Climate Data Record (CDR) Program

Climate Algorithm Theoretical Basis Document (C-ATBD)

Advanced Microwave Scanning Radiometer 2 (AMSR2)

V2 Brightness Temperature – CSU

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REVISION HISTORY

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1. Introduction

1.1 Purpose

The purpose of this document is to describe the algorithm used to create the Colorado State University (CSU) Fundamental Climate Data Record (FCDR) of brightness temperature data from the Advanced Microwave Scanning Radiometer 2 (AMSR2) instrument currently operating on board the first generation of the Global Change Observation Mission - Water (GCOM-W1) satellite. 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 to assist a software engineer performing an evaluation of the code.

1.2 Definitions

None Currently

1.3 Referencing this Document

This document should be referenced as follows:

AMSR2 Brightness Temperature – CSU - Climate Algorithm Theoretical Basis Document, NOAA Climate Data Record Program CDRP-ATBD-1284 Rev. 0 (2022). Available at https://www.ncei.noaa.gov/products/climate-data-records/fundamental

1.4 Document Maintenance

Synchronization between this document and the algorithm is achieved through version and revision numbers. The version and revision numbers found on the front cover of this document can be compared with the values of `VERSION` and `REVISION` in the source file `params.h` and in the FCDR filenames and metadata. If the document applies to the algorithm, then these numbers will match. If they don't match and it is found that the document needs to be updated, then the header comment in the file `amsr2_fcdr.c` should be consulted – under its `HISTORY` section is a description of the changes for each version and revision from which the necessary updates to this document can be made.

2. Observing Systems Overview

2.1 Products Generated

The data product generated by this algorithm is the Fundamental Climate Data Record (FCDR) of brightness temperature (Tb) data from the AMSR2 sensors, including the eight low-resolution sensor channels (Tb10v, Tb10h, Tb18v, Tb18h, Tb23v, Tb23h, Tb36v, Tb36h) and the four high-resolution channels (Tb89v A-Scan, Tb89h A-Scan, Tb89v B-Scan, Tb89h B-Scan), stored in netCDF version 4.0 files that include the necessary metadata and supplementary data fields.

2.2 Instrument Characteristics

Data input to this algorithm is from the AMSR2 instrument on board the GCOM-W1 satellite. The GCOM-W1 satellite is in sun-synchronous polar orbits at an altitude of approximately 700 km and is one of the Afternoon Constellation (A-Train) satellites. The instrument is a conically scanning passive microwave radiometer sensing upwelling microwave radiation at 16 channels covering a wide range of frequencies from 6.9 - 89 GHz. Data is collected along an active scan of 122 degrees across track producing a swath width on the ground of approximately 1450 km with 10 km scene spacing. This configuration is shown in Figure 1 (JAXA, 2013). Detailed specifications for the spacecraft and instrument are found in JAXA (2013).

The channels consist of the following sets: low-resolution channels (6.9 - 36 GHz) and high-resolution channels (89 GHz A- and B-Scans). The Tb from 10 - 89 GHz channels are intercalibrated to GPM GMI. Detailed channel characteristics for all channels are shown in Tables 1-3.

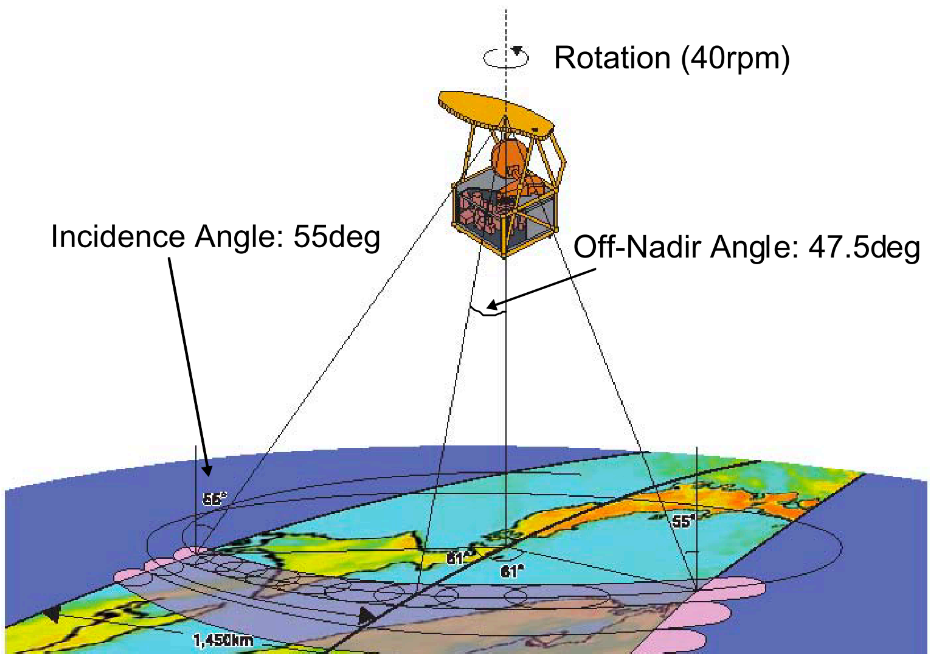

Figure 1: AMSR2 Scan Configuration.

Table 1: Intercalibrated low-resolution window channels (FCDR channels)

Center Frequencies (GHz)	**10.65**	**10.65**	**18.7**	**18.7**	**23.8**	**23.8**	**36.5**	**36.5**
Polarization	V	H	V	H	V	H	V	H
Bandwidth (MHz)	100	100	200	200	400	400	1000	1000
Sensitivity (K)	0.7	0.7	0.7	0.7	0.6	0.6	0.7	0.7
EFOV (along track x across track in km)	41 x 24	41 x 24	22 x 13	22 x 13	26 x 15	26 x 15	12 x 7	12 x 7
Sampling Interval (along track x across track in km)	10.14 x 8.87	10.14 x 8.87	10.14 x 8.87	10.14 x 8.87	10.14 x 8.87	10.14 x 8.87	10.14 x 8.87	10.14 x 8.87

Table 2: Intercalibrated high-resolution window channels (FCDR channels)

Center Frequencies (GHz)	**89 A-Scan**	**89 A-Scan**	**89 B-Scan**	**89 B-Scan**
Polarization	V	H	V	H
Bandwidth (MHz)	3000	3000	3000	3000
Sensitivity (K)	1.2	1.2	1.2	1.2
EFOV (along track x across track in km)	5 x 3	5 x 3	5 x 3	5 x 3
Sampling Interval (along track x across track in km)	10.14 x 4.44	10.14 x 4.44	10.14 x 4.44	10.14 x 4.44

Table 3: Low-resolution window channels (no intercalibration applied)

Center Frequencies (GHz)	**6.9**	**6.9**	**7.3**	**7.3**
Polarization	V	H	V	H
Bandwidth (MHz)	350	350	350	350
Sensitivity (K)	0.34	0.34	0.43	0.43
EFOV (along track x across track in km)	61 x 35	61 x 35	61 x 35	61 x 35
Sampling Interval (along track x across track in km)	10.14 x 8.87	10.14 x 8.87	10.14 x 8.87	10.14 x 8.87

Channel characteristics shown above are from:

- JAXA (2013), Table 2-8 (Bandwidth), Table 2-12 (Sensitivity), Table 2-13 (EFOV), and Sections 2.2.7.3 and 2.2.7.4 (Sampling Interval).
- Okuyama and Imaoka (2015).

3. Algorithm Description

3.1 Algorithm Overview

The algorithm operates on input from NASA AMSR2 level 1C files, which are generated from the JAXA AMSR2 level 1B products, containing the RFI checked and GPM GMI intercalibrated Tb for channels 10.65 – 89 GHz. The input data is processed through several stages for re-mapping and re-formatting, and processed data are output in the final FCDR files.

3.2 Processing Outline

The steps of this algorithm include reading the input, the above specified sequential processing stages each of which can be turned on or off with a flag and writing the output data file. Each stage is described in this section. The processing flow is shown in Figure 2.

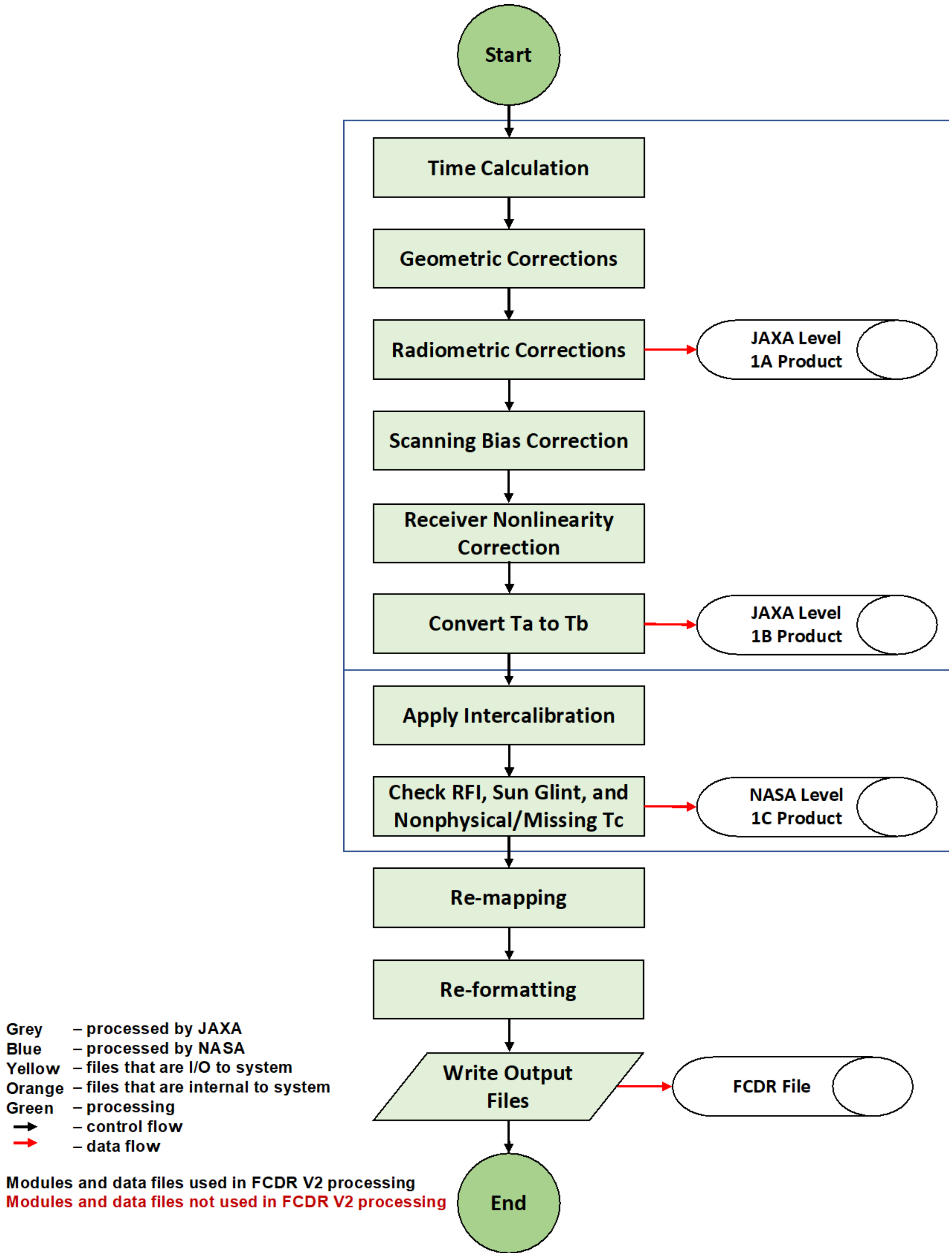

Figure 2: Flowchart for AMSR2 version 2 processing

3.2.1 Read Input

Data from the input NASA AMSR2 level 1C files (see section 3.3) are read and stored in global variables that are accessed by the subsequent steps. Space is allocated to store output data and certain fields are prepopulated from the input data.

3.2.2 Re-mapping and Re-formatting

The NASA AMSR2 level 1C products collect measurement starting and ending at the southernmost point of the orbit in HDF5 format. To be consistent with SSMI(S) FCDR products, the NASA AMSR2 level 1C files are re-mapped starting and ending at the equator shown in Figure 3 and are re-formatted in NetCDF4 format. The quality flags in AMSR2 FCDR files are the same as the NASA AMSR2 level 1C files as shown in Table 4 (NASA Goddard Space Flight Center Code 610.2/PPS and GPM Intercalibration (X-CAL) Working Group, 2022).

Table 4: Quality flags for the NASA AMSR2 level 1C products and NOAA AMSR2 FCDR products

Quality flags	Meaning
0	Good
1	Warning – Possible sun glint, 0 <= sun glint angle < 20 degrees
2	Warning – Possible radio frequency interference
3	Warning – Degraded geolocation data
4	Warning – Data corrected for warm load intrusion
-1	Error – Data are missing from file or are unreadable
-2	Error – Invalid Tb or nonphysical brightness temperature (Tb < 40K or Tb > 350K)
-3	Error – Error in geolocation data
-4	Error – Data are missing in one channel
-5	Error – Data are missing in multiple channels
-6	Error – Latitude/longitude values are out of range
-7	Error – Non-normal status modes

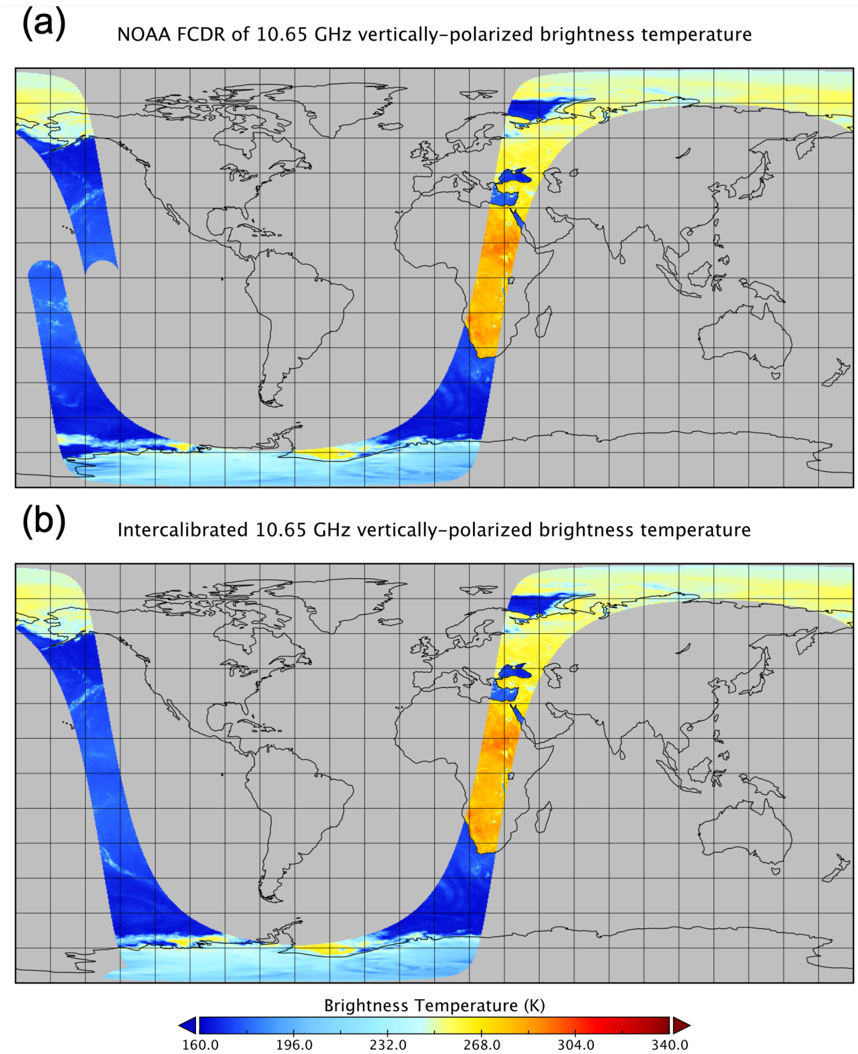

Figure 3: Examples of AMSR2 granules for (a) NOAA FCDR and (b) NASA level 1C products

3.2.3 Write Output

The output FCDR files (described in section 3.4.4) containing the previous JAXA as well as NASA corrected and intercalibrated Tb values are written out in NetCDF4.

3.3 Algorithm Input

The NASA AMSR2 level 1C files are intercalibrated to GPM GMI and are also checked for possible RFI and sun glint influenced as well as unphysical and missing pixels by using the JAXA AMSR2 level 1B products (NASA Goddard Space Flight Center Code 610.2/PPS and GPM Intercalibration (X-CAL) Working Group, 2022). From the AMSR2 sensor raw data, the JAXA AMSR2 level 1B products are produced through several stages. Among them, the main procedures include time calculation, geometric corrections, radiometric corrections, scanning bias correction, receiver nonlinearity correction, brightness temperature calculation and quality control (JAXA, 2013).

3.4 Theoretical Description

The software developed for the AMSR2 FCDR processing is a stepwise approach described in Section 3.2. This involves reading the input NASA AMSR2 level 1C file along with the necessary data coefficient files etc. and applications of re-mapping as well as re-formatting.

3.4.1 Physical and Mathematical Description

3.4.1.1 Physical Background

Passive microwave sensors, such as the AMSR2, measure the microwave radiation emitted by Earth's surface and atmosphere and interacting with the atmosphere through absorption, scattering, and transmission before reaching the sensor. The amount of absorption and scattering of radiation as it travels through the atmosphere depends on the wavelength (or equivalently, frequency) of the radiation and on the state of the atmosphere (e.g. amount of water vapor, rain, cloud, etc.).

The emission of radiation from Earth's surface and atmosphere is described by Planck's blackbody radiation law with the deviation of real materials from ideal blackbodies accounted for by the emissivity (ε) of the material. The brightness temperature (Tb) of a scene retrieved by AMSR2 at a frequency depends on the scene's actual temperature:

$$Tb = \varepsilon \, T_{actual} \tag{1}$$

How the emitted radiation is modified by the atmosphere before reaching the sensor provides information on the state of the atmosphere. Information about carbon dioxide, oxygen, water vapor, liquid water and ice is inferred from AMSR2 data by exploiting known changes in the thermal spectrum due to selective absorption, emission, and scattering of radiation. The GCOM-W1 "SHIZUKU" Data Users Handbook (JAXA, 2013) provides theory of remotely sensed electromagnetic radiation especially microwave radiation, and how it is used to retrieve brightness temperature and other parameters.

3.4.1.2 Sensor Characteristics

The physical sensor characteristics and configuration are described in Section 2.2.

3.4.2 Data Merging Strategy

The original sampling provided by the NASA AMSR2 level 1C files is re-arranged in the output FCDR data such that the orbit data starts and ends at the equator, consistent with FCDR record of SSMI and SSMIS sensors. Other than orbit definitions, the resulting FCDR Tb is fully consistent level 1C file which is intercalibrated to be physically consistent with the observed Tb from the calibration reference sensor (i.e. GPM GMI). No attempt was made to correct AMSR2 Tbs for the local observing time and/or differences in the view angle or EIA between AMSR2 and GMI. Retrievals algorithms must account for physical differences between sensors.

Details on the processing steps involved in the algorithm are provided in Section 3.2. Additional details are provided in a series of CSU technical reports (Sapiano et al. 2010; Sapiano and Berg 2012, 2013; Berg and Sapiano 2013) and in journal publications (Berg et al. 2016; Berg et al. 2018; Kroodsma et al. 2021).

3.4.3 Algorithm Output

For each input NASA AMSR2 level 1C files, the algorithm produces an output FCDR file in NetCDF4 format. There are approximately 14 files per sensor per day and each file is approximately 50 Mbytes. Empty files containing only global metadata fields are produced for orbits with no available input level 1C data. The FCDR file contains the final JAXA as well as NASA corrected and intercalibrated Tb for 10 - 89 GHz channels along with pixel latitude and longitude, time for each scan, spacecraft position, quality flags, sun-glint angle, and fractional orbit number with the necessary metadata and supplementary data fields. A total of two sets of variables are provided, including the eight low-resolution sensor channels (Tb10v, Tb10h, Tb18v, Tb18h, Tb23v, Tb23h, Tb36v, Tb36h) and the four high-resolution channels (Tb89v A-Scan, Tb89h A-Scan, Tb89v B-Scan, Tb89h B-Scan). The data are truncated to the nearest 0.001 degree for the lat/lon values and to the nearest 0.01 K for the Tb and view angles. Internal NetCDF data compression is used to compress the files.

4. Test Datasets and Outputs

4.1 Test Input Datasets

No test datasets were used to characterize the algorithm performance. Validation of the resulting FCDR data is described in Section 5.5.

4.2 Test Output Analysis

4.2.1 Reproducibility

As with the version 1 intercalibration (Sapiano et al. 2012, 2013), multiple intercalibration approaches were used to check for consistency and provide an estimate on the residual uncertainties (Berg et al. 2016, 2018; Kroodsma et al. 2021).

4.2.2 Precision and Accuracy

The calibration accuracy of the AMSR2 Tb is tied to that of the reference sensor (i.e. GPM GMI), which has been shown to be extremely well calibrated (Wentz and Draper, 2016; Berg et al. 2016, 2018), within 0.5 K absolute for all channels. While uncertainties in the intercalibration estimates vary by channel and scene temperature, it is generally within ~1.0 K for all channels.

5. Practical Considerations

5.1 Numerical Computation Considerations

This algorithm doesn't use parallelization. No problems with matrix inversions are expected. Failure of the geolocation algorithm to produce a valid latitude and longitude can lead to missing pixel geolocation in rare instances. There are round-off errors in computations and conversions between different data types, which are expected and within the tolerance of the algorithm.

5.2 Programming and Procedural Considerations

The code implementing this algorithm uses standard procedural programming constructs such as: user-defined data structures to manage input and output data fields; control structures; functions; etc. No unusual programming techniques or optimizations are used as ease of maintainability was an important design criterion. Specific features of the code include:

- A pattern used throughout much of the code is to loop through all the scans of an orbit granule, for each scan to loop through channels, and for each of these sets of channels to loop through all pixels and all channels.
- Each of the eight sequential processing stages of the algorithm can be turned on or off with a flag (these stages are described in section 3.2). This is useful for comparison and validation of individual processing stages.
- Error and exception conditions are handled by direct checking of conditions/return codes in the main control flow, not by a language-supported exception construct.
- For efficiency (both execution speed and working storage space), extensive use of global variables is made.
- The source code is expected to build, and the resulting program to run, on a considerable range of different platforms. For more information on this, see section 5.6.

5.3 Quality Assessment and Diagnostics

See discussion on Section 5.5 on Validation. This includes application of geophysical retrievals and comparisons with AMSR2 FCDR datasets.

5.4 Exception Handling

Error and exception conditions are handled by direct checking of conditions/return codes in the main control flow rather than by a language-supported exception construct.

5.4.1 Conditions Checked

The following conditions identify errors that necessitate that the program terminate. They are trapped and the program prints a suitable message, then exits gracefully with a non-zero status indicating the type of error.

- If an incorrect number of arguments are supplied to the program, a usage message is printed, and it exits with status 1.
- If there is an error opening or reading an input file, the program prints an error message and exits with status 1.
- If there is an error creating or writing to an output file, the program prints an error message and exits with status 2.

5.4.2 Conditions Not Checked

The following possible error condition is not checked for:

- In the unlikely event that the program would run out of memory, it would crash.

5.4.3 Conditions Not Considered Exceptions

Where data fields are missing, quality flags are set and for those quality issues classified as serious the corresponding data fields are set to indicate missing data. All corrections/conversions are applied only to non-missing data and if any processing stage identifies certain data as missing, it remains missing for all future processing stages. This is considered normal processing and not an exception condition.

5.5 Algorithm Validation

5.5.1 Validation during Development

The following methods were employed to validate the resulting FCDR data.

1) Visual inspections and verification of the various corrections applied to the data. As detailed by Berg et al. 2013, 2016, 2018 and Kroodsma et al. 2021, to verify the pixel geolocation, monthly images of gridded ascending minus descending Tb maps were checked using the final roll, pitch, yaw, delta EIA and timing offset values for each sensor and compared to maps based on the original TDR data. The results show consistent improvement.

2) Implementation of multiple intercalibration approaches as mentioned in Berg et al. 2016, 2018 and Kroodsma et al. 2021. The use of multiple approaches was done to check for consistency between independent calibration techniques and to provide an

estimate of the residual uncertainties. Differences tend to be larger for warm scenes but are generally quite consistent.

3) Application to geophysical retrievals. We are working with several different thematic CDR or TCDR developers to use the CSU FCDR with their algorithms. That effort is ongoing, but since the ultimate measure the FCDR is the consistency of the TCDRs or geophysical retrievals, we will continue to work to solicit feedback from various communities.

5.6 Processing Environment and Resources

The code was originally developed and run in a processing environment described by the features listed in Table 5.

Table 5: Processing environment

Hardware	Dell PowerEdge Server
Memory	64GB
Processor	18 dual core Intel Xeon CPU E5-2695 @ 2.1 GHz (Hyperthreading enabled so appears as 72 CPUs)
Operating system	CentOS Linux release 8 (64-bit)
Programming language	C
Compiler	icc (64-bit)
External libraries	hdf5, netcdf, mfhdf, df, hdf5_hl, jpeg, z, imf

The code has been designed to facilitate running it on different platforms by means of the following methods:

1. The Makefile which controls the build process, including compiling and linking.

2. The majority of the code is platform-independent.

3. The platform-dependent parts of the code are separated from the rest and found in the file `sgdp4h.h`. This file contains code to:

    a. Detect the platform;
    b. For functions that will be used from platform-dependent built-in libraries, load the relevant libraries;
    c. Handle the precision differences of data types on different platforms.

To build the code in a new environment, follow these steps:

1. Ensure that the required external libraries listed in Table 5 are installed (for hdf, netcdf, jpeg, z, imf).

2. Examine the Makefile and set the compiler command if different for the new environment. Also comment/uncomment lines if necessary to select 32-bit or 64-bit environments.

3. Run the make command to create the executable program `amsr2_fcdr` from the source code.

Performance:

1. Using a single CPU on the system detailed above takes approximately 30 seconds wall clock time to run a single file.

2. Using approximately ten processors, the entire AMSR2 FCDR data record can be reprocessed within a couple of days.

3. No temporary storage is required to run the algorithm. The only storage required is for the input and output files. The software with the necessary correction files etc. is less than 200 Mbytes.

6. Assumptions and Limitations

6.1 Algorithm Performance

Near real-time monitoring of the input Tc and corresponding calibration data are provided on the web site (http://rain.atmos.colostate.edu/FCDR). Other than this, however, there is no near real-time assessment of the data and thus the quality of the output FCDR data is dependent on the quality of the input level 1C data. As such, the near real-time data is labeled as an interim climate data record (ICDR) instead of an FCDR indicating that it has not been fully vetted for climate applications. Every 6-12 months we will transition this to FCDR status once we have had a chance to run geophysical retrievals and look at the resulting data in more detail.

6.2 Sensor Performance

The sensitivity of the AMSR2 instruments is shown in Tables 1 and 2 and varies from 0.6 to 1.2 K for the 10 – 89 GHz channels.

7. V2 Enhancements

Several enhancements were implemented for the V2 FCDR processing.

7.1 Intercalibration reference sensor

The original V1 FCDR dataset included a relative intercalibration correction using DMSP F13 as the reference. This was done since there was no community consensus regarding an absolute calibration reference for microwave sensors. Since then, the launch and Cal/Val of the GPM GMI instrument have shown it to be extremely well calibrated and stable for all channels, which includes corresponding 10 – 89 GHz channels.

8. Future Enhancements

Quality control is always an issue that could be improved, and potential further improvements should be explored. The primary goal for future enhancements, however, should be to address issues identified by users.

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Appendix A. Acronyms and Abbreviations

Acronym or Abbreviation	Definition
AMSR2	Advanced Microwave Scanning Radiometer 2
CATBD	Climate Algorithm Theoretical Basis Document
CDR	Climate Data Record
FCDR	Fundamental Climate Data Record
GCOM-W	Global Change Observation Mission - Water
NCDC	National Climatic Data Center
NOAA	National Oceanic and Atmospheric Administration
NRL	Naval Research Laboratory
SDR	Sensor Data Record (contains Tb data)
SGP4	Simplified General Perturbations orbital model
SSM/I	Special Sensor Microwave/Imager
SSMIS	Special Sensor Microwave Imager/Sounder
TA	Antenna Temperature
TB	Brightness Temperature
TDR	Temperature Data Record (contains Ta data)