Electro-Optical Space Situational Awareness (EOSSA)

File Format Description Document

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Release 4

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Revision History

Version	Date	Revision Description
1.0	March 02, 2012	First version of SOI data format
1.1	April 13, 2012	Minor corrections and additional information
2.0	May 30, 2012	Major additions based on MIT/LL suggestions
2.1	September 25, 2012	Minor corrections to keywords and descriptions
2.1.1	October 02, 2012	Minor corrections to keywords and descriptions
2.3	October 22, 2012	New tables for keywords
2.3.1	November 19, 2012	Minor corrections to keywords and descriptions
2.3.1	March 27, 2013	Change in distribution statement
3.0	August 16, 2013	Major revision of document layout. More extensive background and more detailed descriptions.
3.1	December 11, 2013	Minor revisions to descriptions and keyword changes. Additions based on feedback from AF community. Changed some required fields in Data table to optional.
3.1.1	February 18, 2014	Minor revisions to descriptions and keywords.
3.1.1	April 10, 2014	Minor additions and changes to descriptions, keyword names and data column names for additional clarity.
3.1.1	April 10, 2014	Added keywords and data columns for differential photometry
3.1.1	April 10, 2014	Specified fields for astrometry as keywords and data columns
3.1.1	April 10, 2014	Moved some fields from header to data table to provide flexibility
3.1.1	July 22, 2014	Updated Appendix G
3.1.1	July 22, 2014	New descriptions of OBJTYPE, OBJNUM, and OBJECT fields in the Binary Table Extension Header Keywords Tables.
3.1.1	December 17, 2014	Updated the binary data table field, Tel_State_Vec, to be required for space-based sensors with sensor state vector (S/S). Removed this field from Table 9- EOSSA Optional Data Columns – In Prioritized Order.
3.1.1	December 17, 2014	Updated the binary table header fields, SPFNUM & SPFNAMn, to be required for All. Removed these fields from Table 8- EOSSA Binary Table Header Optional Keywords Prioritized.
3.1.1	May 15, 2015	Corrected call out to SPFSMGn in Appendix C. Added statement to Appendix E for clarity.
3.1.1	June 25, 2019	• Updated descriptions to increase clarity and correct mistakes • Added standardization of the order of reporting spectral filters • Added notes columns to tables • Updated EOSSA example • Added appendix to provide equations to calculate various angles • Added appendix describing how to generate EOSSA files of simulated EO data • Added appendix describing how to generate EOSSA files of LWIR radiometry data with and without images.

3.1.1	April 20, 2020	• Appendix F mistakes corrected.
3.1.1	January 10, 2021	• Double precision floating point (8 bits) default value was clarified to be -9999.0
3.1.1	March 12, 2021	• Added definition of UCT • Added clarification that the CLASSIF keyword should be present in both the primary FITS header and the binary table extension header • Moved specialty tables to appendices: Required Keywords for Ground-based Sensors and Required Keywords for Space-based Sensors
3.1.1	May 13, 2021	• Prepared Distribution A version of Release 4 document

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1.0 Introduction

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 Situational Awareness (SSA) purposes, the EO SSA community of interest and stakeholders in Space Domain Awareness (SDA) require a file format protocol for reporting the extracted information used for SDA from these datasets. This file format for EO SSA data products is thusly named EOSSA.

This description document briefly summarizes the development of the EOSSA file format in the remainder of this section. In Section 2.0, relevant background material is discussed with particular emphasis on why the information in EOSSA is needed and a brief primer on Flexible Image Transport System (FITS) formats. Section 3.0 describes the EOSSA file format in detail starting with additions to Version 3.1.1 since the Release 3 documentation (see the Revision History table for changes, updates, and modifications). Here each parameter in the header and the table are described. The parameters are presented separately for ground-based and space-based sensors in additional tables found in the Appendices in this new release. Section 4.0 provides guidance for the data provider on how to prepare their data into EOSSA data products.

1.1 Purpose

There are various telescope systems producing photometric data products of various types. As such, a format that is consistent, contains required information for processing pedigree, captures observing conditions, and yet is flexible is required. These telescope systems can collect data differently at different spectral regimes and at difference cadences. Therefore, the EO data products can vary both in size and type depending on the sensor and/or collection mode. A standardized and extensible format must be able to handle this variability. The EOSSA format has been developed to accommodate any of these varieties.

1.2 Objective

This 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 fields for specific parameters containing crucial data about the object, the sensor, the collection, and the processing. These parameters are essential for understanding RSO phenomenology.

1.3 Choice of FITS Binary Table Extension Format

The chosen format, 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, and headers and tables for data extracted from the images, and 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. This extension has two sections. The first section is the binary table header. The second is the binary data table. Top-level details of FITS are presented in Section 2.4. The details of EOSSA are discussed in Section 3.0.

A hierarchical data format (HDF5) has many of these features. However, its biggest drawback to our purpose is that the files are large and require a lot of storage space. Secondly, no standardized HDF5 file structure has been developed, and there is no high-level Application Programming Interface (API). Therefore, the FITS standard is used.

2.0 Background

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.

In Sections 2.1–2.3, some of the most critical, yet controversial data fields in EOSSA are discussed. Section 2.4 provides the necessary background on the FITS formats to understand how to build an EOSSA file.

2.1 Importance of Metadata to Exploitation of EO Data for SSA

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

2.2 Importance of Data Pedigree

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 collection. With the fields in EOSSA populated, one can more easily know if the data was saturated, the uncertainties are large, or some other anomaly is present. If none of these problems exist, new collections will be an inefficient use of the sensor and waste valuable time. EOSSA allows one to make an informed decision on how to schedule new collections for complementary data and execute smarter follow-on tasking.

2.3 Importance of Calibrations

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 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 described in Appendix A. With the collection 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, historical trending of data, and facilitates RSO characterization and change detection with higher confidence results more quickly.

2.4 Short Description of FITS

A FITS block is a sequence of 2880 bytes aligned on 2880-byte boundaries in the FITS file; blocks are most commonly either a header block or a data block. Each FITS structure consists of an integral number of FITS blocks. A FITS file is composed of a primary Header and Data Unit (HDU), which is a required feature of every FITS file. The primary HDU starts with the first FITS block of the FITS file.

A FITS file may also contain conforming extensions and other special records, both of which are optional (an EOSSA file must contain a BINTABLE extension). A FITS file containing one or more extensions following the primary HDU is sometimes referred to as a Multi-Extension FITS (MEF) file. The first FITS block of each subsequent FITS structure should be the FITS block immediately following the last FITS block of the preceding FITS structure. For example, in an EOSSA file, the first FITS block of the BINTABLE extension FITS structure is the FITS block immediately following the FITS block containing the primary HDU [1]. For longer descriptions and for help to data providers, reference the following links to the FITS Standard document and the User's Guide: http://fits.gsfc.nasa.gov/standard30/fits_standard30aa.pdf and http://fits.gsfc.nasa.gov/users_guide/usersguide.pdf. As an introduction to ESSOA, data providers can also see the conference paper published about EOSSA [2].

2.4.1 Definitions of Primary and Extension Header Keywords

The primary HDU is always the first component of a FITS file and must consist of one or more header blocks. The primary HDU's purpose is to provide information on the overall contents of the file. The required keywords of a primary HDU are SIMPLE, BITPIX, NAXIS, NAXISn, and END. The SIMPLE keyword must be the first keyword in the primary HDU. The required primary HDU keywords must appear in the order stated (SIMPLE, BITPIX, NAXIS, NAXISn) with no other intervening keywords. Other keywords may appear between NAXISn and END keywords. These keywords are listed in Table 1.

Table 1 - Primary Header Keywords

#	Keyword	Description	Example	Notes
1	SIMPLE	The value field shall contain a logical constant with the value T if the file conforms to FITS standard. This keyword is mandatory for the primary header and must not appear in extension headers. A value F signifies that the file does not conform to FITS standard.	SIMPLE = T	
2	BITPIX	The value field shall contain an integer. The absolute value is used in computing the sizes of data structures. It shall specify the number of bits that represent a data value in the associated data array. The only valid values of BITPIX are in Table 2. Writers of FITS arrays should select a BITPIX data type appropriate to the form, range of values, and accuracy of the data in the array.	BITPIX = 16	
3	NAXIS	The value field shall contain a non-negative integer no greater than 999 representing the number of axes in the associated data array. A value of zero signifies that no data follow the header in the HDU.	NAXIS = 2	
4	NAXISn, n = 1,…,NAXIS	The NAXISn keywords must be present for all values n = 1,…, NAXIS, in incrementing order of n, and for no other values of n. The value field of this indexed keyword shall contain a non-negative integer representing the number of	NAXIS1 = 250 NAXIS2 = 300	

#	Keyword	Description	Example	Notes
		elements along axis n of a data array. A value of zero for any of the NAXISn signifies that no data follow the header in the HDU. If NAXIS is equal to 0, there shall not be any NAXISn keywords.		
	Custom	Placeholder for other non-required fields within FITS file format or fields that the data provider might want to define. Such as those defined in order to create an EOSSA FITS document.	DATE = ‘2006-10-22’	
	CLASSIF	Classification level of the data contained within the file	‘UNCLASS’, ‘CONF’, ‘SECRET’, etc.	This is required for the primary header and the FITS binary table extension header.
last	END	This keyword has no associated value. Bytes 9 through 80 shall be filled with ASCII spaces. The END keyword marks the logical end of the header and must occur in the last 2880-byte FITS block of the header.	END	

Table 2 - BITPIX Values

Value	Data Represented
8	Character or unsigned binary integer
16	16-bit two’s complement binary integer
32	32-bit two’s complement binary integer
64	64-bit two’s complement binary integer
-32	IEEE single precision floating point
-64	IEEE double precision floating point

After the primary HDU, other blocks can be added to the FITS file. As mentioned before, blocks are most commonly either header or data blocks. This document discusses two types of FITS extensions: image and binary table (BINTABLE). These extensions contain both a header block and a data block, in other words, a Header Data Unit (HDU).

An important feature of the EOSSA format is the ability for both analysts and contributing sensors to define and provide additional sensor information or metadata while maintaining format compatibility without modification. A FITS file may contain multiple HDUs/extensions; in other words, a FITS file can contain both a binary table extension and an image extension or any combination of FITS extensions. For example, the user may want to include a second binary table extension in order to include a spectral bandpass table. Likewise, the user may choose to add an image extension in order to include a focal plane image within the EOSSA file. Other examples of sensor information that would be useful to provide are tables representing a sensor’s quantum efficiency and filter spectral response.

Every extension to a FITS file requires a specific set of header keywords for its header block. These header keywords are used to describe the data unit that follows the header unit. The extension header keywords required for any extension in FITS are shown in Table 3.

Table 3 - Required Keywords for Any Extension Header

#	Keyword	Description	Example	Notes
1	XTENSION	The value field shall contain a character string giving the name of the extension type. This keyword is mandatory for an extension header and must not appear in the primary header.	XTENSION=␣’BINTABLE’[1]	
2	BITPIX	Same description as Table 1.	BITPIX = 8	
3	NAXIS	Same description as Table 1.	NAXIS = 2	
4	NAXISn, n = 1,…, NAXIS	Same description as Table 1. NAXIS1 is the number of bytes in each row for a BINTABLE extension. NAXIS2 is the number of rows in data table for a BINTABLE extension.	NAXIS1 = 410 NAXIS2 = 10 (for a 10 row table)	
5	PCOUNT	The value field shall contain an integer that shall be used in any way appropriate to define the data structure, consistent with Equation (1). In IMAGE extensions, this keyword must have the value 0; in BINTABLE extensions, it is used to specify the number of bytes that follow the main data table in the supplemental data area called the heap.	PCOUNT = 0	
6	GCOUNT	The value field shall contain an integer that shall be used in any way appropriate to define the data structure, consistent with Equation (1). This keyword must have the value 1 in the IMAGE and BINTABLE extensions.	GCOUNT = 1	
	Custom	Placeholder for other non-required fields within FITS file format or fields that the data provider might want to define, such as those		

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[1] The ␣ and lower case keyword do not need to be specified by the provider. This is done by the library that aids in writing the FITS/EOSSA file. See the FITS Standard for more information on the XTENSION keyword and the formatting shown [1].

#	Keyword	Description	Example	Notes
		defined in order to create an EOSSA FITS document.		
last	END	Same description as Table 1.	END	

The total number of bits in the extension data array (exclusive of fill that is needed after the data to complete the last 2880-byte data block) is given by the following expression:

$$N_{bits} = |BITPIX| \times GCOUNT \times (PCOUNT + NAXIS1 \times NAXIS2 \times \ldots \times NAXIS_m), \quad \textbf{(1)}$$

where N_{bits} must be non-negative and is the number of bits excluding fill; m is the value of NAXIS; and BITPIX, GCOUNT, PCOUNT, and the NAXISn represent the values associated with those keywords. If $N_{bits} > 0$, then the data array should be contained in an integral number of 2880-byte FITS data blocks. The header of the next FITS extension in the file, if any, should start with the first FITS block following the data block that contains the last bit of the current extension data array [1].

2.4.2 Description of FITS Binary Table Extension

The binary table extension uses a compact binary format in order to store numerical values within a table. Each field of a binary table can contain an array of values rather than a simple scalar as in ASCII tables. The required keywords of a binary table extension are XTENSION, BITPIX, NAXIS, NAXISn, PCOUNT, GCOUNT, TFIELDS, and END. The first keyword in a binary table extension shall be XTENSION=␣'BINTABLE'.

The required binary table extension keywords must appear in the order stated (XTENSION, BITPIX, NAXIS, NAXISn, PCOUNT, GCOUNT, TFIELDS) with no other intervening keywords. Other keywords may appear between the TFIELDS and END keywords.[2] This is the same as the required keywords for any extension table (with the addition of TFIELDS following GCOUNT), as seen in Table 3. However, after the TFIELDS keyword, there must contain the keyword TTYPEn and keyword TFORMn for n=1, 2, …, k where k is the value of TFIELDS; a recommended keyword is TUNITn for n=1, 2, …, k where k is the value of TFIELDS. These two keywords are used only when TFIELDS is not equal to zero. Below, in Table 4, is an example and detailed description of the keywords beginning at TFIELDS to END specific to a binary table extension.

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[2] The additional keywords specific to the EOSSA binary table are given in Section 3.5.

Table 4 - Binary Table Extension Header Keywords

#	Keyword	Description	Example	Notes
8	TFIELDS	The value field shall contain a non-negative integer representing the number of fields (columns) in each row of the data table.	TFIELDS = 1	
9	TTYPEn	The value field of this indexed keyword shall contain a character string giving the name of field n.	TTYPE1 = UTC_Begin_Exp	
10	TFORMn	The value field of this indexed keyword shall contain a character string of the form *r*T. It describes the value which will be in the nth field/column of the data table. Reference rows 10 and 11 below for details.	TFORM1 = 27A	
11	TUNITn	The value field shall contain a character string describing the physical units in which the quantity in field n is expressed.	TUNIT1 = char	
12	Custom	Placeholder for other non-required fields within FITS file format or fields that the data provider might want to define, such as those defined in order to create an EOSSA FITS document.	(EXTNAME, CLASSIF, VERS, etc.)	
last	END			

More discussion on the TFORM keyword is warranted. The repeat count *r* is the ASCII representation of a non-negative integer specifying the number of elements in field n. The default value of *r* is 1; the repeat count need not be present if it has the default value. A zero element count, indicating an empty field is permitted. The data type T specifies the data type of the contents of field n. Only data types in Table 5 are permitted in the TABLE extension. As seen in [1], there are other forms for floating point numbers, but their maximum bit value, which is used in EOSSA as the placeholder value, is machine-dependent. This means that the numeric values will not be constant, which is required for a machine-reader to identify that the keyword has no valid value.

The format codes must be specified in uppercase. Fields of type P or Q are the TFORM for image array descriptors for 32-bit (8-bit byte) and 64-bit (16-bit byte) respectively and should be used if images are included in the EOSSA file. Table 5 lists the number of bytes each data type occupies for the corresponding TFORM. The first field of a row is numbered 1. The total number of bytes n_{row} in a table is given by:

$$n_{row} = \sum_{i=1}^{TFIELDS} r_i b_i, \tag{2}$$

where r_i is the repeat count for field *i*, b_i is the number of bytes for the data type in field *i*, and TFIELDS is the value of that keyword, which must equal the value of NAXIS1.

Table 5 – Valid TFORM Values in TABLE Extensions and Their Descriptions[3]. Note *w* is the width of the field in characters and *d* is the number of digits to the right of the decimal.

TFORMn value	Description	8-bit Bytes	Placeholder Value	Notes
A*w*	Character	1	"NULLSTRING"	
J*w*	32-bit integer	4	-2147483648 (max negative 32 bit integer)	
D*w*.*d*	Double precision floating point	8	-9999.0	
L	Logical	1	False	

The values of TTYPEn, TFORMn, and TUNITn for EOSSA files are specified in Section 3.7.

After writing the binary table extension header block to the file, the main data table block follows. The table is constructed from a two-dimensional byte array. The number of bytes in a row shall be specified by the value of the NAXIS1 keyword, and the number of rows shall be specified by the NAXIS2 keyword of the associated header. Within a row, fields shall be stored in order of increasing column number, as determined from the n of the TFORMn keywords. The number of bytes in a row and the number of rows

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[3] Complete TFORM table can be found in [1].

in the table determines the size of the byte array. Every row in the array shall have the same number of bytes. The first row hall begin at the start of the block immediately following the last header block. Subsequent rows shall begin immediately following the end of the previous row, with no intervening bytes, independent of the FITS block structure [1].

Each row in the array shall consist of a sequence from 0 to 999 fields as specified by the TFIELDS keyword. The number of elements in each field and their data type shall be specified by the TFORMn keyword in the associated header. A separate format keyword must be provided for each field. The location and format of fields shall be the same for every row. Fields may be empty, if the repeat count specified in the value of the TFORMn keyword of the header is 0. Writers of binary tables should select a format appropriate to the form, range of values, and accuracy of the data in the table. An example of a simple FITS file with a binary table extension is in Appendix B.

2.4.3 Description of FITS Image Extension

The FITS image extension is nearly identical in structure to the primary HDU and is used to store an array of data or a stack of array data. Multiple image extensions can be used to store any number of arrays in a single FITS file. A FITS IMAGE extension may contain a single image or multiple images (i.e., image cube). The first keyword in an image extension shall be XTENSION= ␣'IMAGE ␣␣␣'[4]. The keywords required in the header of an image extension are shown in Table 3.

3.0 EOSSA File Format Specifications

In this section, we introduce the details of the EOSSA file format. The first section has been added to introduce the major additions to the EOSSA specifications since the last release. Next, an overview containing general remarks is in Section 3.2. Sections 3.3 - 3.5 are about required, optional, and custom keywords. In Sections 3.6 and 3.7, respectively, the component data fields required in an EOSSA file are described. As discussed previously, the EOSSA is a FITS binary extension table, and, as such, it is a binary table extension composed of a header and a binary data table. The appropriate keywords vary somewhat on the basing of the sensor. Therefore, the keywords specific to ground-based and space-based sensors are listed in Sections Appendix K and Appendix L, respectively. Finally in Section 3.8 is a prioritized list of the optional keywords.

3.1 Additions to Format since Release 3

Since Release 3 of EOSSA v3.1.1, several useful, additional data types and metadata fields have been identified and corrections and modifications in various places as recorded in the Revision History were made. Release 4 documents these additions to share with the SSA community. There are two additional data types that are included in this release. The first is simulated data and how to format simulations into EOSSA is described in Appendix H. The second addition is Long-Wave InfraRed (LWIR) radiometry with and without images. The custom keywords developed for this data type are described in Appendix J.

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[4] More information on the XTENSION keyword can be found in the FITS Standard [1].

There are columns in the EOSSA binary table extension that refer to angles and these are expected to be generated by the data provider. Because angles are inherently ill-defined with respect to their origin, sign conventions, and range, definitions and sign conventions have been established and these angles are now defined for EOSSA data providers in Appendix I. Note that not all the angles defined in this appendix are required fields.

The special tables of keywords and data columns for ground-based sensors and space-based sensors were moved into appendices for improved clarity of Section 3.0 where the header keywords and binary table data columns for EOSSA are defined. These sections can now be found in Appendix K and Appendix L, respectively.

The final addition to Release 4 of the EOSSA File Specification Document is to standardize the order in which spectral filter data is reported. The specification of the order of the filters in the EOSSA format allows for automated analysis tools to process the spectral filter data in a meaningful way. Further work is needed to standardize the filter names of the common astronomical photometric systems and will be in a future release of this document.

3.1.1 Order of Spectral Filter Names ('SPFNAMn')

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 a photometric system, e.g., 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' is required to be listed in order of increasing wavelength[5] 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, 'SPFNAM3' is the filter with the third shortest wavelength, and finally 'SPFNAM4' is the filter with the longest wavelength.

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[5] The location of a filter in wavelength space can be determine in a variety of ways. The astronomical community uses the term 'effective wavelength' to indicate the location of the filter in wavelength space. There are several definitions of effective wavelength. See M. Fukugita, T. Ichikawa, J. E. Gunn, M. Doi, K. Shimasaku and D. P. Schneider, "The Sloan Digital Sky Survey Photometric System," *The Astronomical Journal ,* vol. 111, pp. 1748-1756, 1996. It should not be necessary to determine the position of a filter with such exacting accuracy. In general, it is often clear by-eye what the order of increasing wavelength is for a set of broad-band filters. Using an estimate of the location of a filter in wavelength space will allow the spectral filter names to be sorted according to increasing 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.

3.2 Overview

The fields presented in Table 1, Table 3, and Table 4 are the core elements of EOSSA. The sections that comprise EOSSA are the primary header (Table 1) and the binary table extension. The latter contains a HDU, and the required header keywords are found in Table 3 and Table 4. To create an EOSSA file, the keywords in Table 6 (Section 3.3) would be inserted into the positions within Table 4 labeled “Custom”. The TTYPE values shown in Table 4 are given in Table 7 (Section 3.5).

Some fields, at first glance, appear redundant, but they are not because some sensors prefer reporting the parameter one way, while other sensors prefer reporting the parameter the other way. Redundancy in the fields was chosen over having multiple file types dependent on these reporting preferences. Any fields (redundant and/or optional) that the sensor cannot provide must be filled in with the value reserved for representing an empty field. See Table 5 for the Placeholder column that contains the “default” value to use, which depends on the field type.

Similarly, if a required field cannot be filled for any reason, this field shall be filled with the value reserved for representing an empty field. See Table 5 for the appropriate value (denoted Placeholder), which depends on the field type. For example, if the “OBJECT” field in Table 6, row 24, is unable to be filled, the user shall fill the field with “NULLSTRING” because the field is of type character (‘A’ - specified under the format column).

A major advantage of using FITS is that it makes EOSSA flexible. While there are two required parts, additional parts can be added and will not break the format. For example, another binary table extension could be added that contains a spectral transmission table for filters. Another example is that an image extension (containing raw or processed image(s)) could be an additional part of the file. An example of adding images to EOSSA can be found in Appendix J.2.

3.3 Required Keywords and Data Columns

A few of the required keywords in EOSSA are required for a FITS file of any type. Other required keywords come from the required list for FITS binary table extensions. The major of required keywords come from the necessity to have 1) the ability to recreate the observation geometry for analysis purposes and 2) the ability to investigate the circumstances of the data collection for troubleshooting or to gain insight into the data analysis results. These tasks can be manual and time-intensive and if the data provider has to be contacted and their archives searched for answers, the time and cost increases even more.

3.4 Optional Keywords and Data Columns

The goal is to have all keywords in the EOSSA format populated with information. However, to be realistic, we have identified the minimum number of fields that are essential for the data provider to fill as "required." The data provider should strive to populate keywords pertaining to details of measurement errors, calibration errors, and processing details. Other keywords are for "derived" parameters used in analysis and are also listed as optional from the data provider's perspective. To aid the data provider in prioritizing their software development tasks and incrementally improve their EOSSA product, Section 3.8 contains a table with the prioritized optional keywords (Table 8). Data users who need specific derived parameters are responsible for populating the existing keywords required for their purposes or adding their own custom keywords (see Section 3.5). This will require users to not only read EOSSA files but to read, append, and write EOSSA files.

Data providers should use keywords that provide information about specific sensor settings, e.g., spectral filters, neutral density filters, etc., when they are used in the data collection even though they are not strictly required keywords. This information is critical to proper understanding and analysis of the data product, but since it does not apply in every case and is a capability that is not current present for some data providers, these types of keywords have been deemed optional.

3.4.1 Extensibility of the Binary Table Extension Header

EOSSA is flexible in that the data provider can define their own "custom" keywords to the binary table extension without breaking the format. FITS and EOSSA allow the user to define and include other keywords in the header after the required keywords. The option of custom keywords allows the user to further describe the data contained in the data unit in any way the user desires. For instance, a keyword containing the version number of the image reduction and processing software could be an additional field in the header.

3.4.2 Extensibility of Binary Table Data Columns

The user may wish to add different information to the binary data table by adding "custom" data columns to the binary table. FITS and EOSSA allows for the user to define and include further data columns after the required data columns. The option of custom data columns allows the user to provide more detailed information in the binary table in any way the user desires. Radiant intensity (Watts/sr) could be an additional data table column, for instance, which would be useful for infrared measurements.

3.5 Adding Custom Keywords and Data Columns

EOSSA has the flexibility for the data provider to add their own keywords and data columns that suit their particular data product. Release 4 documents two of those types of efforts regarding simulated data and LWIR data (see Appendix H and Appendix J).

To assist data providers in the creation of custom fields in EOSSA, the next two sections provide guidelines and best practices to keep in mind when considering adding custom fields to your EOSSA file. Section 3.5.1 is about creating header keywords and Section 3.5.2 covers creating custom data columns in the binary table (new TTYPEs).

3.5.1 Binary Table Header Keywords

- Ensure the custom keyword is not already in use as an EOSSA header keyword.
- Header keywords are always capitalized following FITS convention.
- To conform to FITS standard, use a custom keyword that has a maximum (possible) length of 8 characters.
- Use a custom keyword that abbreviates or truncates the ‘thing’ that you are trying to provide to the user. By doing this, it will be more transparent to the user what the custom keyword is providing. For example, the existing header keyword spectral filter name has the keyword ‘SPFNAM’.
    - Review the EOSSA header keywords to get a sense for this convention to ensure that your keyword is EOSSA-like.
- Provide a comment to indicate to the user what the custom field’s value represents.
    - Without this the custom keyword is of little use to others.
- Ensure the custom keyword is the appropriate length to allow for an integer number of that keyword, if appropriate, e.g. ‘SPFNAMn’.
    - If the custom keyword is associated with a filter, like that of ‘SPFNAMn’, ensure that the custom keyword is the appropriate length to leave enough characters for the integer number at the end of the string. ‘SPFNAMnn’ has two available characters after ‘SPFNAM’ within the FITS convention of 8 characters, allowing for up to 99 filters to be included in an EOSSA file. Therefore, if the custom keyword was directly associated with the filters used for collection, it would then need to be the appropriate length.
        - For example, if an EOSSA provider wanted to provide additional information regarding the filters used to collect data whose name is given in ‘SPFNAMn’, such as the effective wavelength of each filter, then they might use a custom keyword like ‘EFFWAV’. This keyword has two characters available after ‘EFFWAV’, allowing this keyword to be used for up to 99 filters, the same as the header keyword ‘SPFNAMn’.

3.5.2 Binary Table Column Fields/Keywords

- Ensure the custom keyword is not already in use as an EOSSA data table column keyword.
- Naming convention is to separate the words with underscores and abbreviate individual words in order to keep the name from becoming too long, e.g., ‘UTC_Begin_Exp’.
    - The first letter of each character string separated by an underscore begins with a capital letter.
    - All caps can be used where appropriate, such as an abbreviation, e.g., UTC and JD.
- For each data column, i.e., TTYPE, provide the TFORM and TUNIT.

3.6 EOSSA Binary Table Extension Header Keywords

In this section, the keywords used in the EOSSA binary extension table header are listed and described. In Table 6, the keywords are listed. The first column is a reference number for the keyword. The second column is the “Required” field. This column contains notations that identify if the parameter is required. The requirement is based on the type of sensor. They are:

- S/S - space-based sensor when the sensor orbital information is included as a state vector
- S/T - space-based sensor when the sensor orbital information is given in a TLE
- G - ground-based sensor
- All – keyword is required by All sensors regardless of type

The third column contains the EOSSA-user-defined keyword. The rest of the columns contain a description of what information the field should contain, the appropriate units and format, and in most cases, an example. In some cases, notes can be found in the last column. All values in the example columns are fictitious. In all, there are 56 keywords for the EOSSA binary extension table header.

Table 6 – EOSSA Binary Table Extension Header Keywords

#	Req'd.	Keyword	Description	Units	Format	Example(s)	Notes
1	All	EXTNAME	Filename of the FITS binary extension table file.		A		
2	All	CLASSIF	Security classification level of the data contained in the file.		A	'UNCLASS', 'CONF', 'SECRET', etc.	
3	All	VERS	Version number of the EOSSA data format.		A	'1.0', '2.5', '3.0', '3.1.1'	
4	All	OBSEPH	Observer type, i.e., ground-based, space-based with a TLE for the sensor, or space-based with a state vector for the sensor.		A	'GROUND', 'TLE', 'STATE'	
5		ARRAY	Name of the detector from which the radiometry was extracted.		A	'Main array', 'SOI window', 'Photometer', 'NULLSTRING', etc.	
6		PHOTTYP	Some systems have terms for the data products. This is where the product type is identified.		A	'Metric', 'Long', 'Color', 'Light Curve', 'Signature', 'NULLSTRING', etc.	
7		BASING	The type of sensor basing is identified here.		A	'Ground', 'Space', 'Air', 'Sea'	
8	All	TELESCOP	Telescope site name or SSN sensor identifier.		A	'AMOS', 'RME', 'SENSOR510'	
9	G	TELLAT	Geographical latitude of the telescope.	degrees N	D		
10		TELLATU	Uncertainty in the telescope latitude.	degrees	D		

#	Req'd.	Keyword	Description	Units	Format	Example(s)	Notes
11	G	TELLONG	Geographical longitude of the telescope.	degrees E	D		For a space-based sensor, this field does not need to exist.
12		TELLONGU	Uncertainty in the telescope longitude.	degrees	D		
13	G	TELALT	Distance above sea level of the telescope.	m	D		
14		TELALTU	Uncertainty in the altitude of the ground-based sensor.	m	D		
15	S/T, S/S	OBSTYPE	If the space-based sensor has a space catalog number, the string 'SCN' is the value; otherwise 'NULLSTRING' is the value.		A	'SCN' or 'NULLSTRING'	
16	S/T	OBSNUM	If OBSTYPE='SCN', the space catalog number of the space-based sensor is the value; otherwise, -2147483648.		J	12345	Field 16 is not required for S/S. What is meant by a space-based state vector sensor is that the sensor TLE is not contained within the EOSSA file but that the position of the sensor is reported via a state vector. Therefore, the sensor TLE is not required to determine the

#	Req'd.	Keyword	Description	Units	Format	Example(s)	Notes
							position/velocity of the sensor, so the Space Catalog Number is not required. It is desired that the information (OBSNUM, i.e., the Space Catalog Number) be reported. Note that including the Space Catalog Number of such sensors can sometimes change the classification level of the EOSSA data file.
17	All	OBSNAME	Telescope name.		A	'SENSOR510', 'AEOS', 'MT16', 'RMERaven',etc.	
18	S/T	OBSTLE1	Sensor Truncated TLE Line 1. First line of TLE without preceding '1' (67 characters).		A		
19	S/T	OBSTLE2	Sensor Truncated TLE Line 2. Second line of TLE without preceding '2' (67 characters).		A		
20	All	OBJEPH	Target object ephemeris source.		A	'STATE', 'TLE'	
21	All	OBJTYPE	If the target has a space catalog number, the string		A	'SCN', 'NULLSTRING'	

#	Req'd.	Keyword	Description	Units	Format	Example(s)	Notes
			'SCN' is the value. If another catalog is used to identify the object, the name of that catalog is the value. Otherwise 'NULLSTRING' is the value.				
22	All	OBJNUM	If OBJTYPE = 'NULLSTRING', -2147483648 is the value. Otherwise, the identification number of the object from the catalog in OBJTYPE is the value.		J	12345	
23		UCTFLAG	Identifier flagging the object as a UCT.		L	1: true, 0: false	Uncorrelated tracks (UCT)
24	All	OBJECT	Common name of target object if available or a name that the data provider uses to identify the object. Otherwise, 'NULLSTRING'.		A	'GALAXY14', 'NULLSTRING', etc.	
25	All	TLELN1	Target Object Truncated TLE Line 1. First line of TLE without preceding '1' (67 characters). 'NULLSTRING' for UCTs.		A		UCT be definition will not have a TLE.
26	All	TLELN2	Target Object Truncated TLE Line 2. Second line of TLE without preceding '2' (67 characters). 'NULLSTRING' for UCTs.		A		
27		INSTRUME	Sensor or instrument name (could be the same as OBSNAME if only one sensor on the telescope).		A	'BASS', 'VISIM, 'FLASH', 'RMERaven', etc.	

#	Req'd.	Keyword	Description	Units	Format	Example(s)	Notes
28	All	SPFNUM	The value is the number of spectral filters used.		J	2	If the sensor is only panchromatic, then SPFNUM = 1.
29	All	SPFNAMn	The SPFNAMn keywords must be present for all values n=1,…, SPFNUM, in incrementing order of n, and for no other values of n.		A	SPFNAM1='B' SPFNAM2='R' SPFNAM1='O'	If the sensor has no spectral filters, and Field 28 'SPFNUM' is set to 0, then Field 29 must always have at least one Spectral filter defined. This is because the detector itself acts as a spectral filter even if the sensor does not have separate spectral filter capability. Use 'P' for PAN or 'O' for OPEN to describe no special filter present at the sensor.
30		SPZMFLn	This is the in-band average irradiance of a 0th mag source. The SPZMFLn keywords must be present for all values n=1,…,	W/m^2/nm	D	SPZMFL1=8.24E-11 SPZMFL2=5.77E-11	

#	Req'd.	Keyword	Description	Units	Format	Example(s)	Notes
			SPFNUM, in incrementing order of n, and for no other values of n.				
31		SPFSMGn	This is the in-band solar magnitude at 1 A.U. The SPFSMGn keywords must be present for all values n=1,…, SPFNUM, in incrementing order of n, and for no other values of n. See Appendix C to generate this value for each spectral filter.	mag	D	SPFSMG1=-26.09 SPFSMG2=-27.26	
32		ZEROPTn	This is the value for the zero-point calculated for each filter denoted in SPFNAM. It is the difference between the catalog mag and instrumental mag for a set of standard stars.	mag	D	ZEROPT1 = 12.56 ZEROPT2 = 12.42	***For use with All Sky photometry.*** The ZEROPTn keywords must be present for all values n=1,…, SPFNUM, in incrementing order of n, and for no other values of n.
33		ZEROPUn	This is the uncertainty in the zero point for the filter denoted in SPFNAM.	mag	D	ZEROPU1 = 0.03 ZEROPU2 = 0.05	For use with All Sky photometry. The ZEROPUn keywords must be present for all values n=1,…, SPFNUM, in incrementing order of n, and

#	Req'd.	Keyword	Description	Units	Format	Example(s)	Notes
							for no other values of n.
34		EXTINCn	The extinction coefficient computed for the nth filter. The EXTINCn keywords must be present for all values n=1,…, SPFNUM, in incrementing order of n, and for no other values of n. These are the kappas described in Appendix A. -9999.0 for space-based sensors.	mag/airmass	D	EXTINC1 = 0.302 EXTINC2=0.145	
35		EXTINUn	This is the uncertainty in the extinction coefficient for the nth filter. The EXTINUn keywords must be present for all values n=1,…, SPFNUM, in incrementing order of n, and for no other values of n. -9999.0 for space-based sensors.	mag/airmass	D	EXTINU1=0.008 EXTINU2=0.005	
36		CCOEFn	Color coefficient for filter n for a space-based sensor where there is no atmospheric extinction. The CCOEFn keywords must be present for all values n=1,…, SPFNUM, in incrementing order of n, and for no other values of n. See Appendix D for description.	mag	D		

#	Req'd.	Keyword	Description	Units	Format	Example(s)	Notes
37		NDFNUM	The value is the number of neutral density[6] filters used.		J	2	If there are no Neutral Density filters, Field 37 'NDFNUM' should be set to 0 and the rest of the fields left out.
38		NDFNAMn	The NDFNAMn keywords must be present for all values n=1,…, NDFNUM, in incrementing order of n, and for no other values of n.		A	NDFNAM1='ND1' NDFNAM2='ND10'	
39		NDFTRAn	The transmission of the nth neutral density filter. The NDFTRAn keywords must be present for all values n=1,…, NDFNUM, in incrementing order of n, and for no other values of n.		D	NDFTRA1=0.10 NDFTRA2=1E-10	If Neutral Density Filters are not a sensor option, then the fields do not need to exist.
40		NDFTRUn	This is the uncertainty in the transmission for the nth filter. The NDFTRUn keywords must be present for all values n=1,…, NDFNUM, in incrementing order of n, and for no other values of n.		D	NDFTRU1=0.001 NDFTRU2=0.005	
41		GAIN	Some sensors have gain settings. This value is the gain used during the observation.	e-/ADU	D	1	

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[6] A neutral density filter is a clear or grey filter that equally attenuates all wavelengths of the input signal and is typically used to avoid saturation of the detector.

#	Req'd.	Keyword	Description	Units	Format	Example(s)	Notes
			If no gain is used, the value = 1.				
42		PIXARRYW	Pixel array size (width).	pixels	J	512	
43		PIXARRYH	Pixel array size (height).	pixels	J	512	
44		PIXMIN	Minimum valid pixel value. This is typically 0.	DN	J	0	
45		PIXMAX	Maximum valid pixel value. This is defined as 2^(number of bits per pixel). For example, a CCD with 16-bit pixels would have a maximum valid pixel value of 2^16 = 65536. This can represent the saturation value of the detector, but some sensors will saturate at a value significantly lower than full well depth. This is the Analog-to-Digital Conversion (ADC) saturation value.	DN	J	65536	
46		STARCAT	Name and version of photometric star catalog used. The source of the standard stars observed by the sensor.		A	'USNO-B'	
47		ACALDP1n	Common optical distortion fit in the X axis from astrometric calibration. ACALDP1n is an identified Astrometric CALibration Distortion Parameter for the X axis for n = 1-9 distortion terms added		A	ACALDP11 = '3.6783e-2 r + 0.32e-4 x^2 – 0.12e-5 y^2' (X axis)	

#	Req'd.	Keyword	Description	Units	Format	Example(s)	Notes
			to WCS values in the binary data table (ACAL, CRPIX, ACAL_CRVAL, ACAL_CD).			ACALDP12 = '4.367e-7 cos(t-0.35)'	
48		ACALDP2n	Common optical distortion fit in the Y axis from astrometric calibration. ACALDP2n is an identified Astrometric CALibration Distortion Parameter for the Y axis for n = 1-9 distortion terms added to WCS values in the binary data table (ACAL, CRPIX, ACAL_CRVAL, ACAL_CD).		A	ACALDP21 = '4.514e-2 r + 0.32e-4 x^2 – 0.12e-5 y^2' (Y axis) ACALDP22 = '4.367e-7 cos(t-0.35)'	
49		REDALG	Version number of the calibration reduction algorithms. Used for OPAL.		A		
50		COLLID	The collection ID used in OPAL. A string of the mission data frames.		A		If the collection ID of data is longer than 67 characters, do not populate 'COLLID'. Instead, define custom fields of COLLID1,…,COLLIDn such that each COLLIDn contains 68 characters and break up the collection ID into strings of 68 characters where

#	Req'd.	Keyword	Description	Units	Format	Example(s)	Notes
							n is large enough to accommodate the length of the collection ID.
51		CALNUM	Number of OPAL calibration products. Should be 0 for those sensors whose data is not processed by OPAL.		J		
52		CALFILn	The calibration filename for the nth calibration product. The CALFILn keywords must be present for all values n=1,…, CALNUM, in incrementing order of n, and for no other values of n.		A	CALFIL1='biasfilenameOPAL' CALFIL2='flatfilenameOPAL'	
53		PRODIDn	The product ID number for the nth calibration product. The PRODIDn keywords must be present for all values n=1,…, CALNUM, in incrementing order of n, and for no other values of n.		A	PRODID1='98765' PRODID2='98764'	
54		TSTAMPn	The timestamp for the nth calibration product. The TSTAMPn keywords must be present for all values n=1,…, CALNUM, in incrementing order of n, and for no other values of n.	yyyy-mm-ddThh:mm:ss{.sssssss}	A	TSTAMP1='2013-01-01T00:11:33.0' TSTAMP2='2013-01-01T00:12:55.7'	
55		CALTYPn	The calibration type or label for the nth calibration product. The CALTYPn keywords must be present		A	'Bias', 'Flat', 'Bad_Pixel_Map'	

#	Req’d.	Keyword	Description	Units	Format	Example(s)	Notes
			for all values n=1,…, CALNUM, in incrementing order of n, and for no other values of n.				
56		Custom	Placeholder for other fields that the data provider might want to define. See Section 3.4.1.				

3.7 EOSSA Data Column Descriptions (Values of TTYPE)

This section contains the binary data table columns. Table 7 contains all the parameters (data columns or TTYPEn values) used in the EOSSA format. This table is set up identical to Table 6 where the first column contains a reference number for the data column parameter, if it is a required parameter and if so, by what type of sensor, the TTYPEn value or the data column parameter name, and a description of what the parameter is. The next three columns are for the expected units, the appropriate format, and, in most cases, an example. The final column contains notes.

Many of these parameters are highly useful to the analyst in the event of unexpected analysis results when using the radiometric data from the file. With a quick look at some of these fields, the analyst can determine conditions that would dictate that the data be excluded. Some of these frequently occurring conditions are, for example, clouds, saturation, and star contamination. There is a total of 56 data columns in the EOSSA format. Note that each row in Table 7 is a data column in the EOSSA binary data table.

Table 7 – EOSSA Binary Table Extension Data Column Descriptions

#	Req'd.	**TTYPEn values** (data columns)	**Description**	**Units**	**Format** (part of TFORM)	**Example(s)**	**Notes**
1	All	UTC_Begin_Exp	The start time of the exposure in UTC[7].	yyyy-mm-ddThh:mm:ss{.sssssss}	A	'2013-08-01T12:13:14.000'	
2	All	UTC_End_Exp	The end time of the exposure.	yyyy-mm-ddThh:mm:ss{.sssssss}	A	'2013-08-01T12:14:14.000'	
3	All	JD_Mid_Exp	The time of mid-exposure in JD[8]. Be sure the values for this keyword have enough significant digits to express the time to the appropriate fraction of a second.	days	D	2456506.00937	
4		UTC_Unc	Uncertainty in the times reported in UTC.	sec	D	1.0E-7	
5	All	Exp_Duration	Length of the integration or exposure time.	sec	D	30.0	
6		Binning	Array of values are the number of pixels binned in the array (1 X 1, 2 x 2, etc.) first		2J	[1,1]	

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[7] UTC is Coordinated Universal Time.

[8] JD is Julian Date.

#	Req'd.	**TTYPEn values** (data columns)	**Description**	**Units**	**Format** (part of TFORM)	**Example(s)**	**Notes**
			horizontally then vertically[9].				
7		CCD_Temp	Operating temperature of CCD recorded during exposure or measured during calibrations.	K	D	243.160	
8	All	Cur_Spec_Filt_Num	Number of the spectral filter, n, used in the instance of this observation. From SPFNAMn. See Table 6, rows 28 and 29.		J	1	Must be greater than or equal to 1. There must always be at least one spectral filter defined. This is because the detector itself acts as a spectral filter even if the sensor does not have separate spectral filter capability. Use PAN or OPEN to correspond to n=1 filter when no special filter present.
9		ZEROPTD	This is the value for the zero-point	mag	D	12.56	***For use with differential (in-***

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[9] Since this TTYPE value contains two values (i.e., an array), it represents two values within a single column of the data table. (See Section 3.4.1 for more details.)

#	Req'd.	**TTYPEn values** (data columns)	**Description**	**Units**	**Format** (part of TFORM)	**Example(s)**	**Notes**
			calculated for the filter used for this observation/row. It is the difference between the catalog mag and instrumental mag for a set of calibration stars within the frame.				***frame) photometry.*** See Appendix A.
10		ZEROPUD	This is the uncertainty in the zero point for the filter used for this observation/row. For use with differential photometry.	mag	D	0.03	
11		PCal_Num_Stars	Number of stars used in photometric fit count.		J	17	
12		Cur_ND_Filt_Num	The reference number n, in NDFNAMn for the currently used neutral density filter.		J	2	This field is not required if it is not a sensor capability.
13		CCD_Obj_Pos	The x,y centroid position on the CCD of the target object. The first value in the array is the horizontal (x) position; the second is the vertical (y) position.	pixels	2D	[256,256]	

#	Req'd.	**TTYPEn values** (data columns)	**Description**	**Units**	**Format** (part of TFORM)	**Example(s)**	**Notes**
14		CCD_Obj_FWHM	This is the pixel width of the target. This is either a frame-by-frame measurement or a constant point spread function or synthetic aperture used in the extraction.	pixels	D	9	
15		Net_Obj_Sig	Net Object Signal is the average counts (DN) divided by the exposure time in seconds.	DN/sec	D	714.345	
16		Net_Obj_Sig_Unc	Uncertainty in the net object signal value.	DN/sec	D	.0005	
17		Bkg_Sig	This is the background signal at or in the vicinity of the radiometric source position. Specifically, this is the average background count level (DN/pixel) divided by the exposure time in seconds of the background pixels used in the photometric extraction.	DN/pixel/ sec	D	328.123	

#	**Req'd.**	**TTYPEn values** (data columns)	**Description**	**Units**	**Format** (part of TFORM)	**Example(s)**	**Notes**
18		Bkg_Sig_Unc	Estimated 1-sigma uncertainty in the background signal at or in the vicinity of the radiometric source position.	DN/pixel/ sec	D	.0005	
19		Peak_Ap_Cnt	Peak Aperture Raw Counts is the value of the peak pixel in the real or synthetic aperture containing the target signal.	DN	J	65536	
20		Peak_Bkg_Cnt	Peak Background Raw Counts is the largest pixel value used in background signal.	DN	J	3876	
21		SNR_Est	Estimated Signal-to-Noise Ratio (SNR) for the total radiometric signal. Under some algorithms, this can be a constant per target (not per observation). Note: this SNR applies to the total signal of the radiometric source (i.e., Net_Obj_Sig with units DN/sec), not to be confused with the SNR of the signal in		D	10	

#	Req'd.	**TTYPEn values** (data columns)	**Description**	**Units**	**Format** (part of TFORM)	**Example(s)**	**Notes**
			the peak pixel (i.e., DN/pixel/sec).				
22		Mag_ Instrumental	Instrumental magnitude of a sensor before corrections are applied for atmosphere or to transform to standard magnitude scale.	mag	D	-12.34	
23		Mag_Unc	Uncertainty in the instrumental magnitude (Mag_ Instrumental).	mag	D	0.05	
24	All	Mag_Exo_Atm	Exo-atmospheric magnitude is the magnitude of the target on the standard scale with atmospheric effects removed, e.g., m_r in Equation (A- 18).	mag	D	13.21	
25		Mag_Exo_Atm_Unc	This will represent a combination of instrumental magnitude and photometric calibration errors.	mag	D		

#	Req'd.	**TTYPEn values** (data columns)	**Description**	**Units**	**Format** (part of TFORM)	**Example(s)**	**Notes**
26	All	Mag_Range_Norm	Range-normalized magnitude (Mag in #24) using 1000 km[10].	mag	D	3.45	
27		Opt_Cross_Sec	Optical Cross Section computed via the Equation (E- 2) in Appendix E.	m^2/ster	D	10.8	
28		Opt_Cross_Sec_Unc	Uncertainty in the reported optical cross section (#27).	m^2/ster	D	0.3	
29		Obj_State_Vec	Target object state vector in ECI J2000 coordinate frame.	m&m/s	6D	See Section 3.7.1	
30		Sun_State_Vec	Sun state vector in ECI J2000 coordinate frame.	m&m/s	6D		
31	S/S	Tel_State_Vec	Telescope state vector in ECI J2000 coordinate frame.	m & m/s	6D		
32		Num_Cat_Stars	Number of catalog stars in the detector Field Of View (FOV) with the target object. Can be 0 for narrow FOV sensors.		J		
33		Num_Det_Stars	Number of detected stars in the FOV with the target object.		J		

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[10] Range-normalization is done using the distance modulus where the range-normalized magnitude is computed by Equation (A- 19) (see Appendix A).

#	Req'd.	**TTYPEn values** (data columns)	**Description**	**Units**	**Format** (part of TFORM)	**Example(s)**	**Notes**
			Helps identify frames with clouds.				
34		Num_Corr_Stars	Number of correlated stars in the FOV with the target object. Can be 0 for narrow FOV sensors.		J		
35	All	Eph_RA_DE	Predicted Right Ascension and Declination of the Target object from the frame of reference of the sensor (J2000, geocentric velocity aberration). SGP4 and VCMs produce geocentric origin and velocity aberration and subtracting the sensor geocentric position of the sensor places it in its reference frame.	deg	2D	[75.33; -5.001]	
36		Eph_RA_DE_Unc	Uncertainties in #35 RA and Dec values.	deg	2D	[0.01; 0.005]	
37	All	Met_RA_DE	Measured Right Ascension and Declination of the Target object from the frame of reference of the sensor.	deg	2D	[75.31; -5.201]	

#	Req'd.	**TTYPEn values** (data columns)	**Description**	**Units**	**Format** (part of TFORM)	**Example(s)**	**Notes**
38		Met_RA_DE_Cov	Covariance (x^2, y^2, xy) in measured Right Ascension (X) and Declination angles (Y).	deg^2	3D	[0.01; 0.01; 0.005]	
39	G	Eph_AZ_EL	Predicted Azimuth and elevation angles of the target object from a ground-based sensor (no atmospheric refraction correction required). AZ_EL implies apparent topocentric place in true of date reference frame as seen from the observer with aberration due to the observer velocity and light travel time applied.	deg	2D	[92.89; 32.12]	
40	G	Met_AZ_EL	Measured azimuth and elevation angles of the target object from a ground-based sensor (no atmospheric refraction correction required).	Deg	2D	[92.91;32.76]	
41		ACAL_CRPIX	World Coordinate System (WCS) pixel	pixel	2D	[512.0;512.0]	

#	Req'd.	TTYPEn values (data columns)	Description	Units	Format (part of TFORM)	Example(s)	Notes
			origin in astrometric fit [2].				
42		ACAL_CRVAL	WCS equatorial coordinate origin corresponding to CRPIX in astrometric fit.	deg	2D	[77.41; -5.362]	
43		ACAL_CD	WCS 2x2 affine transform CD matrix in astrometric fit.	deg	4D	[-0.0003018; 8.333e-6; -8.333e-6; 0.0003018]	
44		ACAL_Num_Stars	Number of stars used in astrometric fit.		J	32	
45	G	Sun_AZ_EL	Azimuth and elevation angles of the sun from a ground-based telescope (no atmospheric refraction correction required).	Deg	2D	[273.91; -25.77]	
46	All	Tel_Obj_Range	Distance from the sensor to the target object during the observation.	m	D	3.578683E7	
47		Obj_Sun_Range	Distance from the target object to the sun during the observation.	m	D	1.47098074E11	
48		Solar_Phase_Ang	SPA. This is the angle between the RSO-sun vector and the RSO-	deg	D	30.5	

#	Req'd.	**TTYPEn values** (data columns)	**Description**	**Units**	**Format** (part of TFORM)	**Example(s)**	**Notes**
			observer vector. Defined in Appendix I, Section I.3.				
49		Phase_Ang_Bisect	Solar PAB vector. The vector that bisects the SPA. The PAB is the angle that is ½ of the value in #48. Calculate the point on the RA/DEC (ECI J2000.0) sphere that a vector at this angle would intersect. Defined in Appendix I, Section I.7.	deg	2D	[270.66, 0.00]	
50		Long_Phase_Ang	Longitudinal phase angle. The component of the SPA found by projecting all three points of the angle into the orbital plane of the target object. Defined in Appendix I, Section I.4.	deg	D	31.86	
51		Lat_Phase_Ang	Latitudinal phase angle. The difference in the sun's declination and the observer's declination as seen from the target object. Defined	deg	D	-36.1	

#	Req'd.	**TTYPEn values** (data columns)	**Description**	**Units**	**Format** (part of TFORM)	**Example(s)**	**Notes**
			in Appendix I, Section I.5.				
52		Orbit_Ang	OA. The angle between the center of the earth and the sun's projection into the orbital plane of the target, as seen from the target object. Defined in Appendix I, Section I.6.	deg	D	54.4	
53		Solar_Disk_Frac	Fraction of the sun that is illuminating the target object. This indicates if the target is in the Earth's penumbra or umbra. (It is 0 when the object is in umbra and 1 when the object is fully illuminated.) See Appendix F on how to compute this value.		D	1.0	
54		TOES	"Time Off Element Set". Calculated by OPAL using ROTAS doc formulas; along-track residual (delta-t). -9999.0 for sensors		D		

#	Req'd.	**TTYPEn values** (data columns)	**Description**	**Units**	**Format** (part of TFORM)	**Example(s)**	**Notes**
			not processed by OPAL[11].				
55		DOES	"Degrees Off Element Set". Calculated by OPAL using ROTAS doc formulas; out-of-plane residual (beta). -9999.0 for sensors not processed by OPAL.		D		
56		Custom	Placeholder for other fields that the data provider might want to define. See Section 3.5.				

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[11] Rodehorst, M., MIT/LL, Personal communications regarding OPAL processing and algorithms, and ROTAS_Theoretical_1997.doc, 2012 – 2103.

3.7.1 Example of TTYPE #29- Obj_State_Vec – A 6D Data Column

In Table 7, TTYPE #29 (row 29) is a six-dimensional vector. A vector or array in the data table is stored in one column of the data table as, in this case, six values. As an example of the object state vector entry for Obj_State_Vec is the following:

Obj_State_Vec

4.19E+07 -4488264.615 -4092244.581 373.3350678 2976.300355 641.8166555

Any TTYPE value that is a vector or an array with *m* elements, where *m* >= 2, will be in the same column in the data table and contain *m* values.

3.8 Prioritization of Optional Keywords

Table 8 and Table 9 below list the optional keywords in the binary table header and data columns respectively in prioritized order. These prioritized lists are suggestions to assist the data providers in organizing their software development tasks and incrementally improving their EOSSA data products.

Table 8 – EOSSA Binary Table Header Optional Keywords Prioritized

Priority	Sensor Basing	Keyword	Description	Units	Format	Example(s)	Notes
1	All	BASING	The type of sensor basing is identified here.		A	'Ground', 'Space', 'Air', 'Sea'	
2	All	PHOTTYP	Some systems have terms for the data products. This is where the product type is identified.		A	‘Metric’, ‘Long’, ‘Color’, ‘Light Curve’, Signature’, ‘NULLSTRING’, etc.	
3	All	ARRAY	Name of the detector from which the radiometry was extracted.		A	‘Main array’, ‘SOI window’, ‘Photometer’, ‘NULLSTRING’, etc.	
4	All	INSTRUME	Sensor or instrument name (could be the same as OBSNAME if only one sensor on the telescope).		A	‘BASS’, ‘VISIM, ‘FLASH’, ‘RMERaven’, etc.	
5	G	TELLATU	Uncertainty in the telescope latitude.	degrees	D		
6	G	TELLONGU	Uncertainty in the telescope longitude.	degrees	D		
7	G	TELALTU	Uncertainty in the altitude of the ground-based sensor.	m	D		
8	All	SPZMFLn	This is the in-band average irradiance of a 0^{th} mag source. The SPZMFLn keywords must be present for all values n=1,…, SPFNUM, in	$W/m^2/nm$	D	SPZMFL1=8.24E-11 SPZMFL2=5.77E-11	

Priority	Sensor Basing	Keyword	Description	Units	Format	Example(s)	Notes
			incrementing order of n, and for no other values of n.				
9	All	SPFSMGn	This is the in-band solar magnitude at 1 A.U. See Appendix C to generate this value for each spectral filter.	mag	D	SPFSMG1=-26.09 SPFSMG2=-27.26	
10	G	EXTINCn	The extinction coefficient computed for the nth filter.	mag/airmass	D	EXTINC1 = 0.302 EXTINC2 = 0.145	These are the kappas described in Appendix A. (Placeholder value should be used for space-based sensors.)
11	All	ZEROPTn	This is the value for the zero-point calculated for each filter denoted in SPFNAM. It is the difference between the catalog mag and instrumental mag for a set of standard stars.	mag	D	ZEROPT1 = 12.56 ZEROPT2 = 12.42	***For use with All Sky photometry.*** The ZEROPTn keywords must be present for all values n=1,…, SPFNUM, in incrementing order of n, and for no other values of n.
12	G	EXTINUn	This is the uncertainty in the extinction coefficient for the nth filter. -9999.0 for space-based sensors.	mag/airmass	D	EXTIINU1=0.008 EXTIINU2=0.005	
13	All	ZEROPUn	This is the uncertainty in the zero point for the filter denoted in SPFNAM.	mag	D	ZEROPU1 = 0.03 ZEROPU2 = 0.05	For use with All Sky photometry. The ZEROPUn keywords must be present for all values n=1,…,

Priority	Sensor Basing	Keyword	Description	Units	Format	Example(s)	Notes
							SPFNUM, in incrementing order of n, and for no other values of n.
14	All	CCOEFn	Color coefficient for filter n for a space-based sensor where there is no atmospheric extinction. See Appendix D for description.	mag	D		
15	All	NDFNUM	The value is the number of neutral density[12] filters used.		J	2	
16	All	NDFNAMn	The NDFNAMn keywords must be present for all values n=1,…, NDFNUM, in incrementing order of n, and for no other values of n.		A	NDFNAM1='ND1' NDFNAM2='ND10'	
17	All	NDFTRAn	The transmission of the nth neutral density filter.		D	NDFTRA1=0.10 NDFTRA2=1E-10	
18	All	NDFTRUn	This is the uncertainty in the transmission for the nth filter		D	NDFTRU1=0.001 NDFTRU2=0.005	
19	All	GAIN	Some sensors have gain settings. This value is the gain used during the observation. If no gain is used, the value = 1.	e-/ADU	D	1	
20	All	PIXMAX	Maximum valid pixel value, this is defined as 2^(number of bits per pixel). For example, a CCD with 16-bit pixels,	DN	J	65536	

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[12] A neutral density filter is a clear or grey filter that equally attenuates all wavelengths of the input signal and is typically used to avoid saturation of the detector.

Priority	Sensor Basing	Keyword	Description	Units	Format	Example(s)	Notes
			would have a maximum valid pixel value of 2^16 = 65536. This can represent the saturation value of the detector, but some sensors will saturate at a value significantly lower than full well depth. This is the Analog-to-Digital Conversion (ADC) saturation value.				
21	All	PIXMIN	Minimum valid pixel value. This is typically 0.	DN	J	0	
22	All	PIXARRYW	Pixel array size (width).	pixels	J	512	
23	All	PIXARRYH	Pixel array size (height).	pixels	J	512	
24	All	STARCAT	Name and version of photometric star catalog used. The source of the standard stars observed by the sensor.		A	'USNO-B'	
25	All	REDALG	Version number of the calibration reduction algorithms. Used for OPAL.		A		
26	All	ACALDP1n	Common optical distortion fit in the X axis from astrometric calibration. ACALDP1n is an identified Astrometric CALibration Distortion Parameter for the X axis for n = 1-9 distortion terms added to WCS values in the binary data table (ACAL, CRPIX, ACAL_CRVAL, ACAL_CD).		A	ACALDP11 = '3.6783e-2 r + 0.32e-4 x^2 – 0.12e-5 y^2' (X axis) ACALDP12 = '4.367e-7 cos(t-0.35)'	

Priority	Sensor Basing	Keyword	Description	Units	Format	Example(s)	Notes
27	All	ACALDP2n	Common optical distortion fit in the Y axis from astrometric calibration. ACALDP2n is an identified Astrometric CALibration Distortion Parameter for the Y axis for n = 1-9 distortion terms added to WCS values in the binary data table (ACAL, CRPIX, ACAL_CRVAL, ACAL_CD).		A	ACALDP21 = ‘4.514e-2 r + 0.32e-4 x^2 – 0.12e-5 y^2’ (Y axis) ACALDP22 = ‘4.367e-7 cos(t-0.35)’	
28	All	COLLID	The collection ID used in OPAL. A string of the mission data frames.		A		
29	All	CALNUM	Number of OPAL calibration products. Should be 0 for those sensors whose data is not processed by OPAL.		J		
30	All	CALFILn	The calibration filename for the nth calibration product. The CALFILn keywords must be present for all values n=1,…, CALNUM, in incrementing order of n, and for no other values of n.		A	CALFIL1=’biasfilenameOPAL’ CALFIL2=’flatfilenameOPAL’	
31	All	PRODIDn	The product ID number for the nth calibration product. The PRODIDn keywords must be present for all values n=1,…, CALNUM, in incrementing order of n, and for no other values of n.		A	PRODID1=’98765’ PRODID2=’98764’	

Priority	Sensor Basing	Keyword	Description	Units	Format	Example(s)	Notes
32	All	TSTAMPn	The timestamp for the nth calibration product. The TSTAMPn keywords must be present for all values n=1,…, CALNUM, in incrementing order of n, and for no other values of n.	yyyy-mm-ddThh:mm:ss{.ssssss}	A	TSTAMP1='2013-01-01T00:11:33.0' TSTAMP2='2013-01-01T00:12:55.7'	
33	All	CALTYPn	The calibration type or label for the nth calibration product. The CALTYPn keywords must be present for all values n=1,…, CALNUM, in incrementing order of n, and for no other values of n.		A	'Bias', 'Flat', 'Bad_Pixel_Map'	
34	All	Custom	Placeholder for other fields that the data provider might want to define. See Section 3.5				
35	All	UCTFLAG	Identifier flagging the object as a UCT.		L	1: true, 0: false	

Table 9 – EOSSA Optional Data Columns – In Prioritized Order

Priority	**Sensor Basing**	**TTYPEn values** (data columns)	**Description**	**Units**	**Format** (part of TFORM)	**Example(s)**	**Notes**
1	All	TOES	"Time Off Element Set". Calculated by OPAL using ROTAS doc formulas; along-track residual (delta-t). -9999.0 for sensors not processed by OPAL.		D		
2	All	DOES	"Degrees Off Element Set". Calculated by OPAL using ROTAS doc formulas; out-of-plane residual (beta). -9999.0 for sensors not processed by OPAL.		D		
3	All	Custom	Placeholder for other fields that the data provider might want to define. See Section 3.5.				
4	All	Eph_RA_DE_Unc	Uncertainties in Table 7, row 36, RA and Dec values.	degrees	2D	[0.01; 0.005]	
5	All	Met_RA_DE_Cov	Covariance (x^2, y^2, xy) in measured Right Ascension (X) and Declination angles (Y).	deg^2	3D	[0.01; 0.01; 0.005]	
6	All	UTC_Unc	Uncertainty in the times reported in UTC.	sec	D	1.0E-7	
7	All	Solar_Phase_Ang	Solar Phase Angle[13]. This is the angle between the RSO-sun vector and the RSO-observer vector.	degrees	D	30.5	
8	All	Phase_Ang_Bisect	Solar phase angle bisector vector. The vector that bisects the solar phase angle. The phase angle	degrees	2D	[270.66, 0.00]	

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[13] This is the canonical solar phase angle defined by the angle between the sun and the observer as seen from the target object.

Priority	**Sensor Basing**	**TTYPEn values** (data columns)	**Description**	**Units**	**Format** (part of TFORM)	**Example(s)**	**Notes**
			bisector is the angle that is ½ of the value in row 7. Then calculate the point on the RA/DEC (ECI J2000.0) sphere that a vector at this angle would intersect. See Section I.7 in Appendix I.				
9	All	Opt_Cross_Sec	Optical Cross Section computed via Equation (E- 2) in Appendix E.	m^2/ster	D	10.8	
10	All	Opt_Cross_Sec_Unc	Uncertainty in the reported optical cross section (row 9).	m^2/ster	D	0.3	
11	All	Obj_Sun_Range	Distance from the target object to the sun during the observation.	m	D	1.47098074E11	
12	All	Solar_Disk_Frac	Fraction of the sun that is illuminating the target object. This indicates if the target is in the Earth's penumbra or umbra. (It is 0 when the object is in umbra and 1 when the object is fully illuminated.) See Appendix F on how to compute this value.		D	1.0	
13	All	Obj_State_Vec	Target object state vector in ECI J2000 coordinate frame.	m&m/s	6D		See Section 3.7.1
14	All	Sun_State_Vec	Sun state vector in ECI J2000 coordinate frame.	m&m/s	6D		
15	All	Mag_Instrumental	Instrumental magnitude of a sensor before corrections are applied for atmosphere or to transform to standard magnitude scale.	mag	D	-12.34	
16	All	ZEROPTD	This is the value for the zero-point calculated for the filter used for this observation/row. It is the	mag	D	12.56	***For use in Differential***

Priority	**Sensor Basing**	**TTYPEn values** (data columns)	**Description**	**Units**	**Format** (part of TFORM)	**Example(s)**	**Notes**
			difference between the catalog mag and instrumental mag for a set of calibration stars within the frame.				***(in-frame) Photometry.*** See Appendix A.
17	All	PCal_Num_Stars	Number of stars used in photometric fit count.		J	17	
18	All	Net_Obj_Sig	Net Object Signal is the average counts (DN) divided by the exposure time in seconds.	DN/sec	D	714.345	
19	All	Bkg_Sig	This is the background signal at or in the vicinity of the radiometric source position. Specifically, this is the average background count level (DN/pixel) divided by the exposure time in seconds of the background pixels used in the photometric extraction.	DN/pixel/sec	D	328.123	
20	All	Peak_Ap_Cnt	Peak Aperture Raw Counts is the value of the peak pixel in the real or synthetic aperture containing the target signal.	DN	J	65536	
21	All	Peak_Bkg_Cnt	Peak Background Raw Counts is the largest pixel value used in background signal.	DN	J	3876	
22	All	SNR_Est	Estimated SNR for the total radiometric signal. Under some algorithms, this can be a constant per target (not per observation). Note: this SNR applies to the total signal of the radiometric source (i.e., Net_Obj_Sig with units		D	10	

Priority	**Sensor Basing**	**TTYPEn values** (data columns)	**Description**	**Units**	**Format** (part of TFORM)	**Example(s)**	**Notes**
			DN/sec), not to be confused with the SNR of the signal in the peak pixel (i.e., DN/pixel/sec).				
23	All	Binning	Array of values are the number of pixels binned in the array (1 X 1, 2 x 2, etc.) first horizontally then vertically[14].		2J	[1,1]	
24	All	CCD_Obj_Pos	The x,y centroid position on the CCD of the target object. The first value in the array is the horizontal (x) position, the second is the vertical (y) position.	pixels	2D	[256,256]	
25	All	CCD_Obj_FWHM	This is the pixel width of the target. This is either a frame-by-frame measurement or a constant point spread function or synthetic aperture used in the extraction.	pixels	D	9	
26	All	CCD_Temp	Operating temperature of CCD recorded during exposure or measured during calibrations.	K	D	243.160	
27	All	Mag_Unc	Uncertainty in the instrumental magnitude (Mag_ Instrumental).	mag	D	0.05	
28	All	Mag_Exo_Atm_Unc	This will represent a combination of instrumental magnitude and photometric calibration errors.	mag	D		
29	All	Net_Obj_Sig_Unc	Uncertainty in the net object signal value.	DN/sec	D	.0005	

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[14] Since this TTYPE value contains two values (i.e., an array), it represents two values within a single column of the data table. (See Section 3.4.1 in the file for more details.)

Priority	**Sensor Basing**	**TTYPEn values** (data columns)	**Description**	**Units**	**Format** (part of TFORM)	**Example(s)**	**Notes**
30	All	Bkg_Sig_Unc	Estimated 1-sigma uncertainty in the background signal at or in the vicinity of the radiometric source position.	DN/pixel/sec	D	.0005	
31	All	ZEROPUD	This is the uncertainty in the zero point for the filter used for this observation/row. For use with differential photometry.	mag	D	0.03	
32	All	Num_Cat_Stars	Number of catalog stars in the detector FOV with the target object. Can be 0 for narrow FOV sensors.		J		
33	All	Num_Det_Stars	Number of detected stars in the FOV with the target object. Helps identify frames with clouds.		J		
34	All	Num_Corr_Stars	Number of correlated stars in the FOV with the target object. Can be 0 for narrow FOV sensors.		J		
35	All	ACAL_CRPIX	WCS pixel origin in astrometric fit [2].	pixel	2D	[512.0;512.0]	
36	All	ACAL_CRVAL	WCS equatorial coordinate origin corresponding to CRPIX in astrometric fit.	deg	2D	[77.41; -5.362]	
37	All	ACAL_CD	WCS 2x2 affine transform CD matrix in astrometric fit.	deg	4D	[-0.0003018; 8.333e-6; -8.333e-6; 0.0003018]	
38	All	ACAL_Num_Stars	Number of stars used in astrometric fit.		J	32	

4.0 Guidelines for Saving Processed Data into EOSSA

For implementing the EOSSA format, the following information should be helpful.

4.1 Recommended Approach

Libraries supporting FITS currently exist for most programming languages and platforms. These libraries can usually be statically or dynamically linked depending on the user's preference. When creating your own EOSSA files, it is important to choose a library with binary table writing functionality. Recommended libraries include CFITSIO for C or C++ projects, nom.tam.fits for Java projects, and CSharpFITS for C# projects. A full list can be found at the official FITS Libraries Guide (reference http://fits.gsfc.nasa.gov/fits_libraries.html).

Each entry in the table lists the library's ability to read and write (denoted with "r" and "w", respectively) various FITS data types in addition to the access level provided to the user. For example, CFITSIO provides low-level access to information within a FITS file. This might be useful to someone who wants to directly modify array values within a binary table entry. Other packages providing medium or high-level support will have less freedom in how they access FITS data with the tradeoff of being simpler and more abstract to use. Finally, these libraries generally provide both example code and guides that may be useful to a new user.

4.1.1 Human Readable EOSSA

An EOSSA file is written in a binary file format. This is ideal for computers as the information can be stored and accessed in an efficient manner, but it also means the data will not be human-readable. Having a binary EOSSA format also allows for compact and lossless data transmission. However, it can become burdensome to exchange information contained within an EOSSA file with someone without FITS reading abilities. In these cases, it may be useful to have a human-readable EOSSA file that contains all pertinent EOSSA information in an ASCII or PDF format. Simple text files with tables written in a tab- or comma-separated formats are generally acceptable in this case. See Appendix G for a human readable EOSSA example file (all values are fictional representatives and are not real values).

A helpful tool for viewing and editing any FITS format image or table is available from NASA/GSFC at http://heasarc.gsfc.nasa.gov/ftools/fv/. Fv is a small self-contained graphical program that runs on Windows PCs, most UNIX platforms, and Mac OS systems. This program will be helpful during development and testing of any code generating EOSSA files.

4.2 Alternate Approaches

While using established FITS libraries, which is recommended for creating EOSSA files, not all platforms support the FITS data types required for this work. MATLAB, for example, does not currently provide binary table writing support for FITS. However, there are a few alternate approaches available to MATLAB users.

1. Output a human readable EOSSA file (Appendix G) from MATLAB. This file could then be passed through a standalone converter written in C, C++, C#, or Java that outputs a functioning EOSSA file.
2. Run a C, C++, or Java subroutine in MATLAB. For C and C++, this is accomplished by building a MEX (MATLAB executable) file. For Java, a JAR (Java archive) is required. When done correctly, these items can be called in the same way as any other MATLAB function.
3. Write your own FITS functionality using MATLAB. While this is a very arduous task, the FITS Standard provides in-depth descriptions of the requirements to do so [1].

References

[1] Pence , W.D., Chiappetti , L., Page, C. G., Shaw, R. A., Stoble, E., 2010, A&A, 524, A42

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

[3] Greisen, E. W. & Calabretta, M. R., 2002, A&A, 395, 1061

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Acronyms

A.U.	Astronomical Unit
ADC	Analog-to-Digital Conversion
API	Application Programming Interface
ASCII	American Standard Code for Information Interchange
COL	Column
CCD	Charge-Coupled Device
EO	Electro-Optical
EOSSA	Electro-Optical Space Situational Awareness
FITS	Flexible Image Transport System
FOV	Field Of View
GSFC	Goddard Space Flight Center
HDF	Hierarchical Data Format
HDU	Header and Data Unit
JAR	Java ARchive
JD	Julian Date
LEO	Low Earth Orbit
LWIR	Long-Wave InfraRed
MEF	Multi-Extension FITS
MEX	MATLAB EXecutable
MIT/LL	Massachusetts Institute of Technology/Lincoln Laboratory
NASA	National Aeronautics and Space Administration
OCS	Optical Cross Section
OPAL	Optical Processing Algorithms at Lincoln
PRF	Point Response Function
PSF	Point Spread Function
ROI	Region of Interest
RSO	Resident Space Object
SAT	SVST Analysis Tool
SNR	Signal-to-Noise Ratio
SSA	Space Situational Awareness
SST	Space Surveillance Telescope
SVST	Satellite Visualization and Signature Tool
TASAT	Time-Domain Analysis Simulation for Advanced Tracking
TLE	Two Line Element set
UCT	UnCorrelated Track
UTC	Coordinated Universal Time
WCS	World Coordinate System
ZA	Zenith Angle

Appendix A Definition of Apparent RSO Magnitudes

Original contribution of Ray Russell, Remote Sensing Dept., The Aerospace Corporation (retired)

The logarithmic magnitude system used to quantify the flux of nighttime (celestial and man-made) objects may seem awkward and backward at first, given that brighter objects have smaller magnitudes, and the negative magnitudes are thus the brightest of all, but it has the advantage of closely approximating the behavior of the human eye in judging relative brightness, which is what led the ancient Greeks and Pogson, in 1856, to adopt it. Being logarithmic, it easily shows a large dynamic range. One additional advantage of the magnitude system is that for small differences in magnitude, the magnitude difference is essentially the linear percentage change in brightness. Thus, an object that is 5% brighter than another object will have a magnitude about 0.05 smaller. Similarly, if one is addressing uncertainties or error bars, a 5% uncertainty will translate into a 0.05 uncertainty in the magnitude.

A.1 Basics of the Magnitude System

The apparent magnitude of an object is denoted by a lowercase m, in contrast to the absolute magnitude, denoted by M, which refers to the brightness of the object at a standard distance. We will only be dealing with apparent magnitude, m, in this discussion. Here, we will take the object to be a satellite or other man-made object and denote parameters related to it with the subscript “r” (for Resident Space Object, or RSO). The magnitude of the RSO is defined in terms of a reference object’s brightness, which we will take to be Vega, or alpha Lyrae, or some other reference star in the more general case, and denote parameters related to the star with an “s” for star or standard. Other stars could be used, with appropriate changes in some of the values below, but as Vega has been used by astronomers for a long time as the “standard candle,” it seems appropriate to cite it here as a specific example of a reference star. The definition of the apparent magnitude in a given passband is:

$$m_r = -2.5 * \log_{10}\left(\frac{I_r}{I_s}\right) + m_s \quad \textbf{(A- 1)}$$

where:

- m_r = the apparent magnitude over some wavelength (color) range or passband. For the eye, or visual magnitude, the range is approximately 5100–6100 Angstroms (full width at half maximum response), with a peak at 5500 Å, but the same methodology can be applied to an arbitrary filter passband/sensor combination. The same filter/passband must be used for both the measurement of the RSO and the reference star when deriving the magnitude of the object
- I_r = the in-band intensity, e.g., in Watts/cm^2, of the RSO without the attenuation of the earth’s atmosphere
- I_s = the in-band intensity of the reference star, e.g., Vega, above the earth’s atmosphere
- m_s = apparent in-band magnitude of the reference star (an example of a reference star is Vega, or alpha Lyrae, which is defined here to be zero magnitude at all wavelengths/passbands; others may assign a magnitude of as much as +/- 0.04 magnitudes to Vega at some wavelengths, and other reference stars may be used and will have different magnitudes and the magnitude is likely to vary with filter/passband)

Note that Equation (A- 1) calls out the “common” or base 10 log, not the natural log, so a magnitude difference of 5 corresponds to a factor of 100 in brightness.

A.2 Basics of Atmospheric Calibrations

We will now consider a sensor on the ground looking through a telescope at an RSO or star at some angular distance from straight overhead (i.e., from the zenith). This angular distance is defined as the Zenith Angle (ZA), and the ZA is the complement of the elevation angle (EL) from local horizontal. The elevation angle is sometimes referred to as the altitude, but this can be confusing, as altitude is usually used for the height above mean sea level or above the ground. The amount of air from the sensor to space along the zenith is called “one airmass” for that site. One airmass from the top of a tall mountain is clearly less than one airmass from sea level, but for this work, it is the relative amount of air as a function of angle from zenith that matters. As the angle from the zenith increases, the amount of air (in a plane parallel atmosphere) will increase proportionally to the secant of the ZA, sec (ZA), or 1/cos(ZA). This amount of air is referred to as the airmass, and at ZA = 60 degrees, the airmass = 2. When the airmass gets larger than about 3 airmasses, corrections related to the spherical nature of the atmosphere and the properties of the atmosphere require correction terms (see the discussion in *Stars and Stellar Systems, Vol. II, Astronomical Techniques*, p. 179-181, by Hardie, for example). For the discussion here, we will simply use the sec (ZA) for the airmass.

The light from the RSO or star will pass through the earth’s atmosphere where it will be attenuated by absorption and scattering. The scattering may take more than one form, as there may be scattering by small particulates (water drops, ice crystals, or volcanic dust or ash, for example) or there may be scattering/bending of the rays or distortions of the wavefront by cells of air with different indices of refraction along the path of the light through the atmosphere. This will result in a smearing out of the image in the telescope focal plane. If this occurs, the approach outlined here with extinction coefficients can still work if 1) The magnitude of the smearing by the atmosphere is constant, and 2) The fraction of light in the image collected and reported is the same for the RSO and for the star.

The amount of signal from a point target reported by an instrument will be a function of the instrument’s optical transmission, detector quantum efficiency (or equivalent) and electrical gain, as well as the effects of the earth’s atmosphere. For many instruments, the signal on a point target will need to be extracted from the data, and the details of how that is done (PSF or PRF fitting, or background determination and subtraction in aperture photometry are two examples) is a separate topic. However, for a stable instrument, the sensor effects will be the same (or corrected by the sensor’s calibration, as for the linearity correction and integration time normalization, for example), and the attenuation through the atmosphere is what must be additionally corrected. For this task, we may use extinction coefficients. Consider that the signal of the star (after point source extraction from the data) will be given by:

$$S_s(X_s) = C * S_{os} * e^{-\kappa_\lambda \chi_s} \; or \qquad \textbf{(A- 2)}$$

$$S_{os} = [S_s(X_s) * e^{\kappa_\lambda \chi_s}]/C \qquad \textbf{(A- 3)}$$

where:

- S_s (X_s) = the signal out of the instrument when viewing the reference star (e.g., Vega) through an airmass = X_s
- C = a constant that represents the properties of the sensor's response + telescope + filter throughput
- S_{os} = the amount of signal the sensor would produce if the measurement of the star were made without the atmospheric attenuation (the exo-atmospheric signal for the very distant star)
- κ_λ = the extinction coefficient at a wavelength, λ, or for the particular bandpass filter being used (note the kappas, κ's, are positive in this equation, so the measured signal in Equation (A- 2) is decreased for increasing airmass, X_s, as it should be)

If high accuracy is required and a bandpass of even modest spectral width is used, extinction coefficients that are wavelength dependent will need to be used together with models for spectral energy distributions of both the star and the RSO for the most accurate results. For this discussion, we will assume that a bandpass average κ value will be adequate.

Similar equations can be written for the RSO with the subscript r:

$$S_r(X_r) = C * S_{or} * e^{-\kappa_\lambda \chi_r} \ or \tag{A- 4}$$

$$S_{or} = [S_r(X_r) * e^{\kappa_\lambda \chi_r}]/C \tag{A- 5}$$

where:

- S_r (X_r) = the signal out of the instrument when viewing the RSO through an airmass = X_r
- C = the same constant as above that represents the properties of the sensor's response + telescope + filter throughput
- S_{or} = the amount of signal the sensor would produce if the measurement of the RSO were made (still from the ground) without the atmospheric attenuation
- κ_λ=same extinction coefficient as above

The exo-atmospheric apparent magnitude of the RSO is the desired quantity. As the unattenuated signals (subscript o) are proportional to the intensities of the RSO and star, we can use Equation (A- 1) to write the apparent magnitude of the RSO as:

$$m_r = -2.5 * \log_{10}\left(\frac{S_{or}}{S_{os}}\right) + m_s. \tag{A- 6}$$

By substitution, we now have:

$$m_r = -2.5 * \ \log_{10} \frac{\frac{S_r \chi_r e^{\kappa_\lambda \chi_r}}{C}}{\frac{S_s \chi_s e^{\kappa_\lambda \chi_s}}{C}} + m_s \tag{A- 7}$$

which can be simplified to:

$$m_r = -2.5 * \ \log_{10}\left\{\frac{S_r}{S_s} e^{\kappa_\lambda(\chi_r - \chi_s)}\right\} + \ m_s \tag{A- 8}$$

and rewritten as:

$$m_r = -2.5\{\log_{10} S_r - \log_{10} S_s + \log_{10} e^{\kappa_\lambda(\chi_r - \chi_s)}\} + m_s. \tag{A- 9}$$

If the star and the RSO were observed at the same ZA (i.e., $X_r = X_s$), then this becomes:

$$m_r = -2.5 \log_{10} S_r + 2.5 \log_{10} S_s + m_s. \tag{A- 10}$$

We can assign (define) the sum of the last two terms to be an instrumental magnitude for the standard star, and denote that by $m_{im\,s}$, so Equation (A- 10) becomes:

$$m_r = -2.5 \log_{10} S_r + m_{im\,s}. \tag{A- 11}$$

If the sensor design is such that the use of longer integration times produces more signal (versus simply producing a more accurate average signal value) and the star is observed for the same integration time ($t_{int\,s}$) as the RSO ($t_{int\,r}$), then Equation (A- 11) is adequate to use.

If, however, the size of the signal depends upon the integration time and the integration times used for the star and RSO are different, Equation (A- 10) needs to be modified to account for any difference in integration (or exposure) time by simply dividing the measured signals by integration times. This yields:

$$m_r = -2.5 \log_{10}\left(\frac{S_r}{t_{int\,r}}\right) + 2.5 \log_{10}\left(\frac{S_s}{t_{int\,s}}\right) + m_s. \tag{A- 12}$$

If Vega is used, we have defined $m_s = 0$ for all wavelengths. In the most general case of any reference star, there are different airmasses for the star and RSO, and/or different integration times for the star and for the RSO. Then Equation (A- 9) becomes:

$$m_r = -2.5\left\{\log_{10}\left(\frac{S_r}{t_{int\,r}}\right) - \log_{10}\left(\frac{S_s}{t_{int\,s}}\right) + \log_{10} e^{\kappa_\lambda(\chi_r - \chi_s)}\right\} + m_s. \tag{A- 13}$$

Equation (A- 13) can be simplified using the rules for logarithms with different bases, which states:

$$\log_{10}(y) = \frac{\ln y}{\ln 10} = \frac{\ln y}{2.303}. \tag{A- 14}$$

Thus with:

$$y = e^{\kappa_\lambda(\chi_r - \chi_s)} \tag{A- 15}$$

and

$$\ln e^a = a. \tag{A- 16}$$

Then Equation (A- 13) becomes:

$$m_r = -2.5 \log_{10}\left(\frac{S_r}{t_{int\,r}}\right) + 2.5 \log_{10}\left(\frac{S_s}{t_{int\,s}}\right) - \frac{2.5 * \kappa_\lambda(\chi_r - \chi_s)}{2.303} + m_s \tag{A- 17}$$

or more simply:

$$m_r = -2.5\log_{10}\left(\frac{S_r}{t_{int\,r}}\right) + 2.5\log_{10}\left(\frac{S_s}{t_{int\,s}}\right) - 1.086 * \kappa_\lambda(\chi_r - \chi_s) + m_s. \qquad \textbf{(A- 18)}$$

Equation (A- 18) then can be used to compute the exo-atmospheric magnitude of an RSO given the standard star catalog magnitude and that the atmospheric κ_λ has been computed.

The magnitude value in Equation (A- 18) represents the energy flux received by the detector, which is a function of the object's intrinsic brightness and its distance or range from the observer. It is common to take out the effect of range by normalizing to a standard distance, say 1000 km. To accomplish this, the distance modulus should be used, where the range-normalized magnitude, M_r, is calculated by:

$$M_r = m_r - 5\log_{10}\frac{d}{D} \qquad \textbf{(A- 19)}$$

where:

- m_r is the exo-atmospheric magnitude from Equation (A- 18)
- d is the distance of the target to the sensor
- D is the standard distance used to remove the range effect (1000 km is commonly used, which is the value expected to be used to range-normalize in the EOSSA format; in this case, the actual range, d, then should also be in km)

A.3 References

[A1] Hardie, R. H., "Photoelectric Reductions," p. 179-181, in Stars and Stellar Systems, Volume II, Astronomical Techniques, ed. by W. A. Hiltner, ©1962, University of Chicago.

Appendix B Simple FITS File with Binary Table Extension

This is a simple example of a FITS file with a binary table extension.

```
//Primary Header begin
SIMPLE   = T
BITPIX   = 8
NAXIS    = 0
EXTEND   = T
NEXTEND= 0
DATE     = 2012-04-16T23:22:59.1030
END//Primary Header end
//Binary Table Extension begin
//Binary Table Extension Header begin
XTENSION= BINTABLE
BITPIX   = 8
NAXIS    = 2
NAXIS1   = 27
NAXIS2   = 3
PCOUNT   = 0
GCOUNT   = 1
TFIELDS  = 1
TFORM1   = 27A
TTYPE1   = UTC_Begin_Exp
TUNIT1   = char
END//Binary Table Extension Header end
//Binary Table Extension data table begin
Row      UTC_Begin_Exp
1        2002-12-14T04:31:01.9520000
2        2002-12-14T04:31:04.2850000
3        2002-12-14T04:31:06.7040000
//Binary Table Extension data table end
//Binary Table Extension end
```

Appendix C Spectrophotometric Data for the Sun

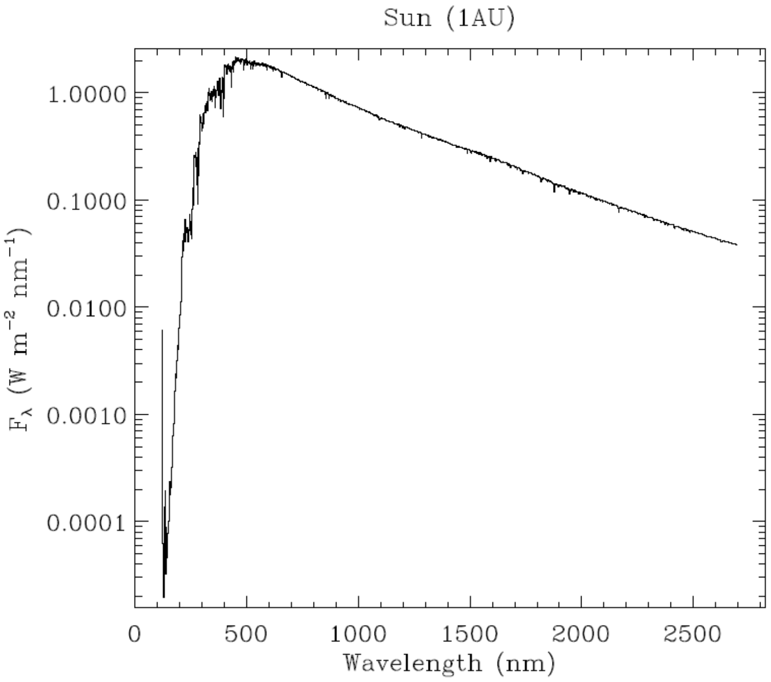
Taken from Space Telescope Science Institute web site

The solar flux is integrated over each the spectral band used by the sensor for a range of 1 A.U. This data set and figure are from the Space Telescope Science Institute web site. The data set is too large to include in this Word document, but is included as an attachment to the distribution of the EOSSA document. The following is a short example of the contents of the sun_reference_stis_001.fits file.

To calculate the solar magnitude in the specific sensor spectral band(s), integrate the flux from the cut-on to the cut-off wavelength, then convert the flux to in-band magnitude and report that value in the EOSSA binary table extension header parameter #31 in Table 6, SPFSMGn.

```
Wavelength (nm), Flux (W m^-2 nm^-1)
   119.500    8.86150e-005
   120.500    6.94500e-004
   121.500    6.08100e-003
   122.500    1.43700e-003
   123.500    6.26950e-005
   124.500    4.07550e-005
   125.500    3.37800e-005
   126.500    4.16250e-005
   127.500    2.41500e-005
   128.500    1.95450e-005
   129.500    4.66800e-005
   130.500    1.38100e-004
   131.500    4.48100e-005
   132.500    4.64950e-005
   133.500    1.93050e-004
   134.500    5.06300e-005
   135.500    4.19650e-005
   136.500    3.43250e-005
   137.500    3.22600e-005
   138.500    4.49450e-005
   139.500    8.89900e-005
   140.500    6.81950e-005
   141.500    4.61250e-005
   142.500    5.12100e-005
   143.500    5.57900e-005
   144.500    5.57050e-005
```

From this list of wavelength and flux, a figure like the one in Figure C-1 below can be created.



C:\work\DAS\BPGS_Cal_Stars\sun_reference_stis_001.ps (created Thu Jan 03 07:27:39 2008)

Figure C-1 – Solar Reference Spectrum from 0.12 – 2.7 microns.

C.1 Reference

[C1] http://www.stsci.edu/hst/observatory/cdbs/calspec.html

Appendix D Photometric Color Terms

Contributed by Dr. John V. Lambert (The Boeing Company, retired)

The general standard photometric equation for in-band magnitude is:

$$m_{cat} = m_o - 1.086 * (k'X - k''CX) + eC + z \tag{D- 1}$$

where:

- m_{cat} is the catalog magnitude (in whatever band)
- m_o is the instrumental magnitude
- X is the air mass
- k' is the atmospheric extinction
- C is a color (e.g., B-V)
- k" is an atmospheric extinction color correction term (usually second order and not always used)
- e is the color correction term (CCOEFn in the EOSSA table header)
- z is the zero point

For space-based sensors, we can drop the atmospheric air mass terms since X=0. However, the color correction term, e, is still in play and is useful to include in order to understand the status of the filter and how it is degrading with time.

Generally, the color term is a transformation term used to correct for smaller differences between the instrumental and the standard bands. This correction is standard for most narrowband astronomical observations, and several SSA sensors also use it. For our very broadband (panchromatic) SSA systems, a single, first order color correction term is probably not sufficient to transform broadband CCD measurements into a standard astronomical band. Including the color transformation term "e" in the photometric equation would allow for correction of this residual magnitude error.

What currently is shown as an optional field is CCOEFn, which is the value of the coefficient for the (B-R) color correction term, that is, parameter “e” in Equation (D- 1). This would support the standard astronomical approach. These color transformation terms are a key part of the calibration process used in converting instrumental measurements to reported standard magnitudes. As such, they are already computed by SSN sensors and so can be reported in the EOSSA format.

Note to providers and users using OPAL[15]

The approach used in OPAL where the reference stars are converted into the broad sensor band should be better. According to the OPAL documentation (dated 12 Sept 2011) on the color correction calculation in Section 2.1, there is an example plot on page 18 that shows there is still a residual slope in the sensor-band based magnitude residual (S-R) as a function of the reference star (B-R) until things fall apart for (B-R)>2 [D1]. OPAL does include this color correction, and examples are shown in the OPAL documentation

---

[15] Optical Processing Architecture at Lincoln (OPAL) code written by MIT/Lincoln Laboratory and used by some EO SSN sensors.

as equations 2.1 (for a linear correction) and 2.2 (for a quadratic correction). Rather than the single color term e(B-R) shown above, there would be two: e1(B-R) + e2(B-R)^2. The second term would be zero if only a linear calculation was used, but there could still be some associated uncertainty. The recommendation is to always use the quadratic solution and report e2 (even if it were very small) just to standardize the reporting process along with each term's uncertainties. E2 can be added as an optional field in EOSSA. What currently is shown as an optional field is CCOEFn, which is the value of the coefficient for the (B-R) color correction term, that is, parameter "e" in Equation (D- 1). This would support the OPAL calibration approach.

D.1 References

[D1] OPAL Calibration Algorithms Description Document Version 0.1, Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, MA, September 12, 2011.

Appendix E Calculation of Optical Cross Section for EO SSA Purposes

Contributed by Dr. Doyle T. Hall (Omitron Inc. formerly with The Boeing Company)

In EOSSA, we use the Optical Cross Section (OCS) that is a body's "differential cross section for photon scattering." It has units of m^2/steradians and can be calculated using a formula from Hall's 2004 paper:

$$OCS = R_o{}^2 * \left(\frac{F_o}{F_s}\right) \tag{E- 1}$$

where:

- R_o is the range from the target to the observing sensor in meters
- F_o is the band-averaged irradiance measured by the observer (photon flux m^{-2} s^{-1} nm^{-1})
- F_s is the band-averaged irradiance of the sun incident on the target (photon flux m^{-2} s^{-1} nm^{-1})

But a more convenient form when working with magnitudes is:

$$OCS = R_o{}^2 * 10^{(-0.4*(m_o - m_s))} \tag{E- 2}$$

where:

- m_o is the in-band magnitude measured by observer
- m_s is the in-band magnitude of sun at the target

When using the EOSSA range-normalized magnitudes, $M_o = m_o(R_o\text{=1000km}, R_{sun}\text{=1 AU})$, then R_o = 10^6 m and m_s is the solar magnitude at 1 AU tabulated in the EOSSA header quantity SPFSMGn for M_o in Filter n (see Appendix C and parameters #31 and #32 in Table 6).

Here is some code from one of Hall's MATLAB functions to calculate a matrix of OCS values and uncertainties from the range-normalized magnitudes and uncertainties:

```
expo = 12.0 - 0.4*(data.Mag_Range_Norm - hedr.SPFSMG1);
base = 10.0 * ones(size(expo));
data.Opt_Cross_Sec = base .^ expo;
data.Opt_Cross_Sec_Unc = data.Opt_Cross_Sec .* data.Mag_Unc / (2.5 / log(10));
```

E.1 References

[E1] Hall, D.T., Africano, J., Kervin, P., Kelecy, T., Kremeyer, K., Lambert, J., Okada, J., Ross, J., Sydney, P., "*AMOS Measurements of the Physical Properties of NaK Droplets*", 2004 AMOS Conference, Wailea, Hawaii, 2004.

Appendix F Calculation of the Fraction of the Sun that is Illuminating the RSO

This appendix was prepared to support the EOSSA data provider in this calculation. The vast majority of this information was taken directly from the TASAT User's Manual, Doc ID. ABQ-107-0002, June 12, 2008, Chapter 4, though some modifications were made.

TASAT also determines the lighting conditions for the target. That is, whether it is illuminated directly by the sun or whether it is in the Earth's shadow. There will be cases of partial illumination and total solar eclipses caused by the Earth with regularity. The eclipse conditions can be determined with the help of Figure 0-1. Let R_s be the radius of the Sun, R_p be the radius of the planet, and S be the distance between the centers of the Sun and the planet. The distance C from the planet's center to the apex of the Sun's shadow can be computed from

$$C = \frac{R_p S}{R_s - R_p} \tag{1}$$

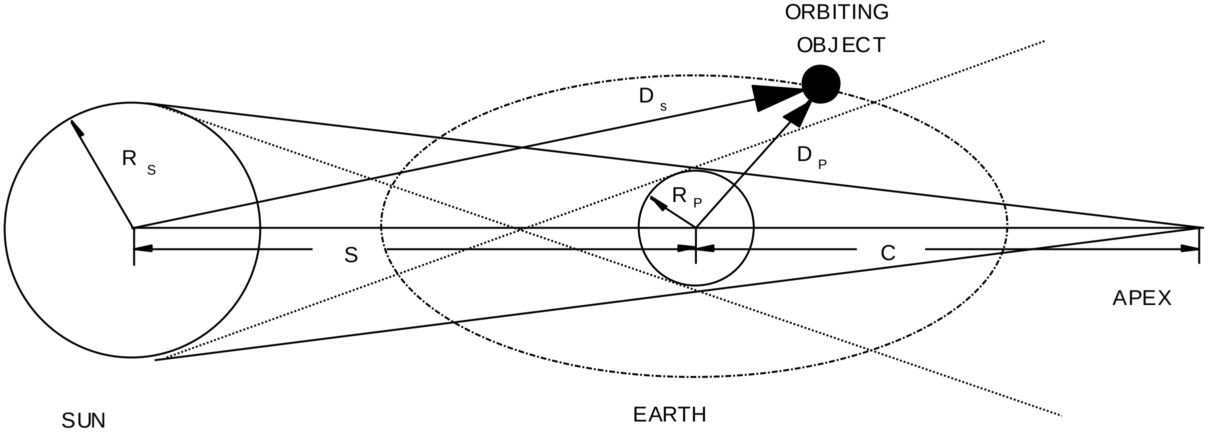


Figure 0-1. Illustration of Eclipse Geometry

The size of the Earth's shadow cone the at its mean distance from the Sun is C_E = 1.385x10^6 km and the angular radius is ρ_{ce} = 0.264°. For the Moon, the mean distance is C_M = 3.75x10^5 km and ρ_{cm} = 0.266°. The length of the shadow cone of the Moon is just less than the semi-major axis of the Moon's orbit around the Earth of 3.84x10^5 km. Eclipses of the Sun seen on the Earth are most often annular eclipses. When they are total eclipses they are seen only over a very narrow band of the Earth's surface. The maximum radius of the Moon's shadow cone at the distance of the Earth's surface is 135 km.

To develop specific eclipse conditions, let $\boldsymbol{D_s}$ be a vector from the orbiting spacecraft to the Sun and $\boldsymbol{D_p}$ be a vector from the spacecraft to the center of the planet. We assume that there are no atmospheric effects and that we are concerned with eclipses seen by objects of negligible size, such as spacecraft. The conditions for the satellite to see a total eclipse of the Sun are exactly the same for a transit of the satellite as viewed from the apex of the shadow cone. Similarly, the conditions for the spacecraft to see a partial eclipse are nearly the same as those for occultation of the spacecraft viewed from point in the direction of the Sun equidistant from the planet as the apex of the shadow cone. Three quantities of interest are the angular radius of the Sun, ρ_S, the angular radius of the planet, ρ_P, and the angular separation, θ, between the Sun and planet as viewed by the spacecraft. See Figure 0-2.

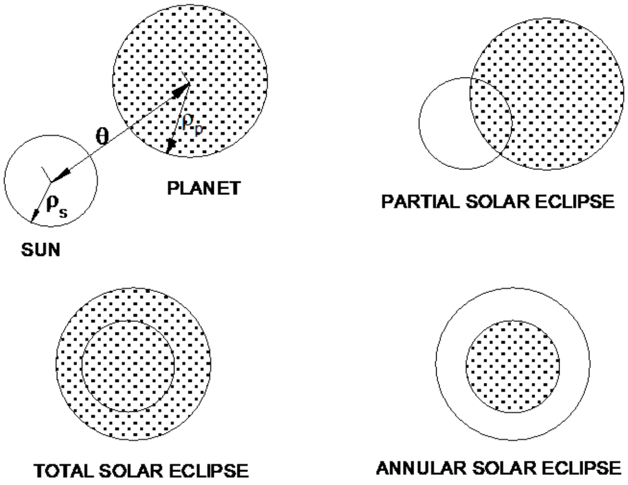


Figure 0-2. Solar Eclipse Geometry

These are given by:

$$\rho_S = sin^{-1}\left(\frac{R_S}{\|D_S\|}\right)$$
$$\rho_P = sin^{-1}\left(\frac{R_P}{\|D_P\|}\right) \tag{2}$$
$$\theta = cos^{-1}\left(\frac{D_S \bullet D_P}{\|D_S\| \cdot \|D_P\|}\right)$$

The necessary and sufficient eclipse conditions are

1. Partial Eclipse:

$$\|D_S\| > S \text{ and } \rho_P + \rho_S > \theta > |\rho_P - \rho_S| \tag{3}$$

2. Total Eclipse:

$$S < \|D_S\| < (S + C) \text{ and } \rho_P - \rho_S > \theta \tag{4}$$

3. Annular Eclipse:

$$S + C < \|D_S\| \text{ and } \rho_S - \rho_P > \theta \tag{5}$$

The surface brightness of the Sun is nearly uniform over the surface of the disk. Therefore the intensity, I, of the illumination on the spacecraft during a partial or an annular eclipse is directly proportional to the area of the solar disk that can be seen by the spacecraft. The fraction of the fully illuminated intensity, I/I_0, is computed from:

1. Partial Eclipse:

$$\begin{aligned}\frac{I}{I_0} = 1 - \frac{1}{\pi(1-\cos\rho_s)}[\pi - \cos\rho_s \cos^{-1}\left(\frac{\cos\rho_p - \cos\rho_s \cos\theta}{\sin\rho_s \sin\theta}\right) \\ - \cos\rho_p \cos^{-1}\left(\frac{\cos\rho_s - \cos\rho_p \cos\theta}{\sin\rho_p \sin\theta}\right) \\ - \cos^{-1}\left(\frac{\cos\theta - \cos\rho_s \cos\rho_p}{\sin\rho_s \sin\rho_p}\right)]\end{aligned} \tag{6}$$

2. Annular Eclipse:

$$\frac{I}{I_0} = 1 - \left(\frac{1-\cos\rho_p}{1-\cos\rho_s}\right) \tag{7}$$

F.1 Reference

[F1] SOFTWARE USER'S MANUAL FOR TIME-DOMAIN ANALYSIS SIMULATION FOR ADVANCED TRACKING (TASAT), Doc ID. ABQ-107-0002, June 12, 2008, Northrop Grumman Information Technology, Science and Engineering Applications Division, 2600 Yale Blvd. SE, Albuquerque, NM 87106.

Appendix G Example of an EOSSA File

This appendix shows an example of the contents of an EOSSA file. Table G-1 shows the primary header of the EOSSA file. The format of the primary header is described in Section 2.4. The binary table extension header is shown in Table G-2. The binary data table is described in Section G.2.2 in Table G-3 and Table G-4. The latter extends over several pages. The TTYPEn values in Table G-3 are described in more detail in Section 3.7 Table 7.

G.1 Primary Header Example

Table G-1 - EOSSA Primary Header Example

Header Keyword	Keyword Value	Comment
SIMPLE	T	file does conform to FITS standard
BITPIX	8	number of bits per data pixel
NAXIS	0	number of data axes
EXTEND	T	FITS dataset may contain extensions
COMMENT FITS (Flexible Image Transport System) format is defined in 'Astronomy		
COMMENT and Astrophysics', volume 376, page 359; bibcode: 2001A&A...376..359H		
CLASSIF	'UNCLASS'	Security classification level of the data contained in the file

G.2 Binary Table Extension

G.2.1 Binary Table Header Example

Table G-2 - EOSSA Binary Table Extension Header Example

Header Keyword	Keyword Value	Comment
BITPIX	8	8-bit bytes
NAXIS	2	2-dimensional binary table
NAXIS1	406	width of table in bytes
NAXIS2	57	number of rows in table
PCOUNT	0	size of special data area
GCOUNT	1	one data group (required keyword)

Header Keyword	Keyword Value	Comment
TFIELDS	27	number of fields in each row
TTYPE1	'UTC_Begin_Exp'	label for field 1
TFORM1	'19A	data format of field: ASCII Character
TUNIT1	'yyyy-mm-ddThh:mm:ss{.sssssss}'	physical unit of field
TTYPE2	'UTC_End_Exp'	label for field 2
TFORM2	'19A	data format of field: ASCII Character
TUNIT2	'yyyy-mm-ddThh:mm:ss{.sssssss}'	physical unit of field
TTYPE3	'JD_Mid_Exp'	label for field 3
TFORM3	'D	data format of field: 8-byte DOUBLE
TUNIT3	'days	physical unit of field
TTYPE4	'Exp_Duration'	label for field 4
TFORM4	'D	data format of field: 8-byte DOUBLE
TUNIT4	'sec	physical unit of field
TTYPE5	'Cur_Spec_Filt_Num'	label for field 5
TFORM5	'J	data format of field: 4-byte INTEGER
TUNIT5	'num	physical unit of field
TTYPE6	'Cur_ND_Filt_Num'	label for field 6
TFORM6	'J	data format of field: 4-byte INTEGER
TUNIT6	'num	physical unit of field
TTYPE7	'Mag_Exo_Atm'	label for field 7
TFORM7	'D	data format of field: 8-byte DOUBLE
TUNIT7	'mag	physical unit of field
TTYPE8	'Mag_Exo_Atm_Unc'	label for field 8
TFORM8	'D	data format of field: 8-byte DOUBLE
TUNIT8	'mag	physical unit of field
TTYPE9	'Mag_Range_Norm'	label for field 9
TFORM9	'D	data format of field: 8-byte DOUBLE
TUNIT9	'mag	physical unit of field
TTYPE10	'SNR_Est	label for field 10
TFORM10	'D	data format of field: 8-byte DOUBLE
TUNIT10	'num	physical unit of field
TTYPE11	'Mag_Instrumental'	label for field 11
TFORM11	'D	data format of field: 8-byte DOUBLE

Header Keyword	Keyword Value	Comment
TUNIT11	'mag	physical unit of field
TTYPE12	'Obj_State_Vec'	label for field 12
TFORM12	'6D	data format of field: 8-byte DOUBLE
TUNIT12	'm&m/s	physical unit of field
TTYPE13	'Tel_State_Vec'	label for field 13
TFORM13	'6D	data format of field: 8-byte DOUBLE
TUNIT13	'm&m/s	physical unit of field
TTYPE14	'Tel_Obj_Range'	label for field 14
TFORM14	'D	data format of field: 8-byte DOUBLE
TUNIT14	'm	physical unit of field
TTYPE15	'CCD_Obj_Pos'	label for field 15
TFORM15	'2D	data format of field: 8-byte DOUBLE
TUNIT15	'pixels	physical unit of field
TTYPE16	'Net_Obj_Sig'	label for field 16
TFORM16	'D	data format of field: 8-byte DOUBLE
TUNIT16	'DN/sec	physical unit of field
TTYPE17	'Airmass	label for field 17
TFORM17	'D	data format of field: 8-byte DOUBLE
TUNIT17	'num	physical unit of field
TTYPE18	'Longitudinal_Phase_Angle'	label for field 18
TFORM18	'D	data format of field: 8-byte DOUBLE
TUNIT18	'deg	physical unit of field
TTYPE19	'Sun_State_Vec'	label for field 19
TFORM19	'6D	data format of field: 8-byte DOUBLE
TUNIT19	'm&m/s	physical unit of field
TTYPE20	'Eph_RA_DE'	label for field 20
TFORM20	'2D	data format of field: 8-byte DOUBLE
TUNIT20	'deg	physical unit of field
TTYPE21	'Met_RA_DE'	label for field 21
TFORM21	'2D	data format of field: 8-byte DOUBLE
TUNIT21	'deg	physical unit of field
TTYPE22	'Eph_AZ_EL'	label for field 22
TFORM22	'2D	data format of field: 8-byte DOUBLE

Header Keyword	Keyword Value	Comment
TUNIT22	'deg	physical unit of field
TTYPE23	'Met_AZ_EL'	label for field 23
TFORM23	'2D	data format of field: 8-byte DOUBLE
TUNIT23	'deg	physical unit of field
TTYPE24	'Sun_AZ_EL'	label for field 24
TFORM24	'2D	data format of field: 8-byte DOUBLE
TUNIT24	'deg	physical unit of field
TTYPE25	'Solar_Phase_Ang'	label for field 25
TFORM25	'D	data format of field: 8-byte DOUBLE
TUNIT25	'deg	physical unit of field
TTYPE26	'Phase_Ang_Bisect'	label for field 26
TFORM26	'2D	data format of field: 8-byte DOUBLE
TUNIT26	'deg	physical unit of field
TTYPE27	'Solar_Disk_Frac'	label for field 27
TFORM27	'D	data format of field: 8-byte DOUBLE
TUNIT27	'num	physical unit of field
EXTNAME	'37737_SSO_180718091734-180718190346.eossa'	Filename of this FITS bi
CLASSIF	'UNCLASS	Security classification level of the data conta
VERS	'3.1.1	Version number of the EOSSA_data format
OBSEPH	'GROUND	Observer type, i.e. ground-based, space-based w
PHOTTYP	'Signature'	This is where the product type is identified
BASING	'GROUND	The type of sensor basing is identified here
TELESCOP=	'	Telescope site name or SSN sensor identifier
TELLAT	-31.2733	Telescope Geographical Latitude
TELLONG	149.064	Telescope Geographical Longitude
TELALT	1165	Telescope Geographical Altitude
OBSNAME	'Kestrel	Telescope name
OBJEPH	'TLE	Target Object Ephemeris Source
OBJTYPE	'SCN	If the target has a space catalog number, the s
OBJNUM	37737	If OBJTYPE='SCN', the space catalog number of t
UCTFLAG	F	Identifier flagging the object as a UCT
OBJECT	'Tianlian-1-02'	Common name of target object if available
TLELN1	'37737U	

Header Keyword	Keyword Value	Comment
TLELN2	'37737	
SPFNUM	1	The value is the number of spectral filters use
SPFNAM1	'R	Spectral filter name
SPFSMG1	-27.1194	In-band solar magnitude at 1 A.U.
ZEROPT1	18.99	This is the value for the zero-point calculated
EXTINC1	0.1	The extinction coefficient computed for the nth
PIXMIN	0	Minimum valid pixel value, this is typically 0
PIXMAX	65535	Maximum valid pixel value, this is defined as 2
STARCAT	'Landolt_2009'	Name and version of photometric star catalog us

G.2.2 Binary Table Example

Table G-3 - EOSSA Binary Table Columns

Column #	TTYPEn Values
1	'UTC_Begin_Exp'
2	'UTC_End_Exp'
3	'JD_Mid_Exp'
4	'Exp_Duration'
5	'Cur_Spec_Filt_Num'
6	'Cur_ND_Filt_Num'
7	'Mag_Exo_Atm'
8	'Mag_Exo_Atm_Unc'
9	'Mag_Range_Norm'
10	'SNR_Est
11	'Mag_Instrumental'
12	'Obj_State_Vec'
13	'Tel_State_Vec'
14	'Tel_Obj_Range'
15	'CCD_Obj_Pos'
16	'Net_Obj_Sig'
17	'Airmass
18	'Longitudinal_Phase_Angle'
19	'Sun_State_Vec'
20	'Eph_RA_DE'
21	'Met_RA_DE'
22	'Eph_AZ_EL'
23	'Met_AZ_EL'
24	'Sun_AZ_EL'
25	'Solar_Phase_Ang'
26	'Phase_Ang_Bisect'
27	'Solar_Disk_Frac'

Table G-4 - Columns in the Binary Table of an EOSSA File (Example)

Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7	Column 8	Column 9	Column 10
'2018-07-18T09:17:35'	'2018-07-18T09:17:55'	2458318	20	1	**-2.1E+09**	11.7454	0.0341	3.871487	33.34
'2018-07-18T09:18:31'	'2018-07-18T09:18:51'	2458318	20	1	**-2.1E+09**	11.6289	0.0311	3.75503	36.89
'2018-07-18T09:20:22'	'2018-07-18T09:20:42'	2458318	20	1	**-2.1E+09**	11.7092	0.033	3.835416	34.55
'2018-07-18T09:21:12'	'2018-07-18T09:21:32'	2458318	20	1	**-2.1E+09**	11.5681	0.0295	3.694354	39.11
'2018-07-18T09:25:00'	'2018-07-18T09:25:20'	2458318	20	1	**-2.1E+09**	11.4547	0.0269	3.581129	43.45
'2018-07-18T09:25:48'	'2018-07-18T09:26:08'	2458318	20	1	**-2.1E+09**	11.5514	0.029	3.677866	39.89
'2018-07-18T09:28:35'	'2018-07-18T09:28:55'	2458318	20	1	**-2.1E+09**	11.3584	0.025	3.484994	47.28
'2018-07-18T10:14:00'	'2018-07-18T10:14:20'	2458318	20	1	**-2.1E+09**	10.9719	0.0189	3.100543	67.74
'2018-07-18T11:12:30'	'2018-07-18T11:12:50'	2458318	20	1	**-2.1E+09**	10.5481	0.0148	2.679177	99.34
'2018-07-18T11:14:12'	'2018-07-18T11:14:32'	2458318	20	1	**-2.1E+09**	10.5651	0.015	2.696243	96.8
'2018-07-18T12:10:17'	'2018-07-18T12:10:37'	2458318	20	1	**-2.1E+09**	9.9956	0.0124	2.128715	148.73
'2018-07-18T12:12:00'	'2018-07-18T12:12:20'	2458318	20	1	**-2.1E+09**	10.0612	0.0125	2.194369	143.39
'2018-07-18T12:14:36'	'2018-07-18T12:14:56'	2458318	20	1	**-2.1E+09**	10.1495	0.0128	2.282749	134.55

Column 11	Column 12	Column 13	Column 14	Column 15
-7.0964	[-1.27550694e+07; -4.01816911e+07; 6.93958990e+04; 2.92745358e+03; -9.29671816e+02; -1.50829282e+02]	[-3.88302972e+06; -3.83463014e+06; -3.29243337e+06; 2.79625672e+02; -2.83155026e+02; 0.00000000e+00]	37564928	[1696.; 1654.]
-7.2128	[-1.25910292e+07; -4.02334163e+07; 6.09491212e+04; 2.93122920e+03; -9.17693002e+02; -1.50848732e+02]	[-3.86733835e+06; -3.85045481e+06; -3.29243337e+06; 2.80779626e+02; -2.82010793e+02; 0.00000000e+00]	37564183	[1694.; 1664.]
-7.1325	[-1.22652601e+07; -4.03339585e+07; 4.42035260e+04; 2.93856840e+03; -8.93904251e+02; -1.50879846e+02]	[-3.83604546e+06; -3.88163153e+06; -3.29243337e+06; 2.83053068e+02; -2.79728879e+02; 0.00000000e+00]	37562707	[1676.; 1686.]
-7.2737	[-1.21182534e+07; -4.03783844e+07; 3.66594526e+04; 2.94181144e+03; -8.83169378e+02; -1.50890631e+02]	[-3.82186735e+06; -3.89559214e+06; -3.29243337e+06; 2.84071092e+02; -2.78694995e+02; 0.00000000e+00]	37562042	[1671.; 1696.]
-7.3871	[-1.14458886e+07; -4.05741504e+07; 2.25373955e+03; 2.95610311e+03; -8.34071634e+02; -1.50914365e+02]	[-3.75657389e+06; -3.95859328e+06; -3.29243337e+06; 2.88665208e+02; -2.73933720e+02; 0.00000000e+00]	37559014	[1659.; 1738.]
-7.2905	[-1.13039287e+07; -4.06139363e+07; -4.98997053e+03; 2.95900783e+03; -8.23705440e+02; -1.50914043e+02]	[-3.74269498e+06; -3.97171781e+06; -3.29243337e+06; 2.89622264e+02; -2.72921654e+02; 0.00000000e+00]	37558377	[1658.; 1746.]
-7.4835	[-1.08089576e+07; -4.07484760e+07; -3.01910315e+04; 2.96883102e+03; -7.87561896e+02; -1.50898510e+02]	[-3.69405174e+06; -4.01700011e+06; -3.29243337e+06; 2.92924302e+02; -2.69374533e+02; 0.00000000e+00]	37556164	[1646.; 1777.]
-7.8713	[-2.55941646e+06; -4.20782315e+07; -4.38087848e+05; 3.06605122e+03; -1.85215246e+02; -1.47494375e+02]	[-2.82838421e+06; -4.66717805e+06; -3.29243337e+06; 3.40336030e+02; -2.06249053e+02; 0.00000000e+00]	37520748	[1663.; 1751.]
-8.2965	[8.16846008e+06; -4.13498983e+07; -9.35879244e+05; 3.01339896e+03; 5.97947127e+02; -1.34597680e+02]	[-1.55466333e+06; -5.23118821e+06; -3.29243337e+06; 3.81464305e+02; -1.13367851e+02; 0.00000000e+00]	37478710	[1704.; 1835.]
-8.2795	[8.47559184e+06; -4.12877652e+07; -9.49582263e+05; 3.00888359e+03; 6.20365939e+02; -1.34086190e+02]	[-1.51571132e+06; -5.24260692e+06; -3.29243337e+06; 3.82296971e+02; -1.10527425e+02; 0.00000000e+00]	37477574	[1698.; 1852.]
-8.8502	[1.82449947e+07; -3.79840205e+07; -1.36781992e+06; 2.76854345e+03; 1.33338643e+03; -1.13242242e+02]	[-1.96749893e+05; -5.45376912e+06; -3.29243337e+06; 3.97695163e+02; -1.43472301e+01; 0.00000000e+00]	37443549	[1709.; 1875.]
-8.7847	[1.85296314e+07; -3.78456141e+07; -1.37944549e+06; 2.75847009e+03; 1.35415781e+03; -1.12489698e+02]	[-1.55782141e+05; -5.45509304e+06; -3.29243337e+06; 3.97791704e+02; -1.13598142e+01; 0.00000000e+00]	37442624	[1697.; 1891.]
-8.6964	[1.89587358e+07; -3.76319247e+07; -1.39690474e+06; 2.74291720e+03; 1.38547136e+03; -1.11337851e+02]	[-9.37178783e+04; -5.45651217e+06; -3.29243337e+06; 3.97895189e+02; -6.83401627e+00; 0.00000000e+00]	37441237	[1691.; 1912.]

Column 16	Column 17	Column 18	Column 19	Column 20
522.3595	1.48	-41.21	[-6.59819008e+10; 1.25672388e+11; 5.44793650e+10; -2.63498509e+04; -1.17658061e+04; -5.10052372e+03]	[2.52388747e+02; 9.43149527e-02]
581.501	1.48	-40.97	[-6.59833767e+10; 1.25671730e+11; 5.44790796e+10; -2.63497112e+04; -1.17660719e+04; -5.10063892e+03]	[2.52622513e+02; 8.28350377e-02]
540.059	1.48	-40.51	[-6.59863020e+10; 1.25670425e+11; 5.44785138e+10; -2.63494344e+04; -1.17665986e+04; -5.10086726e+03]	[2.53085869e+02; 6.00763192e-02]
615.0355	1.48	-40.28	[-6.59876197e+10; 1.25669837e+11; 5.44782589e+10; -2.63493097e+04; -1.17668359e+04; -5.10097011e+03]	[2.53294588e+02; 4.98232763e-02]
682.743	1.48	-39.36	[-6.59936283e+10; 1.25667156e+11; 5.44770967e+10; -2.63487410e+04; -1.17679178e+04; -5.10143913e+03]	[2.54246344e+02; 3.06301869e-03]
624.65	1.48	-39.14	[-6.59948932e+10; 1.25666591e+11; 5.44768520e+10; -2.63486213e+04; -1.17681456e+04; -5.10153786e+03]	[2.54446714e+02; -6.78178207e-03]
746.149	1.48	-38.44	[-6.59992942e+10; 1.25664627e+11; 5.44760007e+10; -2.63482047e+04; -1.17689380e+04; -5.10188139e+03]	[2.55143832e+02; -4.10320841e-02]
1066.506	1.47	-27.05	[-6.60710960e+10; 1.25632563e+11; 5.44621005e+10; -2.63414035e+04; -1.17818668e+04; -5.10748605e+03]	[2.66519262e+02; -5.95399998e-01]
1577.664	1.45	-12.51	[-6.61635547e+10; 1.25591209e+11; 5.44441735e+10; -2.63326321e+04; -1.17985153e+04; -5.11470321e+03]	[2.81174610e+02; -1.27199048e+00]
1553.173	1.45	-12.05	[-6.61662411e+10; 1.25590006e+11; 5.44436522e+10; -2.63323770e+04; -1.17989990e+04; -5.11491290e+03]	[2.81600574e+02; -1.29061676e+00]
2627.308	1.44	1.95	[-6.62548505e+10; 1.25550305e+11; 5.44264413e+10; -2.63239560e+04; -1.18149545e+04; -5.12182966e+03]	[2.95656530e+02; -1.85916742e+00]
2473.509	1.44	2.36	[-6.62575623e+10; 1.25549089e+11; 5.44259141e+10; -2.63236981e+04; -1.18154428e+04; -5.12204135e+03]	[2.96086881e+02; -1.87497261e+00]
2280.237	1.44	3.01	[-6.62616695e+10; 1.25547247e+11; 5.44251157e+10; -2.63233074e+04; -1.18161824e+04; -5.12236195e+03]	[2.96738689e+02; -1.89870895e+00]

Column 21	Column 22	Column 23	Column 24	Column 25
[2.52388747e+02; 9.43149527e-02]	[45.32198298; 42.70819064]	[45.32198298; 42.70819064]	[280.47088321; -24.74064961]	48.28838
[2.52622513e+02; 8.28350377e-02]	[45.33239003; 42.71849974]	[45.33239003; 42.71849974]	[280.36634064; -24.93673182]	48.08925
[2.53085869e+02; 6.00763192e-02]	[45.3530326 ; 42.73893538]	[45.3530326 ; 42.73893538]	[280.15906886; -25.32558776]	47.69534
[2.53294588e+02; 4.98232763e-02]	[45.36233702; 42.74814097]	[45.36233702; 42.74814097]	[280.06567577; -25.50083079]	47.51824
[2.54246344e+02; 3.06301869e-03]	[45.40480856; 42.79011707]	[45.40480856; 42.79011707]	[279.63952597; -26.3005766]	46.71352
[2.54446714e+02; -6.78178207e-03]	[45.41375837; 42.79895309]	[45.41375837; 42.79895309]	[279.54974165; -26.46907455]	46.54471
[2.55143832e+02; -4.10320841e-02]	[45.44491677; 42.82968951]	[45.44491677; 42.82968951]	[279.23714072; -27.0556514]	45.95908
[2.66519262e+02; -5.95399998e-01]	[45.95437148; 43.32602568]	[45.95437148; 43.32602568]	[274.0210548 ; -36.68857678]	36.88149
[2.81174610e+02; -1.27199048e+00]	[46.59167734; 43.92751402]	[46.59167734; 43.92751402]	[266.436664 ; -49.1757232]	27.56031
[2.81600574e+02; -1.29061676e+00]	[46.60950603; 43.94398288]	[46.60950603; 43.94398288]	[266.18854182; -49.53811521]	27.35564
[2.95656530e+02; -1.85916742e+00]	[47.16255293; 44.44350728]	[47.16255293; 44.44350728]	[256.19990424; -61.37312331]	23.97753
[2.96086881e+02; -1.87497261e+00]	[47.17820001; 44.45728978]	[47.17820001; 44.45728978]	[255.81302915; -61.72893141]	23.99301
[2.96738689e+02; -1.89870895e+00]	[47.20173029; 44.47797579]	[47.20173029; 44.47797579]	[255.21367392; -62.26664883]	24.0307

Column 26	Column 27
[96.28592953; 8.46867384]	1.
[96.40724157; 8.46905622]	1.
[96.64768918; 8.46991774]	1.
[96.75599452; 8.47035052]	1.
[97.2498344 ; 8.47267239]	1.
[97.35379395; 8.47323336]	1.
[97.71546932; 8.47537833]	1.
[103.614184 ; 8.54970899]	1.
[111.20905996; 8.73956779]	1.
[111.42978334; 8.74647039]	1.
[118.71405255; 9.01349189]	1.
[118.93712496; 9.02282167]	1.
[119.2749976 ; 9.03707907]	1.

Appendix H Formatting Simulated Data in EOSSA

This appendix contains a discussion on simulating radiometric data from RSOs and how to format the results into an EOSSA file.

H.1 Introduction

The EOSSA format is intended to include all information relevant to electro-optical observations collected for the purposes of SSA. 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 keywords that should be added 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 user viewing the data later on 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 parameters. Without tracking the parameters that affected the simulation results, the sets of data 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 modeled in EOSSA is given in H.3. This example outlines the standards and considerations for using the EOSSA format to capture simulated data.

This appendix uses an example to show how simulated data shall be reported in EOSSA. This example was created using the Satellite Visualization and Signature Tool (SVST)[16] version 8.3.27, which is a government simulation software package that can provide electro-optical, imaging, modeling and simulations, among other applications. SVST was used to generate passively-illuminated, simulated, photometric signatures of geostationary satellites as observed by a ground-based sensor. The native output of SVST was formatted into EOSSA. Dozens of simulation parameters can be set or modified in SVST, which affect the data produced, so tracking these parameters in EOSSA is critical to ensuring the results are reproducible. The format for reporting simulated data in EOSSA is the same structure described in Section 3.0. In

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[16] SVST uses the comprehensive program called Time-domain Analysis Simulation for Advanced Tracking (TASAT)

addition to the EOSSA-required fields in the binary table extension header, keywords were added to detail all relevant simulation parameters used to generate the data. These are described next.

H.2 EOSSA Keywords Added for Simulated Data

Fields were added to the binary table extension header in order to uniquely describe the simulation parameters that created the data. This example is to simulate real photometric data and as such, the binary table data columns remained the same as the EOSSA files with real data. Table H-1 lists the major simulation keywords that represent the main simulation parameters used. Table H-2 lists the minor simulation parameters that can affect the data produced, but these parameters are rarely changed. SVST contains dozens of additional parameters, but none of these were found to have an effect on these specific simulations and were therefore not added to the EOSSA file. Table H-1 and Table H-2 represent an exhaustive list of only the parameters that must be set in order to perfectly reproduce the simulated data. Any simulated data reported in EOSSA should emulate this formatting and procedure shown here. This ensures consistency in how simulated data is described and maintains the traceability and reproducibility of the data.

Table H-1- EOSSA Major Simulation Keywords (SVST 8.3.27)

#	Keyword	Description	Units	Format	Example(s)	Notes
1	SIMDATA	This represents whether the data is simulated.		A	SIMDATA = T SIMDATA = F	
2	SIMSOFT	This specifies the simulation software and version.		A	SIMSOFT = 'SVST 8.3.27'	
3	SATVERS1	This specifies the SVST Analysis Tool version that produced the EOSSA files and therefore the automation script used to create the .dat files.		A	SATVERS1 = '0.2.0'	SATVERS1 was added in v0.2.0.
4	SATVERS2	This specifies the SVST Analysis Tool version that converted the .dat file to EOSSA file.		A	SATVERS2 = '0.1.2' SATVERS2 = '0.2.0'	
5	CADMODEL	This is the CAD model filename of the target used in the simulation.		A	CADMODEL = 'u.28790.galaxy14.revE0.1_e4.8.5_1.nsm'	
6	MATFILE	This is the filename ("MATTER Filename") of the material database used by the target CAD model.		A	MATFILE = 'Matter5.12_6.0.dat' MATFILE = 'MATTER.DAT'	
7	ILLTYPE	This describes the illumination type used in the simulation.		A	ILLTYPE = 'Passive' ILLTYPE = 'Active (UIRAD)' ILLTYPE = 'Active + Passive'	
8	ILLNUM	The value is the number of illuminators used in the simulation.		J	ILLNUM = 1 ILLNUM = 2 ILLNUM = 3 ILLNUM = 4	

#	Keyword	Description	Units	Format	Example(s)	Notes
9	ILLNAMn	The ILLNAMn keywords are present for all values n=1,…,ILLNUM in incrementing order of n, and for no other values of n. These keywords specify each illuminator used in the simulation.		A	ILLNAM1 = ‘Solar’ ILLNAM2 = ‘Lunar’ ILLNAM3 = ‘Earth’ ILLNAM4 = ‘Thermal’	In the SVST Sensor Render Tool, Solar corresponds to “Solar Illumination”, Lunar to “Lunar Illumination”, Earth to “Earth Background”, and Thermal to “Thermal Emission”.
10	RENDPIXW	The value is the width of the rendered pristine image dimensions in pixels.	pixels	J	RENDPIXW = 32 RENDPIXW = 256	
11	RENDPIXH	The value is the height of the pristine image dimensions in pixels.	pixels	J	RENDPIXH = 32 RENDPIXH = 256	
12	BUSATTX	The value is the bus attitude about the X-axis.	degrees	D	BUSATTX = 0.0 BUSATTX = 1.0	
13	BUSATTY	The value is the bus attitude about the Y-axis.	degrees	D	BUSATTY = 0.0 BUSATTY = 1.0	
14	BUSATTZ	The value is the bus attitude about the Z-axis.	degrees	D	BUSATTZ = 0.0 BUSATTZ = 1.0	
15	SOLPOFF	The value is the solar panel offset from Sun pointing.	degrees	D	SOLPOFF = 0.0 SOLPOFF = 10.0	
16	DISHATTX	The value is the dish attitude about the X-axis.	degrees	D	DISHATTX = 0.0 DISHATTX = 5.0	
17	DISHATTY	The value is the dish attitude about the Y-axis.	degrees	D	DISHATTY = 0.0 DISHATTY = 5.0	
18	DISHATTZ	The value is the dish attitude about the Z-axis.	degrees	D	DISHATTZ = 0.0 DISHATTZ = 5.0	
19	TIMESTEP	The value specifies the time step of the simulation.	seconds	D	TIMESTEP = 900.0 TIMESTEP = 3600.0	

Table H-2 - SVST Analysis Tool (v0.2.0) – EOSSA Minor Simulation Keywords (SVST 8.3.27)

#	Keyword	Description	Units	Format	Example(s)	Notes
1	GEMODECB	This specifies which camera mode to use for the simulation. This keyword represents the SVST parameter geomModeCB.		J	GEMODECB = 0 GEMODECB = 1 GEMODECB = 2 GEMODECB = 3 GEMODECB = 4 GEMODECB = 5 GEMODECB = 6	GEMODECB = 0 sets the camera mode as “Normal Platform Sensors: Scenario Geometry”. This is the default camera mode. GEMODECB = 1 sets the camera mode as “Virtual Sensors around Target: Scenario Geometry”. GEMODECB = 2 sets the camera mode as “Solar Sensor: Scenario Geometry”. GEMODECB = 3 sets the camera mode as “Normal Platform Sensors: Scenario Geometry – Target RA/DEC Views”. GEMODECB = 4 sets the camera mode as “Normal Platform Sensors: Scenario Geometry – Target Euler Perturbation”. GEMODECB = 5 sets the camera mode as “Virtual Sensors: Parametric Laboratory Frame Camera Geometry”. GEMODECB = 6 sets the camera mode as “Virtual Sensors: Imported camera/light positions”.
2	CLAFRECB	If CLAFRECB = ‘true’, the Sensor Render Tool form is closed upon completion of rendering. This keyword represents the SVST parameter closeAfterRenderingCB.		A	CLAFRECB = ‘true’ CLAFRECB = ‘false’	If CLAFRECB = ‘true’, the SVST automation script (SVST Analysis Tool v0.2.0) will not function properly.

#	Keyword	Description	Units	Format	Example(s)	Notes
3	RENOBJCB	The value determines which scenario object is rendered. RENOBJCB = 0 sets the “Target” as the object to be rendered. RENOBJCB = 1 sets the “Main Platform” as the object to be rendered. If any auxiliary sites exist, these may also be set as the object to be rendered. This keyword represents the SVST parameter renderedObjectCB.		J	RENOBJCB = 0 RENOBJCB = 1	
4	ARRDIMCB	The value determines what square pristine image dimensions in pixels to use in rendering the object. This keyword represents the SVST parameter arrayDimCB.		J	ARRDIMCB = 0 ARRDIMCB = 1 ARRDIMCB = 2 ARRDIMCB = 3 ARRDIMCB = 4 ARRDIMCB = 5 ARRDIMCB = 6	Values ARRDIMCB = 0-5 correspond to square dimensions of 32*2^(ARRDIMCB). ARRDIMCB = 6 chooses a value of “Other”, which allows custom values of the keywords RENDPIXW & RENDPIXH to be used as the pristine image dimensions.
5	RENFOVCB	This specifies what sizing method the sensor uses to fit the target into the view port. This keyword represents the SVST parameter renderIfovCB.		J	RENFOVCB = 0 RENFOVCB = 1 RENFOVCB = 2 RENFOVCB = 3	RENFOVCB = 0 uses “Best Fit (fixed IFOV angle)”. This is the default method. RENFOVCB = 1 uses “Best Fit (best IFOV angle per frame)”. RENFOVCB = 2 uses “User Defined angular spacing”. RENFOVCB = 3 uses “User Defined lateral ray separation”.

#	Keyword	Description	Units	Format	Example(s)	Notes
6	USRFOVED	This is a parameter related to RENFOVCB. If RENFOVCB = 0 or 1, USRFOVED sets the margin around the best fit bounding box. If RENFOVCB = 2, USRFOVED sets the IFOV ray angular divergence. If RENFOVCB = 3, USRFOVED sets the ray separation distance at the target plane. This keyword represents the SVST parameter userIFOVED.	If RENFOVCB = 0 or 1, units are %. If RENFOVCB = 2, units are micro-radians. If RENFOVCB = 3, units are meters.	D	USRFOVED = 0.0 USRFOVED = 1.0 USRFOVED = 7.5	
7	VIXFORRB	This specifies the viewing transformation to use. This keyword represents the SVST parameter viewXformRB.		A	VIXFORRB = ‘Perspective’ VIXFORRB = ‘Orthographic’	Perspective is a pin-hole camera. Orthographic is collimated rays.
8	DTRCB	If DTRCB = ‘true’, uniformly random ray aiming is done for anti-aliasing rays. This keyword represents the SVST parameter dtrCB.		A	DTRCB = ‘true’ DTRCB = ‘false’	If DTRCB = ‘true’, some randomness will always be present in the signature. Therefore, results will not be perfectly reproducible.
9	DRTNUMED	The value specifies the number of randomly aimed rays per pixel. This keyword represents the SVST parameter drtNumED.		A	DRTNUMED = ‘1’ DRTNUMED = ‘10’	DRTNUMED is included in the header only if DTRCB = ‘true’. The format is a string of an integer.

#	Keyword	Description	Units	Format	Example(s)	Notes
10	POVRSACB	If POVRSACB = ‘true’, pixel over-sampling is enabled. This keyword represents the SVST parameter pixelOversampleCB.		A	POVRSACB = ‘true’ POVRSACB = ‘false’	If POVRSACB = ‘true’, some randomness will always be present in the signature. Therefore, results will not be perfectly reproducible.
11	OVRSAED	The value specifies the number of oversample rays (n by n) to cast per pixel. This keyword represents the SVST parameter oversampleED.		A	OVRSAED = ‘1’ OVRSAED = ‘3’	OVRSAED is included in the header only if POVRSACB = ‘true’. The format is a string of an integer.
12	RECURCB	If RECURCB = ‘true’, adaptive recursive pixel subdivision is enabled. This keyword represents the SVST parameter recurCB.		A	RECURCB = ‘true’ RECURCB = ‘false’	
13	RECURED	The value specifies the number of child generations to recurse before stopping. This keyword represents the SVST parameter recurED.		A	RECURED = ‘1’ RECURED = ‘3’	RECURED is included in the header only if RECURCB = ‘true’. The format is a string of an integer.
14	TRSMCB	If TRSMCB = ‘true’, a separate ray trace is performed for small primitives. This keyword represents the SVST parameter tracesmallCB.		A	TRSMCB = ‘true’ TRSMCB = ‘false’	
15	ENRECCB	If ENRECCB = ‘true’, secondary child rays are traced at intercepts. This keyword represents the SVST parameter enableRecursiveCB.		A	ENRECCB = ‘true’ ENRECCB = ‘false’	

#	Keyword	Description	Units	Format	Example(s)	Notes
16	PATHTRCB	If PATHTRCB = 'true', path-tracing algorithms are used for the transmitted rays at each intercept. This keyword represents the SVST parameter pathTraceCB.		A	PATHTRCB = 'true' PATHTRCB = 'false'	PATHTRCB is included in the header only if ENRECCB = 'true'. If ENRECCB = 'true' and PATHTRCB = 'true', some randomness will always be present in the signature. Therefore, results will not be perfectly reproducible. No effect is seen in the simulation results if ENRECCB = 'true' and PATHTRCB = 'false', but the simulation run times are increased.
17	MGENBDE	The value specifies the max number of reflected generations to terminate recursion. This keyword represents the SVST parameter maxGenerationsBDE.		J	MGENBDE = 1 MGENBDE = 5	MGENBDE is included in the header only if ENRECCB = 'true' and PATHTRCB = 'true'.
18	MCHRBDE	The value specifies the number of spawned child rays per intercept. This keyword represents the SVST parameter maxChildRaysBDE.		J	MCHRBDE = 1 MCHRBDE = 10	MCHRBDE is included in the header only if ENRECCB = 'true' and PATHTRCB = 'true'.

#	Keyword	Description	Units	Format	Example(s)	Notes
19	ITEMPSCB	The value determines which “Initial Temperature Options” to use. ITEMPSCB = 0 uses “Model Assigned Defaults”. ITEMPSCB = 1 uses “User Temperature”. ITEMPSCB = 2 uses “Ambient Temperature”. ITEMPSCB = 3 uses “Static Equilibrium”. ITEMPSCB = 4 uses “Dynamic Solver”. This keyword represents the SVST parameter initTempsCB.		J	ITEMPSCB = 0 ITEMPSCB = 1 ITEMPSCB = 2 ITEMPSCB = 3 ITEMPSCB = 4	ITEMPSCB is included in the header only if thermal emission (ILLNAMn = ‘Thermal’) is included in the simulation. If thermal emission is not included, ITEMPSCB has no effect on the results. If ITEMPSCB = 0, the results are reproducible. If thermal emission is included in the simulation and ITEMPSCB is not set to 0, there are additional keywords needed (not present in SVST Analysis Tool v0.2.0) for the results to be reproducible.
20	RENENGCB	The value determines what alternate rendering engine to use. RENENGCB = 0 sets the rendering engine to “None”. RENENGCB = 1 sets the rendering engine to “TASAT”. RENENGCB = 2 sets the rendering engine to “SPIRITS”. This keyword represents the SVST parameter renderEngineCB.		J	RENENGCB = 0 RENENGCB = 1 RENENGCB = 2	
21	ADDCELCB	If ADDCELCB = ‘true’, celestial objects are added to the background scene. This keyword represents the SVST parameter addCelestialCB.		A	ADDCELCB = ‘true’ ADDCELCB = ‘false’	
22	MODATMCB	IF MODATMCB = ‘true’, atmospheric effects are modeled. This keyword represents the SVST parameter modelAtmCB.		A	MODATMCB = ‘true’ MODATMCB = ‘false’	

#	Keyword	Description	Units	Format	Example(s)	Notes
23	SPBRDFCB	If SPBRDFCB = ‘true’, specular BRDF scattering is included in signatures. This keyword represents the SVST parameter specBRDFCB.		A	SPBRDFCB = ‘true’ SPBRDFCB = ‘false’	
24	SANDMCB	If SANDMCB = ‘true’, shadow/masking calculations in the BRDFs are included. This keyword represents the SVST parameter sANDmCB.		A	SANDMCB = ‘true’ SANDMCB = ‘false’	
25	ANICALCB	If ANICALCB = ‘true’, anisotropic calculations in the BRDFs are included. This keyword represents the SVST parameter anisoCalcCB.		A	ANICALCB = ‘true’ ANICALCB = ‘false’	
26	DIBRDFCB	If DIBRDFCB = ‘true’, diffuse BRDF scattering is included in signatures. This keyword represents the SVST parameter diffuseBRDFCB.		A	DIBRDFCB = ‘true’ DIBRDFCB = ‘false’	
27	NUMSHRCB	The value determines which method is used for modeling shadow rays. This keyword represents the SVST parameter numberShadowRaysCB.		J	NUMSHRCB = 0 NUMSHRCB = 1 NUMSHRCB = 2 NUMSHRCB = 3 NUMSHRCB = 4	NUMSHRCB = 0 sets the method to “None”. NUMSHRCB = 1 sets the method to “Standard”. This is the default method. NUMSHRCB = 2 sets the method to “Adaptive”. NUMSHRCB = 3 sets the method to “Monte Carlo”. NUMSHRCB = 4 sets the method to “Pseudo-Random”.
28	LAMBRHCB	If LAMBRHCB = ‘true’, a fixed hemispherical reflectance is used for all materials. This keyword represents the SVST parameter lambRhCB.		A	LAMBRHCB = ‘true’ LAMBRHCB = ‘false’	

#	Keyword	Description	Units	Format	Example(s)	Notes
29	RHEMIED	The value specifies the fixed, diffuse hemispherical reflectance used. This keyword represents the SVST parameter RhemiED.		D	RHEMIED = 0.5 RHEMIED = 1.0	RHEMIED is included in the header only if LAMBRHCB = ‘true’. The value represents the reflectance, e.g., RHEMIED = 0.5 is 50% reflectance.
30	LAMBERCB	If LAMBERCB = ‘true’, Lambertian diffuse BRDFs are used for all materials. This keyword represents the SVST parameter lambertianCB.		A	LAMBERCB = ‘true’ LAMBERCB = ‘false’	LAMBERCB is included in the header only if LAMBRHCB = ‘false’. If LAMBRHCB = ‘true’, the value of LAMBERCB has no effect.
31	REFIMGCB	If REFIMGCB = ‘true’, the image output is the local region intensity distribution about camera (only applies to illumination type of Passive). This keyword represents the SVST parameter reflImageCB.		A	REFIMGCB = ‘true’ REFIMGCB = ‘false’	
32	RIMFOVAE	The value specifies the full angular FOV of the reflection image. This keyword represents the SVST parameter reflImageFOVAE.	radians	D	RIMFOVAE = 0.97 x (pi/180) (default value) ≈ 0.017	RIMFOVAE is included in the header only if REFIMGCB = ‘true’. The Sensor Render Tool default is to display degrees.
33	RIDIMBDE	The value specifies the square image dimensions in pixels of the reflection image. This keyword represents the SVST parameter reflImageDimBDE.	pixels	J	RIDIMBDE = 1 RIDIMBDE = 5	RIDIMBDE is included in the header only if REFIMGCB = ‘true’. If REFIMGCB = ‘true’, the values of RENDPIXW & RENDPIXH will be incorrectly set to the value of RIDIMBDE, instead of the actual pristine image dimensions.

#	Keyword	Description	Units	Format	Example(s)	Notes
34	COMIMGTY	The value determines which file format is used for the output image. This keyword represents the SVST parameter comboImageTypes.		J	COMIMGTY = 0 COMIMGTY = 1 COMIMGTY = 2 COMIMGTY = 3 COMIMGTY = 4	COMIMGTY = 0 selects “SVST Binary (.svs)” as the output image file format. COMIMGTY = 1 selects “TIFF-PL (.tif)”. COMIMGTY = 2 selects “FITS (.fit)”. COMIMGTY = 3 selects “EOSSA (.eossa)”. COMIMGTY = 4 selects “None”.

H.3 Example of a Simulated EOSSA File

An EOSSA files will be shown as an example of how an EOSSA file for simulated data should look. This file, “28790_KRaven_2018-03-01_R_busX0Y0Z0_solp-5_dishX0Y0Z0.eossa”, was created by running a simulation in SVST using a CAD model for Galaxy 14, a GEO satellite, as the target. The simulation run involved a ground-based sensor observing Galaxy 14 every night for a year. This specific EOSSA example contains the data for one of those nights of observations, as well as all relevant parameters required to reproduce the data. Table H-3 shows the primary header of the EOSSA file. The format of the primary header is described in Section 3.6. The entire binary table extension header is given in Table H-4. The binary data table is described in Table H-5, Table H-6, Table H-7, and Table H-8. The TTYPEn values shown in Table H-5 are described in more detail in Table 7 of Section 3.7.

H.3.1 Primary Header

Table H-3 - EOSSA Primary Header Example for Simulated Data

Header Keyword	Keyword Value	Comment
SIMPLE	T	conforms to FITS standard
BITPIX	8	array data type
NAXIS	0	number of array dimensions
EXTEND	T	FITS dataset may contain extensions
COMMENT FITS (Flexible Image Transport System) format is defined in 'Astronomy		
COMMENT and Astrophysics', volume 376, page 359; bibcode: 2001A&A...376..359H		

H.3.2 Binary Table Extension

H.3.2.1 Binary Table Header

Table H-4 - EOSSA Binary Table Extension Header Example for Simulated Data

Header Keyword	Keyword Value	Comment
XTENSION	'BINTABLE'	binary table extension
BITPIX	8	array data type
NAXIS	2	number of array dimensions
NAXIS1	198	length of dimension 1
NAXIS2	50	length of dimension 2
PCOUNT	0	number of group parameters
GCOUNT	1	number of groups
TFIELDS	17	number of table fields
TTYPE1	'UTC_Begin_Exp'	label for field 1
TFORM1	'23A '	data format of field 1: ASCII Character
TUNIT1	'yyyy-mm-ddThh:mm:ss.sss'	physical unit of field 1
TTYPE2	'UTC_End_Exp'	label for field 2
TFORM2	'23A '	data format of field 2: ASCII Character
TUNIT2	'yyyy-mm-ddThh:mm:ss.sss'	physical unit of field 2
TTYPE3	'JD_Mid_Exp'	label for field 3
TFORM3	'D '	data format of field 3: 8-byte DOUBLE

Header Keyword	**Keyword Value**	**Comment**
TUNIT3	'days '	physical unit of field 3
TTYPE4	'Exp_Duration'	label for field 4
TFORM4	'D '	data format of field 4: 8-byte DOUBLE
TUNIT4	'sec '	physical unit of field 4
TTYPE5	'Cur_Spec_Filt_Num'	label for field 5
TFORM5	'J '	data format of field 5: 4-byte INTEGER
TTYPE6	'Cur_ND_Filt_Num'	label for field 6
TFORM6	'J '	data format of field 6: 4-byte INTEGER
TTYPE7	'Mag_Exo_Atm'	label for field 7
TFORM7	'D '	data format of field 7: 8-byte DOUBLE
TUNIT7	'mag '	physical unit of field 7
TTYPE8	'Mag_Range_Norm'	label for field 8
TFORM8	'D '	data format of field 8: 8-byte DOUBLE
TUNIT8	'mag '	physical unit of field 8
TTYPE9	'Eph_RA_DE'	label for field 9
TFORM9	'2D '	data format of field 9: 8-byte DOUBLE
TUNIT9	'deg '	physical unit of field 9
TTYPE10	'Met_RA_DE'	label for field 10
TFORM10	'2D '	data format of field 10: 8-byte DOUBLE
TUNIT10	'deg '	physical unit of field 10
TTYPE11	'Eph_AZ_EL'	label for field 11
TFORM11	'2D '	data format of field 11: 8-byte DOUBLE
TUNIT11	'deg '	physical unit of field 11
TTYPE12	'Met_AZ_EL'	label for field 12
TFORM12	'2D '	data format of field 12: 8-byte DOUBLE
TUNIT12	'deg '	physical unit of field 12
TTYPE13	'Sun_AZ_EL'	label for field 13
TFORM13	'2D '	data format of field 13: 8-byte DOUBLE
TUNIT13	'deg '	physical unit of field 13
TTYPE14	'Tel_Obj_Range'	label for field 14
TFORM14	'D '	data format of field 14: 8-byte DOUBLE
TUNIT14	'm '	physical unit of field 14

Header Keyword	Keyword Value	Comment
TTYPE15	'Solar_Phase_Ang'	label for field 15
TFORM15	'D '	data format of field 15: 8-byte DOUBLE
TUNIT15	'deg '	physical unit of field 15
TTYPE16	'Long_Phase_Ang'	label for field 16
TFORM16	'D '	data format of field 16: 8-byte DOUBLE
TUNIT16	'deg '	physical unit of field 16
TTYPE17	'Lat_Phase_Ang'	label for field 17
TFORM17	'D '	data format of field 17: 8-byte DOUBLE
TUNIT17	'deg '	physical unit of field 17
EXTNAME	'28790_KRaven_2018-03-01_R_busX0Y0Z0_solp-5_dishX0Y0Z0.eossa'	
CLASSIF	'U//FOUO '	Security classification level
VERS	'3.1.1 '	Version number of EOSSA data format
OBSEPH	'GROUND '	Observer type
TELESCOP	'Kirtland'	Telescope site name or SSN sensor identifier
TELLAT	34.963025	Telescope geographical latitude
TELLONG	-106.497287	Telescope geographical longitude
TELALT	1725.0	Telescope geographical altitude
OBSNAME	'KRaven '	Telescope name
OBJEPH	'TLE '	Target object ephemeris source
OBJTYPE	'SCN '	Name of catalog to identify object
OBJNUM	28790	Identification number of object
OBJECT	'Galaxy14'	Common name of target object
TLELN1	'28790U 05030A 18058.99632628 .00000010 00000-0 00000+0 0 9991'	
TLELN2	'28790 0.0568 294.0548 0002788 48.7392 48.6438 1.00273565 45918'	
SPFNUM	1	Number of spectral filters used
SPFNAM1	'R '	Spectral filter name
SIMDATA	T	Boolean to indicate if data is simulated
SIMSOFT	'SVST 8.3.27'	Simulation software and version
SATVERS1	'0.2.0 '	SVST Analysis Tool version, created dat file
SATVERS2	'0.2.0 '	SVST Analysis Tool version, created EOSSA file

Header Keyword	Keyword Value	Comment
CADMODEL	'u.28790.galaxy14.revE0.1_e4.8.5_1.nsm'	CAD model filename
MATFILE	'Matter5.12_6.0.dat'	Material filename
ILLTYPE	'Passive '	Illumination type
ILLNUM	1	Number of illuminators
ILLNAM1	'Solar '	Illuminator name
RENDPIXW	256	Pixels rendered, width
RENDPIXH	256	Pixels rendered, height
BUSATTX	0.0	Bus attitude about X-axis, degrees
BUSATTY	0.0	Bus attitude about Y-axis, degrees
BUSATTZ	0.0	Bus attitude about Z-axis, degrees
SOLPOFF	-5.0	Solar panel offset, degrees
DISHATTX	0.0	Dish attitude about X-axis, degrees
DISHATTY	0.0	Dish attitude about Y-axis, degrees
DISHATTZ	0.0	Dish attitude about Z-axis, degrees
TIMESTEP	900.0	Time step of simulation, seconds
GEMODECB	0	SVST parameter, geomModeCB
CLAFRECB	'false '	SVST parameter, closeAfterRenderingCB
RENOBJCB	0	SVST parameter, renderedObjectCB
ARRDIMCB	6	SVST parameter, arrayDimCB
RENFOVCB	0	SVST parameter, renderIfovCB
USRFOVED	1.0	SVST parameter, userIFOVED
VIXFORRB	'Orthographic'	SVST parameter, viewXformRB
DTRCB	'false '	SVST parameter, dtrCB
POVRSACB	'false '	SVST parameter, pixelOversampleCB
RECURCB	'false '	SVST parameter, recurCB
TRSMCB	'false '	SVST parameter, tracesmallCB
ENRECCB	'false '	SVST parameter, enableRecursiveCB
RENENGCB	0	SVST parameter, renderEngineCB
ADDCELCB	'false '	SVST parameter, addCelestialCB
MODATMCB	'true '	SVST parameter, modelAtmCB
SPBRDFCB	'true '	SVST parameter, specBRDFCB
SANDMCB	'true '	SVST parameter, sANDmCB

Header Keyword	**Keyword Value**	**Comment**
ANICALCB	'true '	SVST parameter, anisoCalcCB
DIBRDFCB	'true '	SVST parameter, diffuseBRDFCB
NUMSHRCB	1	SVST parameter, numberShadowRaysCB
LAMBRHCB	'false '	SVST parameter, lambRhCB
LAMBERCB	'false '	SVST parameter, lambertianCB
REFIMGCB	'false '	SVST parameter, reflImageCB
COMIMGTY	0	SVST parameter, comboImageTypes
END		

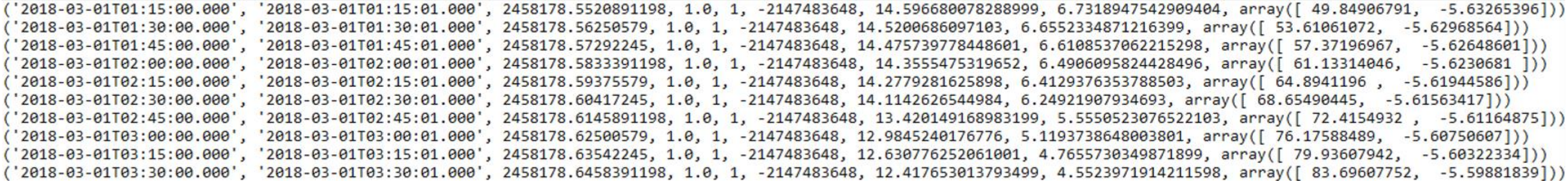
H.3.2.2 Binary Table

Table H-5 - Description of EOSSA Binary Table Columns for Simulated Data

Column #	TTYPEn values
1	UTC_Begin_Exp
2	UTC_End_Exp
3	JD_Mid_Exp
4	Exp_Duration
5	Cur_Spec_Filt_Num
6	Cur_ND_Filt_Num
7	Mag_Exo_Atm
8	Mag_Range_Norm
9	Eph_RA_DE
10	Met_RA_DE
11	Eph_AZ_EL
12	Met_AZ_EL
13	Sun_AZ_EL
14	Tel_Obj_Range
15	Solar_Phase_Ang
16	Long_Phase_Ang
17	Lat_Phase_Ang

Table H-6 - Table 1 of 3 Showing the Columns in the Binary Table of an EOSSA File Containing Simulated Data

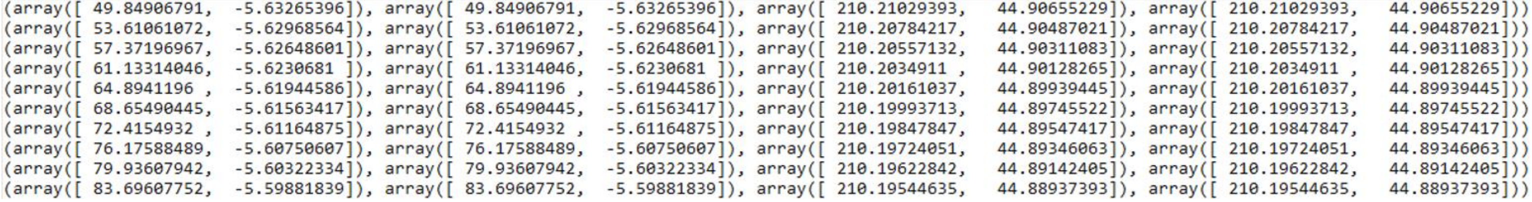
Col 1	Col 2	Col 3	Col 4	Col 5	Col 6	Col 7	Col 8	Col 9



```
('2018-03-01T01:15:00.000', '2018-03-01T01:15:01.000', 2458178.5520891198, 1.0, 1, -2147483648, 14.596680078288999, 6.7318947542909404, array([ 49.84906791,  -5.63265396]))
('2018-03-01T01:30:00.000', '2018-03-01T01:30:01.000', 2458178.56250579, 1.0, 1, -2147483648, 14.5200686097103, 6.6552334871216399, array([ 53.61061072,  -5.62968564]))
('2018-03-01T01:45:00.000', '2018-03-01T01:45:01.000', 2458178.57292245, 1.0, 1, -2147483648, 14.475739778448601, 6.6108537062215298, array([ 57.37196967,  -5.62648601]))
('2018-03-01T02:00:00.000', '2018-03-01T02:00:01.000', 2458178.5833391198, 1.0, 1, -2147483648, 14.3555475319652, 6.4906095824428496, array([ 61.13314046,  -5.6230681 ]))
('2018-03-01T02:15:00.000', '2018-03-01T02:15:01.000', 2458178.59375579, 1.0, 1, -2147483648, 14.2779281625898, 6.4129376353788503, array([ 64.8941196 ,  -5.61944586]))
('2018-03-01T02:30:00.000', '2018-03-01T02:30:01.000', 2458178.60417245, 1.0, 1, -2147483648, 14.1142626544984, 6.24921907934693, array([ 68.65490445,  -5.61563417]))
('2018-03-01T02:45:00.000', '2018-03-01T02:45:01.000', 2458178.6145891198, 1.0, 1, -2147483648, 13.420149168983199, 5.5550523076522103, array([ 72.4154932 ,  -5.61164875]))
('2018-03-01T03:00:00.000', '2018-03-01T03:00:01.000', 2458178.62500579, 1.0, 1, -2147483648, 12.9845240176776, 5.1193738648003801, array([ 76.17588489,  -5.60750607]))
('2018-03-01T03:15:00.000', '2018-03-01T03:15:01.000', 2458178.63542245, 1.0, 1, -2147483648, 12.630776252061001, 4.7655730349871899, array([ 79.93607942,  -5.60322334]))
('2018-03-01T03:30:00.000', '2018-03-01T03:30:01.000', 2458178.6458391198, 1.0, 1, -2147483648, 12.417653013793499, 4.5523971914211598, array([ 83.69607752,  -5.59881839]))
```

Table H-7 - Table 2 of 3 Showing the Columns in the Binary Table of an EOSSA File Containing Simulated Data

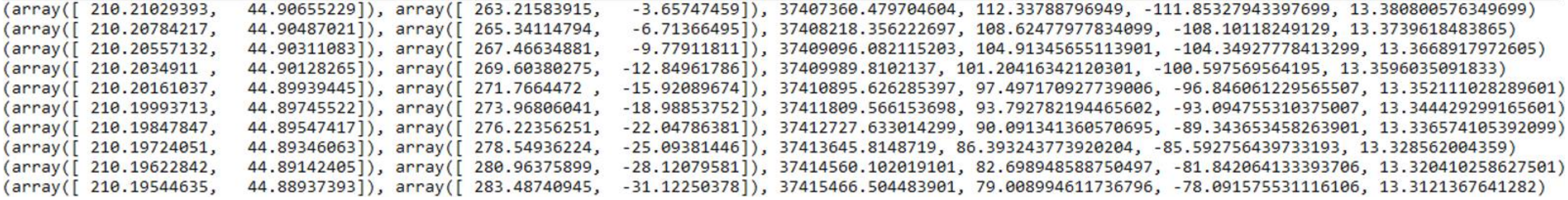
Col 9	Col 10	Col 11	Col 12



```
(array([ 49.84906791,  -5.63265396]), array([ 49.84906791,  -5.63265396]), array([ 210.21029393,    44.90655229]), array([ 210.21029393,    44.90655229]))
(array([ 53.61061072,  -5.62968564]), array([ 53.61061072,  -5.62968564]), array([ 210.20784217,    44.90487021]), array([ 210.20784217,    44.90487021]))
(array([ 57.37196967,  -5.62648601]), array([ 57.37196967,  -5.62648601]), array([ 210.20557132,    44.90311083]), array([ 210.20557132,    44.90311083]))
(array([ 61.13314046,  -5.6230681 ]), array([ 61.13314046,  -5.6230681 ]), array([ 210.2034911 ,    44.90128265]), array([ 210.2034911 ,    44.90128265]))
(array([ 64.8941196 ,  -5.61944586]), array([ 64.8941196 ,  -5.61944586]), array([ 210.20161037,    44.89939445]), array([ 210.20161037,    44.89939445]))
(array([ 68.65490445,  -5.61563417]), array([ 68.65490445,  -5.61563417]), array([ 210.19993713,    44.89745522]), array([ 210.19993713,    44.89745522]))
(array([ 72.4154932 ,  -5.61164875]), array([ 72.4154932 ,  -5.61164875]), array([ 210.19847847,    44.89547417]), array([ 210.19847847,    44.89547417]))
(array([ 76.17588489,  -5.60750607]), array([ 76.17588489,  -5.60750607]), array([ 210.19724051,    44.89346063]), array([ 210.19724051,    44.89346063]))
(array([ 79.93607942,  -5.60322334]), array([ 79.93607942,  -5.60322334]), array([ 210.19622842,    44.89142405]), array([ 210.19622842,    44.89142405]))
(array([ 83.69607752,  -5.59881839]), array([ 83.69607752,  -5.59881839]), array([ 210.19544635,    44.88937393]), array([ 210.19544635,    44.88937393]))
```

Table H-8 - Table 3 of 3 Showing the Columns in the Binary Table of an EOSSA File Containing Simulated Data

Col 12	Col 13	Col 14	Col 15	Col 16	Col 17



```
(array([ 210.21029393,    44.90655229]), array([ 263.21583915,   -3.65747459]), 37407360.479704604, 112.33788796949, -111.85327943397699, 13.380800576349699)
(array([ 210.20784217,    44.90487021]), array([ 265.34114794,   -6.71366495]), 37408218.356222697, 108.62477977834099, -108.10118249129, 13.3739618483865)
(array([ 210.20557132,    44.90311083]), array([ 267.46634881,   -9.77911811]), 37409096.082115203, 104.91345655113901, -104.34927778413299, 13.3668917972605)
(array([ 210.2034911 ,    44.90128265]), array([ 269.60380275,  -12.84961786]), 37409989.8102137, 101.20416342120301, -100.597569564195, 13.3596035091833)
(array([ 210.20161037,    44.89939445]), array([ 271.7664472 ,  -15.92089674]), 37410895.626285397, 97.497170927739006, -96.846061229565507, 13.352111028289601)
(array([ 210.19993713,    44.89745522]), array([ 273.96806041,  -18.98853752]), 37411809.566153698, 93.792782194465602, -93.094755310375007, 13.344429299165601)
(array([ 210.19847847,    44.89547417]), array([ 276.22356251,  -22.04786381]), 37412727.633014299, 90.091341360570695, -89.343653458263901, 13.336574105392099)
(array([ 210.19724051,    44.89346063]), array([ 278.54936224,  -25.09381446]), 37413645.8148719, 86.393243773920204, -85.592756439733193, 13.328562004359)
(array([ 210.19622842,    44.89142405]), array([ 280.96375899,  -28.12079581]), 37414560.102019101, 82.698948588750497, -81.842064133393706, 13.320410258627501)
(array([ 210.19544635,    44.88937393]), array([ 283.48740945,  -31.12250378]), 37415466.504483901, 79.008994611736796, -78.091575531116106, 13.3121367641282)
```

Appendix I Description of Angles Relevant to EOSSA Data Format

This appendix describes and defines various angles relevant to the EO observations of RSOs.

I.1 Introduction

The following information is needed to compute angles reported in EOSSA:

- The position of the RSO
- The position of the observer
- The position of the sun
- The direction of orbital north, a vector perpendicular to the orbital plane, defined as RSO Position×RSO Velocity

The above positional information should be directly available in the EOSSA file. In any case, a valid EOSSA file will contain enough information to compute the needed positions. How to calculate them using the required EOSSA fields can be found in Table I-1.

The angle definitions are generalized for any observation conditions. In the figures of this appendix, we chose to illustrate the angles using a space-based observer because it lends itself to more complex examples than the ground-based observer case.

Note: a right-handed coordinate system is assumed for all of these definitions. The definitions are generalized and will work for any coordinate system (e.g., ECI and ECEF) as long as the positional information is known.

Table I-1 - How to Calculate the Needed Information from an EOSSA File

Sensor Type	Positional Information Needed	How to Calculate
All types	Sun Position	Calculate from the time of observation (JD_Mid_Exp)
	Orbital North	Calculate $RSO\ Position \times RSO\ Velocity$ which can both be found using the TLE
Ground-Based	RSO Position	Propagate from the TLE or convert from Met_AZ_EL or Met_RA_DE
	Observer Position	Convert from TELLAT, TELLONG, and TELALT
Space-Based with TLE of Sensor	RSO Position	Propagate from the TLE or convert from Met_RA_DE
	Observer Position	Propagate from OBSTLE
Space-Based with State Vector of Sensor	RSO Position	Propagate from the TLE or convert from Met_RA_DE
	Observer Position	Given as Tel_State_Vec

I.2 Symbols Definitions

The following definitions are of each symbol used in this appendix:

- $\overrightarrow{RO}$: Vector with its tail at the RSO position and its head at the observer position.
- $\overrightarrow{RS}$: Vector with its tail at the RSO position and its head at the sun position.
- $\vec{N}$ (orbital north): Vector perpendicular to the orbital plane. Defined by $\widehat{RSO} \times \hat{V}$ using a right-handed coordinate system where $\overrightarrow{RSO}$ is the position of the RSO and $\vec{V}$ is the velocity of the RSO.
- $\overrightarrow{vector}_{prjct}$: The *prjct* subscript indicates that a vector is projected into the orbital plane. $\overrightarrow{vector}_{prjct} = \overrightarrow{vector} - \widehat{N} * \left(\overrightarrow{vector} \cdot \widehat{N}\right)$.
- $\widehat{vector}$: The $\widehat{\ }$ circumflex denotes a unit vector. A unit vector is defined as a vector with magnitude 1. Any vector can be converted into a unit vector, while maintaining its direction, by dividing each component by the vector's magnitude: $\widehat{vector} = \frac{\overrightarrow{vector}}{|\overrightarrow{vector}|}$.

The following are descriptions of the objects that appear in each of the figures below:

- RSO (green point): The RSO/satellite which orbits along the large gray circle.
- O. North (blue vector with its tail at the RSO): Orbital north vector perpendicular to the orbital plane.
- Obs (purple point): The observer which orbits along the small gray circle.
- RO (purple vector): Vector from the RSO to the observer.
- RS (orange vector): Vector from the RSO to the sun.
- Unlabeled small blue point: The barycenter of the orbiting system, approximately at the center of the earth.

I.3 Solar Phase Angle

The Solar Phase Angle (SPA) is the angle between the $\overrightarrow{RO}$ vector and the $\overrightarrow{RS}$ vector as pictured in Figure I-1.

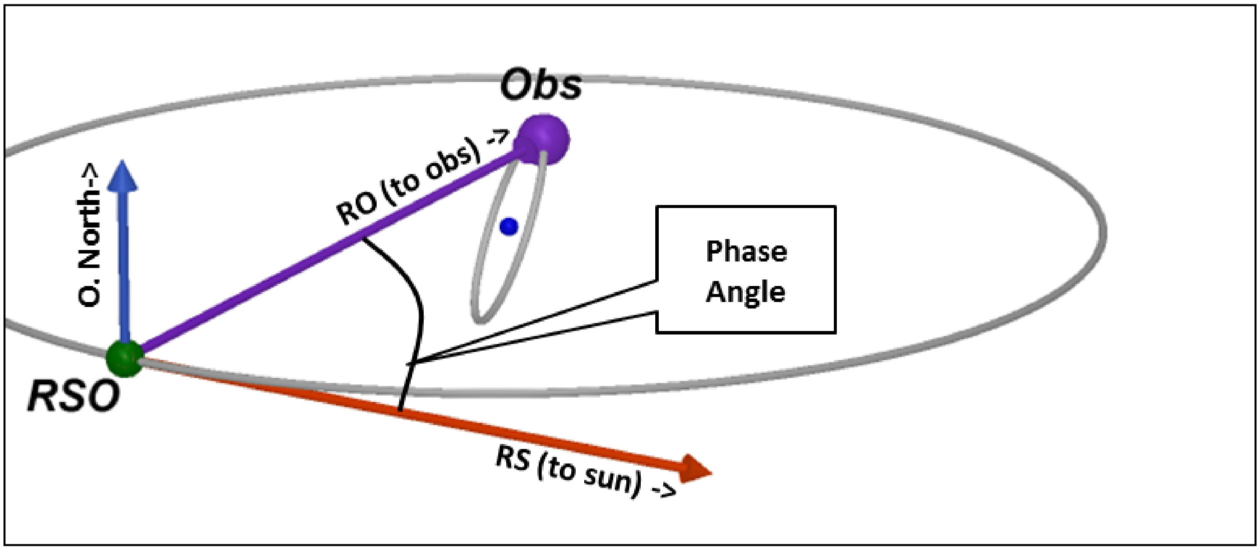


Figure I-1 - Solar Phase Angle

The equation for SPA is defined as:

$$\boldsymbol{SPA} = \begin{Bmatrix} \cos^{-1}\left(\widehat{RS}\cdot\widehat{RO}\right)\ if\left(\widehat{RS}_{prjct}\times\widehat{RO}_{prjct}\right)\cdot\widehat{N}\geq 0 \\ -\cos^{-1}\left(\widehat{RS}\cdot\widehat{RO}\right)\ if\ \left(\widehat{RS}_{prjct}\times\widehat{RO}_{prjct}\right)\cdot\widehat{N}<0 \end{Bmatrix}.$$

I.4 Longitudinal Phase Angle

The Longitudinal Phase Angle (Lon. PA) is the angle between the projections of $\overrightarrow{RO}$ and $\overrightarrow{RS}$ into the orbital plane as shown in Figure I-2. RO(prjctd) in Figure I-2 represents the RO vector projected into the orbital plane. RS(prjctd) in Figure I-2 represents the RS vector projected into the orbital plane.

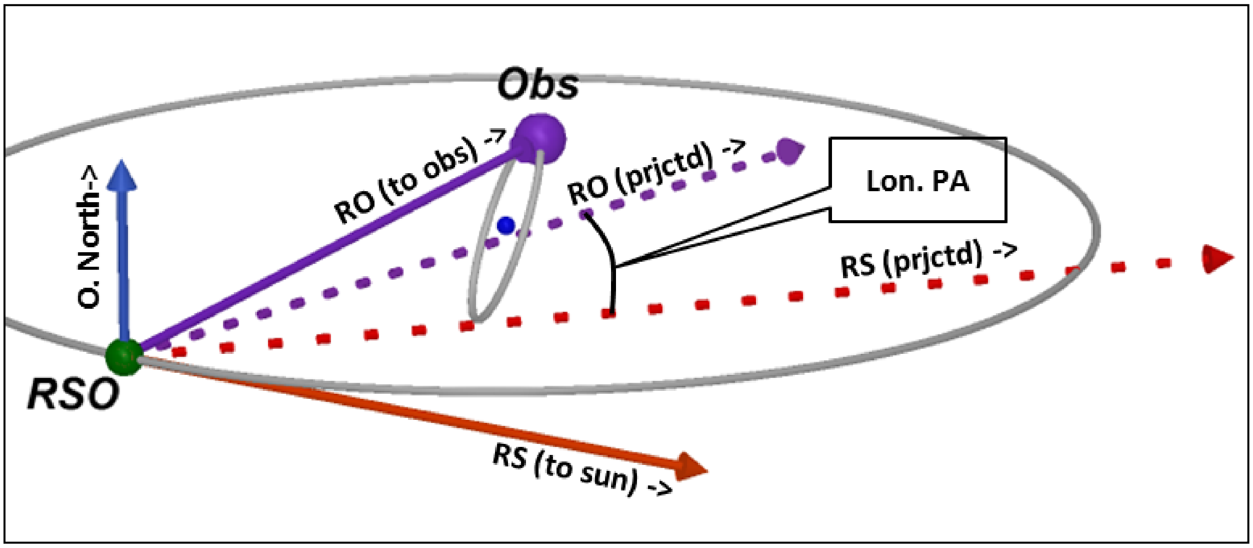


Figure I-2 - Longitudinal Phase Angle

The equation for Lon. PA is defined as:

$$\boldsymbol{Lon.PA} = \left\{ \begin{array}{l} \cos^{-1}\left(\widehat{RS}_{prjct} \cdot \widehat{RO}_{prjct}\right)\ if\left(\widehat{RS}_{prjct} \times \widehat{RO}_{prjct}\right) \cdot \hat{N} \geq 0 \\ -\cos^{-1}\left(\widehat{RS}_{prjct} \cdot \widehat{RO}_{prjct}\right)\ if\ \left(\widehat{RS}_{prjct} \times \widehat{RO}_{prjct}\right) \cdot \hat{N} < 0 \end{array} \right\}.$$

I.5 Latitudinal Phase Angle

The Latitudinal Phase Angle (Lat. PA) is the difference of the observer declination and the solar declination from the perspective of the satellite. The observer declination is the angle between $\overrightarrow{RO}$ and orbital north as shown in Figure I-3. The solar declination is the angle between $\overrightarrow{RS}$ and orbital north as shown in Figure I-3.

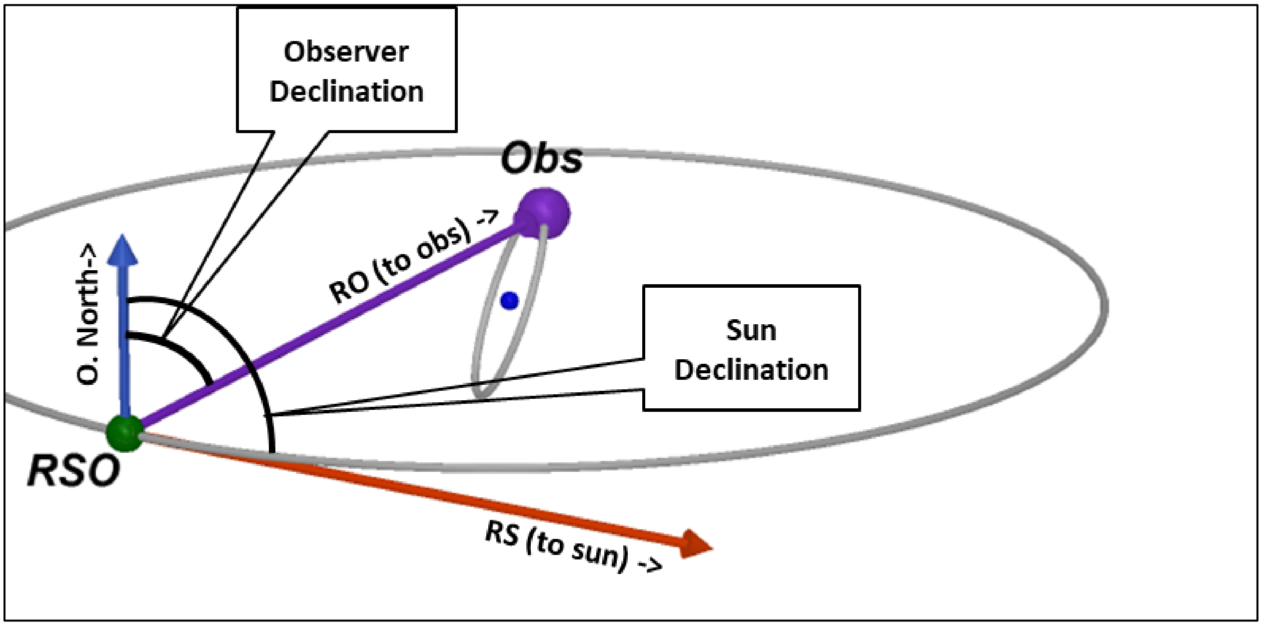


Figure I-3 - Latitudinal Phase Angle

The equation for Latitudinal PA is defined as:

$$\boldsymbol{Lat.PA} = \cos^{-1}(\hat{N} \cdot \widehat{RS}) - \cos^{-1}(\hat{N} \cdot \widehat{RO})$$

I.6 Orbit Angle

The Orbit Angle (OA) is the angle between the projection of $\overrightarrow{RS}$ into the orbital plane and Nadir as in Figure I-4. RS(prjctd) in Figure I-4 represents the RS vector projected into the orbital plane. Nadir in Figure I-4 represents a vector from the RSO to the center of the earth or the origin.

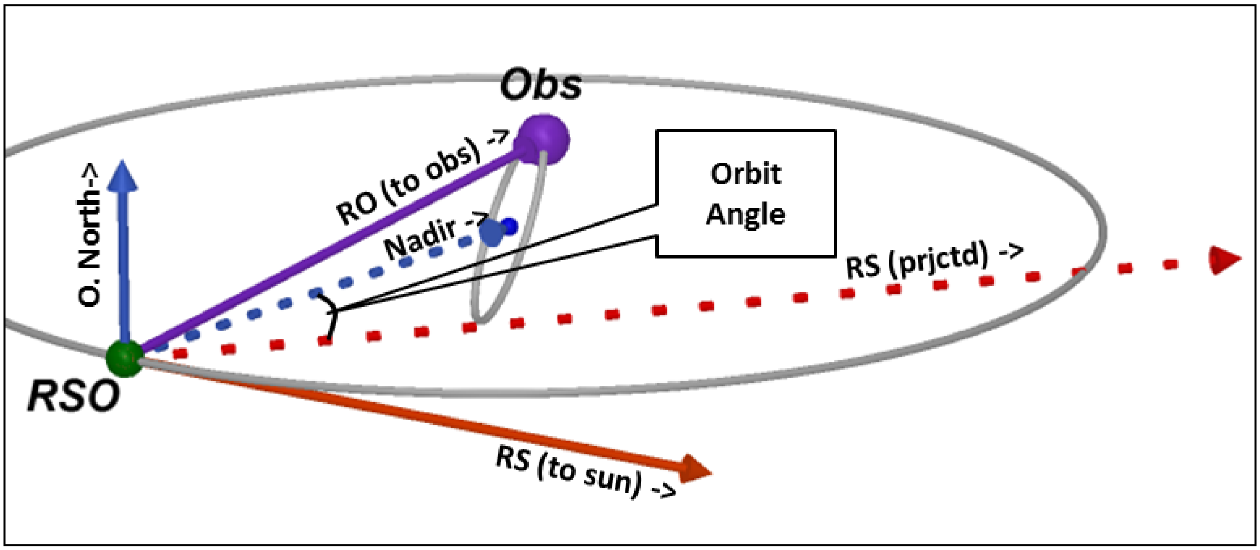


Figure I-4 - Orbit Angle

The equation for OA is defined as:

$$\boldsymbol{OA} = \left\{ \begin{array}{l} \cos^{-1}\left(\widehat{RS}_{prjct} \cdot \widehat{Nad\imath r}\right) \ if \ \left(\overrightarrow{RS}_{prjct} \times \widehat{Nad\imath r}\right) \cdot \widehat{N} \geq 0 \\ -\cos^{-1}\left(\widehat{RS}_{prjct} \cdot \widehat{Nad\imath r}\right) \ if \ \left(\overrightarrow{RS}_{prjct} \times \widehat{Nad\imath r}\right) \cdot \widehat{N} < 0 \end{array} \right\}.$$

I.7 Solar Phase Angle Bisector Vector

The solar Phase Angle Bisector (PAB) is the vector that bisects the phase angle or the angle between $\overrightarrow{RO}$ and $\overrightarrow{RS}$ as shown in Figure I-5. The angle the PAB creates with $\overrightarrow{RO}$ and $\overrightarrow{RS}$ is one-half of the phase angle.

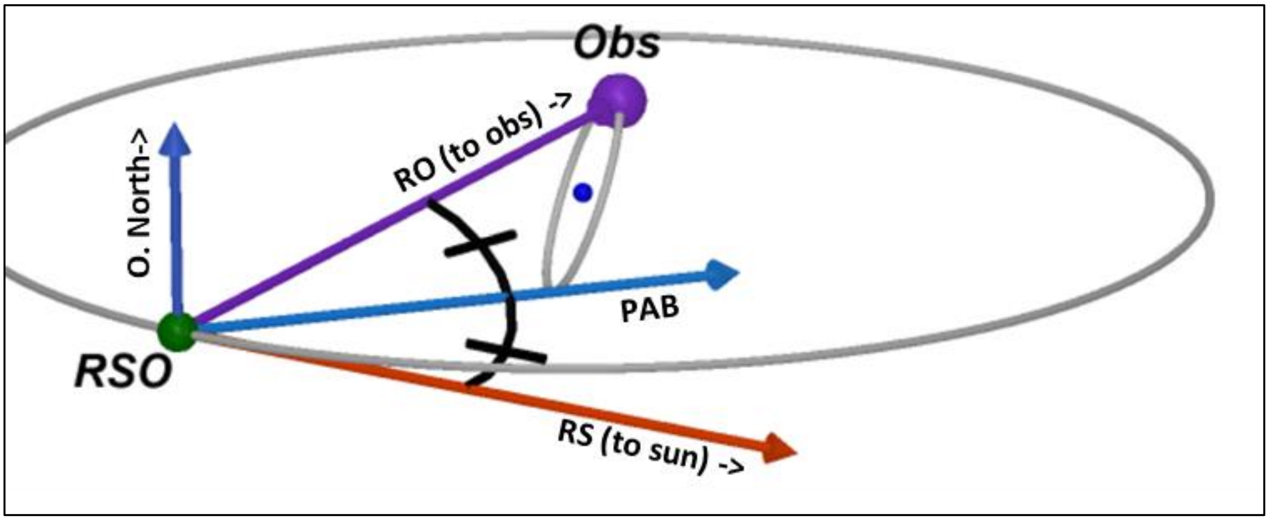


Figure I-5 - Solar Phase Angle Bisector Vector

The equations for PAB as a three-dimensional vector and in terms of Right Ascension (RA) and Declination (DEC) are defined as:

$$\overrightarrow{\boldsymbol{PAB}}_{ECI} = \widehat{RS} + \widehat{RO}$$

$$\overrightarrow{\boldsymbol{PAB}}_{RA} = atan2\left(\frac{\overrightarrow{\boldsymbol{PAB}}_{y}}{\overrightarrow{\boldsymbol{PAB}}_{x}}\right)$$

$$\overrightarrow{\boldsymbol{PAB}}_{DEC} = \operatorname{asin}\left(\frac{\overrightarrow{\boldsymbol{PAB}}_{z}}{\left|\overrightarrow{\boldsymbol{PAB}}_{eci}\right|}\right).$$

I.8 Recommended Binary Table Column Nomenclature

These angles can all be represented in the EOSSA format as optional binary table column fields. The column field descriptions for these angles can be found in Section 3.7 in the rows of Table 7 that are listed in Table I-2 below.

Table I-2 - Table 7 Row Numbers Corresponding to the Angles in This Appendix

Angle	Row Number in Table 7 That Angle Description Can Be Found
Solar Phase Angle	48
Solar Phase Angle Bisector	49
Longitudinal Phase Angle	50
Latitudinal Phase Angle	51
Orbit Angle	52

Appendix J Formatting of Long-Wave InfraRed (LWIR) Radiometry in EOSSA

Contributed by David Witte, Pantera Corp.

Similar to the visible regime of the electromagnetic spectrum, Long-Wave InfraRed (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 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 spatially resolved. We treat the unresolved case in Section J.1; however, data on resolved objects regardless of orbit regime are formatted using these keywords. Section J.2 describes the EOSSA keywords unique to LWIR and a sequence of resolved imagery, which applies to images collected in any waveband. Due to the nature of the image sequence, keywords are defined to describe the parameters of the images.

J.1 LWIR Radiometry for Deep Space RSOs

The required EOSSA fields in the binary table header defined in Section 3.6 Table 6 are required. Additional header keywords for LWIR radiometry are listed in Table J-1. Note the description column that refers back to the base EOSSA keywords in some cases.

The binary table columns are listed in Table J-2. This table encompasses all the columns of the binary table listed in Section 3.7 Table 7. The table adds a column for Type that identifies if it is from the basic EOSSA or it is specific to LWIR.

Table J-1 EOSSA Binary Table Extension Header Keywords for Spatially-Non-Resolved LWIR

LWIR-specific Keyword	Example Value	Description	Description/Comments
CHOPTHRW	30	Chop Throw in microradians	The angular separation in telescope output space between the 'A' and 'B' images position during a Chop Sequence.
CHOPFREQ	6	Chop frequency in Hz	The period of the (nominally) square-wave waveform that represents the telescope secondary mirror position during a Chop Sequence.
SPZMFL1	1800	W/sr of 100m2/350K RSO in filter 1	Intensities of "Zero-magnitude reference RSO," which is 100 m^2 emissivity-area and has temperature = 350 K. These intensities are used to calculate column 24 of the Binary Table, "Mag_Exo_Atm," from the Intensity values in column 22 of the table. (see Table J-2 below)
SPZMFL2	2041	W/sr of 100m2/350K RSO in filter 2	
STARCAT	'CWW-March 2016'	Name & version of LWIR star catalog used	"CWW" = Cohen-Walker-Witteborn. March 2016 is the release date of the current version. (STARCAT is a standard EOSSA keyword, see section 3.6)
BANDPASn	'8.31-9.15 um'	Spectral bandpass of Filter 1	Where n is the number of bandpasses with the bandpass spectral range as the value.
BANDPAS2	'11.04-12.25 um'	Spectral bandpass of Filter 2	Example of second bandpass
ALPHA1	0.1134	Filter 1 value of 1st parameter of AtmosTxmsn model	**DEFAULT:** Values of the two parameters of the LWIR Atmospheric Transmission model. If cal stars were collected, the angularly-closest star to the RSO az/el position is used to adjust the Alpha values from those of the default model. Default Beta values are not adjusted. The adjusted model yields the corrected atmospheric transmission value found in column 27 of the Binary Table (see Table J-2 below), which is what was applied to produce the Intensity estimate in column 22 of the Table. Whatever value of Alpha was used (i.e., default or cal-star-adjusted) is reported in column 28 of the Binary Table. This
BETA1	0.7556	Filter 1 value of 2nd parameter of AtmosTxmsn model	
ALPHA2	0.0531	Filter 2 value of 1st parameter of AtmosTxmsn model	
BETA2	0.8654	Filter 2 value of 2nd parameter of AtmosTxmsn model	

LWIR-specific Keyword	Example Value	Description	Description/Comments
			provides insight into how weather/cloud conditions may have varied over the collection span.
IN2PENJD	2457661.9812732	Time of Penumbra entry if occurred; zero if not	During equinox season, and depending on the total span of observations on the given night, one or both Shadow Transits may have occurred during that span. These four Keywords indicate if either or both possible transits occurred *during the span of observations represented in the LWIR Binary Table (see* Table J-2 *below)*. They DO NOT, however, necessarily imply that data were recorded during any of the transits. That information is captured in fields/columns 40 and 41 of the Binary Table below.
IN2UMBJD	2457661.9830903	Time of Umbra entry if occurred; zero if not	
XITUMBJD	2457662.0207755	Time of Umbra exit if occurred; zero if not	
XITPENJD	2457662.0225926	Time of Penumbra exit if occurred; zero if not	

Table J-2 EOSSA Binary Table Keywords for Spatially-Non-Resolved LWIR

n	TTYPEn	TFORMn	TUNITn	Column Type	Description / Comments
1	'UTC_Begin_Exp'	'24A'	'date'	standard EOSSA	See Section 3.7
2	'UTC_End_Exp'	'24A'	'date'	standard EOSSA	See Section 3.7
3	'JD_Mid_Exp'	'1D'	'days'	standard EOSSA	See Section 3.7
4	'Exp_Duration'	'1D'	'sec'	standard EOSSA	See Section 3.7
5	Cur_Spec_Filt_Num'	'1J'	'num'	standard EOSSA	See Section 3.7
6	'FPA_Temp'	'1D'	'K'	LWIR specific field	Generalization of standard EOSSA parameter 'CCD_Temp' to LWIR. Reports average FPA temperature during the duration of the Chop & Nod recording (if applicable). This will alternate row by row between FPA1 and FPA2, e.g., in accordance with the value of 'Cur_Spec_Filt_Num'.
7	'FPA_Trange'	'1D'	'K'	LWIR specific field	Total range of FPA temperature (Max - Min) over the recording. Ideally, it will be nearly Zero.

n	TTYPEn	TFORMn	TUNITn	Column Type	Description / Comments
8	'Nod_Pairs_Recorded'	'1J'	'num'	LWIR specific field	The total number of Nod Pairs recorded and averaged to create the final Chop/Nod image from which RSO intensity is extracted.
9	'ChopCycles_perChopSeq'	'1J'	'num'	LWIR specific field	Number of Chop Cycles per Chop Sequence. Each Nod Pair consists of two Chop Sequences separated by a Nod. Each Chop Sequence comprises some number of Chop Cycles, whose value is specified in this column. The combination of Nod_Pairs_Recorded and ChopCycles_perChopSeq determines the total duration of a Chop/Nod recording.
10	'PCal_Num_Stars'	'1J'	'num'	standard EOSSA	See Section 3.7. This will typically be 1 but may increase if a more advanced approach for using calibration stars w/ deep space data is defined.
11	'Cal_Star_HRnum'	'1J'	'num'	LWIR specific field	Bright Star Catalog number of the LWIR calibration star used to adjust the atmospheric transmission model parameter 'alpha,' (resulting 'Adjusted_Alpha' is in column 24).
12	'BGrad_Ped_Star'	'1D'	'W/m^2/sr'	LWIR specific field	The mean value of the 'background pedestal' radiance over the Chop/Nod recording of the particular calibration Star (column 11). It represents the combined self-emissions of the atmospheric path and of the uncooled optical train. This can be compared with the corresponding quantity for the RSO (column 18) as a diagnostic of any differences in amount of cirrus between the Star and RSO recordings.

n	TTYPEn	TFORMn	TUNITn	Column Type	Description / Comments
13	'SNR_Est_Star'	'1D'	'num'	LWIR specific field	For deep space objects - Chop/Nod recordings, this is the Peak-Pixel SNR of the final Chop/Nod image of the Cal Star after application of the Chop Nod Matched Filter (CNMF). Note that the peak pixel in such an image is the sum of all RSO image pixels in the finalChop/Nod image before applying the CNMF.
14	'Cur_ND_Filt_Num'	'1J'	'num'	standard EOSSA	See section 3.7.
15	'CCD_Obj_Pos'	'2D'	'pixels'	standard EOSSA	See section 3.7. If multiple FPA's are used and are designated as separate spectral filters, these values should represent the FPA corresponding to the value of Cur_Spec_Filt_Num.
16	'CCD_Obj_FWHM'	'1D'	'pixels'	LWIR specific use of standard EOSSA	See section 3.7. The summation-region diameter of the particular Chop-Nod Matched Filter (CNMF) that yielded the Intensity estimate in column 22.
17	BGrad_Local_Obj'	'1D'	'W/m^2 /sr'	LWIR specific field	This is the mean radiance (i.e., pixel values) of two sample regions above and below the Chop/Nod [– + –] image pattern. It is used as the final Local Background Level that is subtracted from the entire image before applying the Chop/Nod Matched Filter to estimate the object intensity. Because the actual background radiance (column 18) has already been removed via the Chop/Nod processing, the value of BGrad_Local *should* be numerically negligible (e.g., of

n	TTYPEn	TFORMn	TUNITn	Column Type	Description / Comments
					order 1E-10 to 1E-11). This binary table column is therefore provided as a possible diagnostic for explaining any anomalous intensity values (column 22 of the binary table)—e.g., if the value of 'BGrad_Local' suddenly increases (in absolute value) to a non-negligible level, one would expect a corresponding impact on the intensity estimate.
18	'BGrad_Ped_Obj'	'1D'	'W/m^2 /sr'	LWIR specific field	The mean value of the 'background pedestal' radiance over the Chop/Nod recording of the RSO. It represents the combined self-emissions of the atmospheric path and of the uncooled optical train. This is the quantity that can be used as a diagnostic of the presence or absence of cirrus along the line of sight for files containing multiple recordings.
19	'BGped_SigMu_Obj'	'1D'	'num'	LWIR specific field	The NORMALIZED standard deviation (i.e., sigma/mu) in PERCENT of 'BGrad_Ped_Obj' (column 18) over the Chop/Nod recording duration. This can be used as an additional diagnostic of the presence or absence of cirrus along the line of sight, especially if only a single recording is included in the file (i.e., if there is only one or two table rows, one per FPA).
20	'SNR_Est_Obj'	'1D'	'num'	standard EOSSA	See section 3.7. For deep space Chop/Nod recordings, this is the Peak-Pixel SNR of the final Chop/Nod image of the RSO after application of the Chop Nod Matched Filter. Note that the peak pixel in such an image is the sum of all RSO image pixels in the final, unfiltered Chop/Nod image.

n	TTYPEn	TFORMn	TUNITn	Column Type	Description / Comments
21	'NoiseLevel'	'1D'	'W/m^2 /sr'	LWIR specific field	This is the standard deviation of two sampling regions in the final Chop Nod Matched Filter image. It is used to estimate the final noise level, which is then used in the calculation of SNR. This value includes the contributions of both temporal and residual spatial noise.
22	'Inband_Intensity'	'1D'	'W/sr'	LWIR specific field	This is the fundamental 'signature data product' produced by the sensor, representing the measured power density in a specific bandpass filter.
23	'Intensity_Uncert'	'1D'	'W/sr'	LWIR specific field	This is the associated 1-sigma uncertainty associated with the values in column 22. It is provided in watts per steradian in order to facilitate plotting the intensity curves with associated error bars, if desired. The value is obtained by multiplying the intensity data in column 22 by the relative/fractional uncertainty.
24	'Mag_Exo_Atm'	'1D'	'mag'	standard EOSSA	See section 3.7. This is the magnitude version of the intensity values in column 22 but with using an LWIR-appropriate value of the zero-magnitude reference. Specifically, a reference RSO with an emissivity-area of 100 square meters and an effective temperature of 350K is defined as the zero-mag reference. The corresponding in-band intensities are defined in header keywords 'SPZMFL1' and 'SPZMFL2'. The reference RSO was chosen as (nominally) the thermally-brightest RSO one should ever observe. This will yield positive magnitudes for virtually

n	TTYPEn	TFORMn	TUNITn	Column Type	Description / Comments
					all real RSOs, and they should generally be in the range of +1 to +6.
25	'Mag_Exo_Atm_Unc'	'1D'	'mag'	standard EOSSA	See section 3.7. This is the magnitude version of the relative/fractional uncertainty expression. Numerically, the mag version is nearly identical to the fractional value itself.
26	'Mag_Range_Norm'	'1D'	'mag'	standard EOSSA	See section 3.7. The values in this column are identical to those in column 24 since LWIR magnitudes are based on ratios of Intensity in W/sr (e.g., column 22) rather than ratios of irradiance. Intensity is inherently a range-independent quantity, so range normalization is a non sequitur.
27	'Atmos_Txmsn'	'1D'	'num'	LWIR specific field	This is the actual atmospheric transmission applied to each frame of data as part of calculating the RSO Intensity in column 22. It is the result of evaluating the atmospheric transmission at a given elevation angle using the 'Alpha' value shown in column 28 and the 'Beta' value listed in the header keywords.
28	'Adjusted_Alpha'	'1D'	'num'	LWIR specific field	The actual value used for the first parameter of the Atmospheric Transmission model in order to yield the value in column 27. This will ideally be adjusted based on a calibration star collected close in both time and sky position to the RSO

n	TTYPEn	TFORMn	TUNITn	Column Type	Description / Comments
					recording represented by this row in the Binary Table. If a star was available, its BSC number will be in column 9. Also, see the description for the ALPHA and BETA keywords in the header.
29	'Obj_State_Vec'	'6D'	'm & m/s'	standard EOSSA	See section 3.7.
30	'Tel_State_Vec'	'6D'	'm & m/s'	standard EOSSA	See section 3.7.
31	'Eph_RA_DE'	'2D'	'deg'	standard EOSSA	See section 3.7.
32	'Met_RA_DE'	'2D'	'deg'	standard EOSSA	See section 3.7.
33	'Eph_AZ_EL'	'2D'	'deg'	standard EOSSA	See section 3.7.
34	'Met_AZ_EL'	'2D'	'deg'	standard EOSSA	See section 3.7.
35	'Sun_AZ_EL'	'2D'	deg'	standard EOSSA	See section 3.7.
36	'Tel_Obj_Range'	'1D'	'm'	standard EOSSA	See section 3.7.

n	TTYPEn	TFORMn	TUNITn	Column Type	Description / Comments
37	'Solar_Phase_Ang'	'1D'	'deg'	standard EOSSA	See section 3.7.
38	Lat_Phase_Ang	'1D'	'deg'	standard EOSSA	See section 3.7.
39	Long_Phase_Ang	'1D'	'deg'	Standard EOSSA	See section 3.7.
40	Solar_Disk_Frac_Min'	'1D'	'num'	LWIR specific use of standard EOSSA	See section 3.7. The combination of these two fields indicates if a particular Chop/Nod recording (which yields a single row in the Table, but which typically comprises several minutes of observation) straddled all or part of a Shadow Transit. If both 'Min' & 'Max' equal one, the RSO was fully sunlit throughout the recording, and if both are zero, the RSO was fully in Umbra. Either or both being between zero and one signifies the beginning and/or the end of the recording occurred, while the RSO was transiting Penumbra. If 'Min' = 0 and 'Max' = 1, then a complete transition through Penumbra occurred during the recording. NOTE: The precise Penumbra and Umbra crossing times appear as header Keywords.
41	Solar_Disk_Frac_Max'	'1D'	'num'	LWIR specific use of standard EOSSA	

J.2 LWIR Radiometry of Near Earth RSOs with Resolved Images

The required EOSSA fields in the binary table header defined in Section 3.6 Table 6 are required. Additional header keywords for LWIR radiometry with images are listed in Table J-3. The resolved images in this case are from objects in Near Earth (NE) orbit, with a subclass of objects in Low Earth Orbit (LEO).

The binary table columns are listed in Table J-4. This table encompasses all the columns of the binary table listed in Section 3.7 Table 7. The table adds a column for Type that identifies if it is from the basic EOSSA or it is specific to LWIR radiometry with images. Descriptions and comments sometimes contain references to other items designated by the n value of the row and are referred to as columns because the rows in this table represent binary table columns.

Since there are images, another HDU shall be created that contains a header and an image cube. The image header keywords are listed in Table J-5. Image cube format is: 'M' rows x 'M' cols x 'Nimages'--i.e., a cube of square images. The pixel values are single-precision floats and have units of W/cm^2/sr. Each image may be a ROI (Region of Interest) sub-image extracted from a larger parent frame. The square image dimensions M x M are constant, but the value of 'M' is specific to the particular pass of the particular RSO. Specifically, the ROI size is required to hold the largest image of the RSO. This largest image typically occurs near culmination, i.e., where the RSO is at the closest slant range, but the exact time also depends on the RSO shape and attitude profile.

The other images in the cube will likely be smaller than the largest image. Within the parent frames (the largest images), the ROI is generally rectangular and is computed frame-by-frame based on the RSO image extent in the row and column directions. For all the images smaller than the largest one, we recommend that these smaller ROIs should be centered within the MxM array and padded with zeros around the periphery. Zero padding of even the largest image will usually occur in one dimension (row or column) due to the usually rectangular ROIs in the parent frames. For example: If the largest image occupied a 40 row x 50 column ROI in the parent frame, the cube in the EOSSA file would be 50 x 50 x N images, and the largest image would have five rows of zeros at the top and bottom of its particular layer in the cube.

In the case of having data from two FPAs, as an example, the cube would consist of interleaved FPA1/FPA2 ROI pairs, analogous to how the Radiometry Binary Table consists of interleaved rows. In this case, the total # of images in the cube, 'Nimages' will be twice the number of pairs, 'Npairs'. In the case where data from only one FPA is recorded, the 'value of 'Nimages' will simply be the number of images from that FPA.

Table J-3 EOSSA Binary Table Extension Header Keywords for LWIR Radiometry with Images

LWIR-specific Keyword	Example Value	Descriptive CMT	Description / Comments
SPZMFL1	1800	W/sr of 100m2/350K RSO in Filter 1	Intensities of "Zero-magnitude reference RSO," which is 100 m^2 emissivity-area and has temperature = 350 K. These intensities are used to calculate column 17 of the Binary Table, "Mag_Exo_Atm," from the intensity values in column 15 of the table.
SPZMFL2	2041	W/sr of 100m2/350K RSO in Filter 2	
STARCAT	'CWW-March 2016'	Name & version of LWIR star catalog used	"CWW" = Cohen-Walker-Witteborn
BANDPAS1	'8.31-9.15 um'	Spectral bandpass of Filter 1	
BANDPAS2	'11.04-12.25 um'	Spectral bandpass of Filter 2	
NCALSTR1	10	# of calibration stars fit to AtmTx model in Filter 1	These numbers are constant per Filter for any given NE/LEO pass, and replace the optional column "PCal_Num_Stars" in the Binary Table (Table J-4).
NCALSTR2	10	# of calibration stars fit to AtmTx model in Filter 2	
ALPHA1	0.1134	Filter 1 value of 1st parameter of AtmosTx model	For these keywords, let us assume there are two focal planes with two different bandpasses (Filter 1 and Filter 2), which could be extended for n filters. Assuming a LEO Star calibration was available in reducing the LEO RSO data, these values reflect the resulting calibration-star-based, spectral-band-dependent models of Atmospheric Transmission-vs.-Elevation. ALPHA & BETA are the two model parameters, and CSTRUNC is the fractional Uncertainty of the model fit (normalized RMS of residuals). If a star calibration was not available, the values will be those of the default model (which happen to be the Example Values shown at left).
BETA1	0.7556	Filter 1 value of 2nd parameter of AtmosTx model	
CSTRUNC1	0.050	RMS Uncertainty of AtmosTx model for filter 1	
ALPHA2	0.0531	Filter 2 value of 1st parameter of AtmosTx model	
BETA2	0.8654	Filter 2 value of 2nd parameter of AtmosTx model	
CSTRUNC2	0.050	RMS Uncertainty of AtmosTx model for filter 2	

LWIR-specific Keyword	Example Value	Descriptive CMT	Description / Comments
FPA1TEMP	11.103	Average Temperature (K) of FPA1 during recording	These four quantities provide performance diagnostics of the cryogenic cooling for an example sensor with two focal planes. These keywords would be repeated for each different focal plane.
FPA1TRNG	0.597	Max-Min range of FPA1 Temp during recording	
FPA2TEMP	11.063	Avg Temperature (K) of FPA2 during recording	
FPA2TRNG	0.547	Max-Min range of FPA2 Temp during recording	
PENJD	2456324.9874996	Time of most recent Penumbra crossing before end of pass	These two parameters permit defining the Orbital Phase of the LEO RSO. Comparing the Penumbra- and Umbra-crossing times also permits one to determine whether the most recent terminator crossing was 'sun-into-shadow' vs. 'shadow-into-sun'.
UMBJD	2456324.9875921	Time of most recent Umbra crossing before end of pass	
EERTS2E	0	Space to Earth Reflection Time; zero if N/A	If either or both of these values are non-zero, then an "Earth Edge Reflection event" occurred during the pass. A 'space-to-earth' transition will produce a rapid increase in measured intensity, while an 'earth-to-space' transition will produce a rapid intensity drop. It is possible to have either type, or even both of them, during a pass. If a particular event type did not occur during the pass, the keyword value will be zero.
EERTE2S	2456325.0036866	Earth to Space Reflection Time; zero if N/A	

Table J-4 EOSSA Binary Table Keywords for LWIR Radiometry and Images

n	TTYPEn	TFORMn	TUNITn	Column Type	Description / Comments
1	'UTC_Begin_Exp'	'24A'	'date'	standard EOSSA	See Section 3.7
2	'UTC_End_Exp'	'24A'	'date'	standard EOSSA	See Section 3.7
3	'JD_Mid_Exp'	'1D'	'days'	standard EOSSA	See Section 3.7
4	'Exp_Duration'	'1D'	'sec'	standard EOSSA	See Section 3.7
5	'Cur_Spec_Filt_Num'	'1J'	'num'	standard EOSSA	See Section 3.7
6	'Cur_ND_Filt_Num'	'1J'	'num'	standard EOSSA	See Section 3.7
7	'CCD_Obj_Pos'	'2D'	'pixels'	standard EOSSA	See Section 3.7. If multiple FPA's are used and are designated as separate spectral filters, these values should represent the FPA corresponding to the value of Cur_OSpec_Filt_Num.
8	'BGgate_Horz'	'1D'	'pixels'	LWIR specific field	These two parameters are a generalization of the standard EOSSA quantity "CCD_Obj_FWHM." A rectangular 'Background Gate' is 'drawn' around the object image frame-by-frame. The image's aspect ratio and orientation in the Horizontal & Vertical directions vary over the pass, so the background (BG) gate dimensions, which are what these two columns specify, adapt to this. Note that these values do not include the 2-pixel-wide (for example) "Rectangular Annulus" that circumscribes the BG gate. The product of "BGgate_Horz" & "BGgate_Vert" gives the total number of pixels summed to yield the intensity estimate of the object.
9	'BGgate_Vert'	'1D'	'pixels'	LWIR specific field	

n	TTYPEn	TFORMn	TUNITn	Column Type	Description / Comments
10	'BGrad_Local'	'1D'	'W/m^2/sr'	LWIR specific field	This is the mean radiance value of the Rectangular Annulus pixels. It is used as the final Local Background Level that is subtracted from the entire image before performing the pixel-summation step to estimate the object intensity. Because the actual background radiance (column 12 below) has already been removed before the Background Gate is defined, the value of BGrad_Local *should* be numerically negligible (e.g., of order 1E-10 to 1E-11). This binary table column is therefore provided as a possible diagnostic for explaining any anomalous intensity values (column 15 of this table)—e.g., if the value of 'BGrad_Local' suddenly increases (in absolute value) to a non-negligible level, one would expect a corresponding impact on the intensity estimate.
11	'BGrad_Ped'	'1D'	'W/m^2/sr'	LWIR specific field	This is the true 'background pedestal' radiance level that represents the combined self-emissions of the atmospheric path and the uncooled optical train. This is the quantity that can be used as a diagnostic of the presence or absence of cirrus along the line of sight.
12	'SNR_Est'	'1D'	'num'	standard EOSSA	See Section 3.7. For LEO passes, this is Peak-Pixel SNR. Its reciprocal seems to be a good estimator of the precision of a time-series of intensity values.

n	TTYPEn	TFORMn	TUNITn	Column Type	Description / Comments
13	'NoiseLevel'	'1D'	'W/m^2/sr'	LWIR specific field	This is the standard deviation of the Rectangular Annulus pixels. It is used to estimate the final noise level, which is then used in the calculation of SNR. This value includes the contributions of both temporal and residual spatial noise.
14	'Inband_Intensity'	'1D'	'W/sr'	LWIR specific field	This is the fundamental 'signature data product' produced by the sensor representing the measured power density in a specific bandpass filter.
15	'Intensity_Uncert'	'1D'	'W/sr'	LWIR specific field	This is the associated 1-sigma uncertainty associated with the values in column 14. It is provided in watts per steradian in order to facilitate plotting the intensity curves with associated error bars, if desired. The value is obtained by multiplying the intensity data in column 14 by the relative/fractional uncertainty.
16	'Mag_Exo_Atm'	'1D'	'mag'	standard EOSSA	See Section 3.7. This is the magnitude version of the intensity values in column 14 but with using an LWIR-appropriate value of the zero-magnitude reference. Specifically, a reference RSO with an emissivity-area of 100 square meters and an effective temperature of 350K is defined as the zero-mag reference. The corresponding in-band intensities are defined in header keywords 'SPZMFL1' and 'SPZMFL2'. The reference RSO was chosen as nominally the thermally-brightest RSO one should ever observe. This will yield positive magnitudes for virtually all real RSO, and they should generally be in the range of 1 - 6.

n	TTYPEn	TFORMn	TUNITn	Column Type	Description / Comments
17	'Mag_Exo_Atm_Unc'	'1D'	'mag'	standard EOSSA	See Section 3.7. This is the magnitude version of the relative/fractional uncertainty expression. Numerically the magnitude version is nearly identical to the fractional value itself.
18	'Mag_Range_Norm'	'1D'	'mag'	standard EOSSA	See Section 3.7. This is a required EOSSA column but has no real meaning for LWIR data, so it is populated with the -9999.0 placeholder value.
19	'Atmos_Txmsn'	'1D'	'num'	LWIR specific field	Provided for convenience, this is the actual atmospheric transmission applied to each frame of data. It is the result of evaluating the transmission of the atmosphere for the given elevation angle and the 'alpha' and 'beta' values listed in the header keywords (see Table J-3 above).
20	'Obj_State_Vec'	'6D'	'm & m/s'	standard EOSSA	See Section 3.7.
21	'Tel_State_Vec'	'6D'	'm & m/s'	standard EOSSA	See Section 3.7.
22	'Eph_RA_DE'	'2D'	'deg'	standard EOSSA	See Section 3.7.
23	'Met_RA_DE'	'2D'	'deg'	standard EOSSA	See Section 3.7.
24	'Eph_AZ_EL'	'2D'	'deg'	standard EOSSA	See Section 3.7.
25	'Met_AZ_EL'	'2D'	'deg'	standard EOSSA	See Section 3.7.
26	'Sun_AZ_EL'	'2D'	deg'	standard EOSSA	See Section 3.7.
27	'Tel_Obj_Range'	'1D'	'm'	standard EOSSA	See Section 3.7.
28	'Solar_Phase_Ang'	'1D'	'deg'	standard EOSSA	See Section 3.7.
29	'Solar_Disk_Frac'	'1D'	'num'	standard EOSSA	See Section 3.7.

n	TTYPEn	TFORMn	TUNITn	Column Type	Description / Comments
30	'RSO_Detected'	'1J'	'num'	LWIR specific field	Flag that indicates in each frame of data whether or not the RSO signal met a minimum detection threshold.

Table J-5 EOSSA Image Header Keywords for LWIR Images

n	TTYPEn	TFORMn	TUNITn	Column Type	Description / Comments
1	'JD_Mid_Exp'	'1D'	'days'	standard EOSSA	See Section 3.7. Columns 1-3 have the same meanings as the corresponding TTYPEs in the Radiometry Binary Table.
2	'Cur_Spec_Filt_Num'	'1J'	'num'	standard EOSSA	
3	'SNR_Est'	'1D'	'num'	standard EOSSA	
4	'NoiseLevel'	'1D'	‘W/cm^2/sr’	LWIR specific field	Same as Column 13 of Radiometry Binary Table, except now in units of 'W/cm2/sr' (instead of 'W/m2/sr') in order match units of Image Cube contents.
5	'Met_AZ_EL'	'2D'	'deg'	standard EOSSA	See Section 3.7. Columns 5-9 have the same meanings as the corresponding TTYPEs in the Radiometry Binary Table.
6	'Obj_State_Vec'	'6D'	'm & m/s'	standard EOSSA	
7	'Tel_State_Vec'	'6D'	'm & m/s'	standard EOSSA	
8	'Tel_Obj_Range'	'1D'	'm'	standard EOSSA	
9	'Solar_Phase_Ang'	'1D'	'deg'	standard EOSSA	

Appendix K Required Keywords for Ground-Based Sensors

Since many data providers will not have both a ground-based sensor and a space-based sensor, for convenience, the binary table extension header keywords and data table TTYPE fields are described for a ground-based observer in this section in Table 10 and Table 11. These tables contain only the required fields. The complete set of fields, particularly related to calibrations and errors are highly desired. Space-based data providers should see Section Appendix K for similar tables for their case.

K.1 Ground-based Header Keywords

These are the keywords required for the binary table extension header when a ground-based sensor is employed. There are 17 keywords.

Table 10 - EOSSA Binary Table Extension Header Keywords Required for a Ground-based Sensor

#	Req'd.	Keyword	Description	Units	Format	Example(s)	Notes
1	All	EXTNAME	Filename of the FITS binary extension table file.		A		
2	All	CLASSIF	Security classification level of the data contained in the file.		A	'UNCLASS', 'CONF', 'SECRET', etc.	
3	All	VERS	Version number of the EOSSA data format.		A	'1.0', '2.5', '3.0', '3.1.1'	
4	All	OBSEPH	Observer type, i.e., ground-based, space-based with a TLE for the sensor, or space-based with a state vector for the sensor.		A	'GROUND', 'TLE', 'STATE'	
5	All	TELESCOP	Telescope site name or SSN sensor identifier.		A	'AMOS', 'RME', 'SENSOR510'	
6	G	TELLAT	Geographical latitude of the telescope.	degrees N	D		
7	G	TELLONG	Geographical longitude of the telescope.	degrees E	D		
8	G	TELALT	Distance above sea level of the telescope.	m	D		
9	All	OBSNAME	Telescope name.		A	'SENSOR510', 'AEOS', 'MT16', 'RMERaven',etc.	
10	All	OBJEPH	Target object ephemeris source.		A	'STATE', 'TLE'	
11	All	OBJTYPE	If the target has a space catalog number, the string 'SCN' is the value. If another catalog is used to identify the object, the name of that catalog is the value. Otherwise, 'NULLSTRING' is the value.		A	'SCN', 'NULLSTRING'	
12	All	OBJNUM	If OBJTYPE = 'NULLSTRING',		J	12345	

#	Req'd.	Keyword	Description	Units	Format	Example(s)	Notes
			-2147483648 is the value. Otherwise, the identification number of the object from the catalog in OBJTYPE is the value.				
13	All	OBJECT	Common name of target object if available or a name that the data provider uses to identify the object. Otherwise, 'NULLSTRING'.		A	'GALAXY14'	
14	All	TLELN1	Target Object Truncated TLE Line 1. First line of TLE without preceding '1' (67 characters). 'NULLSTRING' for UCTs.		A		
15	All	TLELN2	Target Object Truncated TLE Line 2. Second line of TLE without preceding '2' (67 characters). 'NULLSTRING' for UCTs.		A		
16	All	SPFNUM	The value is the number of spectral filters used.		J	2	
17	All	SPFNAMn	The SPFNAMn keywords must be present for all values n=1,…, SPFNUM, in incrementing order of n, and for no other values of n.		A	SPFNAM1='B' SPFNAM2='R'	

K.2 Ground-based Table Column Descriptions

These are the required data table TTYPEn fields for data from a ground-based sensor. In this case, n = 14.

Table 11 - EOSSA Binary Table Extension Data Column Descriptions for a Ground-based Sensor

#	**Req'd.**	**TTYPEn values** (data columns)	**Description**	**Units**	**Format** (part of TFORM)	**Example(s)**	**Notes**
1	All	UTC_Begin_exp	The start time of the exposure in UTC.	yyyy-mm-ddThh:mm:ss{.ssssss}	A	'2013-08-01T12:13:14.000'	
2	All	UTC_End_exp	The end time of the exposure.	yyyy-mm-ddThh:mm:ss{.ssssss}	A	'2013-08-01T12:14:14.000'	
3	All	JD_Mid_Exp	The time of mid-exposure in JD. Be sure the values for this keyword have enough significant digits to express the time to the appropriate fraction of a second.		D	2456506.00937	
4	All	Exp_Duration	Length of the integration or exposure time.	sec	D	30.0	
5	All	Cur_Spec_Filt_Num	The reference number, n, in SPFNAMn for the currently used spectral filter.		J	1	
6	All	Cur_ND_Filt_Num	The reference number n, in NDFNAMn for the		J	2	

#	Req'd.	**TTYPEn values** (data columns)	**Description**	**Units**	**Format** (part of TFORM)	**Example(s)**	**Notes**
			currently used neutral density filter.				
7	All	Mag_Exo_Atm	Exo-atmospheric magnitude is the magnitude of the target on the standard scale with atmospheric effects removed, e.g., m_r in Equation (A- 18).	mag	D	13.21	
8	All	Mag_Range_Norm	Range-normalized magnitude (Mag in #7) using 1000 km.	mag	D	3.45	
9	All	Eph_RA_DE	Predicted Right Ascension and Declination of the Target object from the frame of reference of the sensor (J2000, geocentric velocity aberration). SGP4 and VCMs produce geocentric origin and velocity aberration and subtracting the sensor geocentric position of the sensor places in its reference frame.	deg	2D	[75.33; -5.001]	
10	All	Met_RA_DE	Measured Right Ascension and Declination of the Target object from the	deg	2D	[75.31; -5.201]	

#	Req'd.	**TTYPEn values** (data columns)	**Description**	**Units**	**Format** (part of TFORM)	**Example(s)**	**Notes**
			frame of reference of the sensor.				
11	G	Eph_AZ_EL	Predicted Azimuth and elevation angles of the target object from a ground-based sensor (no atmospheric refraction correction required). AZ_EL implies apparent topocentric place in true of date reference frame as seen from the observer with aberration due to the observer velocity and light travel time applied.	deg	2D	[92.89; 32.12]	
12	G	Met_AZ_EL	Measured azimuth and elevation angles of the target object from a ground-based sensor (no atmospheric refraction correction required).	deg	2D	[92.91;32.76]	
13	G	Sun_AZ_EL	Azimuth and elevation angles of the sun from a ground-based telescope (no atmospheric refraction correction required).	deg	2D	[273.91; -25.77]	
14	All	Tel_Obj_Range	Distance from the telescope to the target	m	D	3.578683E7	

#	Req’d.	**TTYPEn values** (data columns)	**Description**	**Units**	**Format** (part of TFORM)	**Example(s)**	**Notes**
			object during the observation.				

Appendix L Required Keywords for Space-Based Sensors

The binary table extension header keywords and data table, TTYPE, fields are described for the two cases of a space-based observer. Table 12 and Table 13 (Sections L.1 and L.2) are for a data provider with a space-based sensor whose orbital information can be reported in TLE format. Data providers with a space-based sensor whose orbital information is only reported in state vectors should utilize Table 14 and Table 15 in Sections L.3 and L.4. These tables contain only the required fields. The complete set of fields, particularly related to calibrations and errors, are highly desired.

L.1 TLE-Based Sensor Header Keywords

These are the keywords required for the binary table extension header when the data is collected with space-based sensor whose orbital information is reportable in TLE format. There are 18 keywords.

Table 12 - EOSSA Binary Table Extension Header Keywords Required for a Space-based Sensor with a TLE

#	Req'd.	Keyword	Description	Units	Format	Example(s)	Notes
1	All	EXTNAME	Filename of the FITS binary extension table file.		A		
2	All	CLASSIF	Security classification level of the data contained in the file.		A	‘UNCLASS’, ‘CONF’, ‘SECRET’, etc.	
3	All	VERS	Version number of the EOSSA data format.		A	'1.0', '2.5', ‘3.0’, ‘3.1.1’	
4	All	OBSEPH	Observer type, i.e., ground-based, space-based with a TLE for the sensor, or space-based with a state vector for the sensor.		A	‘GROUND’, ‘TLE’, ‘STATE’	
5	All	TELESCOP	Telescope site name or SSN sensor identifier.		A	‘AMOS’, ‘RME’, ‘SENSOR510’	
6	S/T, S/S	OBSTYPE	If the space-based sensor has a space catalog number, the string ‘SCN’ is the value; otherwise, ‘NULLSTRING’ is the value.		A	'SCN' or ‘NULLSTRING’	
7	S/T	OBSNUM	If OBSTYPE=’SCN’, the space catalog number of the space-based sensor is the value; otherwise -2147483648.		J	12345	
8	All	OBSNAME	Telescope name.		A	‘SENSOR510’, ‘AEOS’, ‘MT16’, ‘RMERaven’,etc.	
9	S/T	OBSTLE1	Sensor Truncated TLE Line 1. First line of TLE without preceding '1' (67 characters).		A		
10	S/T	OBSTLE2	Sensor Truncated TLE Line 2. Second line of TLE without preceding '2' (67 characters).		A		
11	All	OBJEPH	Target object ephemeris source.		A	'STATE', 'TLE'	

#	Req'd.	Keyword	Description	Units	Format	Example(s)	Notes
12	All	OBJTYPE	If the target has a space catalog number, the string 'SCN' is the value. If another catalog is used to identify the object, the name of that catalog is the value. Otherwise, 'NULLSTRING' is the value.		A	'SCN', 'NULLSTRING'	
13	All	OBJNUM	If OBJTYPE = 'NULLSTRING', -2147483648 is the value. Otherwise, the identification number of the object from the catalog in OBJTYPE is the value.		J	12345	
14	All	OBJECT	Common name of target object if available or a name that the data provider uses to identify the object. Otherwise, 'NULLSTRING'.		A	'GALAXY14'	
15	All	TLELN1	Target Object Truncated TLE Line 1. First line of TLE without preceding '1' (67 characters). 'NULLSTRING' for UCTs.		A		
16	All	TLELN2	Target Object Truncated TLE Line 2. Second line of TLE without preceding '2' (67 characters). 'NULLSTRING' for UCTs.		A		
17	All	SPFNUM	The value is the number of spectral filters used.		J	2	
18	All	SPFNAMn	The SPFNAMn keywords must be present for all values n=1,…, SPFNUM, in incrementing order of n, and for no other values of n.		A	SPFNAM1='B' SPFNAM2='R'	

L.2 TLE-Based Sensor Data Table Column Descriptions

These are the required data table TTYPEn fields for data from a space-based sensor. In this case, n = 11. Note that the data table TTYPE fields do not change if the space-based sensor has a TLE or state vector.

Table 13 - EOSSA Binary Table Extension Data Column Descriptions for a Space-based Sensor

#	**Req'd.**	**TTYPEn values** (data columns)	**Description**	**Units**	**Format** (part of TFORM)	**Example(s)**	**Notes**
1	All	UTC_Begin_exp	The start time of the exposure in UTC.	yyyy-mm-ddThh:mm:ss{.ssssss}	A	'2013-08-01T12:13:14.000'	
2	All	UTC_End_exp	The end time of the exposure.	yyyy-mm-ddThh:mm:ss{.ssssss}	A	'2013-08-01T12:14:14.000'	
3	All	JD_Mid_Exp	The time of mid-exposure in JD. Be sure the values for this keyword have enough significant digits to express the time to the appropriate fraction of a second.		D	2456506.00937	
4	All	Exp_Duration	Length of the integration or exposure time.	sec	D	30.0	
5	All	Cur_Spec_Filt_Num	The reference number, n, in CALFILn for the currently used spectral filter.		J	1	
6	All	Cur_ND_Filt_Num	The reference number n, in NDFNAMn for the		J	2	

#	Req'd.	**TTYPEn values** (data columns)	**Description**	**Units**	**Format** (part of TFORM)	**Example(s)**	**Notes**
			currently used neutral density filter.				
7	All	Mag_Exo_Atm	Exo-atmospheric magnitude is the magnitude of the target on the standard scale with atmospheric effects removed, e.g., m_r in Equation (A- 18).	mag	D	13.21	
8	All	Mag_Range_Norm	Range-normalized magnitude (Mag in #7) using 1000 km.	mag	D	3.45	
9	All	Eph_RA_DE	Predicted Right Ascension and Declination of the Target object from the frame of reference of the sensor (J2000, geocentric velocity aberration). SGP4 and VCMs produce geocentric origin and velocity aberration and subtracting the sensor geocentric position of the sensor places in its reference frame.	deg	2D	[75.33; -5.001]	
10	All	Met_RA_DE	Measured Right Ascension and Declination of the Target object from the	deg	2D	[75.31; -5.201]	

#	Req'd.	**TTYPEn values** (data columns)	**Description**	**Units**	**Format** (part of TFORM)	**Example(s)**	**Notes**
			frame of reference of the sensor.				
11	All	Tel_Obj_Range	Distance from the telescope to the target object during the observation.	m	D	3.578683E7	

L.3 State Vector-Based Sensor Header Keywords

These are the keywords required for the binary table extension header when a space-based sensor with a state vector is employed. There are 15 keywords.

Table 14 - EOSSA Binary Table Extension Header Keywords Required for a Space-based Sensor with a State Vector

#	Req'd.	Keyword	Description	Units	Format	Example(s)	Notes
1	All	EXTNAME	Filename of the FITS binary extension table file.		A		
2	All	CLASSIF	Security classification level of the data contained in the file.		A	'UNCLASS', 'CONF', 'SECRET', etc.	
3	All	VERS	Version number of the EOSSA data format.		A	'1.0', '2.5', '3.0', '3.1.1'	
4	All	OBSEPH	Observer type, i.e., ground-based, space-based with a TLE for the sensor, or space-based with a state vector for the sensor.		A	'GROUND', 'TLE', 'STATE'	
5	All	TELESCOP	Telescope site name or SSN sensor identifier.		A	'AMOS', 'RME', 'SENSOR510'	
6	S/T, S/S	OBSTYPE	If the space-based sensor has a space catalog number, the string 'SCN' is the value; otherwise 'NULLSTRING' is the value.		A	'SCN' or "NULLSTRING"	
7	All	OBSNAME	Telescope name.		A	'SENSOR510', 'AEOS', 'MT16', 'RMERaven',etc.	
8	All	OBJEPH	Target object ephemeris source.		A	'STATE', 'TLE'	
9	All	OBJTYPE	If the target has a space catalog number, the string 'SCN' is the value. If another catalog is used to identify the object, the name of that catalog is the value.		A	'SCN', 'NULLSTRING'	

#	Req'd.	Keyword	Description	Units	Format	Example(s)	Notes
			Otherwise, 'NULLSTRING' is the value.				
10	All	OBJNUM	If OBJTYPE = 'NULLSTRING', -2147483648 is the value. Otherwise, the identification number of the object from the catalog in OBJTYPE is the value.		J	12345	
11	All	OBJECT	Common name of target object if available or a name that the data provider uses to identify the object. Otherwise, 'NULLSTRING'.		A	'GALAXY14'	
12	All	TLELN1	Target Object Truncated TLE Line 1. First line of TLE without preceding '1' (67 characters). 'NULLSTRING' for UCTs.		A		
13	All	TLELN2	Target Object Truncated TLE Line 2. Second line of TLE without preceding '2' (67 characters). 'NULLSTRING' for UCTs.		A		
14	All	SPFNUM	The value is the number of spectral filters used.		J	2	
15	All	SPFNAMn	The SPFNAMn keywords must be present for all values n=1,…, SPFNUM, in incrementing order of n, and for no other values of n.		A	SPFNAM1='B' SPFNAM2='R'	

L.4 State Vector-Based Sensor Data Table Column Descriptions

These are the required data table TTYPEn fields for data from a space-based sensor. In this case, n = 11. Note that this is the same table as Table 13 and is repeated here only for convenience.

Table 15 - EOSSA Binary Table Extension Data Column Descriptions for a Space-based Sensor

#	**Req'd.**	**TTYPEn values** (data columns)	**Description**	**Units**	**Format** (part of TFORM)	**Example(s)**	**Notes**
1	All	UTC_Begin_exp	The start time of the exposure in UTC.	yyyy-mm-ddThh:mm:ss{.ssssss}	A	'2013-08-01T12:13:14.000'	
2	All	UTC_End_exp	The end time of the exposure.	yyyy-mm-ddThh:mm:ss{.ssssss}	A	'2013-08-01T12:14:14.000'	
3	All	JD_Mid_Exp	The time of mid-exposure in JD. Be sure the values for this keyword have enough significant digits to express the time to the appropriate fraction of a second.		D	2456506.00937	
4	All	Exp_Duration	Length of the integration or exposure time.	sec	D	30.0	
5	All	Cur_Spec_Filt_Num	The reference number, n, in CALFILn for the currently used spectral filter.		J	1	
6	All	Cur_ND_Filt_Num	The reference number n, in NDFNAMn for the		J	2	

#	Req'd.	**TTYPEn values** (data columns)	**Description**	**Units**	**Format** (part of TFORM)	**Example(s)**	**Notes**
			currently used neutral density filter.				
7	All	Mag_Exo_Atm	Exo-atmospheric magnitude is the magnitude of the target on the standard scale with atmospheric effects removed, e.g., m_r in Equation (A- 18).	mag	D	13.21	
8	All	Mag_Range_Norm	Range-normalized magnitude (Mag in #7) using 1000 km.	mag	D	3.45	
9	S/S	Tel_State_Vec	Telescope state vector in ECI J2000 coordinate frame.	m&m/s	6D		See Section 3.7.1
10	All	Eph_RA_DE	Right Ascension and Declination of the Target object from the frame of reference of the sensor (J2000).	deg	2D	[75.33; -5.001]	
11	All	Met_RA_DE	Measured Right Ascension and Declination of the Target object from the frame of reference of the sensor.	deg	2D	[75.31; -5.201]	
	All	Tel_Obj_Range	Distance from the telescope to the target object during the observation.	m	D	3.578683E7	