Climate Data Record (CDR) Program

Climate Algorithm Theoretical Basis Document (C-ATBD)

Geostationary IR Channel Brightness Temperature – GridSat B1

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1. Introduction

1.1 Purpose

The purpose of this document is to describe the algorithm submitted to the National Climatic Data Center (NCDC) by NCDC/RSAD that will be used to create the Gridded Satellite (GridSat) Geostationary Infrared Channel Brightness Temperature (GridSat-B1) Climate Data Record (CDR), using the global geostationary satellites. The actual algorithm is defined by the computer program (code) that accompanies this document, and thus the intent here is to provide a guide to understanding that algorithm, from both a scientific perspective and in order to assist a software engineer or end-user performing an evaluation of the code.

1.2 Definitions

Equations and Definitions are provide throughout the C-ATBD as needed for clarification or explanation

1.3 Referencing this Document

This document should be referenced as follows:

Geostationary IR Channel Brightness Temperature – GridSat B1 - Climate Algorithm Theoretical Basis Document, NOAA Climate Data Record Program CDRP-ATBD-0571 by CDRP Document Manager Rev. 1 (2015). Available at http://www.ncdc.noaa.gov/cdr/operationalcdrs.html

1.4 Document Maintenance

As the algorithm is updated, this document will be checked for consistency with any changes and updated as necessary.

2. Observing Systems Overview

2.1 Products Generated

The GridSat-B1 data product provides infrared (IR) window brightness temperature data for the globe (limited to 70° South to 70° North). Initially it spanned 1980-2012 but is now being updated quarterly. Geostationary satellite imager data are remapped to ~8 km resolution every 3 hours. The coverage of the satellites and navigation accuracy do vary in time, with more gaps in the earlier period (e.g., from 1980-1983). Other channels are included in the data – such as visible reflectance and infrared water vapor – but whose inter-calibration and long term stability are not as mature as the IR window channel data (Knapp 2008a).

2.2 Instrument Characteristics

The data derive from meteorological, geostationary satellite data collected for the ISCCP project. These include most of the data for meteorological sensors since 1980. The specific satellites, sensors and channel characteristics are detailed in Knapp (2008b).

3. Algorithm Description

3.1 Algorithm Overview

The overall process of the GridSat algorithm is in converting a set of geostationary imagery files into calibrated data on an equal-angle grid at a time resolution which matches the temporal resolution of the data (3-hourly). This includes using quality control (QC) data, navigation of pixels from the satellite projection to gridded points, and calibrating pixel data to a standardized calibration reference. The following is an outline of the processing steps to accomplish this re-mapping of data. It is followed by a more detailed description of the various parts of the processing.

It should be noted that this really isn't a very complex process. It does not involve a radiative transfer model. The basic steps are to calibrate the data (convert from digital counts to brightness temperatures), and navigate the data (estimate a temperature for each grid cell viewed by the satellite), then store the appropriate data in a netCDF file.

3.1.1 Out of Scope

This document describes the portion of the algorithm that merges the B1U files into the GridSat file. At present, the production of the creation of the B1U files and the satellite intercalibration are not described in detail. The satellite intercalibration is described by Knapp (2008a, 2012); Knapp and Kossin (2007)

3.2 Processing Outline

While the concept of remapping data and providing calibrated information is conceptually simple, the details of each step can be complex. The overall outline is:

1. Prepare satellite data for calculations,
2. Process each satellite image and map to the fixed grid,
3. Check the inter-satellite calibration, and
4. Write out the final file (and a supplement file).

The following describes each of these steps.

The following algorithm summary references steps in Figure 1, the processing flow of the algorithm. Again, only details of the merging algorithms are provided at present. Any reference in the document to steps in the algorithm are to the lettered steps in Figure 1

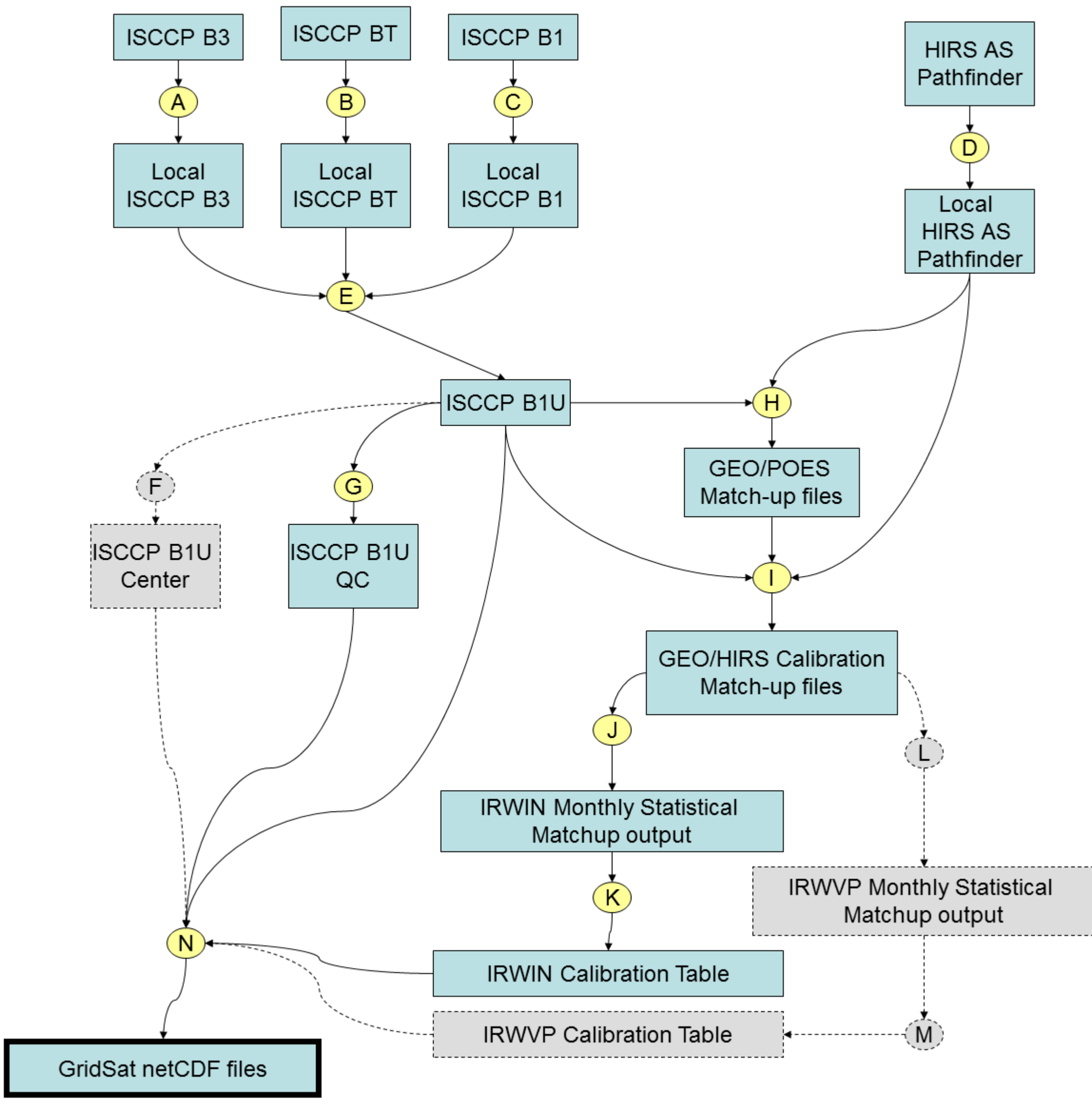

Figure 1: GridSat data flow diagram. Each blue box represents a set of files. The grayed boxes represent optional processing (e.g., calibration of the water vapor channel or ISCCP B1U image centering). The yellow circles represent algorithms with inputs and outputs connected by arrows. The primary GridSat algorithm (b1u_2_gridsat.pro) is represented by Step N.

3.2.1 Algorithm Preparation

While the primary processing algorithm is the `b1u_2_grisat.pro` IDL procedure, there are some steps to prepare files and data for processing.

First, the ISCCP B1 files are converted to B1U files. This simplifies processing and allows the data to be used by other systems. It involves no major modifications to the data, but simply reformats the data into a unified format that is essentially the lowest common denominator of all the various B1 formats. This puts similar constraints on date/time information, unifies the definition of particular navigational elements, and combines some of the ISCCP calibration files into the B1U file headers. Inherent in this step is the fact that any B1 files that cannot be read successfully by the B1 reformatter algorithm is not included in the GridSat data output since it effectively could not be read.

Second, a line-by-line QC algorithm processes the imagery at the scan line level and identifies bad scan lines for each channel. This information is stored in an intermediate binary file.

Third, an algorithm performs navigation estimates on the file image. Information in the file header identifies the image center scan line and element (i.e., pixel), however, these can sometimes be in error. This algorithm calculates the middle scan line based on IR data (using it to identify the Earth's limb). This algorithm also calculates an adjustment of some of the navigation elements based on navigation of regions near coastlines.

Fourth, once B1 files are completely converted to B1U, a set of matchup files are created that list all files associated with each synoptic time, that is, a list of B1U files every 3-hours. This is called the 3-hourly GEO/POES matchups files. This file does include POES data in order to facilitate matchups between B1U files and other satellite data. However, for GridSat processing, only the B1U files are incorporated. In fact, the matchup files can be created with only the B1U files present with no effect.

3.2.2 Processing Individual Geostationary Files

The 'b1u_grisat.pro' processes each individual GEO file into gridded data and merges that gridded data with other satellites at coincident times. In general, the steps include: navigation and calibration, parallax correction, and merging with other satellite data.

It is important to note that the grid cells lat/lon data are reverse mapped to determine the nearest pixel. This means that each grid cell has data. The reverse (calculating lat/lon for each pixel, then assigning that to the nearest grid cell) results in unnecessary gaps in the gridded data. In short, there are no gaps in observation in the pixel data, so there should be no gaps in the grid cells.

The data are converted from digital counts to brightness temperatures using lookup tables defined by ISCCP wherever ISCCP calibration is available. When not available, the nominal calibration equation from the data provider is used. The IRWIN data are also normalized to HIRS IRWIN data. This is performed monthly for the ISCCP PoR (because the ISCCP calibration is monthly) and daily when ISCCP calibration is not available.

The calibrated brightness temperatures are then adjusted for view zenith angle effects. The radiances observed by the satellite are contaminated by upper levels, especially for channels with more water vapor contamination. Thus the effect, is more apparent at lower latitudes and is temperature dependent (warmer surfaces have more contamination then surfaces near the tropopause).

Observations at large zenith angles are also impacted by parallax. That is, the effect of tall objects errantly being located at a wrong position. This can easily be corrected given the viewing geometry and the height of the object. The viewing geometry is known accurately. However, the height of the object (tall clouds) is less well known. However, it can be estimated from the temperature of the object using an assumed atmospheric profile. While we apply a standard profile, the errors incurred are rarely more than a pixel difference.

Lastly, the satellite data are merged with other satellite data. In regions of GEO overlap, the GEO having the best (i.e., the lowest VZA) view is used as the primary observation. GridSat also stores secondary and tertiary observations, which allow satellite based corrections, intercomparisons, etc. for users. Data are also stored that allow users to calculate view zenith and azimuth angles, which keeps from having to store them and saves space.

3.2.3 Check Inter-Satellite Calibration

This step was added in GridSat v02r01. In short, it compares the brightness temperatures between satellites in the overlapping regions. If a satellite is significantly different than both of its neighbors, then the calibration of the outlying satellite is adjusted to make it consistent with its neighbors. The correction helps take care of short lived (few images) calibration deviations that aren't caught in the daily or monthly calibration aggregations. More details on this step are provided below.

3.2.4 Write netCDF file

Lastly, the data are written to a CF compliant netCDF file. The visible, infrared window and infrared water vapor channels are included. Also, the overlap channels are included for those interested in reconstructing individual satellite views.

3.3 Algorithm Input

3.3.1 Primary Sensor Data

The primary sensor data for GridSat are the ISCCP B1[1] files provided as part of the ISCCP Cloud Processing, archived at NCDC since 1983 and rescued by NCDC in 2004. The ISCCP B1 files represent a simple subsampling of full resolution geostationary satellite data. The data are subsampled in time to roughly 3 hourly. The data are also subsampled in space to approximate a 10-km spatial resolution. For more details of the creation of B1 files from full resolution, see Knapp (2008b). These files originate from numerous geostationary satellites provided by 7 satellite providers; see Figure 2. The data are provided in more than a dozen formats. Providers use numerous navigation formats. The breadth of formats

[1] B1 is not an acronym, but represents part of the progression from A (raw, full resolution data) to B (subsampled data) to C or D (processed products). B1 is the lowest level of subsampling, sampling to approx. 10 km.

and navigation styles required the conversion of the data to an intermediate format in order to facilitate processing by multiple systems.

The raw, historical ISCCP B1 data are a mess. The data derive from dozens of satellites, multiple space agencies and numerous SPCs (Satellite Processing Centers). The documentation on the various file formats range from non-existent to fully documented. For example, data were originally sent to NCDC on 9-track tape. Normally, this shouldn't matter, but in at least one set of B1 files, the 9-track tape headers remain interspersed in the data files. Therefore, the best uniform documentation on each of the B1 datasets lies in the IDL read routines.

The ISCCP B1 files generally consist of binary files with header blocks that denote instrument orbital parameters, image information, and the image itself. The image is usually interleaved with a scan line header that often has information that could include scan line time, quality and scan number. An exception to this setup is the data from Canada who provided separate B1OA files; so if the corresponding B1OA file is missing, the B1 file cannot be used.

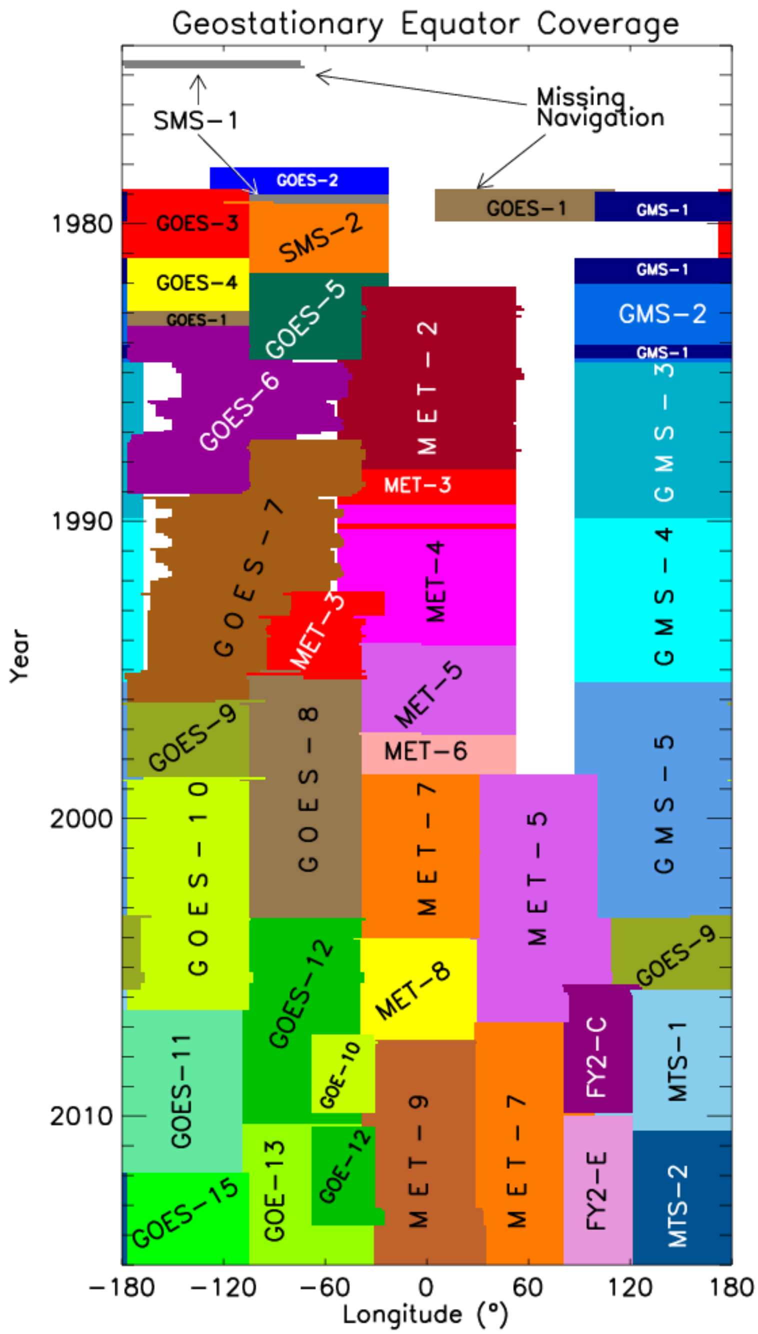

Figure 2: The geostationary quilt – A spatio-temporal representation of the Equatorial coverage of the ISCCP B1 geostationary satellite constellation from 1979 through 2015. The goal of GridSat is to construct a global dataset that minimizes the differences between the satellites into a unified product.

3.3.2 Ancillary Data

The primary ancillary files are the calibration files derived in the monthly and daily calibration processing matchups. These files provide information on the type of adjustments needed for the infrared window and water vapor channels.

3.3.3 Derived Data

3.3.3.1 GOES-POES match files

The GridSat process uses as input a text file that collects all GEO files for that 3-hr time slot. This is produced by match_b1u_poes.pro. This creates a file that matches many different satellite datasets to the ISCCP B1U time series. In particular, the two important parts for GridSat are the list of ISCCP B1U files and the list of HIRS Pathfinder All Sky data. The matchups with the HIRS all Sky data are used to perform the inter-satellite calibration. The list of available B1U files provides the list of B1U files for each 3-hr GridSat file.

3.3.3.2 ISCCP B1U files

Another by-product of the data processing flow is the creation of ISCCP B1U files. These are used by many other NCDC datasets and have also been shared externally. The B1U files are discussed further in section 3.4.7.1. The format of the B1U files is provided in Appendix B.

3.3.3.3 ISCCP B1U QC files

ISCCP B1U Quality Control information files are described in section 3.4.7.2.

3.3.4 Forward Models

Not applicable.

3.4 Theoretical Description

The primary focus of this description is the b1u_2_grisat.pro routine. The other processes of reformatting B1 to B1U or calibrating the B1U files with HIRS are not described here.

3.4.1 Physical and Mathematical Description

The following are some annotations used herein to describe the algorithm.

i/j = Satellite pixels in the satellite coordinates.

x/y = gridcell row and columns in the mapped coordinates.

VZA = Satellite view zenith angle (measured as degrees from normal)

3.4.2 Data Merging Strategy

There are numerous considerations in merging satellite data from multiple GEO satellites. The strategy includes: ignoring satellites, image data quality and view zenith angle.

3.4.2.1 Ignoring Satellites

Satellite data is presently ignored for one of two reasons.

Superfluous data is ignored when there are too many satellites in a given area. For instance, B1U data from both MET-7 and MET-8 is available before MET-8 (the first of the Meteosat Second Generation (MSG) series) was operational. They both were very near 0° longitude. Thus, navigating and selecting the best VZA resulted in instabilities (e.g., alternating scan lines from different satellites) that worked better when one satellite was not processed.

Also, if large portions of a satellite record were corrupted, then the data files are ignored here. For example, GOE-12 data for Jan-May 2012 is corrupted, so it is not included in GridSat processing.

3.4.2.2 Image data quality

Large blocks of data (~1 month or more) can be ignored above. However, image quality control is also applied for each scan line. In this case, as the data are read, the data in bad scan lines are ignored in further GridSat processing.

3.4.2.3 View Zenith Angle

Lastly, the satellite data are merged based solely by selecting the lowest view zenith angle. An upper limit is placed on the view zenith angle: pixels or gridcells with VZA > 'vzalimit', which is hardcoded to 85°. Beyond that, the selection of the pixel representing a given cell is based solely on the satellite with the lowest VZA. This results in:

- Smooth transitions between satellites – often a N/S boundary. The transition occurs at the midpoint between the satellite longitudes.
- Replacement of missing or QC'ed data – Full Disk images with gaps, or partial scans can be partially filled in with data from adjacent satellites.

For each pixel, the satellite id is stored in 'satid' variables. This is written in the netCDF file. The satellite view zenith angles for a given pixel can be calculated by using the subsatellite point for the satellite used for that cell. It also allows the satellite observation to be reconstructed from the multiple views provided.

3.4.3 Numerical Strategy

There are no special numerical optimizations. The primary routine (b1u_2_grisat.pro) can process 1 set of files in roughly 5 minutes. This is optimized by a brute-forced method of spreading jobs out in parallel across numerous machines.

3.4.4 Calculations

The following is a summary of the calculations made in the b1u_2_grisat.pro code. In most cases, the details of the calculations are provided elsewhere in this document.

1) Grid definition

   a) The grid is defined by 'ang', which is units of degree latitude per gridcell. It is hardcoded to 0.07, but can be changed. This would then alter the number of gridcells in GridSat. This sets up lat, lat1, lon, lon1 as the lat/lon values of the gridcells.
   b) Variable corner_lat/lon are defined to help in determining where a satellite is, longitudinally.
2) A loop over iyear allow the routine to be run for various years. However, due to the time needed to process, this is usually limited by passing in the keyword mfile, which is the one 3-hour set of files to process.
3) The next loop (imfile) also is limited to processing only one mfile as passed by the script driving the processing.
4) Loop igeo loops over each geostationary satellite in the merged file listing (mfile). Numerous variables are then instantiated. The maximum number of GEO satellites is limited to 10 (when defining the arrays).
5) After reading the GEO file, the first calculation is to navigate (convert lat/lon to i/j) a few points (corner_lat/lon). This provides the orbital position of the satellite (glat/glon/grad).
6) A set of IF blocks helps to ignore some satellites with known problems or those that aren't needed. This strategy is highlighted in Section 3.4.2.
7) If this satellite should be processed, then more variables are instantiated (zeroed out) and the QC (quality control) file is read in (variable qc).
8) Navigation
   a) The lat/lon points nearby the satellite sub-point are navigated.
   b) The subset 'nearby' limits the calculations to only those points that can be visible from the satellite position. This reduces the number of calculations and saves time.
   c) At geostationary orbit, points more than 75 degrees longitude away from the sub-satellite point are not visible and do not need to be navigated.
   d) Merely calculating the lat/lon of each pixel and then mapping to the grid would result in gaps in the grid because as the VZA increases, the pixel size increases. So here, I calculate the corresponding pixel for each gridcell. At large VZA, adjacent gridcells will correspond to the same pixel. This is appropriate since pixel size changes with lat/lon.
9) Calibration
   a) The calibration is performed by subroutine 'b1u_dn2cal'
   b) This applies the ISCCP calibration (if available).
10) Viewing and illumination angles
   a) Viewing angles (variable 'vza' and 'azi') are calculated by the subroutine 'angles'
   b) The illumination angles (solar zenith and azimuth) are not needed in the calculations, hence the keyword 'satonly'
11) Subset gridcells that are viewed by the satellite: variable 'use'
12) Subroutine 'i2xy' converts the one-dimensional indices in 'use' to x/y indices.
13) IRWIN processing steps
   a) Determine if enough points are valid (nuse > 100)
   b) Check the distribution of points. If it has too few valid points, do not process. ('check_count_distribution')

c) For year >= 2010 or <1983, apply the daily calibration
   i) This is because the monthly calibration was based on an initial ISCCP calibration. However, these years lie outside the initial ISCCP period of record, so an alternative calibration was needed to extend the GridSat calibration record.
d) Apply the daily/monthly calibration adjustment via linear correction (cal_slope/offset)
e) Navigate the satellite pixels (imgi/imgj) to get a lat/lon for each pixel
f) Use 'angles' routine to calculate the VZA for each pixel
g) Apply the Joyce et al. VZA correction procedure: 'szacorr'
   i) (where Joyce et al. define SZA as Satellite Zenith Angle).
   ii) The amount of the correction is recorded in variable 'vza_Adjustment' which is later written to a file. This allows advanced users to un-adjust the IRWIN observations.
h) Parallax correction
   i) Satellite images are impacted by parallax, where tall clouds viewed at large VZAs are displaced from their actual position. This can be corrected geometrically by using an assumed temperature profile.
   ii) This is performed in algorithm 'parallax_correct_swath'
   iii) Parallax correction results in gaps in the IRWIN data. These are filled using nearby points in the 'ifill' loop

14) IRWVP processing
   a) Check the distribution of points. If it has too few valid points, do not process. ('check_count_distribution')
   b) Data are calibrated using the daily calibration (ISCCP never provided a reliable IRWVP inter-calibration).
   c) Parallax correction is applied using the pixel displacements used in the IRWIN routine (for consistency)
   d) There is a routine for IRWVP VZA correction ('geo_hirs_limb_corr'). However, it is not applied since it hasn't been verified.

15) VSCHN
   a) Check the distribution of points. If it has too few valid points, do not process. ('check_count_distribution')
   b) Parallax correction is applied using the pixel displacements used in the IRWIN routine (for consistency)

16) Store satellite data on grids.
   a) Once data are processed, the channels need to be stored on the appropriate grids.
   b) The primary grid is for the views with the lowest VZA ('irtemp' 'satid' and 'gdvzair').
   c) The secondary grid contains the second lowest VZA view ('irtemp2' 'satid2' 'gdvzair2')
   d) The view with the third lowest VZA is stored in a tertiary grid 'irtemp3'
   e) Similarly, the IRWVP and VSCHN is processed, but only the best and 2nd best views are stored here.

17) Once stored, this ends the loop over each geo file.
   a) Thus the following occurs when all the GEO files have been processed for this time period (mfile)

18) Memory clean up – Many of the variables no longer needed are zeroed out (which decreases the memory usage in IDL)
19) Re-check calibration
    a) The routine 'gridsat_check_merge' compares the IRWIN temperatures for the overlapping regions.
    b) If a correction is deemed necessary, the brightness temperatures of one satellite are corrected linearly.
    c) If a satellite is corrected, this adjustment is recorded in the variable 'corr_satellite' and the calibration adjustments are correspondingly adjusted (these are written out as variable attributes in the GridSat file).
20) Ibasin loop
    a) The ibasin loop is a holdover from the origin of the GridSat routine.
    b) The original routine produced ocean basin files for the primary oceanic regions where tropical cyclones are active. Users of those data requested a global file. Thus, it became more efficient to produce the global file only. The result is GridSat.
    c) So while at one point, numerous basins were then defined and output, this is no longer performed. However, remnants of that code remain.
21) Sparse grids
    a) The last set of calculations is performed if too few points are present for a particular grid to warrant writing out all values.
    b) Data can be stored as a 1-D array, however, that requires also writing out the index for those arrays, so the balance point is whether the number of pixels is less than 2/6 of points are filled.
    c) 2-D grids are always written for the primary grids (i.e., the best view zenith angles).
        i) This facilitates file aggregation on these variables.
    d) Sparse grids for the secondary and tertiary files are stored if it is more efficient,
    e) The sparse gridding is selected separately for each grid.
22) The grids and pertinent variables are written to the NetCDF file.
    a) The IDL routine now can create netCDF version 4 files.
    b) Attributes must be specified as CHAR (the default is string) in order for files to be read by GRADS.

The following are some details of the calculations used in merging the B1U files into the final GridSat netCDF file.

3.4.4.1 Navigation Calculations

The navigation calculations perform the conversion between satellite coordinates (e.g., scan line & pixel number) and Earth coordinates (e.g., latitude and longitude). This calculation requires three pieces of information: 1) the location of the satellite relative to the Earth, 2) the attitude of the satellite in its orbit and 3) the instrument's characteristics. The first two are often called O&A for Orbit and Attitude information. In B1U, images are navigated in one of two ways: Keplarian navigation or GVAR navigation. While these methods aren't that different, they were kept separate because the GVAR information is reported in a much different way that is not easily converted to the Keplarian parameters.

3.4.4.1.1 GVAR Navigation

The GVAR navigation[2] is performed following the GVAR procedures[3] written by the ISI Corporation. In fact, the IDL routines are solely based on the Fortran GVAR navigation routines provided by the contractor: ISI corporation. For more information on GVAR navigation, see the Earth Location User's Guide[4].

3.4.4.1.2 Keplarian Navigation

The Keplarian navigation is used for all non-GOES GVAR satellite datasets. Thus, it is for all non-GOES satellites (e.g., Meteosat, FY, SMS) and all GOES satellites prior to GOES-8 (i.e., GOES-1 through -7).

ISCCP B1 files provide O&A information in the file headers (though the Canadian SPC often reported O&A information in a separate B1OA file). This information is converted to determine the satellite location relative to the Earth using Kepler equations. The code in the IDL navigation procedures (e.g., cart2kep.pro, kep2cart.pro, etc.) follow the equations from Kidder and Vonder Haar (1995).

3.4.4.2 Satellite Angle Calculations

Satellite view and azimuth angles are calculated using the location of the satellite relative to the Earth and the individual Earth locations. The view zenith angle is the angle at a specific location on the Earth subtended by the Zenith and a ray pointing toward the satellite. The azimuth angle at the Earth location is the horizontal angle between true North and the ray toward the satellite projected onto the horizontal. The calculations are provided in Appendix C: Calculating zenith and azimuth angles.

3.4.4.3 Parallax Adjustment

Parallax is the apparent displacement of a cloud due to its height above the Earth's Surface. When a tall cloud is viewed at larger view zenith angles (near the horizon) its location will be offset from the calculated position because the navigation algorithm assumes every pixel is observed at the Earth's surface. This is most notable for very tall clouds. This is demonstrated in the difference in views of a hurricane from different geostationary satellites. See Figure 3 and Figure 4 for a demonstration of this correction based on the NCDC Hurricane Satellite (HURSAT) dataset (Knapp and Kossin 2007).

The parallax correction is simply a geometric correction using the VZA and azimuth angle for a given location. The height of the cloud is estimated based on standard profiles for various zonal regions. (The error of this assumption is less than a pixel displacement at the coarse 8km pixel resolution of ISCCP B1). To reduce noise (and slight errors in the profile),

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[2] http://goes.gsfc.nasa.gov/text/goestechnotes.html#navigation
[3] ftp://goes.gsfc.nasa.gov/pub/chesters/nav_FORT/
[4] http://goes.gsfc.nasa.gov/text/ELUG0398.pdf

clouds determined to be less 3km above the surface are not corrected. The correction distance is simple geometry:

$$Dp = Hc * tan(VZA) \quad (1)$$

Where Dp is the distance of the parallax error and Hc is the estimated height of the cloud. This provides the distance from the current pixel location to the corrected location: the magnitude of the correction. The direction of the correction is determined by the azimuth angle which can be converted back to scan line and pixel coordinates using the instrument characteristics.

Lastly, the parallax correction can result in gaps in data. The region behind a tall cloud is obstructed by the cloud. These can be seen in Figure 4 as white areas near large gradients in the brightness temperatures. Since these make up a small amount of pixels, the GridSat algorithm fills in these regions (rather than leave them as missing data). The corrected data is drawn from the nearby region directly away from the satellite sub-point. This results in the filled in values having warmer pixels than the adjacent cold (i.e., tall) clouds.

On a given image, the number of points filled in by parallax correction is small.

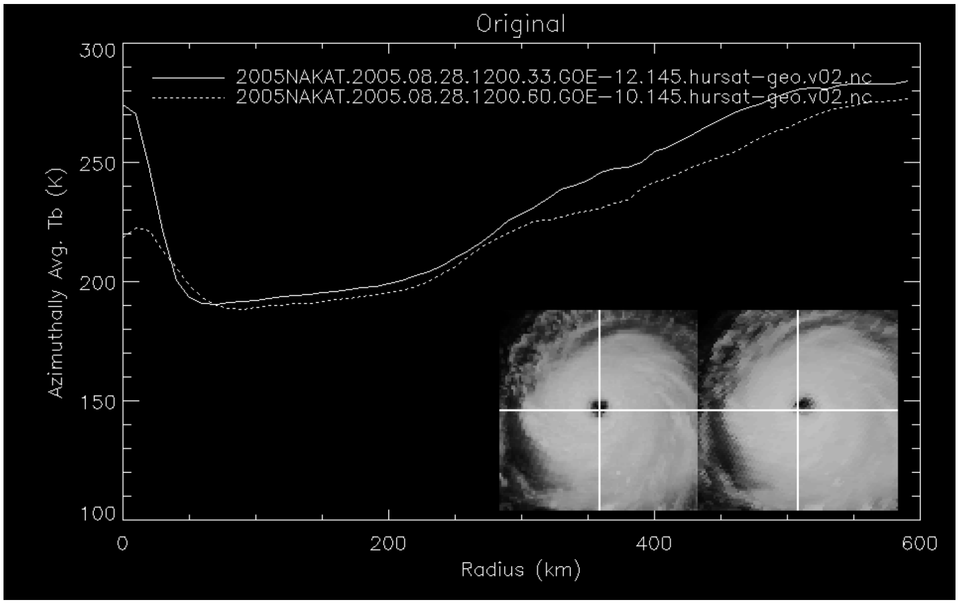

Figure 3: Azimuthal average brightness temperatures centered on Hurricane Katrina from GOES-12 at VZA=33° (solid line) and GOES-10 at VZA=60° (dashed line). The difference between the satellites is primarily caused by the difference in the view angles.

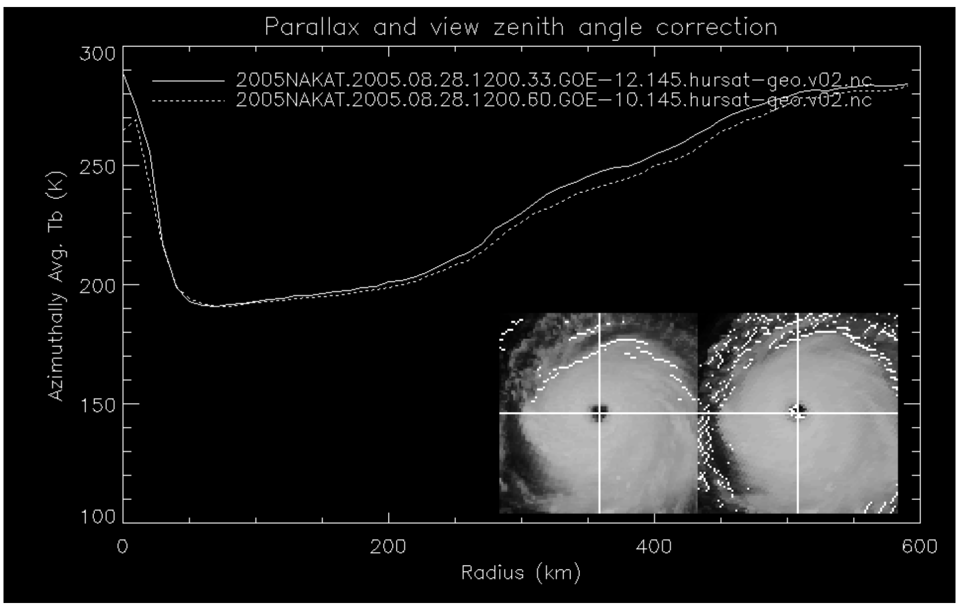

Figure 4: Same as Figure 3 except that the parallax correction and VZA adjustments have been applied to the original data. Parallax correction results in spatial shifts of the image pixels (with more correction in the GOES-10 image on the right). VZA adjustment results in additive corrections to the brightness temperatures. The result is that after both images have been independently corrected, the resulting azimuthally-averaged profile is quite similar.

3.4.4.4 Calibration Recheck & Adjustment

The algorithm performs one last calibration consistency test after all the data have been merged. This is performed in order to catch any GEO images that have poor calibration for one file. This test was included in order to catch a few obvious errors that aren't corrected at the monthly calibration step: algorithm `gridsat_check_merge.pro`.

The idea is simple. Once the data are merged, the overlap regions provide another means to check and correct for inter-satellite calibration errors. The only requirement is to both have a) enough overlap with other satellites to compare brightness temperatures and b) have enough satellites that it is clear which satellite is the outlier (usually satisfied by three or more).

In short, this step compares a given satellite to all other satellites. An outlier is corrected and linearly adjusted to more closely match the other satellites in the image.

This correction is quite rare. From 1983-2012, there were ~1000 satellites adjusted, which accounts for ~1% of the GridSat files during that time.

3.4.4.5 Grid Storage: Sparse vs. Two-dimensional

Data is stored in two ways in order to save space. The sparse storage is more efficient when a large portion of gridcells are missing. The simpler two-dimensional grid is more efficient otherwise. The exception is that the primary grids for each channel (irwin_cdr, irwvp and vschn) are always stored as two-dimensional grids.

For other variables (irwin_2, etc.) the data can be either a 1-dimensional or 2-dimensional variable. The size needed to store the sparse data is:

Ss (bytes) = Np * (4+2+1) = Np * 6

Where Ss is the size of the sparse array, Np is the number of good pixels, and where 4 bytes are needed to store the index of each point, 2 bytes for the cell value and 1 byte for the extra satid variable.

The size required to store the gridded field is:

Sg (bytes) = Nx * Ny * 3

Where Sg is the size of the grid storage in bytes, Nx and Ny are the grid dimensions and 3 bytes are required for each cell: 2 for the brightness temperature and one for the satellite id (satid).

If Ss < Sg, then the data will be stored using the sparse array method. Otherwise, the entire 2-dimensional grid is stored.

3.4.4.6 Packing Data for Efficient Storage

Most variables in GridSat netCDF files are stored as packed floats. These are floats whose values can be derived from scale_factor and add_offset, which are attributes of said variable. This effectively stored the 4-byte floats as 2-byte integers. The loss of precision is not significant for GridSat variables.

3.4.5 Look-Up Table Description

Not applicable. No look-up tables are used in processing this data.

3.4.6 Parameterization

Satellite zenith angle adjustments for the IRWIN data are parameterized. Currently, it uses the algorithm from Joyce et al. (2001). In short, the algorithm, interpolates a correction for each satellite pixel based on the pixel's brightness temperature and VZA. This adjustment also accounts for a dependency of the adjustment based on day of year.

3.4.7 Algorithm Output

The primary algorithm output is the final netCDF file of the merged brightness temperatures. Also, there are some intermediate files that can be used by other algorithms:

- ISCCP B1U files
- ISCCP B1U QC files
- ISCCP B1U/POES match files
- GridSat netCDF file

The following is a summary of the purpose and the content of each file.

3.4.7.1 ISCCP B1U files

ISCCP B1U files were first created in 2004 in an attempt to unify the numerous B1 formats into a format that can easily be read in various languages. Thus, the “U” in B1U stands for Uniform or Unified. There are presently about 18 IDL procedures that read the various B1 formats. It was deemed too complex to translate each of these procedures into other languages. Instead, each of the B1 files is translated into the B1U format, for which there is one read file in IDL (also, NCDC provides a Fortran read file for B1U as well).

The format was produced prior to widespread use of netCDF at NCDC, thus the format is yet another binary format. The documentation for which is provided in Appendix B:ISCCP B1U file format.

The ISCCP B1U file name is nearly identical to the ISCCP B1 file name except the “B1” field is changed to “B1U” and the ISCCP version number is a static “a”. For instance, a typical B1U file name is: ISCCP.B1U.a.MET-7.2001.12.31.2030.EUM.

The contents of the B1U file is divided into blocks, described in Table 1.

Table 1: Listing of ISCCP B1U blocks.

Block ID	Block Name	Summary
0	FILinf	File information block
1	REVinf	Information on the revision of the routines used to create the B1U file
2	IMGinf	Information about the satellite image contained in this file
3	SATinf	Information on the satellite, sensor and channels
4	NAVinf	Navigation information
5	CALinf	Calibration information
6	TGRinf	Test grid information
7	OB1inf	The original B1 file header
8	IMAGE	The prefix interleaved with the B1 data.
9	GVARinf	GVAR information
10	QCinf	Scan line quality check information
11+	*TBD*	*User defined block headers*

The file size of the B1U file will vary. More channels and higher resolution will lead to larger sizes. In 1985, there are about 8,441 B1U files totaling 14 GB (compressed), for an average file size of 1.7MB (compressed). Conversely, files for calendar year 2007 averaged 6.3 MB (compressed) (107 GB in 17,428 B1U files).

The uncompressed sizes are somewhat larger. For example, there are about 342,000 files in the original ISCCP period of record (1983-2009) that totals 2.42 TB uncompressed. The average size of these files is 7.4 MB.

3.4.7.2 ISCCP B1U QC files

There is a Fortran routine that provide scanline-level quality control. It analyzes each channel separately to identify scan lines with errors, missing lines, etc. This file format is a binary file. These files are also small and comprise less than 1 GB per year (e.g., 2007 has 540 MB).

3.4.7.3 ISCCP B1U/POES Match Files

Much of the ISCCP processing requires knowing either a) which ISCCP B1U files correspond to a given synoptic time or b) which POES files correspond to available ISCCP B1U files. The B1U/POES match files provide this mapping. For each available synoptic time, all available B1U files are collected along with other files used in processing (e.g., used by HURSAT). The file format is simple ASCII. The files are small, one year being no larger than 20 MB.

3.4.7.4 GridSat netCDF Files

The primary output of the GridSat processing is the netCDF GridSat file.

It is not the intent of this section to describe all the data and attributes in the self-describing netCDF format. The CDR netCDF conventions and the CF (Climate and Forecasting) convention are both good resources to understand much of the variables and attributes.

4. Test Datasets and Outputs

4.1 Test Input Datasets

No test data are used. The primary test datasets are to process individual time slots that have been identified as having errors and ensuring that the errors are no longer present. In the operational code, these are the files where mfile is hardcoded when the 'debug' keyword is set.

4.2 Test Output Analysis

4.2.1 Reproducibility

Generally, the reproducibility is tested by comparing with previous versions and with the raw B1U data.

4.2.2 Precision and Accuracy

Accuracy and precision are primarily limited by a combination of the sensor, instrument, reporting procedures and the navigational accuracy.

4.2.2.1 Precision

Precision refers to the reproducibility of a measurement/observation. To this end, the precision is more difficult to estimate than the accuracy.

The sensor measure radiation and reports values in terms of digital counts. In the early years, these had 8-bit precision. That is, they had values ranging from 0-255. This limits the precision of a temperature measurement because the range of reportable temperatures has only 255 bins to report (usually the top value is reserved as a missing value). Later instruments (e.g. GOES-8) had 10-bit data providing 4 times the precision.

The precision of GridSat data has not been quantified.

4.2.2.2 Accuracy (or conversely, Systematic Error)

The accuracy of GridSat data is controlled by the inter-calibration with HIRS and the navigational data.

At the sensor, the all geostationary satellite have on-board calibration cavities for the infrared window. This ensures accuracy over time. However, it has been shown that some of the instruments are susceptible to diurnal heating of the cavity, which can affect the calibration. This was largely corrected by each agency prior to B1U collection(?).

For extended periods, the accuracy is expected to be very high (or low systematic error). This is due to the daily and monthly analysis of the individual satellites. The normalization of all IRWIN channels with HIRS ensures that long term systematic biases are small.

Nonetheless, it is possible that a poorly navigated image, or an image with errant calibration information could have large systematic errors. However, this is the exception and not the normal case.

Lastly, the data have been adjusted (or corrected) for VZA effects. This doesn't have a quantified accuracy. But is presumably more accurate at lower angles.

The accuracy of GridSat has not been quantified.

4.2.3 Error Budget

The following issues contribute to errors in the data. Again, little has been done to quantify the errors amounts.

- Navigation – Contributes to random error. Poorly navigated images will have significantly wrong temperature values for a given location. The amount of the error will depend on the heterogeneity of the scene.
- VZA correction – This likely contributes to bias errors. The correction used (Joyce et al) was developed using a limited set of instruments and likely is biased for other (e.g., older) instruments. The amount of error will increase with increasing view zenith angles.
- Inter-calibration – The data have been normalized to the HIRS infrared wind channel. This is largely improves the long-term stability. Errors in the long tem correction (e.g., deviations from the long-term trend or incorrect inter-HIRS adjustments) likely impact the error budget.
- Parallax adjustment – The parallax correction is developed using a standard atmospheric profile. While this profile does differ from the actual temperature profile in most every case, it results in some small error (usually less than a pixel) except at very high latitudes.

5. Practical Considerations

5.1 Numerical Computation Considerations

The algorithm itself isn't entirely complex. While the calibration requires some time to complete, the merging of the files for each 3-hr file completes in about 5 minutes. However, this is very time consuming when attempting to reprocess the entire period of record (nearly 100,000 files to produce). This would take roughly 500,000 minutes or about 300 days. So the lone numerical consideration is how to run the routine in parallel such that the reprocessing is accomplished in a month instead of a year.

5.2 Programming and Procedural Considerations

At present, the most efficient way to process the data is by processing each 3-hrly slot separately. This allows the massive parallelization of the process across multiple processors. Each 3-hrly slot is completely independent.

5.3 Quality Assessment and Diagnostics

Diagnostics are performed in two ways: image QC and hovmuller analysis.

5.3.1 Image quality control

Data are analyzed for quality by creating an image plot of each 3-hourly GridSat file. The routine 'gridsat_2_image.pro' produces PNG files. These can be inspected visually for corrupt data. If images are found with significant corruption, they are removed from processing and the data are reprocessed.

NOTE: This process has only been implemented for dates after Dec. 31, 2012. Prior to 2013, there hasn't been reprocessing for corrupted data found in images. A sample image of good data and corrupt data are provided in Figure 5.

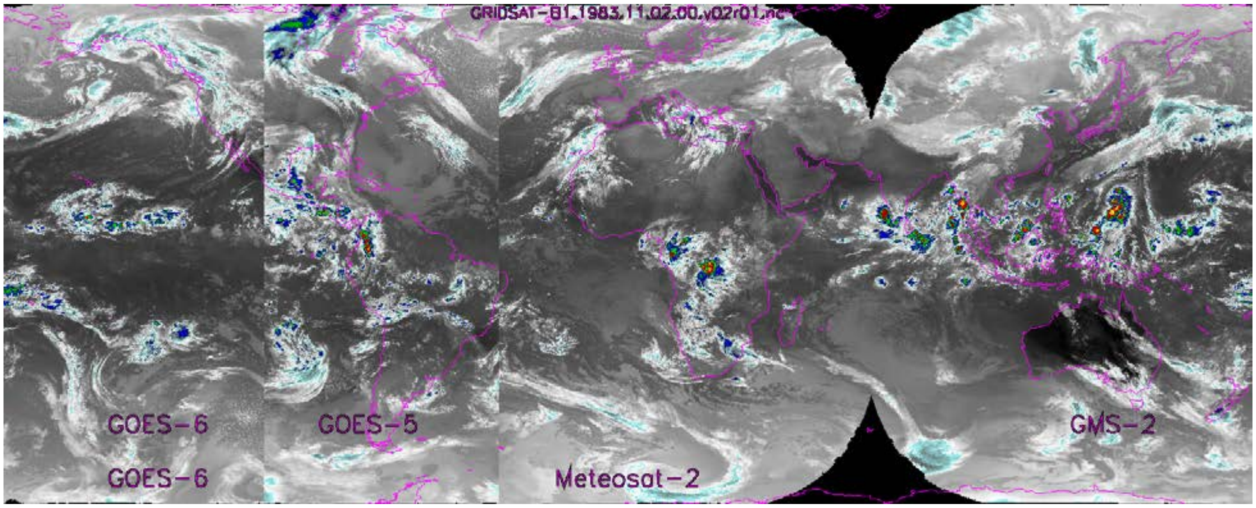

Figure 5: Sample GridSat QC image from Nov. 2, 1983 at 00UTC showing corrupted data from GOES-5.

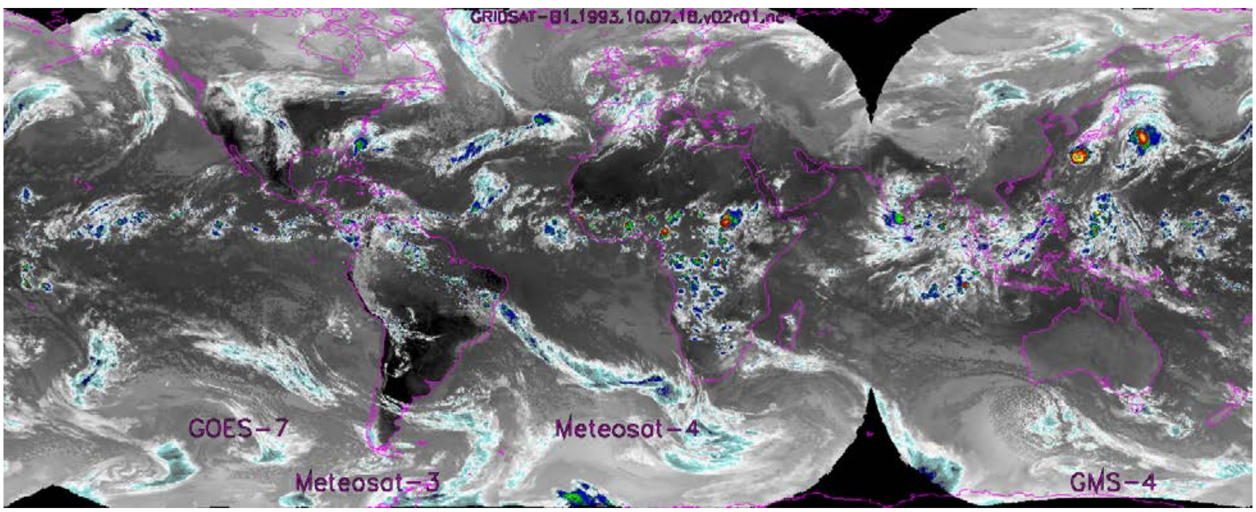

Figure 6: Sample GridSat QC image from Oct. 7, 1993 at 18UTC showing no major issues.

5.3.2 Hovmuller analysis

The hovmuller analysis was the first QC analysis applied to the GridSat data. The idea was that such an analysis should show numerous quality issues. Each time of day (00UTC, … 21 UTC) is plotted on a separate hovmuller plotting one page per year. Such an analysis shows:

- Data gaps (via large regions of missing data),
- Gross calibration issues for particular satellites, often as discolorations for a particular satellite and usually in 1-month chunks.
- Subtle calibration issues (via the longitudinal mean values along the bottom of the image)

- Gross data quality issues via differences in time and space on the plots.

The result is 1 page per hour per year. This produces 8 pages per year or more than 240 pages for the 30+ year period of record of GridSat. Other channels can produce the same number of pages, too.

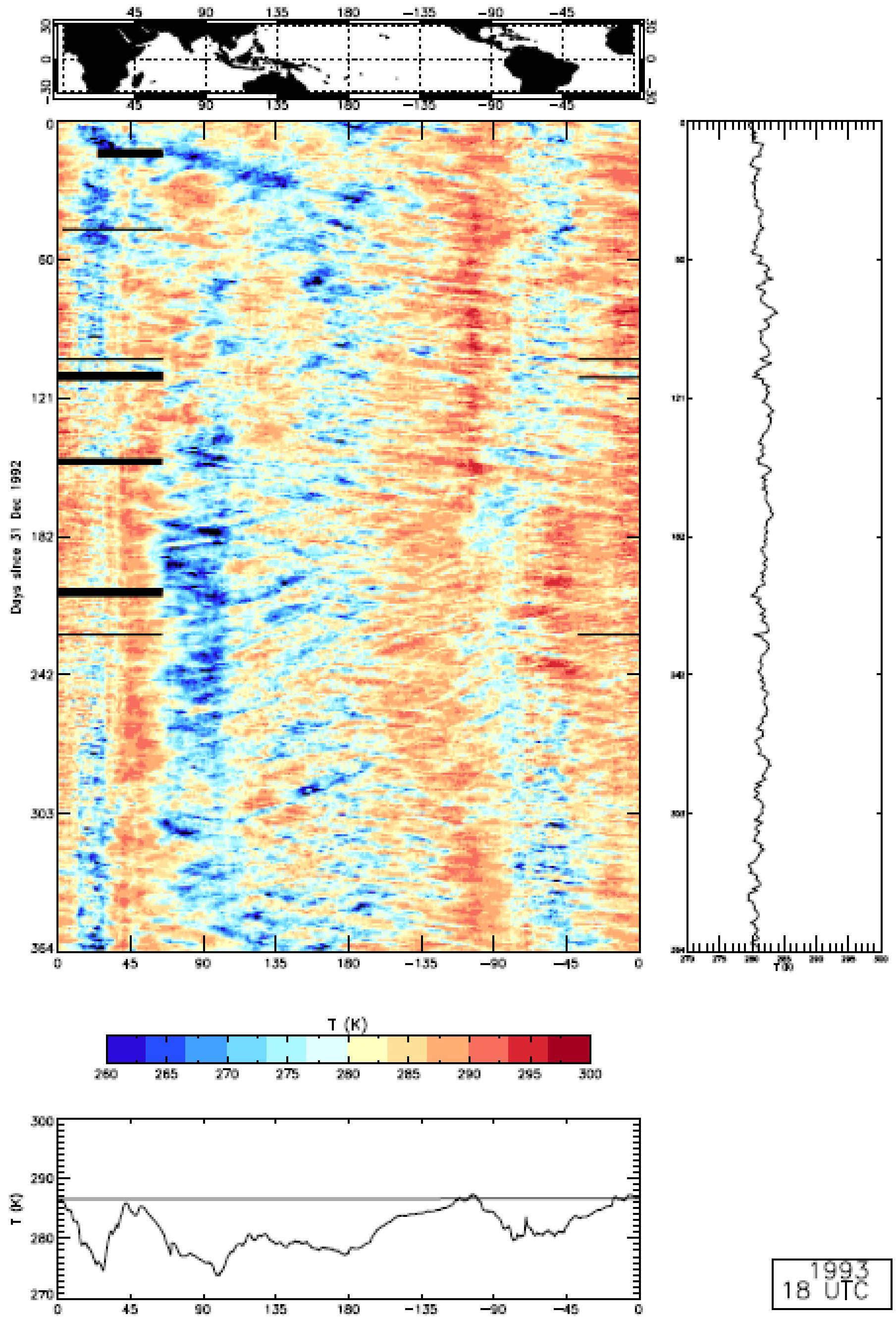

Figure 7: Sample GridSat Hovmuller QC plot for the IRWIN channel from 1993 for all 18UTC

observations. Gaps in Meteosat data appear as black lines in the image. The map at the top shows the region over which data are averaged to produce the hovmuller.

5.4 Exception Handling

The algorithm at present has limited to no exception handling.

5.5 Algorithm Validation

5.5.1 Pre-CDR validation

Prior to GridSat being selected as a CDR, the algorithm had various means of validation:

- ISCCP dependence – The dataset itself is an off-shoot of the ISCCP calibration. Thus, it is based on a tested and validated calibration.
- Calibration development – The ISCCP calibration was also compared with HIRS as a secondary validation effort.
- HURSAT – The Hurricane Satellite dataset was created prior to GridSat. While it doesn't provide a validation of brightness temperatures, it does provide some validation/assurance of the navigation quality of the data. [This is directly applicable since GridSat was based on HURSAT processing in that GridSat is the global extension of the global tropical cyclone-focused HURSAT data]
- GridSat partners – As outlined in Knapp et al. (2011), GridSat had numerous partners during its development that helped ensure data quality.

5.5.2 NCDC Operational Validation

As an operational product, the key to validating GridSat will be the reproducibility of the resulting gridded temperatures. Thus consistency with previous versions (those created by the PI) will be paramount to ensuring high quality data.

5.6 Processing Environment and Resources

The following only captures the merging algorithm.

computer hardware:	The data are processed on Linux servers running CentOS (though there is no significant dependency on this OS).
operating system:	Current processing used CentOS, but can likely be run other Linux-based systems.
programming language(s):	The primary language is IDL. However, other portions of the processing system use BASH and FORTRAN.
Compilers: Lahey Fujitsu	Fortran compiler (lf95) was used for the HIRS-B1U calibration code. IDL 8.3 was used for the IDL processing.

external libraries: None. NetCDF files were created with IDL (Which carries its own netCDF libraries).

total CPU/wall clock time: Using one CPU, would take roughly 390 days. The process was completed in 10.1 days by running the processes in parallel across 8 servers (each having variable CPU/RAM specs).

amount of temporary storage needed during processing
Very little The bulk of the processing is done in memory and then written to the final netCDF file.

6. Assumptions and Limitations

The following is a summary of most of the assumptions and limitations of the GridSat data.

6.1 Algorithm Performance

The following list identifies assumptions in the algorithms used during the design, development and processing of GridSat data.

We assume that:

- The variance of IR Window brightness temperatures are corrected using an algorithm by Joyce et al. (2001). This algorithm assumes that all geostationary satellites have a similar dependence of Tb on VZA.
    - We know this to not be accurate, especially for some older satellites with much broader spectral response functions. However, developing a new VZA correction algorithm that is satellite-dependent is not trivial.
- Navigation algorithms using Keplar elements for navigation assume that the Earth is an oblate spheroid with an Equatorial radius of 6,378,144 meters and a polar radius of 6,356,759 meters. These values were used in historical (older) algorithms to which this algorithm was compared.
- Navigation algorithms based on GVAR navigation assume and Earth Equatorial radius of 6,378,137 meters and a polar radius of 6,356,753.3 meters. These values for radii were provided in the software developed for the NOAA/NESDIS (see footnotes above).
- Any differences between the radii used (7 m in the Equatorial radius and 5.7 m in the polar radius) and other constants have little impact on the navigational accuracy.

6.2 Sensor Performance

The following list identifies the assumptions in the sensors used to construct the GridSat dataset.

We assume that:

- The infrared window channels (near 11 µm) on the various geostationary satellites have similar enough weighting functions that they can be inter-calibrated to a singular value that mimics the HIRS channel 8 IR window.

- The HIRS Ch 8 (for IR window channel intercalibration) and 12 (for IR water vapor channel calibration) will continue to be available for intercalibration of geostationary data.
    - Should the HIRS data no longer be available, it would be possible to develop a new intercalibration process using hyperspectral sounders (e.g., IASI), however, this development work would not be elementary.
- The navigation errors of the satellite data are Gaussian with a small standard deviation. That is, they exist, but they have an average error of zero and rarely occur larger than a few pixels.
    - It is evident that navigation errors are larger in the older satellites (e.g., pre 1990).

6.3 Agency participation

The following identifies assumptions made regarding international agency participation that is required to keep this project ongoing into the future:

We assume:

- Current data provided by Japan Meteorological Agency (JMA) will continue to be provided for currently operational satellites (e.g., MTSAT-2).
- That JMA will continue to provide ISCCP B1 level data in a similar manner[5] for future satellites (e.g., Himawari-8 launched on 7 October 2014) as presently provided for preceding satellites. Any changes to data format, navigation algorithms, calibration algorithms, etc. will be communicated by JMA to NOAA/NCDC.
- Current data provided by EUMETSAT will continue to be provided for currently operational satellites (e.g., Meteosat-7 and MSG-3).
- That EUMETSAT will continue to provide ISCCP B1 level data in a similar manner[6] for future satellites (e.g., plans for Meteosat Third Generation) as presently provided for preceding satellites. Any changes to data format, navigation algorithms, calibration algorithms, etc. will be communicated by EUMETSAT to NOAA/NCDC.
- Current data provided by NOAA/NCDC will continue to be provided for currently operational satellites (e.g., GOES-13 and GOES-15).

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[5] By similar manner, we mean that the spatial resolution will not change. We expect that format changes, navigational changes and calibration differences will occur.
[6] By similar manner, we mean that the spatial resolution will not change. We expect that format changes, navigational changes and calibration differences will occur.

- That NOAA/NESDIS will continue to provide ISCCP B1 level data in a similar manner[7] for future satellites (e.g., plans for GOES-R) as presently provided for preceding satellites. Any changes to data format, navigation algorithms, calibration algorithms, etc. made necessary by new satellite formats will be developed and tested by NOAA/NCDC.
- That NCDC will continue to participate in GEWEX projects in order to continue as the ISCCP Central Archive, which allows NCDC to be the recipient for the ISCCP B1 data.

[7] By similar manner, we mean that the spatial resolution will not change. We expect that format changes, navigational changes and calibration differences will occur.

7. Future Enhancements

The following is an abbreviated list of possible future enhancements:

- Separation of B1U from the GridSat project – As presently described, the production of ISCCP B1U files are an inherent part of the GridSat production. However, since B1U files will be a primary source for ISCCP Cloud processing, the production of these files should be a separate processing flow.
- Improved VSCHN data – Improving the visible channel data to climate quality is a high priority. The ISCCP calibration could and should be applied. However, extending that data beyond the ISCCP initial period of record (83-09) has been developed but not applied.
- Improved IRWVP data – Improving the infrared window channel to climate quality is feasible. The data are already intercalibrated using HIRS water vapor channels (channel 12). However, more QC is needed prior to elevating this data to a CDR variable. One issue to investigate is whether a VZA correction should be applied to IRWVP data or if it should be left as is, without correction.
- Employ improved QC – There are a few options to further QC the GridSat data. 1) Apply the image-by-image QC to each and every 3-hour slot. This is very slow, but it would remove the bulk of the data issues identified by my users. 2) ISCCP is developing a B1 QC algorithm. The results of that QC (if results are available on a per image basis) could be used to remove corrupt/suspect B1U image.
- Improved VZA correction for IRWIN data – The problem with the current VZA correction from Joyce et al. was that it was developed using a limited number of satellites in the early 2000s. Therefore, a more accurate correction could be developed that is satellite specific (desirable since each satellite's IRWIN spectral response function can vary). This would require quite a bit of R&D to develop and implement (the bulk of the work is already done). The implemented solution would reduce inter-satellite artifacts when looking at long-term differences between satellites. It is also speculated that some of the apparent artifacts in other data (e.g., PERSIANN) could be attributed to less accurate VZA adjustments.
- Reduce file size – Presently, the entire file is large and contains all variables. However, most users merely want the best estimate of each channel and some ancillary information. One way to reduce file size would eb to create a secondary file for advanced users that contain the secondary and tertiary views along with other meta-information.

8. References

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Appendix A. Acronyms and Abbreviations

Acronym or Abbreviation	Meaning
B1	B1 is not an acronym. It is the ISCCP name for a certain level of subsampling
B1U	B1 Unified
C-ATBD	Climate Algorithm Theoretical Basis Document
CDR	Climate Data Record
GEO	Geostationary
GridSat	Gridded Satellite
GVAR	GOES VARiable Format
HIRS	High-resolution InfraRed Sounder
HURSAT	Hurricane Satellite
IDL	Interactive Data Language
IR	Infrared
IRWIN	IR Window (~10.5 microns)
IRWVP	IR Water Vapor (~6.7 microns)
ISCCP	International Satellite Cloud Climatology Project
LEO	Low Earth Orbit
NCDC	National Climatic Data Center
NOAA	National Oceanic and Atmospheric Administration
POES	Polar Operational Environmental Satellite
PoR	Period of Record
QC	Quality Control
SPC	Satellite Processing Center (part of ISCCP structure)
VSCHN	Visible Channel (~0.65 microns)
VZA	View Zenith Angle (of a satellite and measured in degrees from normal)

Appendix B. ISCCP B1U file format

The following is a definition of the B1U file format.

Data Types

The data types in the B1 Unified Data Format (B1U) are currently limited to the following types:

- File header blocks will be Int*4 or ASCII
- Line prefix blocks will be Int*2
- Image data will be Int*1 or Int*2

File Header Blocks

File header blocks precede the image data and describe information regarding the B1 image. Come predefined blocks are defined herein, but the structure of this format allows storing additional header information. In the future, "user-defined" blocks could be included in the B1U format:

- Latitude/longitude for each pixel
- Latitude/longitude subsampled (e.g., AVHRR)
- ASCII Comment blocks
- QC information
- Histogram
- GVAR Navigation information
- AVHRR 1b file headers
- Cloud mask

Format Foundation

This format was derived using current understanding of satellite datasets. In particular, the defined block types are recurrent for most of the B1 data while flexibility allows incorporation of other information. The following documents were used to determine the major parameters needed for a complete representation of the satellite data:

- McIdas AREA file documentation – Older formats
- McIdas AREA file documentation – Newer formats (e.g., GVAR)
- Polar Orbiter Data (POD) User's Guide
- GVAR line header information
- NCDC ISCCP B1 File Format Description

File header: File info Block

Purpose: To provide initial file information and define the file header blocks given and the start of the data blocks.

Size: *Variable*

The flexible design of this initial block allows for numerous extra file header blocks to be added at some later date. While updated read programs would be required to read the extra header blocks, older data files would be compatible (since they would still be read by newer software). Thus, if someone wanted the file to contain lat/lon for each pixel, this could be included in a new file header block.

An inherent limitation of this file format that the maximum size of the file is 2 GB, since the maximum value for BSTRT is 2GB. However, this shouldn't be a problem for ISCCP B1 datasets which are no larger than 20 MB.

Fortran	integer*4 TGRinf(24 + 8*nrows*ncols)
C	long B1Hinf[24 + 8*nrows*ncols]
IDL	B1Hinf=lonarr(24 + 8*nrows*ncols)

Index	Name	Description
0	KEY	A 4-byte word that is used to determine if file is Big Endian or not.
1	NBLP	Number of bytes in the line prefix
2	DATLOC	Location of the 1st scan line prefix
3	NSCAN	Number of scan lines
4	NELEM	Number of elements per scan
5	NCHAN	Number of channels
6	NHEAD	Number of file header blocks
7 – 7+3*NHEAD-1	BTYPE(i) BSTRT(i) BLEN(i)	Block type of the ith block (see following table) Starting byte location of the ith block Number of bytes in the ith block

Table – List of BTYPE values

BTYPE	Block type	Description
0	FILinf	File information block
1	REVinf	Information on the revision of the routines used to create the block
2	IMGinf	Information about the satellite image contained in this file
3	SATinf	Info. on the satellite, sensor and channels
4	NAVinf	Navigation information
5	CALinf	Calibration information
6	TGRinf	Test grid information
7	OB1inf	The original B1 file header
8	IMAGE	The prefix interleaved with the B1 data.
9	GVARinf	GVAR information
10	QCinf	Scan line quality check information
11+	*TBD*	*User defined block headers*

File Header: Origination info block

Purpose: To provide data provenance.

Size: **360 bytes**

This block describes:

- data origination – original data filename, format, etc.
- data processing – filename and version of the routine that processed the original file to this format
- times and dates the processing occurred

Fortran	Character*72 REVinf(6)
C	long B1Hinf[6]
IDL	B1Hinf=strarr(6)

Index	Name	Description	Format
0	B1FILE	Original B1 filename	A72
1	B1UVER	CVS Revision info on the b1_2_b1u procedure	A72
2	B1RVER	CVS revision info on the b1read procedure	A72
3	B1SVER	CVS revision info on the b1read_spc_sat procedure	A72
4	CRDATE	Date & Time B1U file was created	A72
5	CALFILE	Filename of ISCCP BT or B3 file from which the calibration table was derived (in the case of MTSAT-1R, or FY-2C, or files which have not yet been processed by ISCCP, it will be the B1 file from which the calibration was taken)	A72

File Header: Image info block

Purpose: To provide complete information on the image data contained in the file

Size: 96 **bytes**

Fortran	integer*4 IMGinf(24)
C	long IMGinf[24]
IDL	IMGinf=lonarr(24)

Index	Name	Description	Scale*
0	DATE	Nominal start date: YYYYJJJ	-
1	TIME	Nominal start time: HHMMSS	-
2	SSS	Sensor number See table XX	-
3	NSCAN	Number of scan lines	-
4	NELEM	Number of elements per scan	-
5	NCHAN	Number of channels	-
6	NBYTE	Number of bytes per element	-
7	SDIRNS	Scan direction: North-South 1 = 1st scan is northernmost 0 = 1st scan is southernmost	-
8	SDIREW	Scan Direction: East-West 1 = 1st pixel is Easternmost 0 = 1st pixel is westernmost	-
9	VISAVG	Flag: 0 = Subsampled Vis. data, or N = N pixels used in averaging Vis. data	-
10	VALID	Flag to determine if record is valid	-
11	VALCOD	If not equal to zero, this VALCOD must match the VALCOD in the line prefix, otherwise the scan is invalid	-
12	IMBTOF	Image data byte offset. e.g., =5 for McIDAS format 10-bit data	-
13	GVARIS	GVAR Imager/Sounder flag 1=Imager 2=Sounder 0=Neither	-

Index	Name	Description	Scale*
14	NBINS	Represents bit depth of data. Value of -9999 represents unreported, so depth is 256. Otherwise, the number represents the number of bins (generally 256 or 1024 for 8 or 10-bit data, respectively). This is used to read the calibration table, which is based on this number.	-
15	SPACE	Estimated IR space value as derived from the b1u_get_center algorithm	
16	IROFF(0)		
17	IROFF(1)		
18	VSOFF(0)		
19	VSOFF(1)		
20-23	SPARE	Spare space for future parameters	

* Values in this block are not scaled.

VALID=0 means that no error checks were flagged, otherwise, some error check found suspect data in the file. Flags are set by bit-value:

Currently, no QA/QC tests are performed for the VALID parameter

SPACE is an estimate of the space value for the IRWIN channel. This value is useful in determining how to display IR data. That is, (for IDL) whether to use:

```
IDL> tvscl,IR
```

Or

```
IDL> tvscl,255-IR
```

IROFF and VISOFF were determined from a coastline matching navigation correction algorithm. They can be used to correct the navigation according to the following. Separate values are provided for IR channels and Visible channels since an offset was found between the channels in early Meteosat data.

For GVAR data (GVARIS = 1):

```
b1u.nav.b1uarea.west_vis_elem = b1u.nav.b1uarea.west_vis_elem + IROFF(0)
b1u.nav.b1uarea.north_bound = b1u.nav.b1uarea.northbound + IROFF(1)
```

and

```
b1u.nav.b1uarea.west_vis_elem = b1u.nav.b1uarea.west_vis_elem + VSOFF(0)
b1u.nav.b1uarea.north_bound = b1u.nav.b1uarea.northbound + VSOFF(1)
```

For non-GVAR data (GVARIS = 0):

B1u.nav(2) = b1u.nav(2) + IROFF(0)

B1u.nav(3) = b1u.nav(3) + IROFF(1)

and

B1u.nav(2) = b1u.nav(2) + VSOFF(0)

B1u.nav(3) = b1u.nav(3) + VSOFF(1)

File Header: Satellite Information

Purpose: To provide complete information on the satellite name, instrument and channels.

Size: **32+26*nchan bytes**

Fortran	Character*20 SATinf(2+nchan*2)
C	SATinf[2+nchan*2]
IDL	SATinf = strarr(2+nchan*2)

Index	Variable	Description	Format
0	SATNAM	Satellite name	A16
1	SENNAM	Sensor Name	A16
2 - 2+Nchan-1	CHNAME	Names of the channels (see following table)	A6(NCHAN)
2+nchan - 2+2*nchan-1	CHINFO	Information about the channel (currently, spectral range)	A20(NCHAN)

Channel Definitions: ISCCP B1U Channel name and corresponding channel designation (letter or number from data provider)

CHNAME	GMS-1-4	GMS-5	GOES-5-7	GOES-8-12	MET 2-6	MET 8
VSCHN	V	V		1	✓	✓
VSSDEV*				✓*		
IRWIN	I	I		4	✓	✓
IRSDEV*				✓*		
IRSPL		J		5		
IRWVP		W		3	✓	✓
IRNIR				2		
IRCO2				6		

* These are only provided by CSU and are the spatial standard deviations of the original resolution satellite image

Notes

- GOES-8-12 refers to the GOES Imager channel numbers.
- JMA provides GOES-9 data in a similar format to the GMS-5, with corresponding channels.

File Header: Navigation block – non GVAR satellites

Purpose: To provide all the necessary information to navigate from the satellite coordinates to earth coordinates (or vice versa).

Size: 800 bytes

Fortran	integer*4 NAVinf(200)
C	long NAVinf[200]
IDL	NAVinf=lonarr(200)

Index	Name	Description	Scale
	IMGDAT	**Data regarding the image size/angle/etc.**	
0	LINST	Image line starting scan [in visible pixel units]	-
1	ELEST	Image element starting scan [in visible pixel units]	-
2	LINCEN	Center line (represents 0º elevation angle)	10
3	ELECEN	Center element (0º scan angle)	10
4	LINRES	Scan line resolution	-
5	ELERES	Element resolution	-
6	LINANG	Angular resolution of 1 scan line (º per line)	10^9
7	ELEANG	Angular resolution of 1 element (º per element)	10^9
8	SPER	Spin period of the satellite (s)	10^6
	KEPLER1	**Keplerian data – *Best Estimate***	
9	KEPSRC	Source for this data	
10	EDATE	Epoch Date: YYYYJJJ	-
11	ETIME	Epoch Time: HHMMSS	-
12	EMSEC	Epoch millisecond: # of milliseconds	-
13	SEMIMA	Semi-major axis	10^2
14	INCL	Inclination of orbital plane (º)	10^3
15	ECCEN	Eccentricity of orbit	10^6
16	MEANA	Mean Anomaly (º)	10^3
17	RGTASC	Right Ascension of the orbit (º)	10^3
18	PERGEE	Perigee of the orbit (º)	10^3
	KEPLER2	**Keplerian data**	
19	KEPSRC	Source for this data	
20	EDATE	Epoch Date: YYYYJJJ	-

21	ETIME	Epoch Time: HHMMSS	-
22	EMSEC	Epoch millisecond: # of milliseconds	-
23	SEMIMA	Semi-major axis	10^2
24	INCL	Inclination of orbital plane (º)	10^3
25	ECCEN	Eccentricity of orbit	10^6
26	MEANA	Mean Anomaly (º)	10^3
27	RGTASC	Right Ascension of the orbit (º)	10^3
28	PERGEE	Perigee of the orbit (º)	10^3
	KEPLER3	**Keplerian data from the TLE**	
29	KEPSRC	Source for this data	
30	EDATE	Epoch Date: YYYYJJJ	-
31	ETIME	Epoch Time: HHMMSS	-
32	EMSEC	Epoch millisecond: # of milliseconds	-
33	SEMIMA	Semi-major axis	10^2
34	INCL	Inclination of orbital plane (º)	10^3
35	ECCEN	Eccentricity of orbit	10^6
36	MEANA	Mean Anomaly (º)	10^3
37	RGTASC	Right Ascension of the orbit (º)	10^3
38	PERGEE	Perigee of the orbit (º)	10^3
	ATTDAT	**Attitude data**	
39	ROLL	Spacecraft roll (º)	10^6
40	PITCH	Spacecraft pitch (º)	10^6
41	YAW	Spacecraft yaw (º)	10^6
	ATTFIT	**Attitude data from fitting the test grid**	
42	ROLL	Spacecraft roll (º)	10^6
43	PITCH	Spacecraft pitch (º)	10^6
44	YAW	Spacecraft yaw (º)	10^6
45	SPRA1	Spin axis right ascension at TIME1 (deg)	
46	SPDC1	Spin axis declination at TIME1 (deg)	
47	SPRA2	Spin axis right ascension at TIME2 (deg)	
48	SPDC2	Spin axis declination at TIME2 (deg)	
	RECINFO	**Rectification information (MET sats only)**	
49	RECFLG	=0, no rectification =1, image rectified to RECLAT,RECLON	-
50	RECLAT	Center latitude of image rectification if applied	10^3

51	RECLON	Center longitude of image if rectification is applied	10^3
	FITINFO	**Parameter goodness of fit information (JMA only)**	
52	RMS	RMS in fitting the test grid	10
53	LINBIAS	Bias of the line calculations	10^3
54	PIXBIAS	Bias of the pixel calculations	10^3
55	LINSTD	Std. Deviation of the line calculations	10^3
56	PIXSTD	Std. deviation of the pixel calculations	10^3
	POSDAT	**Position information**	
57	DATE1	Epoch date: YYJJJ	
58	TIME1	GMT time of day in seconds	
59	X1	Sat. position in inertial coordinates at TIME1 (km)	2^{13}
60	Y1	Sat. position in inertial coordinates at TIME1 (km)	2^{13}
61	Z1	Sat. position in inertial coordinates at TIME1 (km)	2^{13}
62	VX1	Sat. velocity in inertial coord. at TIME1 (km/hr)	2^{13}
63	VY1	Sat. velocity in inertial coord. at TIME1 (km/hr)	2^{13}
64	VZ1	Sat. velocity in inertial coord. at TIME1 (km/hr)	2^{13}
65	SPRA1	Spin axis right ascension at TIME1 (deg)	2^{21}
66	SPDC1	Spin axis declination at TIME1 (deg)	2^{21}
67	ZETA	VISSR alignment: line bias (deg)	2^{21}
68	RHO	VISSR alignment: element bias (deg)	2^{21}
69	ETA	VISSR alignment: skew bias (deg)	2^{21}
70	GAMMA	VISSR alignment: sun pulse to VISSR angle (deg)	2^{21}
71	SRA1	Sun right ascension at TIME1 (deg)	2^{21}
72	SDC1	Sun declination at TIME1 (deg)	2^{21}
73	GRA1	Greenwich right ascension at TIME1 (deg)	2^{21}
74	EST	Eclipse start time on DATE1 (seconds)	
75	EET	Eclipse end time on DATE1 (seconds)	
76-85	CB(0:9)	Chebyshev beta parameters	$273*2^{11}$
86-96	CX(0:10)	Chebyshev X position parameters (km)	2^{13}
97-107	CY(0:10)	Chebyshev Y position parameters (km)	2^{13}
108-118	CZ(0:10)	Chebyshev Z position parameters (km)	2^{13}
119	X2	Sat. position in inertial coordinates at TIME2 (km)	2^{13}
120	Y2	Sat. position in inertial coordinates at TIME2 (km)	2^{13}
121	Z2	Sat. position in inertial coordinates at TIME2 (km)	2^{13}
122	VX2	Sat. velocity in inertial coord. at TIME2 (km/hr)	2^{13}

123	VY2	Sat. velocity in inertial coord. at TIME2 (km/hr)	2^{13}
124	VZ2	Sat. velocity in inertial coord. at TIME2 (km/hr)	2^{13}
125	SPRA2	Spin axis right ascension at TIME2 (deg)	2^{21}
126	SPDC2	Spin axis declination at TIME2 (deg)	2^{21}
127	SRA2	Sun right ascension at TIME2 (deg)	2^{21}
128	SDC2	Sun declination at TIME2 (deg)	2^{21}
129	GRA2	Greenwich right ascension at TIME2 (deg)	2^{21}
	LOCDAT	**Location information**	
130	LOCSRC	Source calculations for following location info (see following table)	-
131	SCAN1	The relative scan number corresponding to …	-
132	GLAT1	Sub-satellite latitude at SCAN1	10^{6}
133	GLON1	Sub-satellite longitude at SCAN1	10^{6}
134	GRAD1	Satellite radius at SCAN1	10^{3}
135	SPRA1	Spin axis right ascension at SCAN1	10^{6}
136	SPDC1	Spin axis declination at SCAN1	10^{6}
137	SCAN2	The relative scan number corresponding to …	-
138	GLAT2	Sub-satellite latitude at SCAN2	10^{6}
139	GLON2	Sub-satellite longitude at SCAN2	10^{6}
140	GRAD2	Satellite radius at SCAN2	10^{3}
141	SPRA2	Spin axis right ascension at SCAN2	10^{6}
142	SPDC2	Spin axis declination at SCAN2	10^{6}
	MISC	**Miscellaneous data**	
143	GOESN	GOES Next flag: 0 = GOES-5/6/7, 1 = GOES-8+	
144	EWADJ	East-west offset between IR & VIS as given in original B1 header	
145	EWADJC	EWADJ calculated using spatial correlation	
146	NAVCHK	Results of checking the navigation (# of tests passed out of 13 tests)	
147	IMGDATE	Image Date: YYJJJ	
148	IMGTIME	Image Time (# of milliseconds since start of day)	
149	NSCAN	# of scan lines in image	
150	NPIX	# of pixels in image	
151	CLIN_COR	Center line correction as determined from forcing the IRWIMAGE to be symmetrical	Float
152	CPIX_0	Center pixel correction based on a symmetrical IR	Float

		image. See below for usage.	
153	CPIX_1		Float
154	CPIX_2		Float
155	CPIX_3		Float
156-199	SPARE	Spare words	

KEPSRC/LOCSRC information

Value	KEPSRC
10	Kepler elements from file header
11	Kepler elements estimated from position 1
12	Kepler elements estimated from position 2
13	Kepler elements from NORAD TLE
14	Kepler elements from B1 line headers
15	Kepler elements calculated for “perfect” geostationary (for use with rectified imagery)
16	Kepler elements estimated by fitting calculations to the test grid
17	Kepler elements from supplementary Kepler files
	LOCSRC
30	Location data from file header
31	Location from [cheb2cart or kep2cart] and cart2earth

File Header: GOES-Next Header

Purpose: To provide the exact navigation header from GOES-Next satellites (i.e. GOES-8, 9, 10, 11, 12, etc).

Size: **2816 bytes**

Description: This file header is intended to be identical to the Navigation & AREA header used by the McIdas (a.k.a. AREA) format.

Index	Description	Scale*
	Navigation header for GVAR from McIDAS format	
0	Navigation type (4 ASCII characters encoded as I*4)	-
1	ASCII string usually a letter followed by 3 integers (encoded as I*4)	
2	Imager scan status IMC active flag is bit 8, 1=active; see OGE table 3-6 bytes 3-6	
3	Not used	
4	Not used	
5	Reference longitude (radians)	10^7
6	Reference distance from nominal (km)	"
7	Reference latitude (radians)	"
8	Reference yaw (radians)	"
9	Reference attitude roll (radians)	"
10	Reference attitude pitch (radians)	
11	Reference attitude yaw (radians)	
12-13	Epoch date/time (in BCD format)	
14	Delta from epoch time (minutes)	10^2
15	Image motion compensation (IMC) roll (radians)	10^7
16	IMC pitch (radians)	
17	IMC yaw (radians)	
18-30	Longitude delta from reference values (rad)	
31-41	Radial distance from reference values (rad)	
42-50	Geocentric latitude delta values	
51-59	Orbit yaw delta values	
60	Daily solar rate	
61	Exponential start time from epoch	
62-116	Roll attitude angle information *(see OGE Table 3-6 bytes 523-742)*	

Index	Description	Scale*
62	Exp. Magnitude	
63	Exp. Time constant	
64	Mean attitude angle	
65	Number of sinusoids/angles	
66	Magnitude of 1st order sinusoid	
67	Phase of 1st order sinusoid	
	…	
94	Magnitude of 15th order sinusoid	
95	Phase of 15th order sinusoid	
96	Number of monomial sinusoid	
97	Order of applicable sinusoid	
98	Order of 1st monomial sinusoid	
99	Magnitude of 1st monomial sinusoid	
100	Phase angle of monomial sinusoid	
101	Angle from epoch at daily solar rate	
102-106	Repeat of 97-101 for 2nd monomial	
107-111	Repeat of 97-101 for 3rd monomial	
112-116	Repeat of 97-101 for 4th monomial	
117-126	Reserved	
127	4-byte ASCII (encoded as I*4)	
128	4-byte ASCII (encoded as I*4)	
129-238	Attitude angles	
129-183	Repeat of words 62-116 for pitch attitude angle	
184-238	Repeat of words 62-116 for yaw attitude angle	
239-254	Reserved	
255	4-byte ASCII (encoded as I*4)	
256	4-byte ASCII (encoded as I*4)	
257-366	Misalignment angles	
257-311	Repeat of words 62-116 for roll misalignment angle	
312-366	Repeat of words 62-116 for pitch misalignment	
367	Year and julian day	
368	Nominal start time of image	
369	Imager/Sounder Flag (1=Imager, 2=Sounder)	
370-378	Reserved	

Index	Description	Scale*
379	Instrument nadir, north/south cycles	
380	Instrument nadir, east/west cycles	
381	Instrument nadir, north/south increments	
382	Instrument nadir, east/west increments	
383	4-byte ASCII (encoded as I*4)	
384	4-byte ASCII (encoded as I*4)	
385-510	Reserved	
511	4-byte ASCII (encoded as I*4)	
512	4-byte ASCII (encoded as I*4)	
513-639	Reserved	
	AREA Header from McIDAS format	
640	Area status	Int*4
641	Area version number	
642	Satellite ID Number (SSS)	
643	Image Date: Year and Day of Year (YYYJJJ)	
644	Image time (GMT) HHMMSS	
645	Upper left line in satellite coordinates (in Vis. Res.) [X Coordinate]	
646	Upper left pixel in satellite coordinates (in Vis. Res.) [Y Coordinate]	
647	Upper Z Coordinate	
648	Number of lines in the image (Y size)	
649	Number of elements in the image (X Size)	
650	# of bytes per pixel data element (2 in original data format, 1 for B1)	
651	Line resolution (Y-res)	
652	Element resolution (X-res)	
653	# of channels/bands (Z-res)	
654	# of bytes in the line prefix	
655	Project number	
656	Creation date (YYYJJJ)	
657	Creation time (HHMMSS)	
658	Filter map for soundings	
659	Image ID Number	
660-663	ID [reserved for radar applications]	Int*4 (4)
664-671	Comment	Char*32 (8)
672	Calibration codicil	

Index	Description	Scale*
673	Navigation codicil	
674	Secondary navigation codicil	
675	Validity code	
676-683	PDL in packed-byte format	Int*4 (8)
684	Band8: where band 8 came from	
685	Actual image start date (YYYJJJ)	
686	Actual image start time (HHMMSS)	
687	Actual image start scan	
688	Length of prefix Document	
689	Length of calibration document	
690	Length of prefix level	
691	Source type	Char*4
692	Calibration type	Char*4
693	Data was averaged (0) or sampled (1)	
694	POES Signal: LAC, GAC, HRPT	
695	POES Ascending or Descending mode	
696	Original source type of data	Char*4
697-703	Reserved	Int*4 (7)

*For more information on Indices 5-61, see OGE Table 3-6, bytes 295-522

File Header: Calibration block

Purpose: To provide the calibration data to convert counts to radiance values (and either brightness temperatures or reflectance units).

Size: **30724 bytes**

Fortran	integer*4 CALinf(1+2*nchan*256)
C	long CALinf[1+2*nchan*256]
IDL	CALinf=lonarr(1+2*nchan*256)

Index	Variable	Description	Scale
0	CVER	ISCCP calibration version number	-
1:2*nchan*256	CTABLE(2,nchan,256)	ISCCP calibration table	10^3

CVER is derived from the ISCCP BT version number. If a BT file exists at the ISCCP web site with a larger version number, then information from that BT should be used in lieu of this calibration table.

There are 2 tables per channel. The first calibrates image counts to radiance in units of W m^{-2} $ster^{-1}$. This calibration is termed “absolute radiance” by ISCCP and is the third table in the BT file. The second table provided here is the “scaled absolute radiance/reflectance” (which is the 6^{th} in the ISCCP BT table). This provides calibration of the image into either Brightness Temperature (K) for IR imagery or scaled reflectance for visible imagery. The actual value provided for visible imagery is best represented by ρ_{sat}:

$$\rho_{sat} = \frac{\pi L_{sat}}{F_o}$$

Where L_{sat} is the satellite-detected radiance and F_o is the top-of-the-atmosphere solar spectral radiation integrated over the sensor spectral response. To determine anisotropic reflectance, one must correct for sun-earth distance and solar zenith angle.

The channel order of the calibration table is in the identical order of the channels in variable CHNAME (from the satellite information header). This was performed through a complex method of matching the channel order of the BT files with the corresponding B3 files. Then, the tables are re-ordered to match the B1 file using the B1 channel information.

However, despite all this effort, the calibration poses one remaining problem: ISCCP (in creating the B3 data) changed the original data in one way: they reversed the scale on some IR imagery to make image counts proportional to radiance. Therefore, one will need to check the image to determine whether DC (digital count) or 255-DC should be used in CTABLE.

File Header: Test grid block

Purpose: Early processing centers provided test grids which contained the line/pixels for a given lat/lon grid.

Size: **24 + 8*nrows*ncols bytes**

This provides a check of the user's navigation routines. In particular, this grid is useful for the GMS navigation, since GMS attitude parameters were calculated by fitting calculations to this grid.

This block is not provided with all satellites, but only for files where the grid exists in the original B1 file.

The length of this block will vary. GMS test grids are 11×11, while GOES test grids are 6×6.

Fortran	integer*4 TGRinf(24 + 8*nrows*ncols)
C	long B1Hinf[24 + 8*nrows*ncols]
IDL	B1Hinf=lonarr(24 + 8*nrows*ncols)

Index	**Name**	**Description**	**Scale**
0	NROWS	Number of test grid rows	-
1	NCOLS	Number of test grid columns	-
2	LAT1	Starting latitude (º)	10
3	LON1	Starting longitude (º)	10
4	DLAT	Latitude step (º)	10
5	DLON	Longitude step (º)	10
6 – 6+2*nrows*ncols-1	GRID(2,NROWS,NCOLS)	Test grid pixel, line pairings	10^2

File Header: Original B1 file header

Purpose: To provide the original B1 headers, which will provide continuity and consistency.

Size: Variable

Providing the B1 header will allows tests that ensure the data was transposed from the original B1 file to the B1U file properly.

Fortran	integer*1 B1Hinf(BLEN(i))
C	byte B1Hinf[BLEN(i)]
IDL	B1Hinf=bytarr(BLEN(i))

Satellite	SPC	# of bytes	Summary
GOES-5/6	UWS	16480	All bytes until the first WORD record is read. This generally includes the initial AREA, NAV, CHEB and DIR records.
GOES-6	CSU	~4400	
GOES-7	AES	~1927	
GOES-7	CSU	~1900	
GOES-8		~14000	
GOES-8	AES	1284	
GOES-9/10/12	CSU	~14000	
MET-3	CSU	100	
MET-2 to 7	EUM	15202	
GMS-1 to 4	JMA	10000	
GMS-5	JMA	21200	
GOES-9	JMA	21200	

Line prefix header

Purpose: To provide image information at the scan level.

Size: 40*nchan*nline

- The line prefix block describes the contents of the line prefix. Not all entries will be included since this header is a conglomerate of all B1 line prefixes.
- Note: The date format is different in this block since this prefix header is I*2 (thus, can not use YYYYJJJ).

Fortran	integer*2 TIMinf(nchan,20,nline)
C	short TIMinf[nchan,20,nline]
IDL	TIMinf=intarr(nchan,20,nline)

Index	Name	Description
0	SCANR	Relative scan number (starts a 1 for first scan in file)
1	SCANA	Absolute scan number
2	CHNUM	Corresponds to the i^{th} channel CHNAME from image block (above), range is [0-NCHAN-1]
3	YEAR	YYYY
4	JDAY	Day of year (aka, julian day): JJJ
5	TIME	Time (GMT): HHMM
6	SEC	Time (GMT): SS
7	MSEC	Time (GMT) milliseconds: mmm
8	EEDGE	Eastern edge of earth's disk
9	WEDGE	Western edge of earth's disk
10	DETID	Detector (or sensor) ID # if provided (-1 if missing)
11	VALCOD	Validity code
12	CHKSUM	CHKSUM if provided in original line prefix
13:19	SPARE	Spare space for future parameters

File Structure

- The File info blocks are written sequentially in the order provided in the BTYPE table. Some blocks are required (e.g., REVinf, PREinf) while others are optional (e.g., for B1 files without a test grid, TGRinf is not written).
- The image data is interleaved with the line prefix. A simple read statement for such is:

IDL

```
IMG = BYTARR(NELEM)

PRE = INTARR(NBLP)

PREFIX = INTARR(NCHANS,NSCANS,20)

IMAGE = BYTARR(NCHANS,NELEM,NSCANS)

FOR J=0,NSCANS-1 DO BEGIN

        FOR C=0,NCHANS-1 DO BEGIN

                READU,1,PRE

                READU,1,IMG

                PREFIX(C,J,*) = PRE

                IMAGE(C,*,J) = IMG

        ENDFOR

ENDFOR
```

File Utilities

The following is a description of the file utilities that will be provided with the b1u data. In general, the navigation routines are currently written, but are in need of "sprucing up" and further testing. Currently, I have written the routines in IDL. Translation to Fortran, C or some other language should be straightforward.

Primary Routines

- B1Uread.pro
    - This routine reads the B1U data and stores file blocks and image data in IDL structures.
- B1U_ij2ll.pro
    - A navigation routine which converts pixel/line couplets to latitude/longitude values.
- B1U_ll2ij.pro
    - A navigation routine which converts latitude/longitude couplets to line/pixel values.
- *B1U_image.pro*
    - *Creates images of the B1U data with coastlines overlaid and outputs imagery to JPG and PNG formats. [Requires ancillary coast data files]*
    - *Not packaged with the preliminary data.*

Appendix C. Calculating zenith and azimuth angles

The following is how zenith and azimuth angles are calculated from satellite positions, Earth locations and date.

Solar Angles

Solar angles are solely dependent upon the location (latitude and longitude) and time. Thus, it is straightforward to calculate solar angles.

The hour angle (h) is defined as the longitude of the sun, which is calculated as:

$$h = -\frac{t-12}{12}$$

where t is the frational GMT time (e.g., for hh:mm:ss then t = hh + mm/60. + ss/3600.)

Solar zenith angle (θ_o) is calculated as:

$$\cos\theta_o = \sin\varphi\sin\delta + \cos\varphi\cos\delta\cos h$$

Where δ is the solar declination angle and varies from -23.45 deg to +23.45 deg through the year and can be approximated as:

$$\delta = -23.45\cos\left(\frac{2\pi J}{365} + \frac{20\pi}{365}\right)$$

Where J is the day of the year.

The solar azimuth angle (φ_o) is calculated as:

$$\sin\phi_o = \frac{\sin(h-\lambda)}{\sin\beta_o}$$

Where:

$$\cos\beta_o = \cos(\varphi)\cos(\lambda - \lambda_s)$$

Note: An assumption is made that the time is constant throughout the image. However, there will be some variation as to when each scan started and ended. A full disk scan takes about 30 minutes to complete and most files were started near the optimal time. A better approximation would be to use the start time of each satellite (which can be determined from the B1 filename) to better estimate the actual image time.

Solar zenith angle calculation provided by: Liou, Kuo-Nan, 1980: **An Introduction to Atmospheric Radiation**, Academic Press, 392 pp.

Satellite Angles

Satellite angles are more cumbersome to calculate. Converse to solar angles, they are largely independent of time. Instead, they depend on satellite orbital characteristics and location on Earth (latitude and longitude).

Satellite angles are based on the beta angle, which is the angle from the center of the Earth subtended by the satellite latitude and longitude (φ_S, λ_S) and point in question on the Earth (φ, λ). The values for (φ_S, λ_S) are stored in the netCDF variables satlat and satlon, respectively.

$$\cos\beta = \cos(\varphi - \varphi_s)\cos(\lambda - \lambda_s)$$

When the satellite has a small inclination angle, this can be approximated as:

$$\cos\beta = \cos(\varphi)\cos(\lambda - \lambda_s)$$

View zenith angle is calculated as:

$$\sin\theta = \frac{42164 \sin\beta}{\sqrt{1.8084 \times 10^9 - 5.3725 \times 10^8 \cos\beta}}$$

Azimuth angle (φ) is calculated as:

$$\sin\phi = \frac{\sin(\lambda_s - \lambda)}{\sin\beta}$$

Assumptions and Notes:

- Spherical Earth is assumed, so angles are less accurate at the limb
- Nominal (circular) geostationary orbital radius (42164. Km above the Equator) is assumed
- View zenith angle calculations should be checked for limits: square roots > 0 and arcsine input limit of [-1,+1], prior to calculation, otherwise an error will occur