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METEOR SEE

DATA PROCESSING

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Data Processing of Solar EUV Instruments on the METEOR Satellite

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ABSTRACT

The Multiple Experiment Transporter into Earth Orbit and Return - Solar EUV Experiment (METEOR-SEE) project will take daily extreme ultraviolet (EUV) irradiance spectra starting in the Summer of 1995. The METEOR-SEE package consists of an EUV grating spectrograph (EGS) and a cluster of 5 soft x-ray photometers (XPs). Both these instruments have flown previously on NASA sounding rockets. Because of the scope of the project, new data processing algorithms had to be developed for the SEE instruments onboard the METEOR satellite. An overview of the data flow describes how satellite data are collected and processed. Detailed descriptions of specific routines will show what data processing entails.

1. INTRODUCTION

Solar EUV radiation is loosely defined as the solar spectrum below 120 nanometers (nm). None of these small wavelengths reach the earth's surface, but rather they are absorbed into the earth's upper atmosphere. As a result, scientists must make all EUV measurements from space. High-energy EUV photons are the primary contributor to the heating of the earth's upper atmosphere. The variability, or change in intensity, of the EUV spectrum can also change by factors of 2 to 100 over a relatively short time span. Both the nature of this variability and its effects on the upper atmosphere are not well understood, and previous long-term EUV studies have been inadequate. For approximately two years, starting in the summer of 1995, METEOR-

SEE will sample the EUV spectrum for longer times at greater resolutions than has ever been done previously.

The METEOR satellite will carry the High Altitude Observatory's (HAO) SEE instrument package. SEE consists of two main instruments: an EUV grating spectrograph (EGS) and a cluster of five XUV photometers (XPs). The EGS is a 1/4 m Rowland circle spectrograph. It breaks up light into its spectral components and detects the spectral intervals using a 1-dimensional 1024 element CODACON array detector. The XPs consists of 5 silicon photodiodes coated with different thin metallic films to act as bandpass filters. This limits the wavelengths of light each photodiode can see. Both detectors have been tested and proven before in NASA sounding rocket flights[1].

Since METEOR-SEE will provide much more data than the sounding rocket flights, SEE personnel had to develop new software to make the data analysis more routine. A primary task of this new software is data processing, or the conversion of unitless data numbers into scientific values.

2. METHODS

Satellites usually store and transmit data digitally. On the METEOR satellite, all analog signals and values are converted to binary data numbers. For example, much of the SEE scientific data are measurements of irradiance, or the amount of light. SEE handles this scientific data not as irradiance but as counts. Counts, as one might expect, are results from the SEE microprocessor counting. For example, a SEE instrument may want to count the number of photons that hit it. The microprocessor counts these photons by incrementing a binary number in memory by one each time the instrument gets hit. The result are several data numbers with meaningless units of counts. The conversion of this unitless binary data into analog values with scientific units (i.e. irradiance) is called a calibration. SEE data processing involves the calibration of all raw SEE data numbers from unitless digital values to meaningful scientific values.

For me, data processing involved developing software procedures and functions that were largely defined by my advisors Tom Woods and Chris Pankratz. They helped to define the procedure's name, the input parameters, the output parameters, and gave suggestions on how to implement it. I am also given any preflight calibration files or calibration values required by the procedure. Calibration data are usually the results of tests done on SEE instruments at the National Institution of Standards and Technology (NIST) Synchrotron Ultraviolet Radiation Facility (SURF). These preflight measurements provided information on how the instruments performed under varying circumstances. Preflight measurements also gave accurate correlations between data numbers and scientific values. After the procedures are written and tested, they are placed in a development holding area on the SEE hard disk. The primary goal during my 10 week visit was to get the data processing software working before METEOR-SEE starts gathering data.

The primary software used by HAO to do data processing is Interactive Data Language (IDL), the UNIX version. IDL is an easy-to-use programming language popular with many scientists. It is optimized to handle entire data arrays, or data sets, at a time. Its ease-of-use, however, can be offset by long processing times, so some experience is needed to optimize IDL code. If needed, IDL can also call faster external C and FORTRAN programs to avoid problems with processing time and to make use of pre-existing code.

3. DATA FLOW

How METEOR-SEE data gets from the satellite to earth is somewhat complicated. This data flow starts with the METEOR-SEE instrument package onboard the satellite. SEE gathers analog data from the instruments and other sensors and converts the analog values into digital data numbers. All SEE data are formatted into convenient packets and sent to the METEOR spacecraft's mass memory. All METEOR data in this mass memory, which include data from several other instruments along with SEE, are then sent to earth via microwave. METEOR will broadcast data twice a day and the transmissions will be received at NASA's Wallops Flight

Facility (WFF). The distributor of all METEOR data, CTA Space Systems, will receive the raw METEOR data at Wallops, extract the SEE data, and send the data via encoded e-mail to HAO. HAO will then automatically decode the data from e-mail, and finally the data will be processed.

4. DATA PROCESSING OVERVIEW

METEOR-SEE data are processed consecutively by three main algorithms: *Level 1, Level 2,* and *Level 3 SEE Processing* . Each level progressively refines the data for clarity and accuracy. *Level 1 SEE Processing* is the largest, most complex algorithm, thus it is the one I have the most work in.

5. LEVEL 1 PROCESSING

The *LEVEL 1* algorithm requires several inputs. These include the raw SEE data (i.e. the decoded files received from Wallops), spacecraft data (orientation, position, and altitude of the METEOR satellite), and any calibration data.

Given these inputs, *Level 1* must then perform basically four data processing tasks. These tasks calibrate the input raw SEE data into scientific units. The tasks include analog calibrations, wavelength calibration, EGS photometric calibration, and XP photometric calibration. Analog calibrations encompass the calibration of miscellaneous non-science data numbers such as temperatures and voltages which aid in instrument health analysis and certain scientific calibrations. The wavelength calibration maps EGS spectral measurements onto an accurate wavelength scale. The EGS an XP photometric calibrations convert EGS and XP instrument data into scientific irradiance units.

Level 1 outputs all the results of these data processing tasks plus a log and summary file. The log and summary files help with the analysis of the performance of the SEE instruments, and they keep a record of the mission.

5.1 EXAMPLE PROCEDURE 1: Calibrate_analogs.pro

This first example procedure describes one aspect of what data processing entails, and it also gives an example of the modular programming method. *Modular programming* describes a technique that is used to limit the complexity and size of programs. Instead of creating a single program for all tasks, individual tasks are assigned to smaller procedures, which are then combined. Level 1 Processing is basically a large modular program with smaller modular programs as its modules. The analog calibrations procedure is an example of one such module. IDL code for all example procedures, such as the following, can be found in APPENDIX A.

calibrate_analogs.pro

inputs - see_record

outputs - calibrated analog and analog standard deviation values

All raw SEE data are organized into see_records for better handling when they are first read at the beginning of *Level 1 Processing* . A see_record contains an array of structures. Each element of the array corresponds to one telemetry data packet. Each packet can be one of four structure types: science, engineering, health, and error. These correspond to each of the four telemetry data packet types (APPENDIX B, Sections 2.5-2.8). A *structure* is a programming term which describes a cluster of variables of any type. For now, however, we will focus only on the content and format of the science and engineering data structures.

Table 1
Science and Engineering Structures

Science	Engineering
1. header	1. header
2. mode	2. mode
3. reclen	3. reclen
4. time	4. time
5. status	5. status
6. analog	6. analog
7. analog_sdev	7. analog_sdev
8. xp_itime	8. dump_addr
9. xp_cnts	9. dump_data
10. egs_itime	10. last_exe_cmd
11. egs_tot_cnts	11. checksum
12. egs_loat_cnts	
13. egs_spectrum	
14. last_exe_mod	
15. checksum	

These lists represent IDL structures and their fields. These structures are taken from sci_rec_10.pro and eng_rec_l0.pro written with the help of Chris Pankratz.

The analog calibrations only work with two see_record structure types: science and engineering (Table 1). Science structures have 15 fields and engineering structures have 11 fields. Each field corresponds to different types of data: i.e. bytes, integers, or arrays (APPENDIX B, sections 2.5-2.8). Calibrate_analogs uses only two fields: analog and analog_sdev (numbers 6 and 7 on both structures in Table 1). The analog field contains SEE analog monitor values averaged over an integration period (usually 60 seconds), and the analog_sdev field contains the corresponding standard deviations of each analog value.

Table 2
Analog and Analog_sdev Structures

1. micro_temp	9. m15v_monitor
2. egs_detector_temp	10. m5v_monitor
3. egs_grating_temp	11. spare
4. xp_temp	12. egs_hv_ps_mon
5. reg_box_temp	13. egs_hv_box_mon
6. heater_temp	14. psd_intentity
7. p5v_monitor	15. psd_x
8. p15v_monitor	16. psd_y

Structures taken from calibrate_analogs.pro.

Each analog field in the science and engineering structures originally contains a 16 element array of short integer data numbers. For easier handling, *calibrate_analogs* converts this array into a 16 field structure (Table 2). Each field contains an integer data number that can range from 0 to 4095. Onboard METEOR-SEE, there is a 12-bit analog to digital (A/D) converter. When an analog signal is sent into the A/D, the output is a 12-bit digital word that is stored as a 16-bit short integer. These short integers are what are in each analog field (Table 2, Fields 1-16). The values of these fields have three types of sources: power supply, thermistor, and Position Sensitive Detector (PSD). This means a field can stand for a voltage (volts), a temperature (^{o}C), or a position (arc-minutes).

Calibrate_analogs calls three different sub-procedures (*calibrate_voltage, calibrate_temperature, and calibrate_raw_psd*) for each of the three different analog sources. These sub-procedures perform the actual calibration of the data numbers into their respective units. *Calibrate_analogs* then returns two arrays of calibrated values, one for the input analog average values and the other for the input analog_sdev values (Table 1, Fields 6 & 7). *Calibrate_analogs* also calls a unique sub-procedure (*read_analog_cal*) to read in the calibration values from a calibration file if they are not already in the computer's memory.

read_analog_cal.pro

inputs - N/A (default calibration file)

outputs - calibration data for temperature, voltage, and PSD

All calibration data are stored in semi-permanent text files on the SEE harddisk. When needed, the data in the text files are read by IDL and stored in memory for subsequent use. The procedures *read_dat.pro* and*write_dat.pro* were specifically written to standardize the reading and writing of text data files such as calibration files. The calibration file for the analog calibrations does not have the standard format, so *read_dat* could not be used. A specific procedure had to be written to handle this non-standard file, and so became *read_analog_cal*. An example data file is given in the APPENDIX A as *analog_cal.dat*.

Read_analog_cal is limited in its application because the calibration file must have a specific format. It is more versatile than *read_dat* because *read_analog_cal* can read multiple data sets; *read_dat* can only handle single data sets. The results of *read_analog_cal* are returned as multiple arrays. The arrays corresponds to each data set in the analog calibration file.

calibrate_voltage.pro

inputs - analog data numbers

outputs - volts

This procedure calibrates fields 7-14 in Table 2. These data-numbers come directly from voltage detectors on various parts of the SEE package. Because the A/D has a linear relationship between voltage and data number, all that is needed for the calibration is a linear equation (APPENDIX B, Section 1.5).

calibrate_temperature.pro

inputs - analog data numbers

outputs - °C

Calibrate_temperature calibrates fields 0-5 in Table 2. These are voltages returned from thermistors which are mounted on various parts of the SEE package. Thermistors are resistors whose resistances vary substantially with changes in temperature. Using ohm's law ($V = I \cdot R$), a constant current is sent through the thermistors and the resulting voltages are read by the A/D. Unfortunately, the temperature/resistance relationship for the thermistors is very non-linear.

To work around this non-linearity, *calibrate_temperature* uses an interpolation. The temperature/resistance relationship for the thermistors were provided to HAO by the manufacturer (VSI Incorporated). From this information, a data set of the temperature versus data number relationship was created. *Calibrate_temperature* interpolates the input data numbers along this data set and the result is the temperature in °C. This information gives an indication of the thermal environment of the SEE package.

calibrate_raw_psd.pro

inputs - analog data numbers

outputs - Sun's relative position (arc-minutes)

This procedure calibrates fields 14 and 15 in Table 2. These fields are the two voltages returned by the PSD. The PSD is a square light-sensitive instrument. When light hits the PSD, a wave of electrons spreads from the point where the light hit the PSD's surface. The intensity of the wave diminishes with the distance from this point. Mounted on the corners of the PSD sensor are voltage detectors. The sum of the two voltage at the top of the PSD gives the Y-axis voltage.

The sum of the two voltages on the side gives the X-axis voltage. By knowing these two X and Y voltages, we can then know where a light source hit the PSD.

A small lens focuses the Sun's light onto the square PSD detector. Since there is a linear relationship between the Sun's angular position and the X and Y voltages, both X and Y calibrations are linear equations resulting is the sun's relative position in arc-minutes (Appendix B, Section 1.5). This is used to get the Sun's offset from the EGS or how far off center from the Sun the EGS is pointing. Other instruments onboard METEOR will also use data from the PSD.

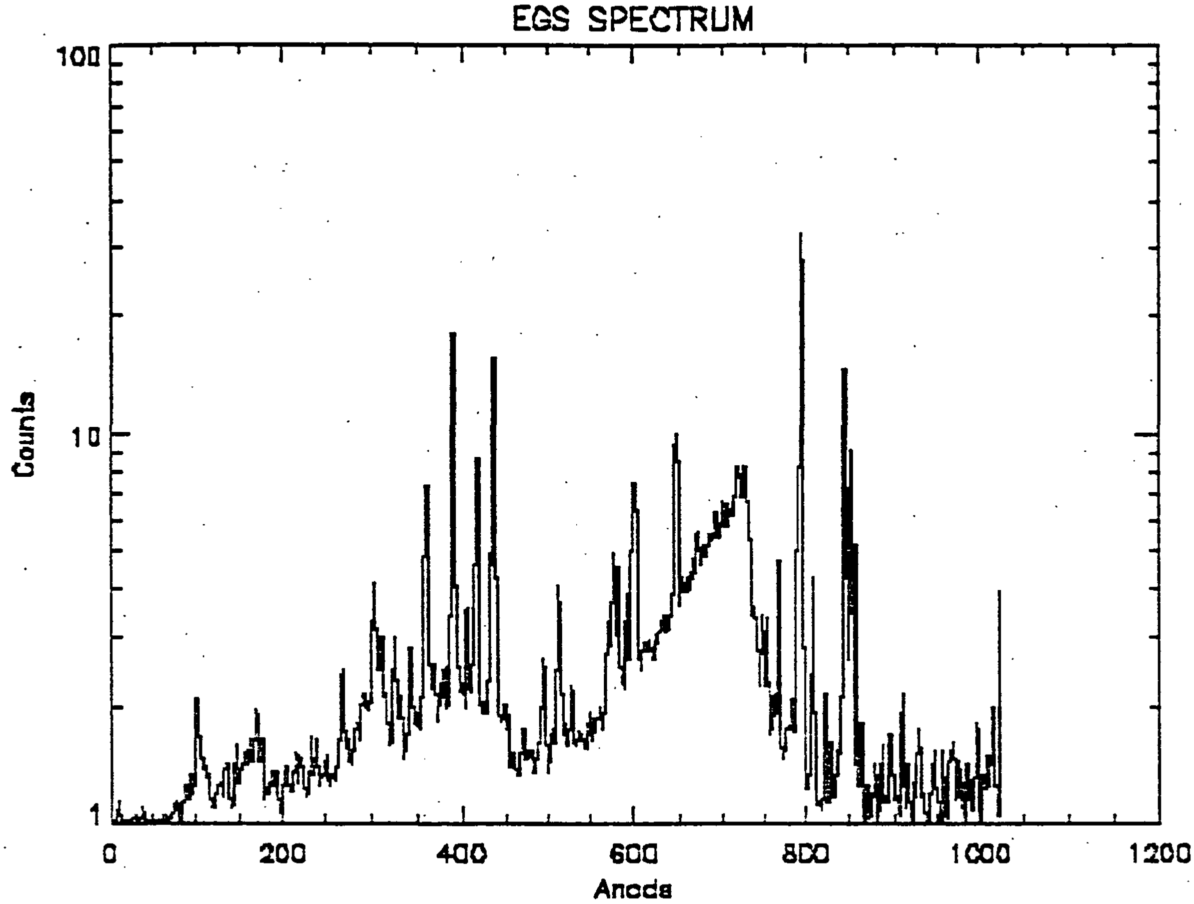
5.2 EXAMPLE PROCEDURE 2: Determine_egs_wave.pro

This following procedure is an example of unexpected complications. Similar procedures were written for similar HAO projects such as UARS-SOLSTICE, so it was recommended that I follow their example. Unfortunately, when finished, this procedure did not work as well as I hoped, so is has since undergone several revisions.

determine_egs_wave.pro

input - EGS spectrum (counts vs. anodes)
output - wavelengths in nm

The EGS instrument measures solar irradiance using a CODACON detector. The CODACON on the EGS consists of a coded one dimensional 1024 element anode array behind a microchannel plate (MCP). Each anode reports its position whenever it is struck with a photon. Because the anodes are coded, the CODACON can give each photon position as a function of anode position. After approximately one minute of counting photons, the result is an EGS spectrum.



This EGS spectrum was taken from a sounding rocket flight of the EGS instrument. Units are in counts vs. anode. Counts are the photon counts per second for each anode. Notice there are 1024 anodes.

The CODACON anodes are aligned with the solar EUV spectrum from roughly 20-120 nm, so anode 1 roughly coincides with 20 nm and anode 1024 roughly coincides with 120 nm. Knowing where the anodes roughly correspond to wavelengths is not good enough, so for complete accuracy a wavelength calibration procedure is needed convert the anodes to wavelengths. The anode alignment with the EUV spectrum, however, is not consistent, so the wavelength calibration procedure also needs to adjust to these inconsistencies.

There are three basic inconsistencies which may occur with the EGS spectrum. The spectrum may shift to the left or right, it may stretch, and it may warp or bend. These are results of any combination of the Sun's angular position, the temperature of the EGS, and the thermal gradient across the EGS optical axis.

Determine_egs_wave calibrates the EGS spectrum in anodes into the proper scientific units of wavelengths (nm). It does this by using certain theoretically determined atomic emission lines in the solar spectrum as a reference spectrum. These emission lines are fixed and theory tells us exactly where they occur within the electromagnetic spectrum. The emission lines appear as peaks or spikes in the EGS spectrum. For the calibration, *Determine_egs_wave* aligns these measured peaks to their correct theoretical positions.

Determine_egs_wave does this calibration in the following way. First, the reference spectrum is created using the theoretical values of the emission lines. *Determine_egs_wave* converts this reference spectrum from wavelength-space to anode-space using a preflight EGS calibration. The reference spectrum is then convolved across the EGS spectrum to see where they best align. This result gives the gross shift, to the left or right, of the spectrum. The measured peaks in the EGS spectrum are then aligned with the theoretical peaks in the reference spectrum which compensates for any warping or stretching in the measured data. Finally, *Determine_egs_wave* computes the center of mass for each peak found to get the exact center of the emission line. The emission lines are now known in anodes and in nanometers, so a polynomial fit is performed for anodes versus nanometers which results in a quadratic equation. All 1024 anodes are then inserted into this quadratic resulting in the 1024 wavelengths for each anode.

6. LEVEL 2 PROCESSING

Level 2 Processing takes the outputs from Level 1 and any calibration files as input. Its main data processing tasks include taking the average of the irradiance measurements for a day and averaging them into one solar spectrum for that day. The resolution of this spectrum is 0.1 nm, or the resolution of the instruments. Level 2 also corrects for any atmospheric absorption that may occur at the spacecraft's altitude of around 400 km.

7. LEVEL 3 PROCESSING

Level 3 Processing takes the results from Level 2 and smoothes out the data to one nm resolution. All reference features, such as the magnitude of the brighter emission lines, are extracted, and data are corrected for any instrument degradation that will occur with time.

8. CONCLUSION

The METEOR-SEE data processing project is still under development. Data from the SEE instruments will be received on the day the METEOR satellite is launched. The launch will occur soon at NASA's WFF on the maiden flight of the Conestoga launch vehicle. METEOR has a planned operational lifetime of two years. The data processing software will evolve as the instruments degrade with time and when calibration parameters are better understood.

9. REFERENCES

1. Woods, T. N., Bailey, S.M., Solomon, S.C., and Rottman, G.J., "Far Ultraviolet and Extreme Ultraviolet Rocket Instrumentation for Measuring the Solar Spectral Irradiance and Terrestrial Airglow.", *Instrumentation for Planetary and Terrestrial Atmospheric Sensing*, Vol. 1745, **140-148**, 1992.