NOAA NESDIS
National Geophysical Data Center

GOES 13-15 MAGE/PD PITCH ANGLES ALGORITHM THEORETICAL BASIS DOCUMENT
Version 1.0

TITLE: GOES 13-15 MAGE/PD PITCH ANGLES
ALGORITHM THEORETICAL BASIS DOCUMENT VERSION 1.0

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GOES 13-15 MAGE/PD PITCH ANGLES
ALGORITHM THEORETICAL BASIS DOCUMENT
VERSION HISTORY SUMMARY

Version Number	**Date**	**Authors**	**Revision Description**	**Reason for Revision**
1.0	September 10, 2014	Juan V. Rodriguez	Initial release	--

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LIST OF ACRONYMS

ATBD	Algorithm Theoretical Basis Document
BRF	body reference frame (spacecraft coordinates)
EPN	earthward-poleward-normal coordinate system
EPS	Energetic Particle Sensor
eV	electron volt
FOV	field-of-view
FWHM	full width at half maximum
GOES	Geostationary Operational Environmental Satellite
IFC	in-flight calibration
keV	kilo-electron-volt
MAG	Magnetometer
MAGED	Magnetospheric Electron Detector
MAGPD	Magnetospheric Proton Detector
MeV	mega-electron-volt
NGDC	National Geophysical Data Center
PAD	pitch-angle distribution
RMS	root-mean-square
SWPC	Space Weather Prediction Center

ABSTRACT

The GOES 13-15 MAGED electron fluxes and MAGPD proton fluxes are currently produced in real time by SWPC. Each MAGE/PD instrument consists of nine telescopes, each of which is approximately coaligned with a telescope from the other instrument. Pitch angles are needed for the full use of these fluxes in science studies and higher-level products. NGDC calculates 1-minute resolution pitch angles using 1-min-averaged magnetometer field vectors and the telescope orientation with respect to the spacecraft body reference frame. At each 1-minute interval, there are nine pitch angles: one pitch angle for all five electron energy channels and all five proton energy channels sharing a look direction. This data set is produced in the form of monthly files for each satellite.

1.0 INTRODUCTION

1.1 Purpose of This Document

The purpose of this document is to describe the theoretical basis and top-level design of the algorithm for calculating pitch angles for the GOES 13-15 MAGED and MAGPD instruments. Product details are also provided.

1.2 Who Should Use This Document

This document is intended for users of the GOES 13-15 MAGED and MAGPD pitch angles product so that they can understand the strengths and weaknesses of the product and use it properly.

1.3 Inside Each Section

Section 2.0 OBSERVING SYSTEM OVERVIEW:
Describes the product generated and the measurements that serve as input to the algorithm.

Section 3.0 ALGORITHM DESCRIPTION:
Describes the development, theory and mathematics of the algorithm. Describes the logical flow of the algorithm, including input and output flow.

Section 4.0 PRODUCT TESTING AND QUALITY METRICS:
Describes the data product quality metrics and the testing of the algorithm during development.

Section 5.0 PRACTICAL CONSIDERATIONS:
Discusses issues involving numerical computation, programming and procedures, quality assessment and diagnostics and exception handling.

Section 6.0 ASSUMPTIONS AND LIMITATIONS:
Describes assumptions regarding input data contents and formats; instrument performance and characterization data; and potential future changes and improvements.

Section 7.0 REFERENCES:
Provides all references mentioned in the ATBD.

Appendix A PRODUCT VERSIONS:
Lists and describes all product versions to date.

Appendix B LIST OF VARIABLES AND METADATA

Lists all variables and their attributes, as well as global attributes.

1.4 Related Documents

GOESN-ENG-048D: EPS/HEPAD calibration and data handbook, GOESN-ENG-048, Rev. D, Assurance Technology Corporation, Carlisle, Mass., May 13, 2011

GOES N Series Data Book, Rev. D, Boeing Satellite Systems, February 2010

2.0 OBSERVING SYSTEM OVERVIEW

2.1 Product Generated

In general, magnetospheric particle fluxes are a function of particle kinetic energy and of the angle that their velocities make with respect to the Earth's magnetic field. This angle is referred to as the 'pitch angle.' The pitch-angle distribution (PAD) is a signature of the recent dynamical history of the fluxes, reflecting phenomena such as drift-shell splitting, wave-particle interactions, field-line stretching, and magnetopause shadowing. GOES 13-15 carry new instruments (Magnetospheric Electron Detector (MAGED) and Magnetospheric Proton Detector (MAGPD)) providing pitch-angle-resolved measurements of magnetospheric electrons and protons. However, the real-time processing that produces the MAGED and MAGPD fluxes does not calculate the pitch angles. The pitch-angle product comprises nine time-series of pitch angles corresponding to each of the MAGE/PD telescopes, at the same intervals as the one-minute averages of the fluxes produced by SWPC. It is calculated from the one-minute averages of the magnetic field vector measured by the GOES 13-15 Magnetometer and knowledge of the look directions of the MAGED and MAGPD.

2.2 Instrument Characteristics

The Magnetospheric Electron Detector (MAGED) and Magnetospheric Proton Detector (MAGPD) each consist of nine solid-state-detector telescopes in a cruciform configuration with five telescopes in the east-west (equatorial) plane and four additional telescopes in the north-south (meridional) plane. Each field-of-view (FOV) has a full-width at half-maximum (FWHM) of approximately 20 degrees. Each MAGED telescope is co-aligned with a MAGPD telescope; therefore, only one pitch angle product is needed. Each telescope makes flux measurements in five energy bands (30-600 keV for MAGED, 80-800 keV for MAGPD). The fluxes are corrected for dead time and for contamination by the other species. For further details on the instruments please see Hanser [2011]. For a example of the transformation of the FOV angular response functions into pitch-angle space, please refer to Jaynes et al. [2013]. In this document, for simplicity, a combined acronym 'MAGE/PD' is used to refer to a shared attribute.

The GOES 13-15 Magnetometer (MAG) comprises a pair of three-axis fluxgate magnetometers mounted on an 8.5-meter boom. The outboard magnetometer is 8.5 m from the spacecraft and the inboard magnetometer is 7.7 m from the spacecraft (GOES-N Series Data Book). To date, the fields from the outboard magnetometer have been used exclusively in the processing. They are available in instrument coordinates, spacecraft body reference frame (BRF) coordinates, and the EPN coordinate system, which is parallel to and has the same origin as the BRF yet depends on the yaw-flip state of the spacecraft. The BRF components are used in the pitch angle calculation since this does not require knowledge of whether the spacecraft is upright or inverted.

3.0 ALGORITHM DESCRIPTION

3.1 Algorithm Overview

Pitch angles for the MAGE/PD telescopes are calculated using the magnetic field from the GOES Magnetometer in the spacecraft body reference frame (BRF). Because the signatures of the in-flight calibrations (IFCs) have not been removed from the BRF components, the contaminated samples are flagged and removed by comparing them with the EPN components, which have had the IFCs removed.

3.2 Processing Outline

1. Remove signatures of in-flight calibrations from field components in spacecraft coordinates (BRF) using information from the EPN data set, in the following order:
    a. If the total field from the EPN set is a fill value, then replace the BRF components with fill values.
    b. If the number of points in the EPN total field does not equal the number of points in the BRF total field, then replace the BRF components with fill values.
    c. If there are any spikes in the total field that are greater than 512 nT, replace all components with fill values.
2. Calculate the total field from the double-precision quadrature sum of Bx, By and Bz in spacecraft coordinates.
3. Calculate pitch angles from the BRF field components and total field.

3.3 Algorithm Input

The inputs to the algorithm consist of 1-minute MAG magnetic fields in the instrument and spacecraft body reference frames. The direction cosines are hard-coded into the pitch-angle calculation procedure.

3.3.1 Primary Data

The input variables, which are defined in Table 1, are read from the MAG 1-minute-cadence monthly netCDF files produced routinely by NGDC (see section 6.2). They are all from Magnetometer #1.

3.3.2 Ancillary Data

No ancillary data are required by the algorithm.

Table 1. GOES magnetometer inputs to MAGE/PD pitch-angle algorithm

Variables	Refresh	Number of values	Units
time_tag	1 min	1 (start of period)	milliseconds since 1970-01-01 00:00:00.0 UTC
BXSC_1, BYSC_1, BZSC_1	1 min	3 (1 per axis)	nT
BTSC_1_NUM_PTS	1 min	1	Number of points in average
HT_1	1 min	1	nT
HT_1_NUM_PTS	1 min	1	Number of points in average

3.4 Theoretical Description

3.4.1 Physics of the Problem

The calculation of the central pitch angle for each MAGED and MAGPD telescope requires knowledge of the look angles of the telescope with respect to the spacecraft body reference frame (BRF) coordinate axes, and the values of the magnetic field components in the BRF as measured by the GOES magnetometer. The pitch angle is the angle that the particle velocity makes with respect to the magnetic field, and therefore is oppositely directed to the telescope look direction. It is the polar angle in a spherical coordinate system where the pole is defined by the local direction of the magnetic field. Because of the relatively few angular measurements by the GOES instruments, we assume that the fluxes are azimuthally isotropic about the magnetic field. Therefore, all angular variation is attributed to pitch angle.

The telescope fields-of-view (FOVs) have a cruciform arrangement, with five telescopes in the north-south fan and four additional telescopes in the east-west fan. This is illustrated in Figure 1. Their angles with respect to the spacecraft axes are given in Table 2. The –Z axis points in the zenith direction, away from the earth. Telescope 1, at the center of the cross, looks in the –Z direction. The most nearly southward looking telescope will have the smallest pitch angles (for particles streaming along the field line) when the field is closer to being dipolar. In Figure 1, this is Telescope 9. The two species and five energy channels per species share one set of pitch angles (one time series per look direction).

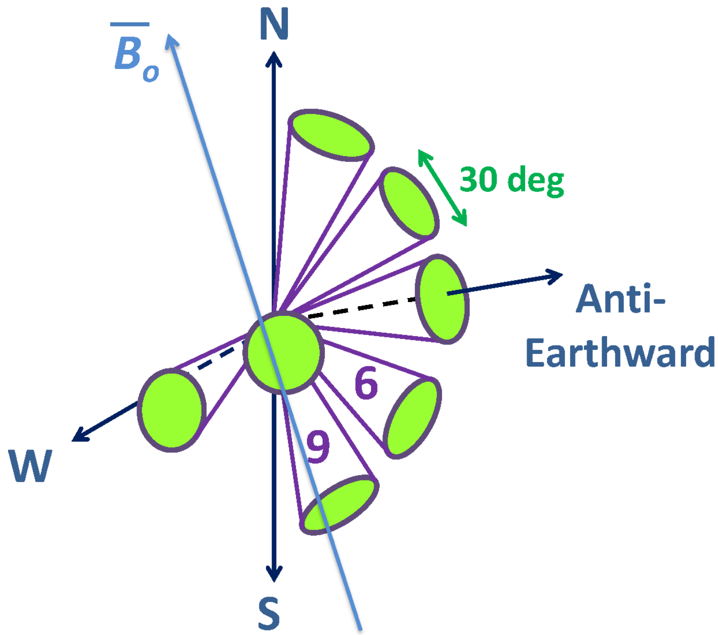

Figure 1. Illustration of MAGE/PD FOVs for an inverted spacecraft. From Jaynes et al. [2013].

Table 2. MAGE/PD telescope field-of-view (FOV) directions in the spacecraft body reference frame (BRF). The east/west/north/south indications assume that the spacecraft is upright. From GOESN-ENG-048 Rev. D, Table 4-1a.

Telescope Number	FOV angle to –Z Axis	FOV in +X or +Y Direction	Equatorial/Polar View
1	0 deg	-	Anti-earth/center
2	35 deg	+X	Equatorial/west
3	70 deg	-X	Equatorial/east
4	35 deg	-X	Equatorial/east
5	70 deg	+X	Equatorial/west
6	35 deg	+Y	Polar/north
7	70 deg	-Y	Polar/south
8	35 deg	-Y	Polar/south
9	70 deg	+Y	Polar/north

3.4.2 Mathematical Description

Definition of Quantities

α_k	pitch angle for telescope k
B_x, B_y, B_z	components of the magnetic field (flux density) vector in spacecraft body reference frame (BRF) coordinates
B_t	magnetic field magnitude
c_{35}, c_{70}	cosine of 35 deg and 70 deg
l_x, l_y, l_z	direction cosines of the particle velocities in the BRF
s_{35}, s_{70}	sine of 35 deg and 70 deg

General Expression

The direction cosines used in the calculation of pitch angle are those of the velocities of the particles measured by the telescope or zone (<u>not</u> those of the telescope look directions!). Given l_x, l_y, and l_z as the BRF direction cosines of the particle velocities measured by telescope k, the central pitch angle for telescope k is given by

$$\alpha_k = \arccos\left(\frac{B_x l_x + B_y l_y + B_z l_z}{B_t}\right) \quad (1)$$

Specific Expressions for Each Telescope

The look directions for each telescope are given in Table 2. Accordingly, the pitch angle expression for each telescope is simplified to the following:

$$\alpha_1 = \arccos[B_z/B_t] \quad (2)$$

$$\alpha_2 = \arccos[(-s_{35}B_x + c_{35}B_z)/B_t] \quad (3)$$

$$\alpha_3 = \arccos[(s_{70}B_x + c_{70}B_z)/B_t] \quad (4)$$

$$\alpha_4 = \arccos[(s_{35}B_x + c_{35}B_z)/B_t] \quad (5)$$

$$\alpha_5 = \arccos[(-s_{70}B_x + c_{70}B_z)/B_t] \quad (6)$$

$$\alpha_6 = \arccos[(-s_{35}B_y + c_{35}B_z)/B_t] \quad (7)$$

$$\alpha_7 = \arccos[(s_{70}B_y + c_{70}B_z)/B_t] \quad (8)$$

$$\alpha_8 = \arccos[(s_{35}B_y + c_{35}B_z)/B_t] \quad (9)$$

$$\alpha_9 = \arccos[(-s_{70}B_y + c_{70}B_z)/B_t] \quad (10)$$

If any of the field values are fill values, then the resultant pitch angle is a fill value as well.

3.5 Algorithm Output

The output variables of the GOES 13-15 MAGE/PD pitch angles algorithm are listed in Table 3. They are written into netCDF and csv files (see section 6.2).

Table 3. Contents of the GOES 13-15 MAGE/PD pitch angles product files

Variables	**Refresh**	**Number of values**	**Units**
time_tag	1 min	1 (start of period)	milliseconds since 1970-01-01 00:00:00.0 UTC
pitch_angles	1 min	9 (1 per telescope)	degrees

4.0 PRODUCT TESTING AND QUALITY METRICS

MAGE/PD pitch angles have been calculated for several studies using earlier versions of this software [Hartley et al., 2013, 2014; Jaynes et al., 2013; Rowland and Weigel, 2012; Turner et al., 2012, 2014]. These studies have provided important scientific validation of this product. There is no error propagation in this product because the misalignment between the magnetometer and the MAGE/PD telescopes is not known. It is probably within a few degrees; the sensitivity to this magnitude of error is illustrated in the next section.

4.1 Sensitivity to Input Errors

One sensitivity study has been performed in which the effect of systematic errors (offset and orientation) on pitch angles are determined using real data. Using GOES-13 measurements from November 2011, the effects on pitch angle of a 4 nT offset (per axis) and a 1, 3 and 5 deg uncertainty (per axis) in the relative orientation of MAGE/PD and MAG were determined. For each error there are eight combinations (three axes, positive or negative error). The root-mean-square (RMS) error is determined over the eight combinations at each one-minute interval. The worst case of these errors is noted, and the RMS over the entire month is also calculated. The results are shown in Table 4. These results indicate that there is not much error magnification in the pitch angle calculation. A 4-nT offset has a similar effect to a 5-deg orientation uncertainty.

Table 4. Errors in pitch angles due to simulated offset and orientation errors.

Error Type	MAG offset		Orientation Uncertainty, MAGE/PD FOV vs. MAG					
Error Magnitude	4 nT		1 deg		3 deg		5 deg	
Error Analysis	RMS	Worst	RMS	Worst	RMS	Worst	RMS	Worst
Pitch Angle	4.0°	6.7°	1.0°	3.8°	3.0°	4.2°	5.0°	7.0°

4.2 Quality Control Plots

The pitch-angle product algorithm automatically produces a quality control (QC) plot that summarizes the pitch angles for a given satellite in a given month. For example, the file name for the QC plot of GOES-15 pitch angles in August 2014 is ‘g15_pitch_angles_1m_qc_20140801-00h_20140831-24h.pdf’. Several examples of QC plots are given here.

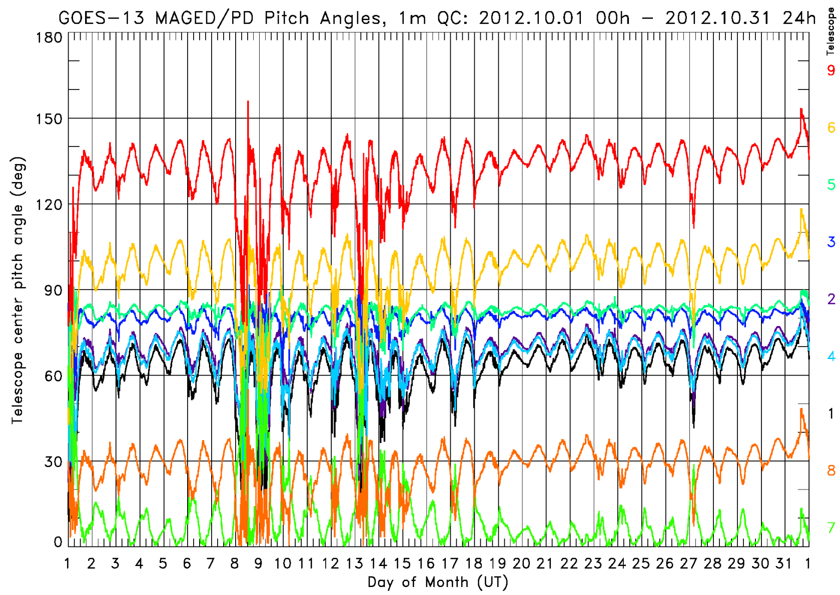

Figure 2. Pitch angles for MAGE/PD on GOES-13, October 2012. The telescope numbers are given in the right margin, color-coded to match the time series. The spacecraft is upright.

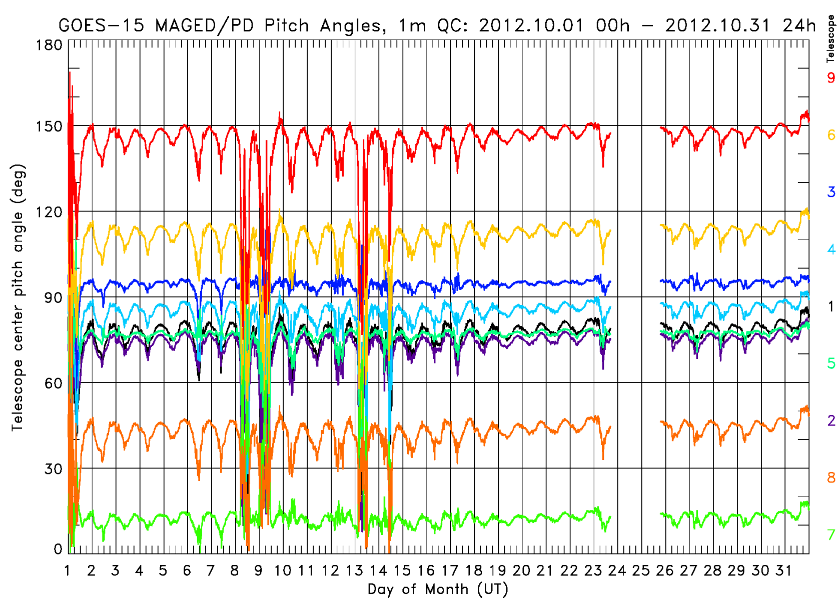

Figure 3. Pitch angles for MAGE/PD on GOES-15, October 2012. The telescope numbers are given in the right margin, color-coded to match the time series. The spacecraft is upright.

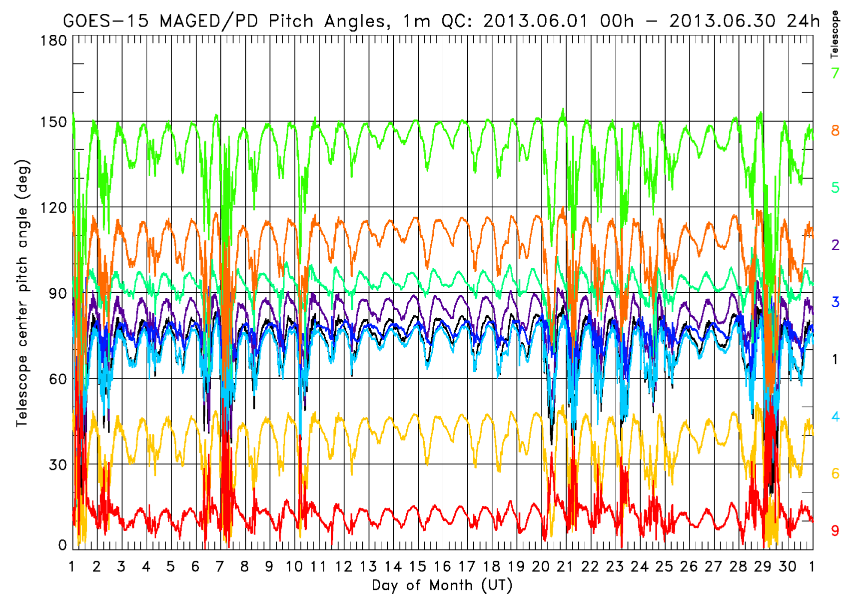

Figure 4. Pitch angles for MAGE/PD on GOES-15, June 2013. The telescope numbers are given in the right margin, color-coded to match the time series. The spacecraft is inverted.

Figure 2 and Figure 3 show the pitch angles for GOES-13 and -15 during October 2012. There are several features of note. First, since both satellites are upright, Telescope 7 usually has the smallest center pitch angle. The smallest pitch angle is on average larger at GOES-15 (GOES-West) than at GOES-13 (GOES-East), because the GOES-15 measurement is closer to the geomagnetic equator and therefore the field is more nearly north-south. On several days (1, 8, 9, 13, 14), the field is highly stretched; one consequence is that Telescope 8 sometimes has the smallest pitch angle.

Figure 4 shows the pitch angles for GOES-15 during June 2013. In this case the satellite is inverted; therefore, Telescope 9 usually has the smallest center pitch angle (Figure 1). During periods when the field is highly stretched, Telescope 6 sometimes has the smallest pitch angle.

5.0 PRACTICAL CONSIDERATIONS

5.1 Numerical Computation Considerations

The inverse cosines need to be calculated precisely or at times the argument could be invalid (e.g., very slightly greater than 1). Therefore, the total field is recalculated from the BRF components using double precision before calculating the pitch angle.

5.2 Programming and Procedural Considerations

Originally developed and tested in IDL 8.2.3 on a 64-bit Windows 7 system. Operating using IDL 8.3 in a Red Hat Enterprise Linux (RHEL) Workstation release 6.5 environment with an Intel Core i7 processsor (3325 MHz).

Main script:
```
goesnop_pitch_angles_1min
```
Custom procedure/function calls:
```
      jvr_days_in_month
      jvr_get_mag_netCDF
            jvr_unix_epoch_to_jday
      jvr_remove_mag_ifcs
      jvr_ht_from_quadrature
      jvr_calculate_pitch_angles
      jvr_write_pitch_angles_ncdf
            jvr_unix_epoch_to_jday
            jvr_days_in_month
            jvr_global_common_pitch_angles_1min
                  jvr_jday_to_utcstr
      jvr_plot_goesn_pitch_angles_ncdf_auto
            jvr_unix_epoch_to_jday
            jvr_xticks_dy
```

5.3 Quality Assessment and Diagnostics

A monthly quality control plot is created showing the time series for all nine pitch angles. See section 4.2 for examples.

5.4 Exception Handling

The primary exception handled by the algorithm is fill values in the data. Since IFCs are not removed prior to the 1-minute averaging of the BRF field components, their presence is identified by looking for fill values in the EPN components and by comparing the number of points in the BRF and EPN averages.

5.5 Algorithm Validation

See section 4.0.

5.6 Acknowledgments

The development of this product was funded in part by the GOES-R Risk Reduction project and in part by NASA Living with a Star TR&T Interagency Purchase Request #NNH13AV99Ito NGDC. Users of these data are encouraged to use the following acknowledgment statement: “The GOES MAGE/PD pitch angles were provided by the NOAA National Geophysical Data Center.”

6.0 ASSUMPTIONS AND LIMITATIONS

6.1 Constants to be Re-evaluated

There are no processing constants to be re-evaluated.

6.2 Input and Output File Contents and Formats

Input Files

Example name for GOES-15, July 2014:
'g15_magneto_1m_20140701_20140731.nc'

Variables used: see Table 1

Output files

Example names for GOES-15, July 2014:
'g15_pitch_angles_1m_20140701_20140731.nc'
'g15_pitch_angles_1m_20140701_20140731.csv'
'g15_pitch_angles_1m_qc_20140701-00h_20140731-24h.pdf'

Variables output: see Table 3

6.3 Performance

See section 4.0.

6.4 Pre-Planned Product Improvements

There are no planned improvements to this product.

7.0 REFERENCES

Hanser, F. A. (2011), EPS/HEPAD calibration and data handbook, Tech. Rep. GOESN-ENG-048D, Assurance Technology Corporation, Carlisle, Mass. [Available at http://www.ngdc.noaa.gov/stp/satellite/goes/documentation.html]

Hartley, D. P., M. H. Denton, J. C. Green, T. G. Onsager, J. V. Rodriguez, and H. J. Singer (2013), Case studies of the impact of high-speed solar wind streams on the electron radiation belt at geosynchronous orbit: Flux, magnetic field, and phase space density, J. Geophys. Res. Space Physics, 118, 6964–6979, doi:10.1002/2013JA018923.

Hartley, D. P., M. H. Denton, and J. V. Rodriguez (2014), Electron number density, temperature, and energy density at GEO and links to the solar wind: A simple predictive capability, J. Geophys. Res. Space Physics, 119, 4556–4571, doi:10.1002/2014JA019779.

Jaynes, A. N., M. R. Lessard, J. V. Rodriguez, E. Donovan, T. M. Loto'aniu, and K. Rychert (2013), Pulsating auroral electron flux modulations in the equatorial magnetosphere, J. Geophys. Res. Space Physics, 118, 4884–4894, doi:10.1002/jgra.50434

Rowland, W., and R. S. Weigel (2012), Intracalibration of particle detectors on a three-axis stabilized geostationary platform, Space Weather, 10, S11002, doi:10.1029/2012SW000816

Turner, D. L., Y. Y. Shprits, M. Hartinger, and V. Angelopoulos (2012), Explaining sudden losses of relativistic electrons during geomagnetic storms, Nature Phys., 8, doi:10.1038/NPHYS2185

Turner, D. L., et al. (2014), Competing source and loss mechanisms due to wave-particle interactions in Earth's outer radiation belt during the 30 September to 3 October 2012 geomagnetic storm, J. Geophys. Res. Space Physics, 119, 1960–1979, doi:10.1002/2014JA019770.

APPENDIX A: PRODUCT VERSIONS

Version numbers are included in the file name (starting with the first revision after version 1.0.0) and as a global attribute 'version' in the file. An example of a v1.0.0 pitch-angle netCDF file name is 'g15_pitch_angles_1m_20140701_20140731.nc'

Version numbers follow the three-number format (x.y.z) used by some space physics data sets in the NASA Goddard Space Physics Data Facility. We use the three numbers to indicate changes as follows:

x A major change, such as a quantitative correction to the processing algorithm, or a largely new algorithm, that significantly affects the variable values. After such a change, it will be recommended that users replace all downloaded files with the new version. Earlier data will be retrospectively processed to include these changes and files will be replaced on the server.

y A minor change, such as (for example) the addition of new variables such as error bars. Some users may choose not to replace all downloaded files with the new version, or at least do not need to redo earlier analyses. Earlier data will be retrospectively processed to include these changes and files will be replaced on the server.

z A patch, such as a correction to metadata. Earlier data will not be retrospectively processed to make this fix until x or y is incremented

The corresponding ATBD version should be x.y.

Version 1.0.0

language = IDL; pitch angles from nominal MAGED/PD telescope orientations

APPENDIX B: LIST OF VARIABLES AND METADATA

Global attributes:

GOES_satellite: 15
version: 1.0.0
version_description: language = IDL; pitch angles from nominal MAGED/PD telescope orientations
conventions: GOES Space Weather
title: GOES Magnetospheric Electron and Proton Detectors Pitch Angles
institution: NOAA
source: Satellite in situ Observations
satellite_id: GOES-15
instrument: Magnetometer (MAG)
process_type: 1-minute Averages
process_level: Level 2
sample_time: 60
sample_unit: seconds
creation_date: 2014-08-15 09:00:06.000 UTC
start_date: 2014-08-01 00:00:00.000 UTC
end_date: 2014-08-14 23:59:00.000 UTC
records_maximum: 44640
records_present: 20160
records_missing: 24480
originating_agency: DOC/NOAA/NESDIS/NGDC
archiving_agency: DOC/NOAA/NESDIS/NGDC

2 variables in file

----
0 time_tag DOUBLE

long_name
Date and time for each observation (beginning of the minute over which the data are averaged)
units milliseconds since 1970-01-01 00:00:00.0 UTC
calendar Gregorian
----
1 pitch_angles FLOAT

description

Pitch angles of MAGED and MAGPD telescopes 1-9 calculated from GOES magnetometer field vector
long_label pitch angle
short_label pas
plot_label pitch angle (deg)
lin_log lin
units degrees
format f9.4
nominal_min 0
nominal_max 180
missing_value -99999