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Processing of ATMS Radiances at the Canadian Meteorological Centre

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Revision history			
Version	Date	Author/modifications	Remarks
0.1	2014/09/18	S. Macpherson	First version (pre-operations)
1.0	2015/06/09	S. Macpherson	Updated version for parallel/ops runs
1.1	2019/07/29	S. Macpherson	Added new satellite NOAA-20

Table of Contents

1. Introduction.

This document is a description of the operational processing of ATMS radiances at the Canadian Meteorological Centre (CMC). The technical aspects of ATMS processing are discussed, including quality control, bias correction, channel selection, data thinning and operational monitoring.

The Advanced Technology Microwave Sounder (ATMS) is a 22 channel cross-track microwave radiometer designed to replace legacy cross-track AMSU-A and AMSU-B/MHS instruments found on the NOAAxx series and MetOp-A,B satellites. It was first introduced on the Suomi NPP (SNPP) satellite launched on 28 October 2011. The second ATMS instrument is found on the NOAA-20 satellite, launched on 18 November 2017, which operates about 50 minutes ahead of Suomi NPP in the same orbit. Sixteen channels are devoted to AMSU-A like temperature sounding channels, while the remaining 6 channels are water vapour sounding channels like AMSU-B/MHS (see Table 1).

Most channels have exact AMSU-A or AMSU-B/MHS counterparts with a few exceptions as highlighted in red in Table 1. There is an extra temperature surface window channel (channel 4 at 51.76 GHz) and two extra 183 GHz water vapour sounding channels (19, 21) that provide enhanced vertical resolution. Window channel 16 (88.2 GHz) is like 89 GHz AMSU-A channel 15 and AMSU-B/MHS channel 1. Channel weighting function profiles are shown in Figure 1.

The ATMS beam widths are 5.2° for channels 1-2, 2.2° for channels 3-16 and 1.1° for channels 17-22. For comparison, beam widths are 3.3° for AMSU-A and 1.1° for AMSU-B/MHS. There are a total of 96 field-of-views (FOV) separated by 1.1°, where AMSU-A has only 30 FOV and AMSU-B 90 FOV. The scan width is wider for ATMS compared to AMSU-A and AMSU-B/MHS.

The temperature sounding channels suffer from higher radiometric noise compared to AMSU-A due to oversampling and shorter integration times per FOV. Techniques must be applied to reduce the noise to levels similar to AMSU prior to data assimilation (see Section 2).

The processing and quality control for ATMS data described in this document is based largely on that applied to the AMSU-A and AMSU-B/MHS instruments.

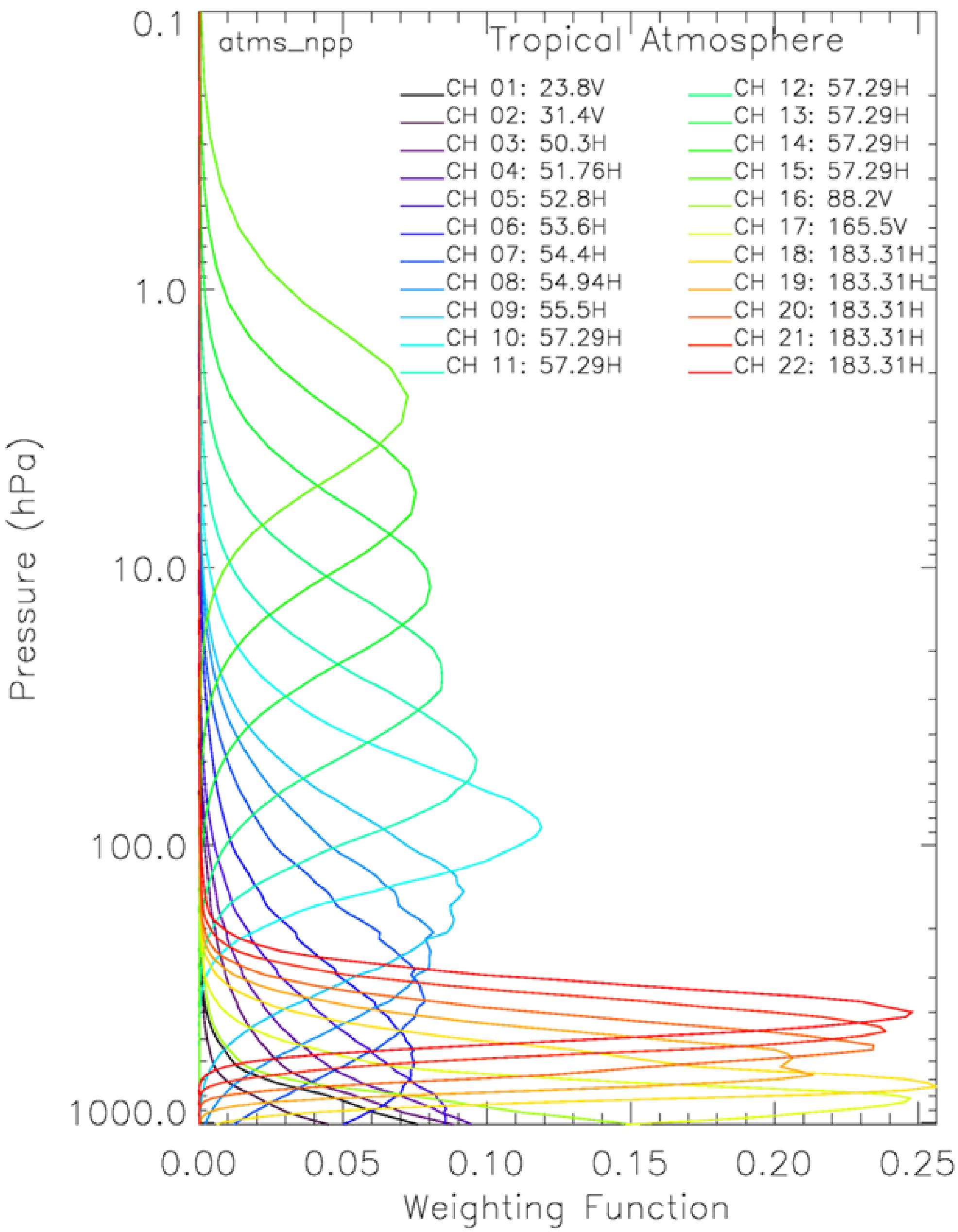

Figure 1. ATMS channel weighting functions.

Channel	AMSU A/B equiv. chan.	Center Freq .(GHz)	Beam Width (degrees)	Characterization
1	1	23.8 V	5.2 (**75 km**)	window-water vapor
2	2	31.4 V	5.2	window-water vapor
3	3 (V)	50.3 **H**	2.2 (**32 km**)	window-surface
4	**new**	51.76 H	2.2	window-surface
5	4 (V)	52.8 **H**	2.2	surface air
6	5	53.596±0.115 H	2.2	4 km ~ 700 mb
7	6	54.40 H	2.2	9 km ~ 400 mb
8	7 (V)	54.94 **H**	2.2	11 km ~ 250 mb
9	8	55.50 H	2.2	13 km ~ 180 mb
10	9	57.2903 H	2.2	17 km ~ 90 mb
11	10	57.2903±0.115 H	2.2	19 km ~ 50 mb
12	11	57.2903 H	2.2	25 km ~ 25 mb
13	12	57.2903±0.322 H	2.2	29 km ~ 10 mb
14	13	57.2903±0.322 ±0.010 H	2.2	32 km ~ 6 mb
15	14	57.2903±0.322 ±0.004 H	2.2	37 km ~ 3 mb
16	15 (89)	87-91(88.20) V	2.2	window H_2O 150 mm
17	2 (150/157)	**165.5** V	1.1 (**16** km)	H_2O 18 mm
18	5	183.31±7.0 H	1.1	H_2O 18 mm
19	**new**	183.31±4.5 H	1.1	H_2O 4.5 mm
20	4	183.31±3.0 H	1.1	H_2O 2.5 mm
21	**new**	183.31±1.8 H	1.1	H_2O 1.2 mm
22	3	183.31±1.0 H	1.1	H_2O 0.5 mm

Table 1. List of ATMS channels. Differences from AMSU instruments are highlighted in red. Yellow shaded cells indicate AMSU-A like temperature channels while blue shaded cells are for AMSU-B/MHS like water vapour channels. Lighter channel numbers in *italics* are not assimilated.

2. Flowchart of ATMS radiance processing.

The flowchart in Figure 2 illustrates the different steps leading to the assimilation of ATMS radiances. The yellow ovals represent an ATMS data BURP file, while a green rectangle is a process. The variables in the ovals are the observed radiance (O), the bias corrected radiance (O'), the trial simulated radiance (P), and the analysis simulated radiance (A). The processes are:

a) "averaging" applied to temperature sounding channel (3-15) radiances in BUFR files, followed by conversion from BUFR to BURP derialt format file;

b) pre-thinning to reduce overall data volume;

c) initial quality control including identification (flagging) of observations affected by cloud water, scattering/precipitation, sea-ice and extreme dryness;

d) application of bias corrections to the radiances (O→ O');

e) computation of innovations (O'-P);

f) data rejection based on innovations, topography, uncorrected data, and initial quality control (c)

g) channel selection (combined with process (f));

h) spatial and temporal thinning of the radiances;

i) assimilation in the 4DEnVar-based assimilation system.

Process (a) is required to reduce the noise level in the temperature sounding channel data, as discussed in Section 1. Fourier techniques are applied to increase the effective ATMS beam width and reduce noise, while retaining the original high sampling frequency. The effect is similar to simple 3x3 averaging.

With 96 field-of-views (FOV) per scan and larger swaths, ATMS has somewhat larger data volumes than the 90 FOV AMSU-B and MHS instruments. Therefore, as done for AMSU-B/MHS, some pre-thinning is required (b) before the data enter the pre-assimilation "background check" stage defined by processes (c) to (h).

Processes (c) to (h) are described in the remainder of this document.

Processing of ATMS radiances

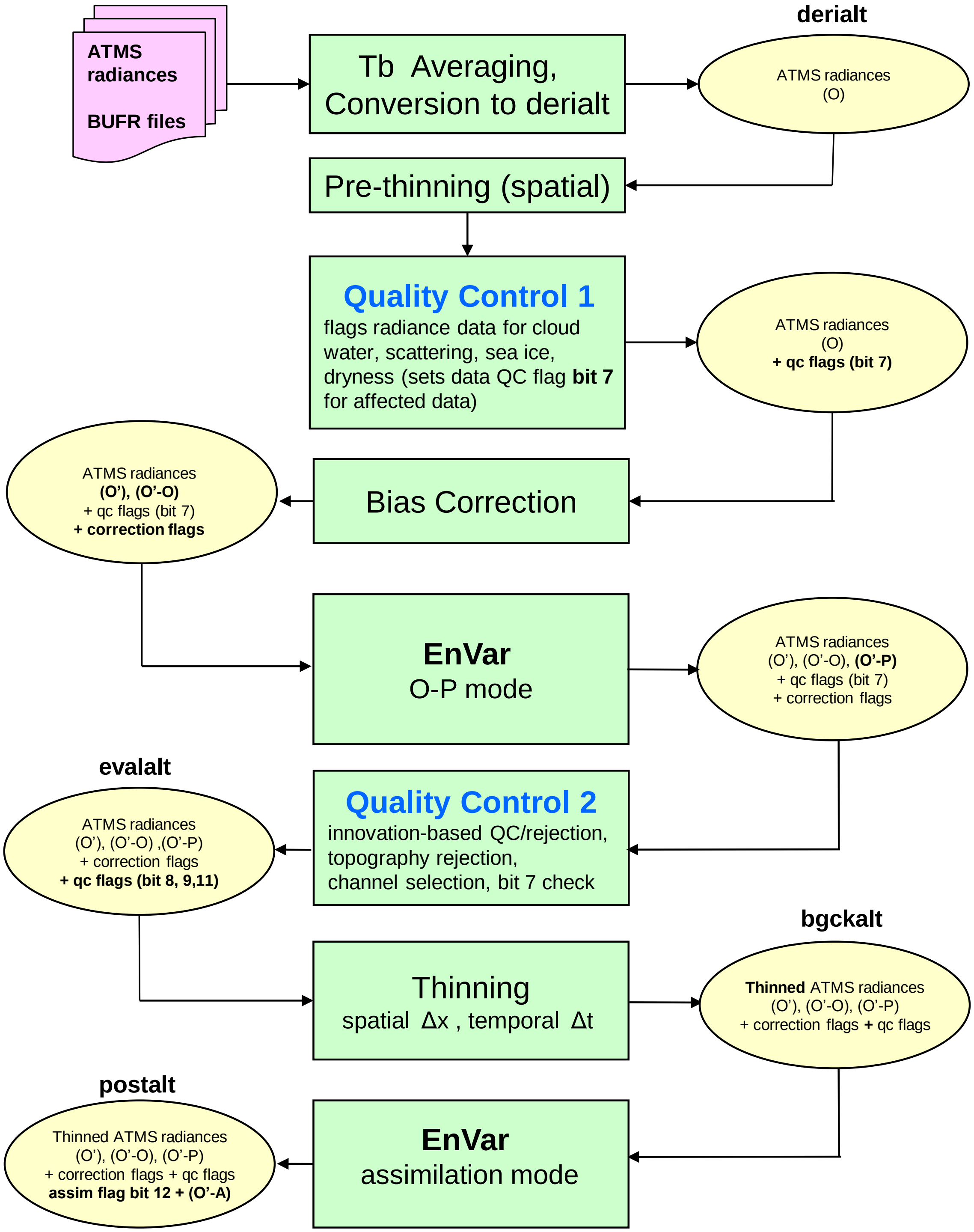

Figure 2. Processing of ATMS radiances.

3. Observed radiance.

ATMS observations are received as BUFR files from an operational NESDIS server in Washington DC. The ATMS_BEAMWIDTH program of the AAPP (ATOVS and AVHRR Pre-processing Package) software package is applied locally to the BUFR files to reduce noise in the temperature sounding channel data, as mentioned in Section 2. The BUFR files are collected over time and merged to create data files every 6 hours (at analysis times) which are then converted to CMC dbase and derivate (BURP) files. The derivate files are input for the pre-assimilation processing shown in Figure 2.

We exclude from assimilation (blacklist) data from window channels (1-4 and 16) that are most sensitive to the underlying surface due to inherent difficulties in their assimilation over land and sea-ice. We also exclude data from extreme FOVs 1 and 96 as O-P monitoring reveals anomalous biases and standard deviations for several channels at these FOV, due to the beam width resampling applied to the data.

In order to reduce computer processing times and memory requirements during pre-assimilation processing, ATMS radiances are pre-thinned, reducing the volume of data by a factor of 10.

Appendix A has a summary of the main BURP descriptors associated with ATMS data.

4. Simulated radiance.

In order to assimilate ATMS radiances, we need to calculate the so-called (O-P) innovation

$y - H(x)$, where:

> y: observed (corrected) radiance (O),
> x: model state (temperature TT,
> *natural log* specific humidity LQ,
> surface pressure PS,
> surface temperature TS,
> surface winds UU and VV),
> H: non-linear observation operator.
> $H(x)$: simulated radiance (P)

Surface winds (UU,VV) are needed by the radiative transfer model to estimate surface emissivity over open water for the surface contribution.

The operator H includes the following:

- horizontal interpolation of the background model state (x) to ATMS observation points;
- vertical interpolation of TT and LQ from the background hybrid levels to the RTTOV radiation model's pressure levels;
- computation of simulated ATMS radiances using the RTTOV fast radiative transfer model.

The EnVar program used to assimilate data computes the innovations. Currently, we use the RTTOV-12 radiative transfer model, maintained and distributed by the EUMETSAT Satellite Application Facility on Numerical Weather Prediction (NWP SAF). The RTTOV web site can be found at: http://www.metoffice.com/research/interproj/nwpsaf/rtm/index.html.

5. Initial Quality Control

The quality control programs can be found here:

https://gitlab.science.gc.ca/atmospheric-observations-quality-control

As done for SSMIS, an initial quality control (QC) step is applied to ATMS data before the bias correction step of the pre-assimilation processing. This includes:

- Determination of open-water points (radiance observation locations situated over ice-free water) using the latest CMC sea-ice analysis (LG field) and the model land/sea mask (MG field). Sea-ice retrieval from the ATMS radiance data is used to supplement the CMC sea-ice analysis to determine sea-ice conditions.

- Determination of cloud liquid water (CLW) and scattering index (SI) over all open-water points and application of the information to reject radiance data for channels sensitive to clouds and precipitation. The radiances are rejected since the EnVar system does not include cloud liquid water or precipitation as part of the model state and is incapable of correctly assimilating such radiances. The CLW and SI thresholds used to reject data are listed in Table 2.

- Rejection of water vapour sounding channel data in extreme dry conditions over land or sea-ice. In very dry conditions, mostly in Polar regions, we do not assimilate water vapour channel data because the dryness results in a significant surface contribution to the observed radiances for these channels.

- Rejection of lower-peaking channels 1-6 and 16-19 over land or sea-ice. Radiances from surface-sensitive channels are not assimilated over land or sea-ice due to uncertainty in the values of the surface emissivity.

- Running a series of quality control checks to detect problems with the radiances or with the ancillary data (surface type, satellite zenith angle, etc.). This includes a check of the special ATMS quality flags that accompany the data.

The initial QC program (*bgck.satqc_atms*) sets the CMC data quality flag bit 7 for all rejected data. It also adds the following 3 new elements to the ATMS data BURP file:

- CLW = cloud liquid water (element 13209)
- SI = scattering index (element 13208)
- information flag (element 25174)

The information flag is an integer where different bits are set to indicate information (e.g. open water points, sea-ice) and certain rejection criteria (e.g. cloud water over a given threshold). See Appendix A for details. The information contained in these 3 new elements can be viewed using the SATPLOT utility to check the performance of the program (see Figures 3 and 4 for examples of CLW and SI plots).

The algorithms used to retrieve cloud liquid water, sea-ice, and scattering index from the ATMS radiances are provided by the Naval Research Laboratory (NRL) in Monterey CA. Two different scattering indices (SI) are computed, one from ECMWF and the other based on the Bennartz-Grody SI. Two types of dryness checks are employed to detect extreme dry conditions. One is the Mean 183 GHz (ch. 18-22) test from NRL and the other uses a simple “Dryness Index”, equal to the difference between channel 22 and 18 brightness temperatures. The thresholds used to reject water vapor channel data for extreme dryness are listed in Table 2.

Quantity	Thresholds	Channels rejected
CLW (over water)	> 0.175 kg/m^2 > 0.200 kg/m^2 missing	1-6, 16-20 7-9, 21-22 1-9, 16-22
SI (ECMWF) (over water)	> 9 > 18 missing	1-6, 16-22 7-9 1-9, 16-22
SI (Bennartz- Grody)	> 10 > 15 missing	1-6 7-9 1-9
Mean 183 GHz	< 240 K or missing	16-22
Dryness Index (over land/ice)	> 0 > -5 > -8	22 21 20

Table 2. Various limits used to reject radiances in initial quality control.

6. Bias correction.

Radiance observations, as well as radiative transfer models, contain important errors. It is essential to remove the radiance biases in order to optimally extract the information content for data assimilation. Radiance biases are evaluated using an "unbiased" 3DVar analysis (A) without any satellite radiances assimilated.

Radiance <*O-A*> biases (<> indicates time average) manifest in two different ways, one of which depends on scan position (FOV) and the second of which is air-mass dependent. This led to a two-step approach at CMC, the first of which is to remove a global bias at each scan position, followed by a second step that removes the remaining bias, using a linear regression between the bias and the following model predictors:

- geopotential thickness of the layer 1000hPa-300hPa (T1);
- geopotential thickness of the layer 200hPa-50hPa (T2);
- geopotential thickness of the layer 50hPa -5hPa (T3);
- geopotential thickness of the layer 10hPa -1hPa (T4)

Predictor T4 is reserved for the highest peaking ATMS channels 14-15.

A different set of regression coefficients are computed for each satellite, instrument and channel. The regression coefficients are recomputed every 6 hours, based on the O-A/predictor statistics of the previous 7 days. Currently coefficients for highest-peaking ATMS channels 14-15 are fixed (static), as done for AMSU-A channels 13-14. The static coefficients are updated periodically as required.

The implementation of this radiance correction at the level of the BURP observation file proceeds in the following way:

1) a data quality flag indicates that a radiance has been corrected (bit 6 is set);
2) the bias correction itself appears as a separate element in the BURP file.

Therefore, it is always possible to re-construct the original observed radiance by using the corrected radiance and its correction. Appendix A has a summary of the main BURP descriptors associated with ATMS data.

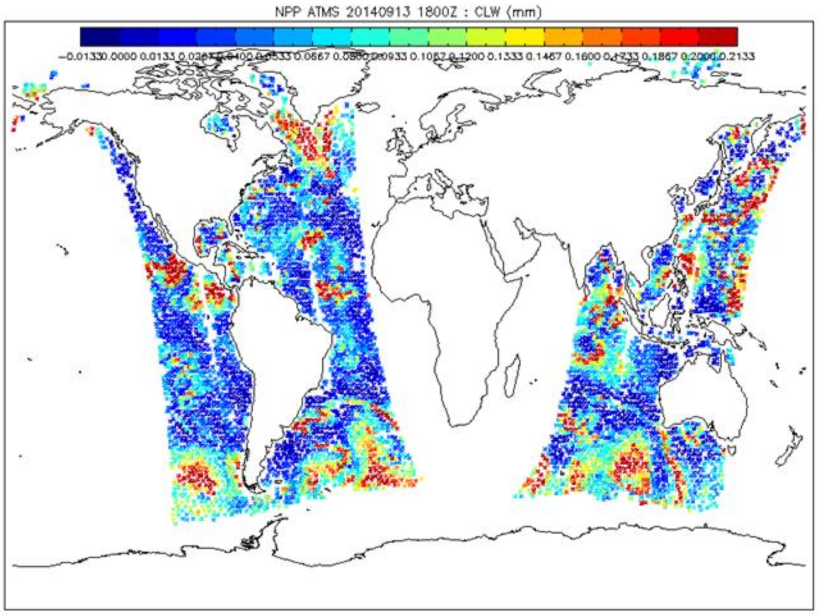

Figure 3. Example of cloud liquid water (CLW) derived from ATMS radiance observations.

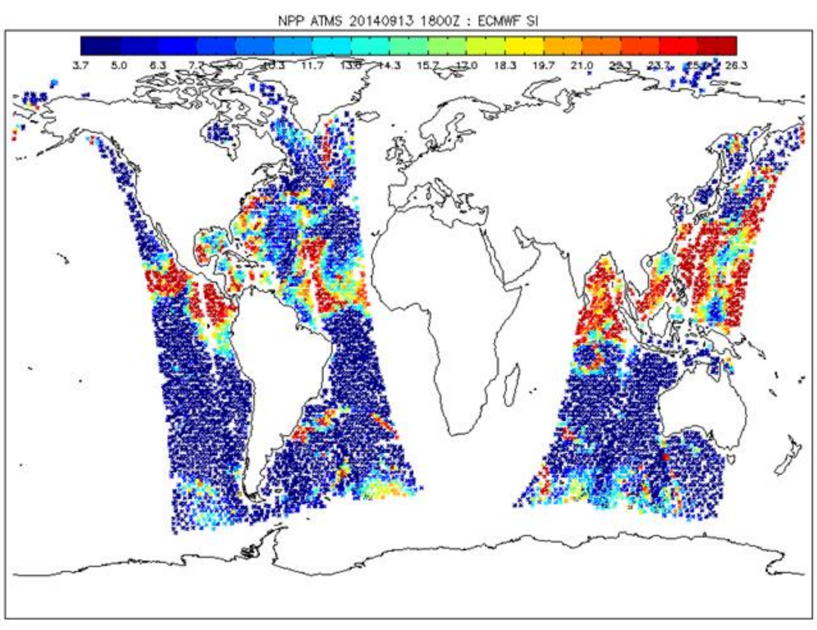

Figure 4. Example of scattering index (SI) derived from ATMS radiance observations.

7. *Second Quality Control and channel selection*

After bias correction and computation of the O-P innovations, ATMS radiances pass another series of quality control checks listed below.

- Check for data rejected in initial QC (Section 5), i.e. check for QC flag bit 7 set and set bit 9
- Reject data over higher terrain for tropospheric channels 7-8 and 20-22 that could "see" the surface in such cases (topography check) and set QC flag bits 9, 18. Over high terrain the surface contribution may be non-zero due to the channels sensitivity to low levels. The height thresholds are listed in Tables 3. The low threshold for channel 7 results in channel 7 being primarily an "open water only assimilated" channel like channels 5-6.
- Check for uncorrected radiances (data QC flag bit 6 not set, see Section 6) and set QC flag bit 11
- O-P (innovation) based rejections (set QC flag bits 9,16)

Channel	**Max model height (m)**
7	250
8	2000
20	2000
21	2250
22	2500

Table 3. Maximum model surface height limits for channel rejection.

The O-P based rejections are outlined below:

- The absolute value of the innovation is compared against a limit defined by a factor ("rogue factor" = 2-4) times the Std(O-P) "errors" found in the *stats_atms_assim* file. If the innovation exceeds this limit, the radiance is rejected.
- Rejection of data for any of channels 1-3 results in automatic rejections for channels 1-6 and 16-17.
- Over open water, if channel 17 Abs(O-P) > 5K, data for channels 17-22 are rejected.

Channel selection is also done at this stage, using information in the "utilize data" (UTIL) column of the file *stats_atms_assim* with current version found in

`/home/scvs400/datafiles/constants/cmda/alt/v3.2.1/statsat`

All data for channels where UTIL=0 are blacklisted by setting QC flag bit 8. Currently channels 1-4 and channel 16 are blacklisted. Note that rejection of channels 5-6 and 17-18 over land or sea-ice is done by the initial QC (Section 5). The channel selection from the QC is summarized in

Table 4, which shows which channels are assimilated over Ocean and which channels are assimilated over Land or Sea-Ice.

The program that does all this is *bgck.atms_inovqc*. All rejected data will have QC flag bits 8, 9 or 11 set, which are the bits the assimilation program (EnVar) uses to screen out rejected data from the analysis.

	Ocean (open water)	**Land or Sea-ice**
Temperature Channels	5-15	7-15 (topo check 7-8)
Water Vapour Channels	17-22	20-22 (topo checked)

Table 4. ATMS channels selected for assimilation.

8. Final thinning

In order not to overwhelm the assimilation system and to provide an appropriate volume of data for the analysis grid, the density of data from all satellites are reduced to a separation of about 150 km. This separation seems to be optimal with the current system, due to the fact that it assumes no correlation of the observational error for radiances and given the rather broad horizontal correlation functions of the background error.

The thinning process for ATMS data is summarized below. A satellite radiance “profile” is defined here as radiance data from multiple channels at given location.

1) Data are separated into time slots, corresponding to each time step of the model background (trial) field. Currently, the time slot delta (dstepobs) is 15 minutes giving a total of 25 time slots in the 6-hour assimilation window.
2) For each time slot, data are grouped into 150 x 150 km square thinning boxes and filtered as described in step (4) below.
3) Complete profiles (data for all channels) are removed in two cases: (1) the number of rejected channels among the assimilatable channels (bit 9 'on' and bit 11 'off') is greater than 80% of the number of assimilatable channels (defined as bit 11 'off') and (2) the profile is located at the extreme left and right edges of the satellite swath (FOVs 1 and 96).
4) Within each box, a priority scheme retains the profile closest to the center of the box. The distance from the center of the box to the chosen profile is limited to 75km.

The thinning program is *bgck.tovsfilt* which is also used for thinning AMSU-A and AMSU-B/MHS data.

9 . Monitoring.

The operational monitoring of ATMS radiances is part of the CMC on-line monitoring system, developed for all observations used in the EnVar assimilation. The address of this web site is the following:

Internal:

http://hpfx.science.gc.ca/~smon400/monitoring/

External:

http://collaboration.cmc.ec.gc.ca/cmc/data_monitoring/

The external site requires a username and password for access that are easily available, by sending a request via e-mail to normand.gagnon@canada.ca

The ATMS monitoring is divided in four parts:

- data reception;
- data quality monitoring;
- data included in the analysis;
- monthly means.

Information is available on the number of ATMS data and their geographical distribution, both on reception and following data thinning. Time series of innovations are also available and their use is mainly to detect any drift in the satellite measurements and/or in the bias correction of the radiances. Maps of 6-hour innovations are available for each satellite, channel and synoptic hour, while monthly means of these are useful in detecting systematic errors in the system, if any should exist.

A few examples are given in Figures 5 and 6. Figure 5a shows an example of the geographical distribution of ATMS data received at CMC and in Figure 5b the distribution of data actually used in the analysis (global run G2) for date July28th , 2019 at 1200 UTC. Figure 6 shows the innovations (O-P) for channel 11 for the same date/time.

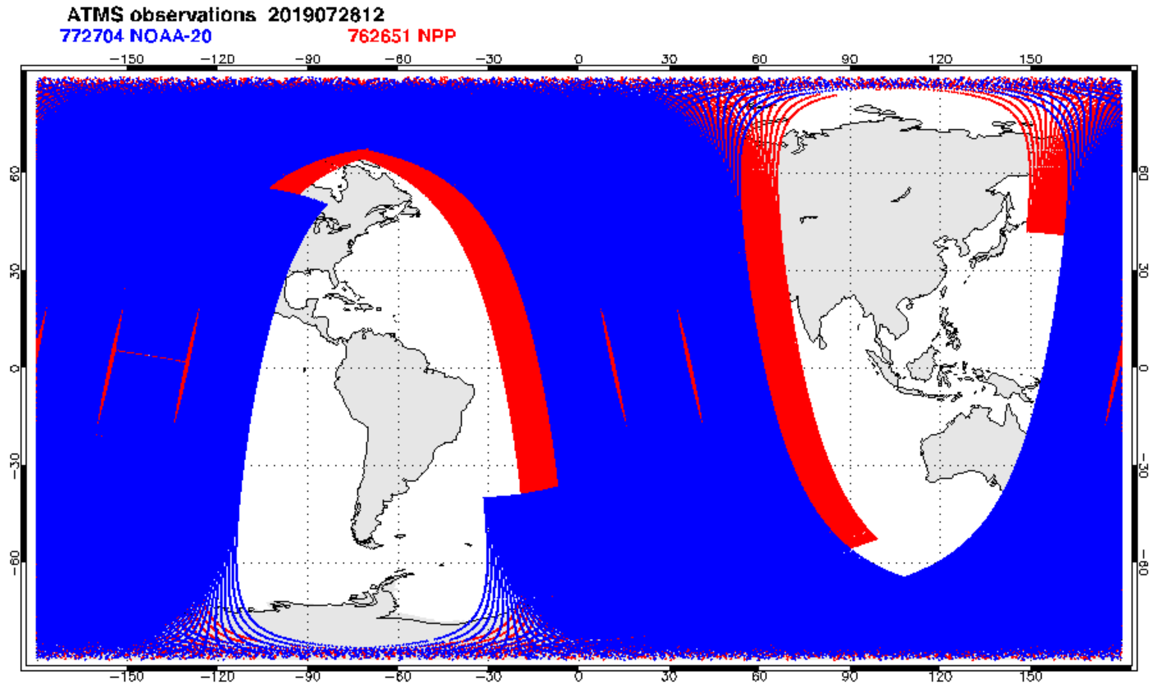

Figure 5a: Distribution map of all ATMS observations received at CMC for 28 July 2019 at 1200UTC.

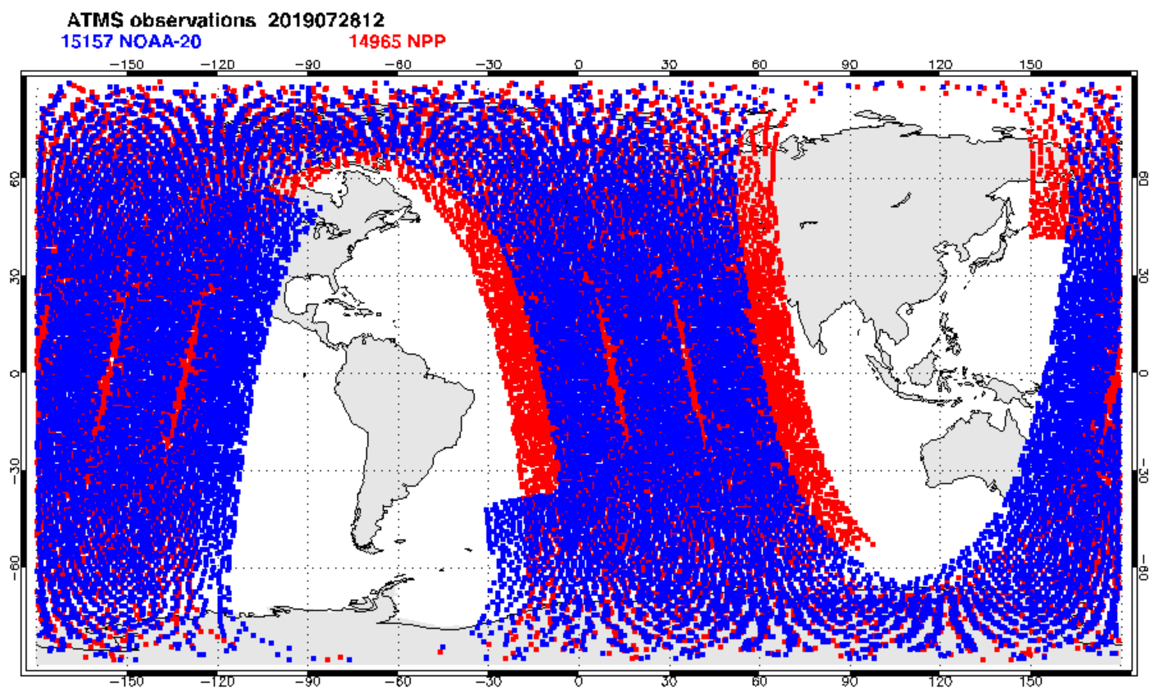

Figure 5b: Same as Fig. 5a but after final thinning (assimilated profiles).

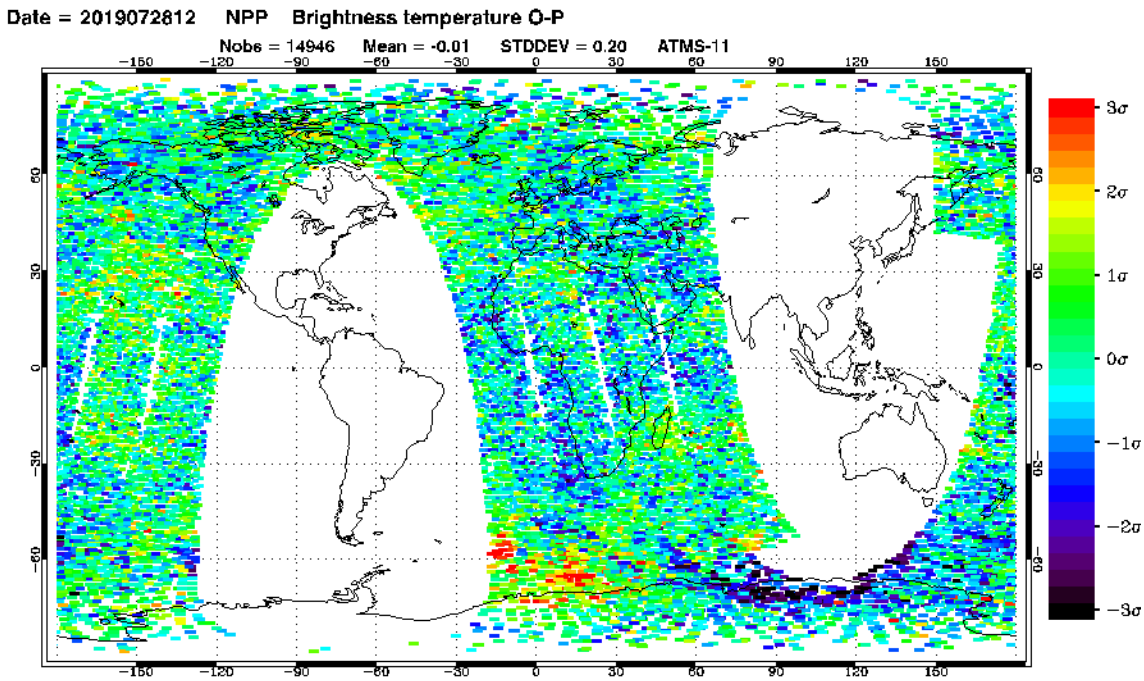

Figure 6: Map of innovation (O-P) values for NPP/ATMS channel 11 brightness temperatures for 28 July 2019 1200UTC. Color values are based on (O-P)/STDDEV, where STDDEV = 0.20K.

10 . References.

11 . Glossary.

AAPP	AVHRR and ATOVS Processing Package
AMSU	Advanced Microwave Sounding Unit
ATMS	Advanced Technology Microwave Sounder
BUFR	Binary Universal Format for Representation [of data]
BURP	Binary Universal Report Protocol
CMC	Canadian Meteorological Centre
EnVar	Hybrid Ensemble-Variational analysis
FGAT	First Guess at Appropriate Time
FOV	Field of view (scan position)
MHS	Microwave Humidity Sounder
NOAA	National Oceanic and Atmospheric Administration
NPP	National Polar-orbiting Partnership
RTTOV	Radiative Transfer for TOVS
SAF	Satellite Application Facility
TOVS	TIROS Operational Vertical Sounder

Appendix A. BURP descriptors for ATMS files (based on BUFR).

NOTE: BURP file code type for ATMS is 192.

Descriptor number	Descriptor
005042	Channel number
012163	Brightness temperature
012233	Brightness temperature correction
001007	Satellite identifier
005040	Orbit number
005043	Field of view number
007024	Satellite zenith angle
008012	Land/sea qualifier (0: land; 1:sea; 2:coast)
013039	Terrain type (0:sea ice; 1:snow on land)
033078-033081	Quality flags
013209	Cloud liquid water (added by bgck.satqc_atms)
013208	Scattering Index (added by bgck.satqc_atms)
025174	Information integer (added by bgck.satqc_atms)

Note that the missing value for burp is -1.

Meaning of the bits in the ATMS Information Integer (element 025174)

Bit	Meaning
0	Open water point away from land/coast/ice
1	Missing Mean 183 GHz
2	Missing cloud liquid water (over open water)
3	Cloud liquid water > low threshold of 0.175 kg/m2
4	Scattering Index > lower troposphere limit
5	Mean 183 GHz < 240 K (extreme dryness)
6	Cloud liquid water > high threshold of 0.200 kg/m2
7	Dryness Index rejection for channel 22
8	Scattering Index > upper troposphere limit
9	Dryness Index rejection for channel 21
10	Sea ice fraction > 0.55 detected
11	Gross error detected in a channel radiance (all channels rejected)