Climate Data Record (CDR) Program

Climate Algorithm Theoretical Basis Document (C-ATBD)

UAH MSU Mean Layer Temperature (MLT)

RESPONSIBILITY

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REVISION HISTORY

Revision	Description	Revised Sections	Date
1.0	Initial submission to CDR Program	New Document	09/22/2011

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ACRONYMS AND ABBREVIATIONS

Acronym or Abbreviation	Meaning
AMSU	Advanced Microwave Sounding Unit-A
CATBD	Climate Algorithm Theoretical Basis Document
CDR	Climate Data Record
MLT	Mean Layer Temperature
MSU	Microwave Sounding Unit
NCDC	National Climatic Data Center
NOAA	National Oceanic and Atmospheric Administration
PRT	Platinum Resistance Thermometer
Ta	Antenna Temperature
Tb	Brightness Temperature
TLS	Lower Stratospheric Temperature
TLT	Lower Tropospheric Temperature
TMT	Mid-Tropospheric Temperature
UAH	The University of Alabama in Huntsville

1.   Introduction

1.1   Purpose

The purpose of this document is to describe the algorithms and procedures submitted to the National Climatic Data Center (NCDC) by Roy W. Spencer and John R. Christy that are currently used as processing steps leading to Climate Data Records (CDRs) of Mean Layer Temperatures (MLTs) for the lower troposphere (TLT), middle troposphere (TMT), and lower stratosphere (TLS), using the Microwave Sounding Unit (MSU) and the Advanced Microwave Sounding Unit (AMSU).

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 performing an evaluation of the code.

1.2   Definitions

The satellite-observed quantity which is interpreted as a measure of deep-layer average atmospheric temperature is the microwave brightness temperature (Tb) measured within the 50-60 GHz oxygen absorption complex. For specific frequencies in this band where the atmospheric absorption is so strong that the Earth's surface is essentially obscured, the rate of thermal emission by the atmosphere is very nearly proportional to the temperature of the air. For example, the lower stratospheric temperature product (TLS) is almost 100% composed of thermal emission from atmospheric molecular oxygen.

In the more general case, the brightness temperature also depends upon the emissivity of the object being measured, as well as its temperature,

$$T_b = \varepsilon\, T \qquad\qquad\qquad (1)$$

As a result, the middle tropospheric temperature (TMT) and lower tropospheric temperature (TLT) products have a component of surface emission "shining through" the atmospheric layer being sensed which, depending upon the surface, may or may not be directly proportional to temperature of that surface.

These sources of contamination have been found to be relatively small (but not totally negligible) in the *time-variations* of the TLT and TMT products, so throughout this document Tb variations will be assumed to be loosely proportional to temperature variations.

(Note: While some call the calibrated satellite-based measurement an "antenna temperature" [Ta] unless antenna pattern corrections are made, such corrections have little impact on climate data records, and so we will not make a distinction between Ta and Tb.)

1.3   Document Maintenance

When requested by NOAA, if there have been any changes in procedures required for the production of the products or if the description of procedures has inadvertent omissions or errors, we will update this C-ATBD.

2.   Observing Systems Overview

2.1   Products Generated

There are three atmospheric layers for which intermediate products are processed:

(1) **TLT** (lower-tropospheric deep-layer average temperature, computed as a weighted difference between view angles of AMSU channel 5, whose heritage comes from MSU channel 2),

(2) **TMT** (mid-tropospheric deep-layer temperature, computed as an average of the central portion of the scan of AMSU channel 5, whose heritage also comes from MSU channel 2), and

(3) **TLS** (lower-stratospheric deep layer temperatures, computed from the central portion of the scan of AMSU channel 9, whose heritage comes from MSU channel 4).

For each of these three atmospheric layers, there are daily 2.5 deg. latitude band (zonal) averages computed, and twice-daily 0.5 deg latitude/longitude grids produced, for each satellite separately. The daily zonal averages are passed directly to John Christy for further processing in which homogenized daily zonal averages and anomalies are constructed. The twice-daily grids are averaged into monthly grids before being passed on for final homogenization where monthly grid point averages and anomalies are computed for public access.

It is critical to understand that the preliminary products computed by Spencer are not the final versions of the products, but are intermediate levels of processing in which the various satellites' products are kept separate. The final, public versions of the UAH products, described here are provided by John Christy (UAH), involving merging of the multiple satellites' intermediate products into continuous climate data records, including separation of the signals into average annual cycle components and anomaly (departures from the average annual cycle) components.

2.2   Instrument Characteristics

The deep layer temperature products described here come from measurements produced by Advanced Microwave Sounding Units (AMSU-As, hereafter "AMSU") flying on NOAA polar orbiting satellites, on NASA's Aqua satellite (operating since mid-1998) and on the European MetOp satellite (operating since late 2006). Before AMSU, the Microwave Sounding Units (MSUs) flew on the NOAA polar orbiters since late 1978.

Processing of the older MSU data, except in the homogenization routines, is not addressed by this document.

These instruments are cross-track through-nadir scanning externally-calibrated passive microwave radiometers. They make brightness temperature measurements at microwave frequencies within the 50-60 GHz oxygen absorption complex, and (in the case of AMSU) at a few microwave frequencies above and below that absorption complex.

The radiometers are designed to measure the weak thermal emission by molecular oxygen (O_2) in the atmosphere. The atmospheric concentration of O_2 is spatially uniform and very stable over time at approximately 20.95%, and so it is a good "tracer" for remotely monitoring of atmospheric temperature variations from space.

From a practical perspective, however, the atmospheric temperature measurement (at least in the troposphere, where weather and climate variations are concentrated) cannot be made without also measuring at least some amount of thermal emission from the Earth's surface shining up through the atmosphere. Therefore, more surface-sensitive channels were included in the AMSU sensor design in order to better correct for this contaminating influence on the atmospheric measurements.

This is important for the wide range of surface backgrounds in different regions, since the intended use of AMSU for monitoring regional temperature variations for input into numerical weather prediction models. We do not, however, perform any such corrections to our products.

The AMSU makes measurements for 15 different channels at 30 footprints within each scan, with a nominal footprint spatial resolution of about 50 km at nadir. Scans are made approximately every 50 km along the satellite track. (The older MSU instruments had only 4 channels, 11 footprints per scan, a resolution of about 110 km at nadir, and scan-to-scan spacing of about 150 km.)

The AMSU measurements are calibrated as "brightness temperatures" (Tb) on each scan of the instrument using a 2-point calibration method. Deep-space views made during every scan of the instrument provide the cold reference point (assumed to be near 3 K), and the hot calibration point is provided by a high-emissivity unheated calibration target internal to the instrument whose temperature is monitored with redundant platinum resistance thermometers (PRTs).

The Earth-viewing measurements are calibrated by interpolating between the cold space view and the warm target view measurements. The AMSU instruments had detailed pre-launch characterization of the instruments, and we use the calibration equation coefficients in the Level 1b orbit files provided by NESDIS, using the calibration equation provided in the document listed below. (In the case of the older MSU instruments, we ignored the NOAA-provided calibration equations, and perform our own linear interpolation, since nonlinearities in the sensor response were not well documented pre-launch.)

Much more information on the characteristics of the AMSUs, their calibration, and Level 1b data format can be found at http://www.ncdc.noaa.gov/oa/pod-guide/ncdc/docs/klm/index.htm. Similar details for the MSUs can be found at http://www.ncdc.noaa.gov/oa/pod-guide/ncdc/docs/podug/index.htm.

3.   Algorithm Description

3.1   Algorithm Overview

The goal is to provide a long-term record of space- and time-averaged deep-layer average temperatures for three atmospheric layers, while minimizing errors due to incomplete spatial sampling, calibration, the varying time-of-day of the measurements, contamination by surface effects on the measurements, and decay of the satellites' orbits over time. The easiest part of this process is the actual calibration of the instrument measurements, which in the absence of contaminating influences from the Earth's surface or hydrometeors in the atmosphere, provides Tb's which are directly proportional to air temperature, which is what we desire to measure.

3.2   Processing Outline

Most of the procedures used in processing of UAH MLT products are described in general terms in a variety of publications, which are listed in the References section, at the end.

The following flow diagrams show the major components of Spencer and Christy's AMSU data processing. Boxes with dotted outlines represent data files, while those with solid outlines represent either Perl or FORTRAN codes. Example data file names are in parentheses.

Prior to the Spencer and Christy processing, the AMSU orbit files are read from the original NOAA files and reformatted for ingest by the Spencer processing codes. Altitude files for each satellite to be processed are also generated to allow corrections for orbital decay to be made. The flow of this preliminary processing is given in Figure 1 (Braswell MLT Processing Flow).
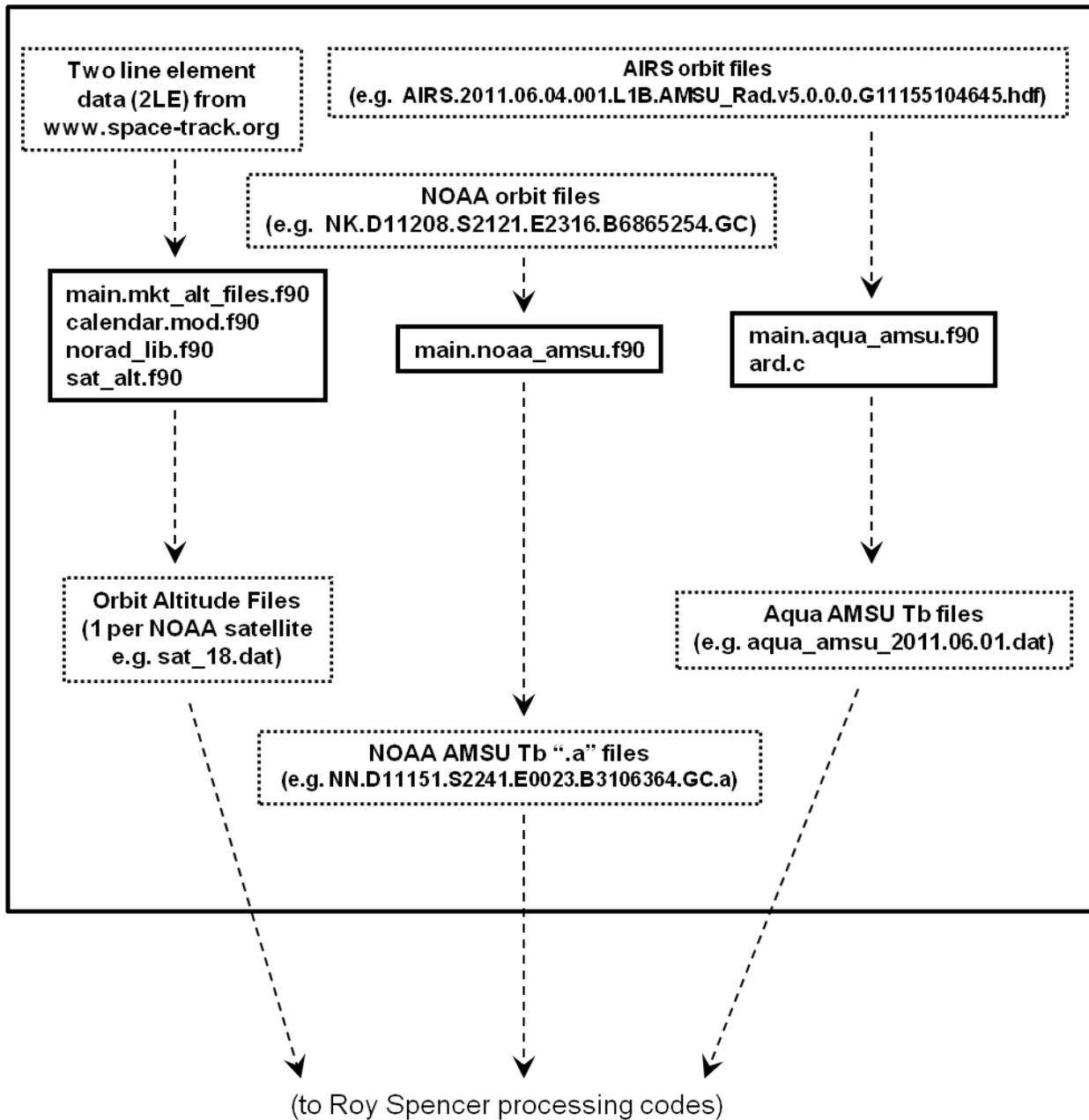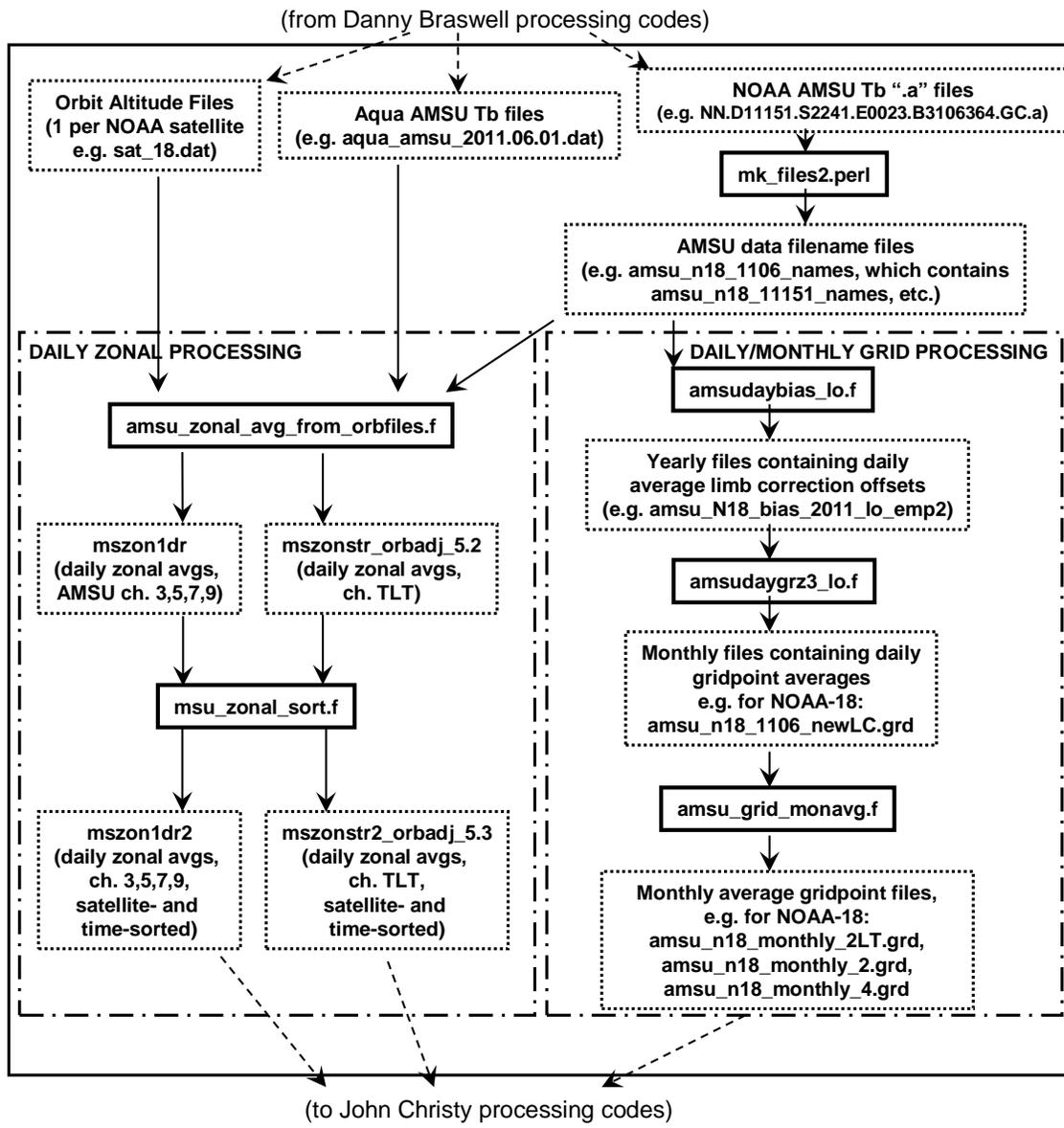
Braswell MLT Processing Flow

Figure 1: Processing flow for Danny Braswell's portion of the AMSU data processing. The output of these processes flow directly into Roy Spencer's processing.

(from Danny Braswell processing codes)

**Orbit Altitude Files
(1 per NOAA satellite
e.g. sat_18.dat)**

**Aqua AMSU Tb files
(e.g. aqua_amsu_2011.06.01.dat)**

**NOAA AMSU Tb "a" files
(e.g. NN.D11151.S2241.E0023.B3106364.GC.a)**

mk_files2.perl

**AMSU data filename files
(e.g. amsu_n18_1106_names, which contains
amsu_n18_11151_names, etc.)**

DAILY ZONAL PROCESSING

DAILY/MONTHLY GRID PROCESSING

amsu_zonal_avg_from_orbfiles.f

amsudaybias_lo.f

**mszon1dr
(daily zonal avgs,
AMSU ch. 3,5,7,9)**

**mszonstr_orbadj_5.2
(daily zonal avgs,
ch. TLT)**

**Yearly files containing daily
average limb correction offsets
(e.g. amsu_N18_bias_2011_lo_emp2)**

amsudaygrz3_lo.f

msu_zonal_sort.f

**Monthly files containing daily
gridpoint averages
e.g. for NOAA-18:
amsu_n18_1106_newLC.grd**

amsu_grid_monavg.f

**mszon1dr2
(daily zonal avgs,
ch. 3,5,7,9,
satellite- and
time-sorted)**

**mszonstr2_orbadj_5.3
(daily zonal avgs,
ch. TLT,
satellite- and
time-sorted)**

**Monthly average gridpoint files,
e.g. for NOAA-18:
amsu_n18_monthly_2LT.grd,
amsu_n18_monthly_2.grd,
amsu_n18_monthly_4.grd**

(to John Christy processing codes)

ROY SPENCER AMSU PROCESSING CODES NOTES:
1) Filename examples provided above are for processing of June, 2011 NOAA-18 AMSU data
**2) because of legacy issues due to transferring from from SGI to Linux-based computers,
all FORTRAN programs reading or writing binary data files are run with a byte-swap option, e.g.
"amsudaybias.exe –WI,-T,-g32767". There are 2 exceptions: running amsu_zonal_avg_from_orbfiles.f
on Aqua AMSU data; and running msu_zonal_sort.f, which reads and writes ASCII files.**
**3) A few of the codes have portions which are not used for routine processing. These were mostly for
testing of new algorithm procedures over the years which were not implemented. Those portions were left
as-is as a reminder of various algorithm changes that were tried.**

Figure 2: Roy Spencer's processing flow diagram. The output of these
processes flow directly into J. Christy's processing.

TLT or Lower Troposphere

Daily Zonal Mean Values

mszonstr2_orbadj_5.4 from Spencer .

↓

Datafile (JC renames: spencer_lt_5.4) .

↓

Execute: tlt_1_5.4
Compute zonal anomalies from NOAA-6 or
NOAA-7, correct for sensor temperature
effect for each satellite separately

↓

Output from tlt_1_5.4:
tlt.ssssss.nna ssssss=sat id, nn=no. .
tlt.noaaxx.ancya annual cycle file
Also input to tlt_2_5.4

↓

Execute: tlt_2_5.4
Merge satellite zonal anomalies into
homogeneous time series accounting
for intersatellite biases

↓

PUBLIC ASCII ZONAL DATAFILES
tltglhmam_5.4 (Monthly)
tltdayamz_5.4 (input to tlt_3_5.4)
tltdayacz8110_5.4
tltday_5.4
tltdayac8110_5.4

↓

Execute: tlt_3_5.4
Calculate monthly zonal
anomalies from daily to match
latitudes used in monthly grids
Output: zmonadjtlt_5.4

Monthly Grid Values

amsu_nNN_monthly_2LT.grd
from Spencer

↓

Execute: readamsug.lt
Converts Spencer's grid files to
format for grid_lt_5.4
output: amsgrdmo6.bin

↓

"cat msgrdmo6.bin
amsgrdmo6.bin > amsgrdmo6"
(concatenates MSU and AMSU)

↓

Execute: grid_lt_5.4
Input: amsgrdmo6 and zmonadjtlt_5.4
Compute grid anomalies, merge
all satellites into homogeneous
time series adjusted to agree with
monthly zonal file zmonadjtlt_5.4

↓

PUBLIC: tltmonamg.YYYY_5.4
PUBLIC: tltmonacg_5.4 (ann cycle)

↓

Execute: NCDCuah.lt
Calculate popular global and
regional anomalies

↓

PUBLIC: uahncdc.lt

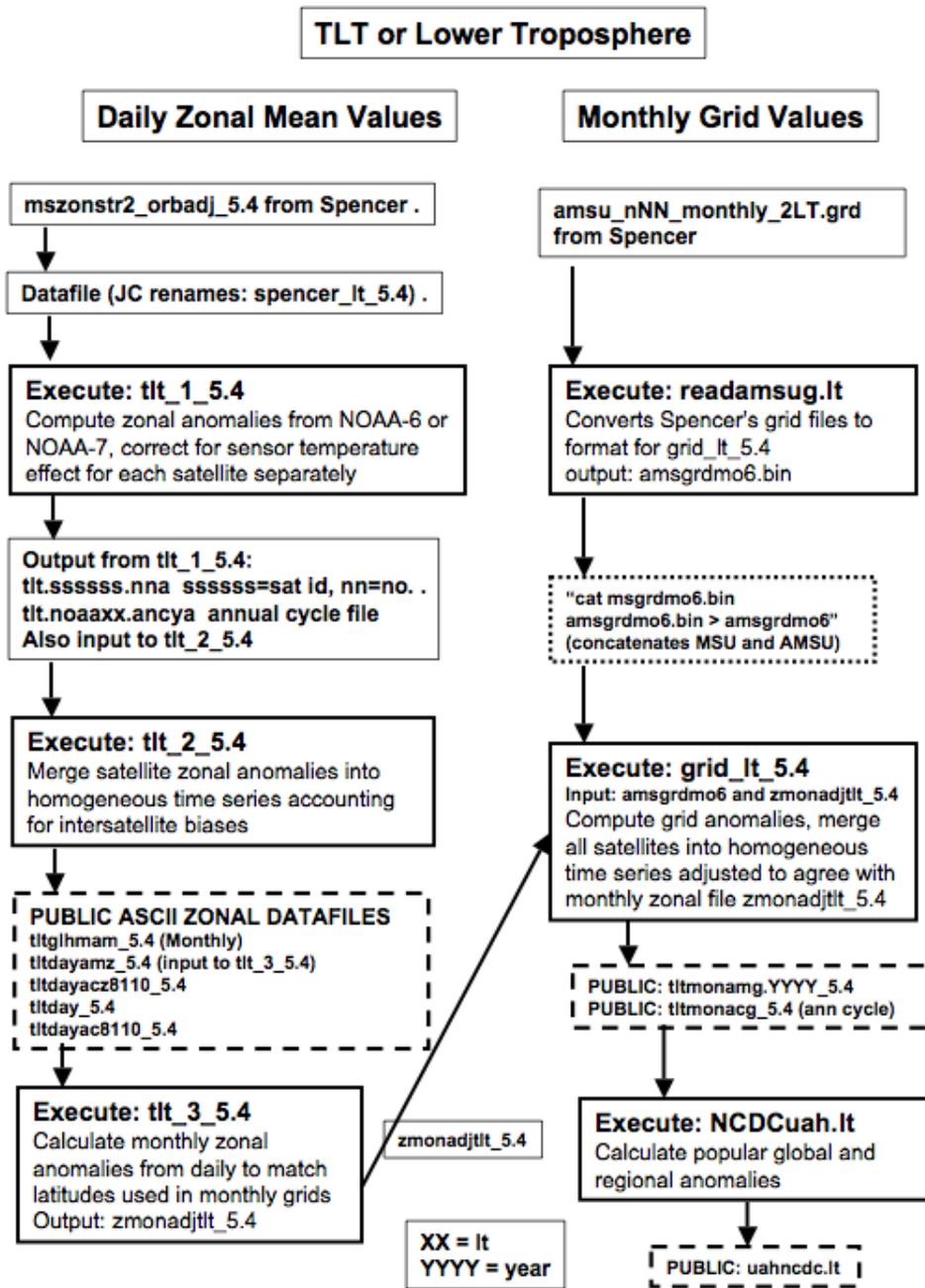zmonadjtlt_5.4

XX = lt
YYYY = year

Figure 3: Flowchart for describing J. Christy's programs that produce
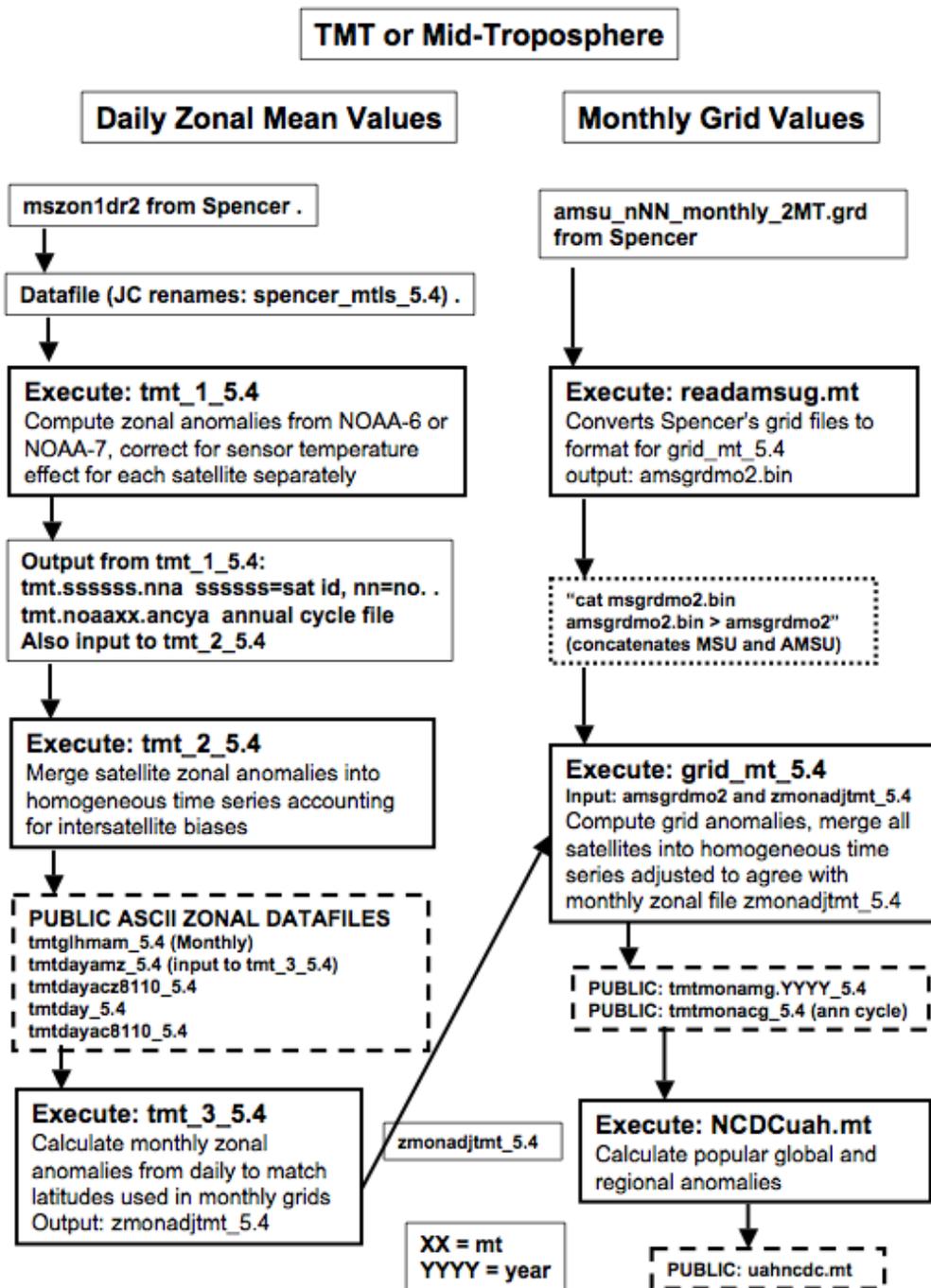public ASCII files of lower tropospheric temperature (TLT).

Figure 4: Flowchart describing J. Christy's program that produce public ASCII files of mid-tropospheric temperature (TMT).
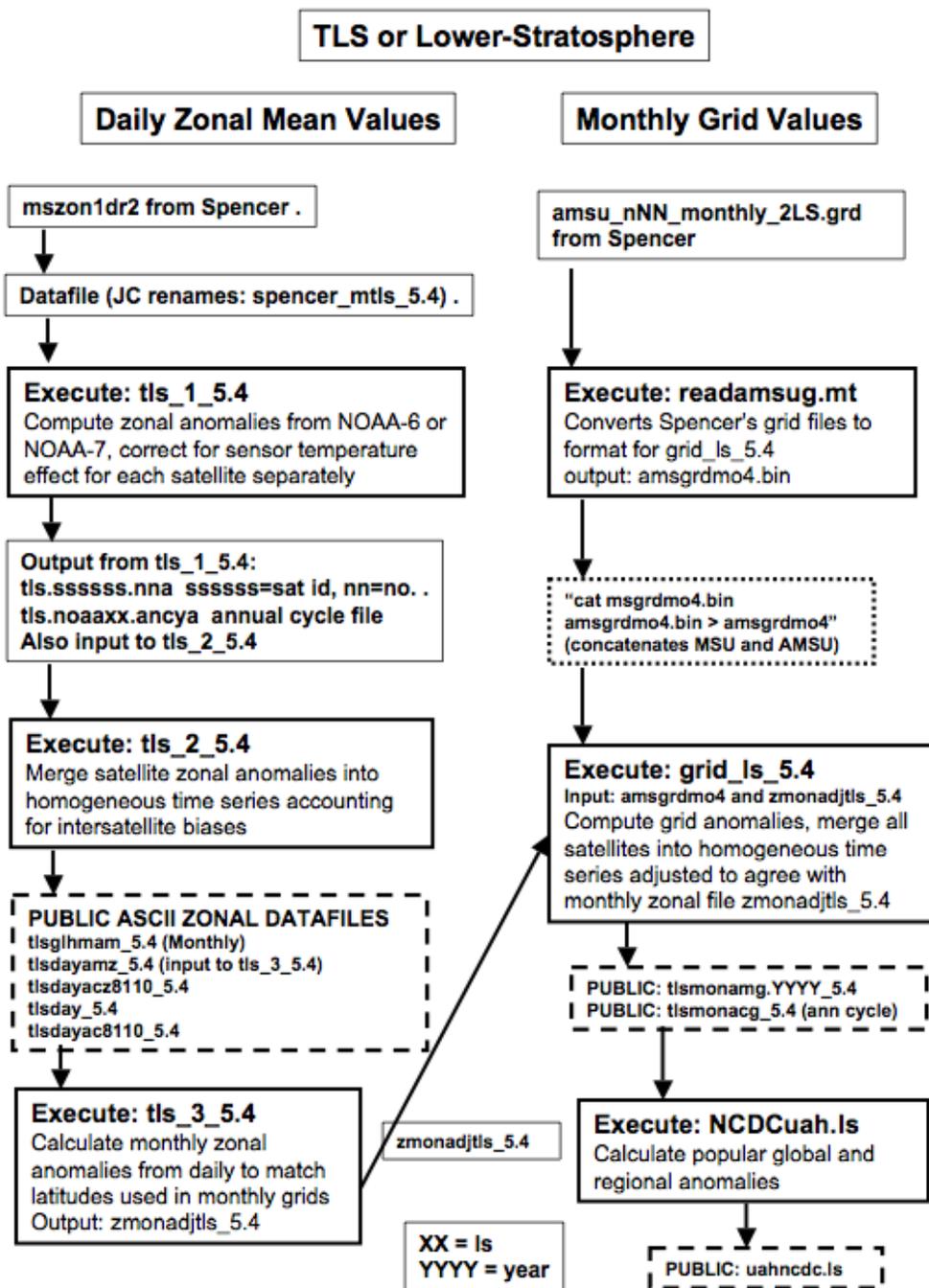
Figure 5:   Flowchart describing J. Christy's programs for producing
public ASCII files of lower stratospheric temperatures (TLS).

3.2.1. *Gathering of the Latest Month's Worth of Data*

The UAH processing procedures are implemented within the first week of each new month after we have determined that all of the AMSU data files have been obtained for the previous month so that a monthly update of the UAH products can be performed.

As of this writing (August 29, 2011) only data from the AMSUs flying on NOAA-15, NOAA-18, and the NASA Aqua satellite are being processed. Danny Braswell has been responsible for gathering these data and putting them in a form which Spencer can easily read and process.

3.2.2. *Creating Files of Filenames*

For the AMSU orbit files from the NOAA satellites, we run a Perl program "mk_files2.perl" which creates a single file of one month of 28 to 31 daily filenames, while each daily file contains a list of approximately 14 AMSU Level 1b orbit file names. These filenames are generated by reading a specified subdirectory and finding orbit files that fall within the user specified month, for a single user specified satellite.

For the Aqua AMSU data, which have a different format and come from a different data provider, there is only one file of global AMSU data per day, so a file of 28 to 31 daily filenames is generated manually.

3.2.3. *Computing Daily Zonal Averages*

The filename files are read by program "amsu_zonal_avg_from_orbfiles.f", run once for each of the separate satellites being processed, which computes and stores one month of daily, 2.5 deg. latitude band average Tb's for:

(1) TMT (avg. of AMSU ch. 5 prints #7 thru #24 [#4 thru #27 for Aqua AMSU]),

(2) TLS (avg. of AMSU ch. 9 prints #7 thru #24 [#4 thru #27 for Aqua AMSU]),

(3) TLT (a multi-view angle retrieval involving a weighted difference between various footprints of ch. 5).

Because the TLT computation is very sensitive to changes in the altitude of the spacecraft, it requires an orbital decay correction. This uses orbit altitude files (one per satellite) created by Danny Braswell for each of the NOAA satellites, all of which undergo various amounts of orbital decay. An adjustment is not needed for the Aqua AMSU TLT product since that satellite's orbit is maintained at a constant altitude with on-board propulsion.

Two additional channels (AMSU channels 3 and 7) also have averages computed and stored, but are not further processed into products. This is a legacy from processing of the older MSU channels 1, 2, 3, and 4, whose AMSU counterparts are channels 3, 5, 7, and 9.

The daily zonal averages are stored in 2 ASCII text files: "mszon1dr" for channels 3, 5 (TMT), 7, and 9 (TLS); and "mszonstr_orbadj_5.2" for the TLT pseudo-channel.

Next, these two files are sorted by program "msu_zonal_sort.f", which reads the files, ignores any duplicate records, and the stores the results sorted by satellite and by time. The resulting files are then passed on to John Christy for further processing, they are "mszon1dr2" and "mszonstr2_orbadj_5.3". There is no sorting algorithm used…the data are simple read into a large multi-dimensional array, then written out again. These 2 output files are then used as input by John Christy to compute a continuous record of data with all of the satellite merged together.

(Note that the output filename appendages "5.2" and "5.3" are rather superfluous, and do not need to correspond with the official dataset versions which John Christy assigns to our final products.)

The file mszon1dr2 contains MSU and AMSU channels used to generate temperature products of the mid-troposphere (MSU-2 and AMSU-5) and lower-stratosphere (MSU-4 and AMSU-9), while mszonstr2_orbadj_5.3 contains data for the lower troposphere (derived from MSU-2 and AMSU-5.) Programs with "tlt", "tmt" and "tls" generate products for the lower-troposphere, mid-troposphere and lower-stratosphere respectively as noted in the flowcharts for each product above (in the following, txx will stand for tlt, tmt and tls).

The program txx_1_5.4 is edited to increase the end-date (in number of days since 1 Jan 1978) of the particular satellites that have data for the new month. Then, txx_1_5.4 is executed which reads mszonstr2_orbadj_5.3 or mszon1dr2 to extract the appropriate channel and to generate anomalies for each of the 13 satellites (TIROS-N through NOAA-18 as of this writing.) Temperature anomalies for morning orbiters are referenced to NOAA-6 and temperatures of afternoon orbiters are referenced to NOAA-7. The anomalies for early spacecraft using MSUs (TIROS-N through NOAA-14) are further adjusted for their spurious response related to the temperature of the instrument itself – the so called hot-target adjustment. The output of txx_1_5.4 contains daily zonal-mean (2.5° Lat) anomalies for each individual spacecraft as well as mean annual cycle temperatures for 82.5°S to 82.5°N from NOAA-6 and NOAA-7.

The program txx_2_5.4 is edited to indicate the new month that is now included for the specific satellites providing data. Note that many of the end-dates for satellites in txx_2_5.4 are earlier than the actual date of last observations for a variety of reasons related to data quality. The individual output spacecraft files from tss_1_5.4 are then read into txx_2_5.4 which performs the intercalibration of the individual spacecraft time series and merges these into a single time series for each latitude (from which hemispheric and global means may be generated.) The basic procedure determines the temperature bias for each latitude between two simultaneously orbiting spacecraft, remove that bias and then merge all of the de-biased time series into one for each latitude. The procedure assumes a set of "backbone" spacecraft, for which the bias for each succeeding spacecraft is removed to match the previous spacecraft. The backbone spacecraft, on which the trend of the time series depends, are NOAA-6,

NOAA-9, NOAA-10, NOAA-11, NOAA-12, NOAA-14, NOAA-15 and AQUA. Anomalies from the other spacecraft, (TIROS-N, NOAA-7, NOAA-8, NOAA-16 and NOAA-18) are essentially used as supplemental data for gap-filling and noise reduction.

Once all anomalies are de-biased and the time series are merged, a reference period is chosen (1981-2010), and anomalies recalculated (by latitude band) to reflect this period as the reference mean annual cycle. The output from txx_2_5.4 includes the publicly available ASCII products as daily global/hemispheric/tropical anomalies (txxday_5.4), daily zonal-mean anomalies (txxdayamz_5.4), monthly global/hemispheric/tropical anomalies (txxglhmam_5.4) with daily mean annual cycles (txxdayac8110_5.4 and txxdayacz8110_5.4).

A program txx_3_5.4 is edited to include the new month and is then executed which utilizes txxdayamz_5.4 as input and converts the daily zonal anomalies to monthly anomalies and shifts the centered, 2.5° latitude bands to 83.75°S to 83.75°N for use in grid_xx_5.4 described below. This output file is zmonadjtxx_5.4.

3.2.4. *Computing Daily and Monthly Gridpoint Averages*

The computation of gridpoint averages involves considerably more FORTRAN code than does the computation of zonal averages. The extra complexity is primarily from:

(1) The removal of "limb-darkening" effects using limb-correction equations. Limb darkening is the decrease in measured brightness temperature as the instruments scan away from nadir. This is due to a longer path length through the atmosphere measured at oblique angles, causing a raising of the weighting function altitude, which leads to lower Tb's due to the general fall-off of temperature with height in the atmosphere, and

(2) Gridpoint assignment, spatial interpolation, and time averaging.

3.2.4.1 *Limb correction equation offset computation*

We use static limb correction equation coefficients, computed empirically with multiple linear regression on a global subset of AMSU data, contained in the following 4 static input files:

"amsu_land_ch1-15_coef4.out"   Land coefficients, AMSU ch. 9 (TLS)

"amsu_land_ch1-15_coef2.out"   Land coefficients, AMSU ch. 5 (TMT)

"amsu_ocean_ch1-15_coef4.out"   Ocean coefficients, AMSU ch. 9 (TLS)

"amsu_ocean_ch1-15_coef2.out"   Ocean coefficients, AMSU ch. 5 (TMT)

The AMSU filename files (described in Section 2) are read by the program "amsudaybias_lo.f", run once for each of the separate satellites being processed, which computes and stores daily, zonal band average differences between limb-corrected Tbs

at all non-nadir footprints versus the uncorrected data near nadir (AMSU prints #15 and #16 straddle nadir).

These average limb correction biases or "offsets" are computed for land and ocean separately, in 10 deg. latitude bands, and for each footprint position. The land/ocean assignment is based upon the percentage of water coverage in each footprint input from the static ASCII file "ih2o50.txt", which contains ~50 km resolution percent water coverage computed on a 1/6 deg. latitude/longitude grid.

These limb correction offsets are then stored in satellite- and year- specific output files.

NOTE: The TLT channel processing does not involve limb correction of the data because the computation of a single TLT value requires an entire scan line of Tb data. This "pseudo-retrieval" of TLT actually uses the limb darkening signal in order to estimate temperature for a lower altitude layer than AMSU channel 5 nominally measures.

3.2.4.2 *Daily gridpoint averaging*

Twice-daily (ascending and descending satellite pass) global grids at 0.5 deg. latitude/longitude are computed for the three primary channels TLT, TMT, and TLS for one or more months using the program "amsudaygrz3_lo.f".

This program reads in the static limb correction coefficient files, the offset files, the percent water coverage file, and the AMSU Level 1b data to compute limb corrected Tb's for each AMSU footprint.   Those Tb's are individually binned into the nearest 0.5 deg lat/lon bin (ascending and descending satellite passes separately) as well as into a number of neighboring bins in the longitudinal direction at higher latitudes to account for convergence of longitude lines (meridians) toward the poles of the Earth. Also, footprints toward the ends of the scans are omitted from the averaging at high latitudes where subsequent orbital swaths overlap, which occurs poleward of about 45 deg. latitude.

Gridpoint averages are then computed for each 0.5 deg. bin containing data, and a self-contained interpolation scheme in the same program is used to interpolate to empty bins. At low latitudes in regions where sequential AMSU orbital swaths do not overlap, there is no interpolation performed.

One month of the resulting twice-daily, 0.5 deg. grids are then stored in three separate files for channels TLT, TMT, and TLS.

Finally, the program "amsu_grid_monavg.f" is run, which simply computes monthly-average gridpoint files from the twice-daily gridpoint files, for all three temperature products.   The resulting output files are channel specific (one each for TLT, TMT, and TLS), which John Christy then uses as input to compute monthly gridpoint anomalies.

At this point the AMSU gridpoint files of each spacecraft from Spencer (i.e. amsu_nNN_monthly_xxx.grd) are read and reformatted in readamsug.xx, which

includes skipping duplicates. The output from readamsug.xx is concatenated onto original monthly grid files from the MSU (i.e. "cat msgrdmoN.bin amsgrdmoN.bin > amsgrdmoN") so that all monthly data for a channel are contained in a single file amsgrdmoN (N = 6 for lt, 2 for mt and 4 for ls.)

Christy then edits grid_xx_5.4 to include the new month. The program is then executed to calculate gridpoint anomalies, debias the fields relative to each satellite and merges the resulting fields into a set of monthly fields whose latitudinal averaged anomalies match those of the daily anomalies. As in the daily zonal process, each monthly field is converted into anomalies by subtracting the mean annual cycle based on NOAA-6 or NOAA-7 depending on the orbit of the target satellite. The anomalies are then debiased in a manner that utilizes the "backbone" satellites listed above except for the use of NOAA-18 rather than AQUA. The time series of each satellite are merged into a single set of monthly gridded anomalies which are then forced to match the monthly zonal anomalies from zmonadjtxx_5.4 (see section 3.2.3).

The output from grid_xx_5.4 are annual files of monthly gridpoint anomalies (2.5°x2.5°) txxmonamg.YYYY_5.4 as well as a file of the mean annual cycle txxmonacg_5.4 for each channel xx and year YYYY for public use. A further program, NCDCuah.xx, is edited to include the latest month then executed, taking as input the monthly gridded anomaly fields. This program produces areal averages that are popular for users in an ASCII output file uahncdc.xx. This file contains global, hemispheric, tropical, extratropical, and polar averages, as well as anomalies for these regions separated by land and ocean.

3.3   Additional Details of Algorithm Input

Further details of the various kinds of data introduced in the previous section are described below.

3.3.1   Primary Sensor Data

The primary sensor data are the AMSU-A Level 1b data files as provided by NOAA/NESDIS, and the AMSU-A data provided by NASA as part of the Aqua AIRS dataset. The NOAA AMSU data input into these programs are already calibrated as Tb's and are contained in "dot-a" (.a) files generated by Danny Braswell, who has also separately provided code to NCDC which generates the dot-a files from the original NOAA/NESDIS Level 1b orbit files.

The Aqua AMSU data files used as input to these programs are reformatted versions of the HDF data files obtained from NASA, the code for which has also been provided separately by Danny Braswell.

3.3.2   Ancillary Data

1) A static ASCII file ("ih2o50.txt") of global gridpoint percent water coverage values, which is used for the limb-correction procedures. This file has values of

percent water coverage from 0 to 100, averaged on a ~50 km spatial scale, and stored on a 1/6 deg. latitude/longitude grid. We computed these values from an old original Fleet Numerical Oceanographic Center (FNOC) 1/6 deg. percent water coverage dataset which we believe is no longer in existence.

2) Satellite-specific orbital altitude files are used as input to the zonal averaging program "amsu_zonal_avg_from_orbfiles.f" to correct the TLT product for orbital decay of the satellites. These files have altitudes computed at 1-minute time resolution from 2-line-element sets during the satellite mission to date, with future altitudes estimated up to one year in advance. The code to create these orbit altitude files has been provided separately by Danny Braswell.

3.3.3   Derived Data

There are two kinds of intermediate sensor-derived data required for processing of the UAH products, both required for limb-correction of the TMT and TLS products, which are in turn used for gridpoint (but not zonal band) averaging.

1) Limb Correction Equation Files:

We computed empirical multi-channel limb correction equations for AMSU channels 5 (TMT) and 9 (TLS) based upon a global dataset sample across all calendar months. A great deal of testing was performed to determine whether theoretical (forward model) based equations, or empirical equations, performed better. It was decided that empirical equations would be used, since we saw evidence of surface emissivity effects that are not well captured by current theory. Limb correction equation coefficients were derived by multiple linear regression for global land and ocean, separately. Testing was also done on latitude- and season- specific equations, but examination of the resulting global imagery revealed discontinuities which were not easily handled. Special testing for the presence of sea ice is done in the code since these ocean areas have emissivity characteristics more like land than ocean. The limb correction filenames were listed in Section 3.2.4.1.

NOTE: There are no limb correction equations for the Aqua AMSU (which is at a lower altitude than the NOAA polar orbiters, 700 km versus ~850 km), because we do not use it for our gridpoint products.

2) Limb Correction Offset Files:

Since there are residual limb correction effects due to seasonal and latitudinal variations in the surface and vertical temperature structure of the atmosphere, it is necessary to compute running average limb correction equation biases, or "offsets". These are a function of AMSU channel, footprint number, ascending or descending pass (day or night), 10 deg. latitude band, and land or ocean (defined with a 50% coverage threshold). While these offsets are computed and stored as daily averages, an 18-day trailing average of these daily values is used by the program "amsudaygrz3_lo.f" after the static limb correction equations are applied.

3.3.4   Forward Models

A forward radiative transfer model developed in-house at UAH by Danny Braswell was used to compute the orbital decay adjustment term for the TLT product. Using a large global radiosonde dataset, we computed how TLT changes as a linear function of altitude and air mass temperature (using TLT itself as a measure of air mass temperature). The dependence of the correction on air mass temperature is required because cold polar air masses have weak temperature lapse rates with height, requiring a weaker orbital decay adjustment, while tropical air masses have much larger temperature lapse rates and so require larger orbital decay adjustments.

NOTE: No orbit decay correction is required for the Aqua AMSU TLT product because the Aqua satellite is maintained at an orbital altitude near 700 km.

3.4   Theoretical Description

Most of the physics and radiative transfer concepts have already been described in previous sections. A few additional details and clarifications follow.

3.4.1   Data Merging Strategy

There is no merging of satellites in the processing performed by Spencer, but is performed in the programs executed by Christy. The general idea is that the individual instruments need time-dependent adjustments for orbital decay (diurnal drift) and the impact of solar heating of the sensor as it drifts to different crossing times where components of the instrument receive time-varying solar radiation. With these adjustments applied, the last step is to de-bias all satellite time series relative to each other, then the anomalies are merged.

3.4.2   Numerical Strategy

IMSL was used to perform multiple linear regression to derive empirical limb correction equation coefficients from a global AMSU dataset.

Spencer uses a "brute force" spatial interpolation scheme for construction of the gridpoint datasets as part of the program "amsudaygrz3_lo.f", which was empirically optimized by visual examination of the resulting global limb-corrected AMSU data as colorized imagery.

In the merging programs, there is some use of median filtering. For the daily zonal mean anomalies, a median filter of a 3-day window is used for the zonal anomalies. For the grid-point anomalies, a 3x3 gridpoint median mask is used. Additionally, the gridpoint fields are smoothed by fourier functions that begin with wave number 1 at the poles and increase to wave number 20 at latitudes 40° and equatorward.

3.4.3   Look-Up Table Description

The necessary static ancillary input datasets have already been described.

3.4.4   Algorithm Output

The various output files have been described above and can be seen in Figs. 1-5.

4.   Output Dataset Quality Evaluation

The quality of Spencer's intermediate data products described here was optimized over a period of several years, mostly between 1990 and 2000, and primarily involved:

(1) Quality of limb corrections used for the gridpoint datasets, which was optimized by examination of global imagery for small-scale artifacts which interrupt the expected smooth variation of deep-layer atmospheric temperatures with horizontal distance.

(2) Quality of the data interpolation scheme, which was also tested by examining global imagery.

Further refinements of various algorithm details were tested based upon the final products produced by John Christy, primarily by examining the statistical level of agreement between simultaneously operating satellites. For example, the TLT product computed from the Aqua AMSU was found to have systematic differences with the TLT products produced from the NOAA satellites, due to an insufficient accounting for the difference in altitudes of the satellites. Adjustments were made to the Aqua AMSU computation of TLT until the systematic differences were largely eliminated. The key statistical parameters that are reduced are the daily intersatellite differences and the intersatellite trend differences calculated during their overlapping observations.

In several publications we have documented many independent comparisons with gridded and regionally-averaged radiosonde datasets. In all gridpoint cases we find that the UAH products show extremely small error characteristics (smaller than those of RSS and STAR.) Since no radiosonde data are used in the construction of the products, such comparisons are completely independent.

5.   Practical Considerations

5.1   Programming and Procedural Considerations

5.1.1 Basic program structure

The codes described here and provided to NOAA have not been optimized in a software engineering sense. Much of the programming structure originated over 20 years ago,

starting around 1989, and was written by the authors who came from a generation of self-taught programmers and have little formal computer programming training. Much of the work was done with little funding support, so no professional programmers were utilized. In Christy's code, there are numerous sections devoted to image creation through NCARgraphics for detection of problems, but which are not necessary for the production of the ASCII files desired by the users.

There is little use of subroutines in Spencer's code, but more in Christy's. Continuity of operational procedures has taken precedence over elegance or speed of execution.

As algorithm enhancements were tested, many were abandoned, but those portions of the code were simply commented out rather than deleted, i.e. they are vestigial in reality. While this is somewhat sloppy from a software design standpoint, the practical advantage of this is to provide a detailed reminder of what has been tried before.

In some cases, rather than having unused code commented out, there are sections which are never branched to in the operational running of the code because an initial adjustable parameter is always assigned a single value. A good example is diurnal adjustment of the AMSU data, for which much code is included, but has never been used operationally. In other cases, a particular ancillary analysis was needed for a publication, but not needed for production runs. These sections are usually commented out.

5.1.1   Program Updating: New Years, New Satellites

Most of the programs have array dimensioning and assignments which must be manually updated every month and year, since (at this writing) they only handle data through July 2011. Similarly, if a new satellite is added, then there are program changes which must be made to accommodate those new datasets.

5.1.2   Binary File Handling, Compile, & Execute Options

The programs were originally developed on an SGI workstation or an IBM mainframe, and then later transitioned to Linux. As a result, all previous binary input and output files had a byte-ordering issue. We retained the SGI handling of binary files, so some of the programs must be run with a byte-swap option used on execute. This might not be an issue if NOAA re-generates all output files from scratch, but if our previous output files are used, there will be a problem.

Also, we have had problems processing of a month's worth of global AMSU data causing some sort of memory size allocation exceedance during a single program execution, which leads to only a portion of the data being processed properly. This is also handled with a special option during execute.

The following are the FORTRAN compile and execute commands that Spencer currently uses:

```
lf95 amsu_zonal_avg_from_orbfiles.f –wide –block 65000 –o amsu_zonal_avg_from_orbfiles.exe
```

```
./amsu_zonal_avg_from_orbfiles.exe -Wl,-T,-g32767  (NOTE: omit the runtime options if Aqua AMSU)

lf95 msu_zonal_sort.f -wide -block 65000 -o msu_zonal_sort.exe
./msu_zonal_sort.exe

lf95 amsudaybias_lo.f -wide -block 65000 -o amsudaybias_lo.exe
./amsudaybias_lo.exe -Wl,-T,-g32767

lf95 amsudaygrz3_lo.f -wide -block 65000 -o amsudaygrz3_lo.exe
./amsudaygrz3_lo.exe -Wl,-T,-g32767

lf95 amsu_grid_monavg.f -wide -block 65000 -o amsu_grid_monavg.exe
./amsu_grid_monavg.exe -Wl,-T,-g32767
```

Christy uses the short-hand execution command, e.g. `./tlt_2_5.4` since the needed file assignments and commands are already incorporated into header and footer in the code.

5.2   Quality Assessment and Diagnostics

When code is executed, a significant amount of intermediate information is printed to the screen, to stored files, or to images. These are all examined each month for unusual output that may indicate a problem. For example, during just a few months' time of data-checking we noticed the temperatures from NOAA-16 were drifting rapidly away from NOAA-15 for AMSU-5. But with only two satellites, there was no immediate way to determine which satellite was at fault. This caused us to examine both satellites at a footprint-by-footprint level of scrutiny to find that the end-of-scan AMSU-5 view angles of NOAA-16 (#30-#32) indicated a rapid change in temperatures not found in #1 - #29. Then, we examined the neighboring vertical channels (4, 6, 7, and 8) which indicated NOAA-16's channel 5 was at odds with its nearby channels while NOAA-15's channel 5 was consistent with its neighboring channels. This was hard evidence that NOAA-16 experienced a problem and led us to discontinue its use.

5.3   Exception Handling

Most programs provide output to the screen so that the results can be examined, and an "istore" variable that can be set in Spencer's code so that the final results are not stored in the output file(s) until the user is confident that the results look reasonable (see above).

A variety of checks throughout all of the programs are made, which are too numerous to list here. Only a couple of examples are provided, below. All checks in the code should already have comments included with them.

Calibrated brightness temperatures outside of limits specified in the computer codes are ignored. If there is slow degradation in an AMSU channel, this will only show up as anomalous values in the products, and so some level of quality checking of the products must be made by an experienced scientist whenever new data are processed (see example above regarding NOAA-16.)

When information on whether a scan line is part of an ascending or descending satellite pass is required, there must be a previous scan line whose center print is no more than 0.6 deg. in latitude different from scan line being processed, otherwise the scan line is ignored.

5.4   Algorithm Validation

Evaluation of the final products was and is performed through Intercomparison to gridded and global radiosonde data and other global datasets on the final products produced by Christy, not on the intermediate products produced by Spencer. Most of the results are contained in publications referenced at the end of this document.

5.5   Processing Environment and Resources

Most programs are written in FORTRAN, while one is Perl. All are run under Linux on the UAH institutional computing facility "Matrix", made up of many processors. The wall clock time required to process one month of global AMSU data from a single satellite varies from less than 2 minutes (zonal averaging) to around 10 minutes (gridpoint averaging). Christy's merging programs usually take less than one minute each to execute. The amount of CPU required to run the various programs is unknown.

6.   Assumptions and Limitations

6.1   Algorithm Performance

As discussed previously, decisions regarding limb correction procedures involving the linear combination of many different channels, or computation of the TLT "pseudo-channel" from various view angles of AMSU channel 5, or how to interpolate the gridpoint products, were optimized based upon how well two different AMSUs flying on different satellites in different orbits agreed with each other in the resulting products.

Thus, the products and procedures used have been optimized to be fairly robust in a statistical sense. Especially when regression is used for the development of a product based upon a huge volume of satellite data, "over-fitting" of the regression equation coefficients is quite common. This potential problem was indeed seen and avoided to the extent possible.

Nevertheless, algorithms using remotely sensed data are never perfect. Thus, the algorithm might or might not be sensitive to long-term changes in (say) surface emissivity, or sensor changes, or satellite orbit changes, depending upon the nature and severity of these various influences.

There has been little effort to explore all of the potential sources of these problems and potential mitigation strategies. Instead, issues are addressed as they arise when anomalies are seen in the products. This limited effort on our part is due to the fact we

are not funded for such activities which would require significant amounts to time (i.e. money.)

6.2   Sensor Performance

There are many problems which can arise in spaceborne measurements from passive microwave radiometers like AMSU, too many to be anticipated. The processing described here assumes the instruments are operating nominally.

If there is a channel failure, we decide how it should be handled based upon what other data are available, and how necessary the channel is to our processing. So far, we have not had a catastrophic failure of any of the primary channels used for our products, which are AMSU channels 5 and 9. There have been periods of up to several days were satellite data were lost somewhere in the communications system, but unrelated to our activities. As of this writing, and with the exception of some gaps just mentioned, we have always had at least one radiometer operating since 16 Nov 1978. Some sensors have experience sufficient problems that we halted their use early (TIROS-N, NOAA-9 channel 2, NOAA-16) but a co-orbiting satellite has always been available to keep the time series continuous and connectable to the previous satellites.

If we lose a channel required for limb correction of those channels (e.g. channel 11 from NOAA-15, which was required for limb correction of the channel 9 data), we must then re-derive limb correction equations and reprocess all previous data from that instrument in order to avoid potential spurious jumps in the time series.

At this writing, the Aqua AMSU channel 5 is experiencing increasing noise. Fortunately, our space- and time- averaging of many footprints has reduced the noise to the point where there is no noticeable negative impact on the products. However, if the problem becomes unmanageable, we will then need to use another AMSU as the "anchor" for long-term stability of the time series, a role which the Aqua AMSU currently fills in John Christy's processing.

7.   Future Enhancements

The most likely future enhancement is the implementation of diurnal cycle corrections for the AMSU products, especially for TLT and TMT. These corrections to the AMSU data have been unnecessary up to this point due to the continuing availability of at least one satellite which does not have substantial drift in its local observation time. The choice of which satellites to use at what times is made by John Christy in his portion of the processing which generally reflects problems as a sensor ages and/or drifts. Diurnal cycle corrections will have the biggest effect on certain land regions where the diurnal cycle is particularly strong.

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