry experts to develop a robust binary table structure to accommodate the unique aspects of spectroscopy and to capture its processing and calibration pedigree. Plans for Release 5 include EOSSA standardization of both these important topics.

5. CONCLUSIONS

We have improved upon the EOSSA version 3.1.1 file format description document in Release 4. These improvements include corrections, additional descriptions and notes, reorganization. The improvements also include new appendices with instructions on how to report in EOSSA format simulated data, LWIR radiometry and imagery, and standardization of the reported order of spectral filters. Additional improvements will be made in the future for standardization of spectral filter names and spectroscopy. Data providers can find the public release version of EOSSA Release 4 FFDD in the conference proceedings of AMOS 2021.

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REFERENCES

[1] W. D. Pence, L. Chiappetti, C. G. Page, R. A. Shaw and E. Stoble, "Definition of the Flexible Image Transport System (FITS), version 3.0," *Astronomy & Astrophysics,* vol. A42, p. 524, 2010.

[2] T. E. Payne, S. Mutschler, N. Shine, D. Meiser, R. Crespo, E. Beecher and L. Schmitt, "A Community Format for Electro-optical Space Situational Awareness (EOSSA) Data Products," in *AMOS Conference,* Wailea, 2014.