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Title : # AATSR 12 Micron Anomaly Review Board – Final Report

Abstract : This document is the final report from the AATSR 12 micron Anomaly Review Board.

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TABLE OF CONTENTS

AMENDMENT POLICY

This document shall be amended by releasing a new edition of the document in its entirety. The Amendment Record Sheet below records the history and issue status of this document.

AMENDMENT RECORD SHEET

ISSUE	DATE	REASON
1	12 Aug 2013	Initial Issue

1. PREFACE

1.1 Purpose and Scope

This document contains the final report following the investigations of the AATSR 12 micron Anomaly Review Board (**ARB**).

1.2 Structure of the Document

After this introduction, the document is divided into a number of major sections as follows:

2 EXECUTIVE SUMMARY
Provides an overview of the work of the ARB

3 INTRODUCTION
Explains the background and objectives of the ARB

4 PROBLEM RECAPITULATION
A statement of the observed discrepancy

5 DISCARDED HYPOTHESIS AND RATIONALE
The various hypotheses that have been investigated and subsequently discarded as a possible cause of the observed discrepancy

6 POSSIBLE CONTRIBUTING FACTORS
The various hypotheses that have been investigated and, whilst felt unlikely to be a possible cause of the observed discrepancy, cannot be discarded

7 RETAINED HYPOTHESIS AND RATIONALE
The various hypotheses that have been investigated and remain a possibility for the cause of the observed discrepancy

8 RECOMMENDATIONS FOR REPROCESSING AATSR
Provides recommendations from the ARB for the reprocessing of AATSR data

9 RECOMMENDATIONS FOR SLSTR
Provides recommendations from the ARB that should be considered in the SLSTR programme

10 RECOMMENDATIONS FOR USERS
Provides recommendations from the ARB for users of AATSR data

11 CONCLUSIONS
The conclusions drawn by the ARB are set out

12 GLOSSARY
The Glossary contains definitions of acronyms, abbreviations and terms used throughout the document.

Additionally, there are many Appendices associated with this report, covering the presentations made at the meetings that were held and the minutes from these meetings. A full listing of these is given in Annex A but the files themselves are provided separately to this document.

1.3 ARB Participation

The AATSR 12 micron Anomaly Review Board was composed of the following persons:

- Peter Dubock (Independent) – Chair
- Siân O'Hara (Telespazio VEGA) – Secretary
- Jack Abolins (RAL)
- Mike Buckley (Astrium)
- Gary Corlett (University of Leicester)
- Gareth Davies (Telespazio VEGA)
- John Delderfield (RAL)
- Craig Donlon (ESA)
- Mike Fletcher (Astrium)
- Johannes Frerick (ESA)
- Philippe Goryl (ESA)
- Gary Hawkins (University of Reading)
- Hugh Kelliher (Space ConneXions)
- David Llewellyn-Jones (University of Leicester)
- Chris Merchant (University of Edinburgh)
- Chris Mutlow (RAL)
- John Remedios (University of Leicester)
- Roger Saunders (MetOffice)
- Dave Smith (RAL)

2. EXECUTIVE SUMMARY

The Anomaly Review Board (ARB) has considered the available evidence for discrepancies in radiometric measurements between AATSR and ATSR-2 for the 12 µm channels. The ARB is convinced of the existence of these discrepancies and that they are due to AATSR.

The ARB has compared brightness temperatures measured by AATSR and IASI at 12 microns over a wide range of temperatures and for a statistically significant set of data. There are temperature dependent differences which vary from +0.4 K for cold scenes to -0.2 K for hot scenes. The ARB is convinced that these differences are due to bias in the AATSR data.

The ARB has focused on the 12 µm channel but has considered data from the 3.7 µm and 11 µm channels and has not observed such large discrepancies at these wavelengths.

The ARB has considered the possible reasons for a reported temperature measurement anomaly with the 12 µm channel of the AATSR on-board Envisat.

The Board was unable to be absolutely conclusive about the cause of the anomaly but considers that the most likely explanation is a combination of two factors:

1. Changes after launch rendering the non-linearity corrections to the data inappropriate. This effect produces biases that are more pronounced at low scene temperatures.
2. An apparent error in the wavelength calibration of the 12 µm channel. This is of the order of 50 nm. This effect produces biases that are more pronounced at higher scene temperatures.

The ARB has processed a limited amount of data to demonstrate the effect of correcting these two factors on the 12 µm Brightness Temperature discrepancies. Observed dependences on scene Brightness Temperature and Total Column Water Vapour show a significant improvement in comparisons of AATSR's 12 µm channel with IASI and ATSR-2.

The ARB recommends to improve AATSR data, taking into account the non-linearity and the wavelength calibration error, and to reprocess a statistically significant quantity of data. The results should be compared with IASI and ATSR-2. Provided they confirm the expected improvement in measurements all AATSR data should then be reprocessed.

The ARB also recommends that all available ATSR-2 data be processed, so that results from the end of the mission, after failure of the on-board data recorders, are not lost. There are also recommendations in the report regarding calibration for future missions.

Finally the ARB proposes that its results are provided to the AATSR user community together with a timetable for implementing the recommendations.

3. INTRODUCTION

The Advanced Along Track Scanning Radiometer (**AATSR**) was an instrument aboard ESA's Envisat satellite, which was launched on 1 March 2002 and ceased to function on 8 April 2012. The primary purpose of the ATSR series was to provide accurate Sea Surface Temperature (**SST**) measurements calibrated against accurate on-board blackbody measurements. After ATSR-1 this objective was extended with other measurements in the visible. The AATSR was a successor to the highly successful ATSR-1 on ERS-1 and ATSR-2 on ERS-2. The programme will be continued by the Sea and Land Surface Temperature Radiometer (**SLSTR**) on Sentinel 3.

The AATSR was an Announcement of Opportunity instrument funded by the UK Department of Energy and Climate Change (**DECC**) and its predecessors. There was a significant contribution from the Australian Department of Innovation, Industry, Science and Research and its predecessors. Matra Marconi (now part of Astrium) was the Prime Contractor for the instrument. Auspace, which has now ceased trading, provided the part of the Australian industrial contribution to the programme that included manufacture and calibration of the Focal Plane Assembly (**FPA**).

During the mission it became clear that there were discrepancies between temperatures measured by the 12 µm channel of AATSR and those from ATSR-2. Similar discrepancies have been observed between the AATSR 12 µm channel and measurements of SST from other instruments. There have been various unsuccessful attempts to explain these discrepancies. An empirical correction as a function of Total Column Water Vapour (**TCWV**) has been implemented in the processing of SST data for climate [Embury and Merchant, 2012[1]].

Following a recommendation from the AATSR Exploitation Board (**AEB**) and Quality Working Group (**QWG**), it was proposed to convene an Anomaly Review Board (ARB) to consider the differences in signal response which have been consistently observed between the ATSR-2 and AATSR signal channels, particularly, though perhaps not exclusively, in the 12 µm wavelength signal channels of the two instruments.

The ARB is composed of many people with experience of the design, manufacture, calibration and usage of the AATSR under an independent chair. Secretarial services to the ARB were provided by Telespazio VEGA under contract to ESA.

The Terms of Reference of the board are:

1. To review the evidence available for the existence of discrepancies in the thermal-infrared radiometric measurements between the AATSR instrument, currently flying on the Envisat satellite, and the ATSR-2 instrument on ERS-2, particularly in the case of the 12 µm wavelength channels of those instruments;

2. To investigate possible reasons for the observed discrepancies with the aim of identifying the most likely explanation;

3. To advise ESA and DECC on any further investigations that may help to determine the cause of the observed discrepancies;

4. To produce a report on the results of their analysis in a form which could be made available to users and other interested parties, in order that they may correct for the discrepancies.

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[1] Embury, O., and C.J. Merchant, 2012. A reprocessing for climate of sea surface temperature from the along-track scanning radiometers: A new retrieval scheme, Remote Sensing of Environment, 116, 47-61.

The ARB met four times:

1. An initial meeting at RAL on 29 February 2012 (IDEAS-VEG-OQC-MIN-0992) to review evidence of the anomaly and to agree a list of potential causes of the anomaly and a set of Action Items to investigate these.
2. A second meeting at RAL on 23 February 2013 (IDEAS-VEG-OQC-MIN-1192) to review the results of the Action Items and decide which issues were worth pursuing and which could be discarded as potential causes of the anomaly.
3. A third meeting at RAL on 30 April 2013 (IDEAS-VEG-OQC-MIN-1254), which was intended to be the close out meeting of the review, but during which it became clear that some further work was needed.
4. A fourth meeting at the headquarters of Finmeccanica in London on 5 June 2013 (IDEAS-VEG-OQC-MIN-1282) where the ARB agreed that the objectives of the ARB had been achieved and considered a draft of this report. The report was finalised by e-mail consultation amongst the members of the ARB.

This report contains the conclusions of the ARB, and is intended to satisfy the requirements of the Terms of Reference.

4. PROBLEM RECAPITULATION

As part of the early AATSR algorithm verification, a set of AATSR and ATSR-2 data products from the overlap period were examined (see Appendix A.04). The focus was on the infrared Brightness Temperatures (**BTs**). There was a noticeable difference between AATSR and ATSR-2 BTs in the 12 µm channel. This difference could not be explained by simulations of radiative transfer variations (unlike the variations seen for the 3.7 µm and 11 µm channels).

Following the reprocessing of all ATSR data into Envisat-format, another analysis was performed (see Appendix A.05). This again found that there was a systematic discrepancy between AATSR and ATSR-2 BTs in the 12 µm channel.

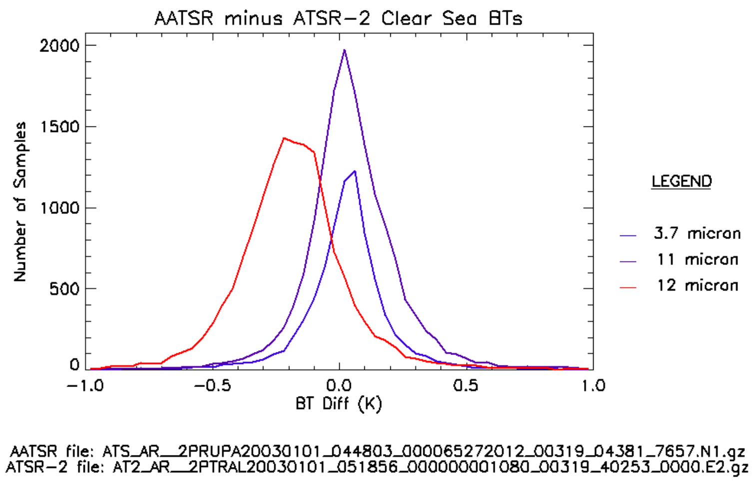

Figure 1: Comparison of AATSR minus ATSR-2 BTs for the nadir view on 1st January 2003

Furthermore, examination of independent validation results indicates that the cause of the unexplained offset is an issue with AATSR, not ATSR-2 (Table 1 and Table 2 in Appendix A.05; slide 6 in Appendix B.02).

A full set of documentation describing the evidence and investigations performed so far was provided to the ARB in advance of the first meeting (Appendices A.01-A.13; also reference the presentations from the meeting, Appendices B.01-B.08). The minutes of this first meeting are provided as Appendix G.01.

Further work was undertaken as a result of the actions arising from the first meeting and as input to the second meeting of the ARB (Appendices C.01-C.10; also reference the presentations from the meeting, Appendices D.01-D.08). The minutes of this second meeting are provided as Appendix G.02.

The discrepancy was found to be consistent at ~ 0.2 K throughout the duration of the AATSR / ATSR-2 overlap period, but there was evidence of variation depending on scene characteristics such as scene temperature (i.e. outside of normal sea surface temperature ranges) and total column water vapour. An example for scene temperature is shown in Figure 2.

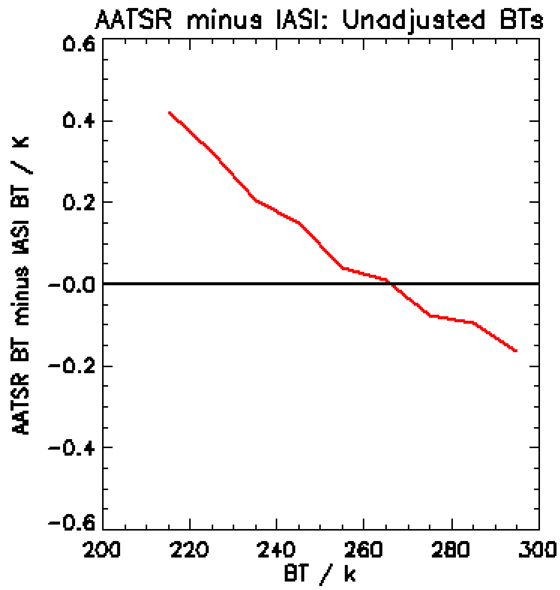

Figure 2: Plot of collocated discrepancies between AATSR and IASI as a function of scene temperature. A strong dependence on scene temperature is observed for the measured discrepancies.

5. DISCARDED HYPOTHESIS AND RATIONALE

5.1 Time Variation

It was considered possible that the measured discrepancy is due to instrument degradation and therefore would change over time.

Comparisons of collocated ATSR-2 and AATSR 10' BTs and SSTs was first reported by Nightingale and Birks for a small set of orbits. They observed an unexplained discrepancy of ~ 0.2 K at 12 μm for clear sky ocean scenes. This analysis was repeated by the University of Leicester, using ATSR-2 data in Envisat format, in addition to an independent validation using drifting buoys and a shipborne in situ radiometer (M-AERI) on data from August 2002 to June 2003, using two orbits from the first day of each month. The offset did not vary noticeably during this period. Results from the University of Leicester analysis are given in Appendix A.05 and Appendix B.02.

The ARB requested that the analysis be extended to cover data from early in the AATSR mission and also to cover data from the end of the ATSR-2 mission. Additional AATSR data was analysed from the commissioning period but it was not possible to analyse late mission ATSR-2 data. The results from this additional analysis are provided in Appendix C.01. Although some variations in the results can be seen, they are most likely seasonal variations due to changing atmospheric conditions and not changes in the instruments.

The discrepancy for clear sky ocean scenes is found to be static and there is no evidence of drift with time (within the limits of this investigation). Note however that there were changes in optical throughput during the life of AATSR and that these changes may contribute towards the bias in measurements of cold scene temperatures (see Section 7.1).

The ARB notes that late mission ATSR-2 data is available only in short segments from the Near-Real Time downlinks used at the end of the ERS-2 mission. The ATSR-2 processor is unable to handle this data, as a result of which it is effectively lost. The ARB strongly recommends that funding be made available to upgrade the processor and process this valuable data, which otherwise would be wasted.

5.2 Geometrical Instabilities

An investigation of solid angle limitations on narrow bandpass filter coatings was performed on the AATSR 12 μm detector channel to assess spectral throughput sensitivity to non-parallel illumination. Spectral tolerances of the filter design, and choice of infrared materials to minimise angle variations were essential prerequisites that were built-in into the succession of ATSR instrument optical designs to minimise sensitivity of wavelength with angle. The use of lead telluride (PbTe) coating material with the highest known refractive index as bandpass cavity layers was specifically incorporated into the multilayer design to maximise the effective index (n^*) of the coating and reduce cone angle sensitivity.

Computational design simulations and experimental assessment of the filter coatings operating under incremental uniformly illuminated cone angle distributions has shown the design to be tolerant to the incident beam geometry between the limits of parallel beam illumination, and < *f*/1 cone angle. Similarly, effects of solid tilt angle provide compliant wavelength displacement at angles beyond the maximum incident beam requirements. This investigation has concluded there is no evidence in support of plausible changes to the optical geometry that would affect the spectral response of the cooled narrow bandpass filter coatings. (Further details are provided in Appendix C.02 and the topic was covered during the second meeting, see Appendix D.01 and Appendix G.02)

5.3 Lookup Table Errors

A potential cause of the observed discrepancy was an error in the calibration, in particular the infrared calibration, as this is the only part that is applied to the channels individually. The algorithm itself was not a potential candidate, as it is common to all channels. The processor documentation (Detailed Processing Model) was checked and found to be in line with the pre-flight calibration algorithm. It was posited that there may have been a coding error but the prototype and operational processors were checked and found to be implemented in the same way. This was presented at the first ARB meeting (see Appendix G.01, with details in Appendix A.13 and Appendix B.06).

Whilst the algorithm and implementations were eliminated as potential causes, it was noted that this did not preclude there having been an error in the creation of the auxiliary file containing the look-up table used in the calibration. Therefore, it was agreed to conduct an independent review of the conversion from blackbody calibration data to the temperature to radiance look-up tables.

Telespazio VEGA undertook this review (see Appendix C.08), comparing the contents of the look-up tables as found in the operational AATSR auxiliary file (ATS_GC1_AX…) with the numbers from the calibration process, supplied by RAL. No significant differences were observed. There were small deviations in the look-up table values (maximum difference of +- 0.000005 %), which could be explained by digitisation differences in the quoted values.

It was concluded that there were no errors in the creation of the look-up tables that were used in the processing of AATSR data and hence this could not be the cause of the observed discrepancy.

5.4 Blackbody Emissivity Calibration Errors

The BlackBody (**BB**) cavity emissivity used in the flight calibration was obtained from calculations using measurements of a sample of the black coating material and modelling to account for the cavity geometry. These values were validated by measurements performed at MSSL by comparisons with a reference blackbody of emissivity > 0.999[2].

As reported in that reference, an error in on-board blackbody emissivity values would give biases in the measured brightness temperatures which would vary with scene temperature. The difference between the calibrated and true brightness temperature, ΔT = BTcal - BTtrue for an emissivity error of - 0.001 are shown in Figure 3. For BTs at the same temperature as the cold BB, the difference is ~ 0.005 K. This is expected because the cold BB is at roughly the same temperature as the fore-optics. As the scene temperature increases to that of the hot BB, the difference is < 0.04 K. The effect is smaller in magnitude to the observed in-flight BT biases but also the opposite sense (i.e. a positive bias not negative).

To achieve a brightness temperature bias of - 0.2 K for a scene at 300 K would require a blackbody emissivity > 1.0 which is not feasible.

[2] *Mason, I.M., Sheather, P.H., Bowles, J.A. and Davies, G., "Blackbody calibration sources of high-accuracy for spaceborne infrared instrument - the Along-Track Scanning Radiometer." Applied Optics, 35, (1996). 629-639*

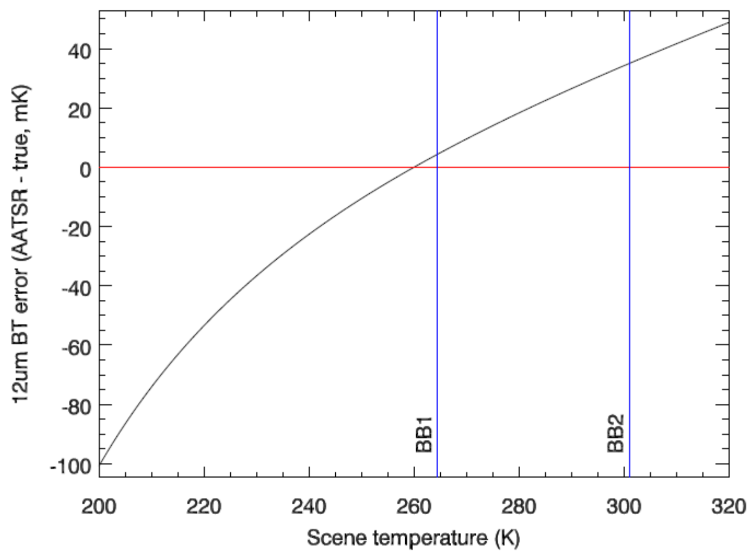

Figure 3: Difference between the calibrated and true brightness temperature at 12 µm, ΔT = BTcal -BTtrue for an emissivity error - 0.001.

As a result of the above it is considered that errors in blackbody emissivity calibration do not contribute to the observed anomaly.

A further conclusion is that the observed anomaly is not due to any physical property of the blackbodies.

5.5 Calibration vs. Real Scene Spectra

It seems possible that incomplete consideration of scene characteristics could explain the measured discrepancies.

To test this hypothesis, AATSR and ATSR-2 Spectral Response Functions (**SRFs**) were applied to IASI spectra recorded over a range of different scene temperatures. The results from these comparisons are provided in Appendix C.04 and Appendix D.03.

Application of the AATSR and ATSR-2 SRFs to IASI spectra did not reproduce the measured discrepancy between AATSR and ATSR-2. However, it was noted that a linear shift of the AATSR SRF of 0.048 µm towards longer wavelengths produced results that were similar to the measured discrepancy over ocean scenes.

It was noted that the observed AATSR minus ATSR-2 differences are in agreement with those observed for AATSR minus IASI differences (at least for the clear sky ocean scenes). Also, it was noted that the observed AATSR minus IASI differences vary with scene temperature. These latter statements are supported by results presented in Appendix A.10, Appendix B.04, Appendix C.05 and Appendix C.06

It was concluded that precise scene characteristics do not explain the anomaly under investigation.

5.6 Spectral Response Shape

The Auspace data for the 12 µm channel is limited to wavelengths up to 13.5 µm because there should be no measurable out of band response. An inspection of the measured spectral responses suggested that the long wavelength response extended beyond 13.5 µm. However measurements on the flight spare did not confirm this.

It was also posited that the suspected calibration error and/or molecular contamination could result in a tilt of the SRF as well as a spectral shift (see Section 7.2).

Signal variations seen in the AATSR visible channels were due to the build-up of water ice and related to the outgassings that were performed throughout AATSR's lifetime[3]. However, since the 12 µm discrepancy does not vary with time, it is unlikely that water ice contamination is the cause.

There were known issues with contamination for Envisat, which was known to be dirtier than ERS-1 and ERS-2, both on the ground and in orbit[4]. An examination of a database of known molecular contaminants revealed that there are substances which would have a greater effect in the 12 µm channel than the other AATSR channels (see Appendix C.09). However, many of these are inconsistent with the observed anomaly; the absorbers presented would act to cut off the long wavelength response, but in order to give rise to the effect seen in the 12 µm channel they would need to cut off the short wavelength. It is possible that there are other substances than those already identified which would have the desired effect.

The source spectral shape is a vital element of the spectral response calibration. The raw data for the background spectra are not available, but can be inferred by comparing the original 'raw' spectral response with the 'corrected' spectral response function, Figure 4. The 'shape' of the background spectrum is assumed to be corrected for the spectral response of the reference detector and drops off quite rapidly between 10 µm to 13 µm. The effect is that the 'raw' spectral response is shifted to lower wavelengths compared to the 'true' spectral response. Hence an error in the background spectrum will affect the measured band centre.

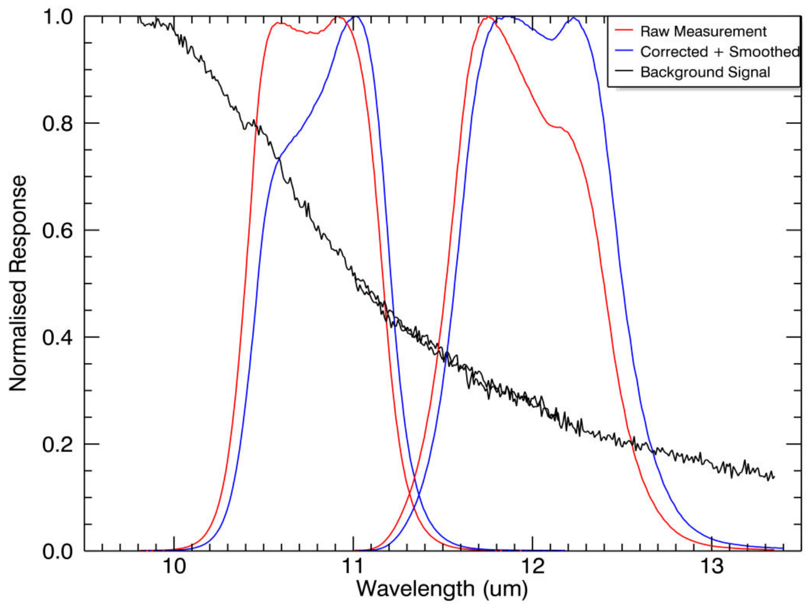

Figure 4: AATSR 10.8 µm and 12 µm spectral response as measured (red), corrected for background signal (blue) and the spectrometer signal.

[3] *Envisat AATSR Instrument Performance – End of Mission Report – PO-TN-RAL-AT-0621*

[4] *TOS-QMC Report: 2004\40*

To investigate these theories, sets of 'modified' spectral responses have been generated (see Appendix E.01). The modifications are within the range of values that are considered to be physically feasible. The modifications are:

- Simulation of out of band long wavelength response (Figure 5, top);
- 'Tilting' the spectral response to simulate a calibration error or molecular contamination. (Figure 5, bottom). The tilts shown in this plot are considered to be a worst case situation.

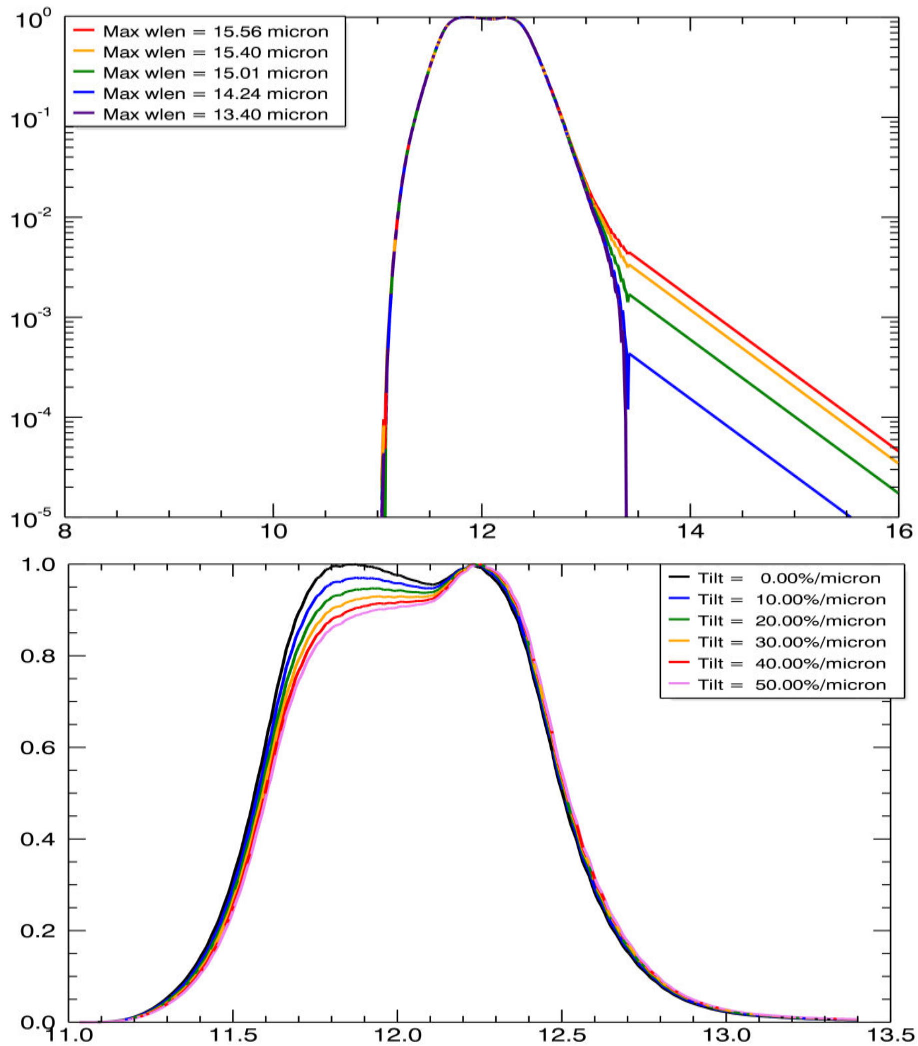

Figure 5: 12 µm spectral response modified with long wavelength response (top) and tilting the background spectrum by n% per micron to simulate the effects of a spectral calibration error or molecular contamination (bottom)

To evaluate the effect of out of band long wavelength response and tilting the spectral response, the following analyses were carried out:

1. Comparison of AATSR vs. IASI BTs with various SRFs as shown in Figure 5;
2. Comparison of AATSR vs. ATSR-2 BTs using IASI radiances with various SRFs as shown in Figure 5;
3. Comparison of AATSR minus ATSR-2 BTs vs. radiative transfer model BTs to ascertain the TCWV dependence with various SRFs as shown in Figure 5.

Results from the three sets of analyses are presented in Appendix E.02, Appendix E.03 and Appendix E.04.

In summary, analyses of the modified SRFs did not reproduce the measured differences from any of the three analysis methods.

6. POSSIBLE CONTRIBUTING FACTORS

6.1 Detector Misalignment

The AATSR FPA field stop is 695 μm square, which creates an image size of 174 μm on the detectors. The flight model (FM02) detectors themselves are 165x175 μm, 11 micron channel and 170x180 μm, 12 micron channel[5].

The effect of the image size closely matching that of the detectors is that any movement of the image across the detector will change the detector output at the vibration frequency i.e. create noise. Ideally, the image should be small compared to the size of the detector so that the image can move around under vibration without modulating the detector output. Clearly the alignment of the detector is also important.

By comparison, the ATSR-1 and ATSR-2 detectors had an active area of at least 190 um square and hence showed no sensitivity to vibration.

Detector size in relation to the field stop size is crucial if susceptibility to vibration induced noise is to be avoided and optical throughput maximised. It also relaxes the alignment requirements placed on the detectors and increases tolerance to launch vibration loads.

It was postulated that detector misalignment could be responsible for reduced optical throughput of the 12 μm channel. This could have occurred since ground calibration was performed, for instance as a result of the launch loads imposed on the FPA. The rationale behind this comes from the history of the FPA and the associated detector procurement (Appendix B.08).

It is reported in Section 7.1 that there is a variable change in optical throughput between on-ground calibration and the first year of operations up to 8.2 %. The ARB considers that misalignment during early orbit lifetime is unlikely. It is however a possible contributing factor to the loss of throughput.

6.2 Temperature Uncertainties During Spectral Calibration

An examination of the FPA thermometer calibration coefficients used during ground testing, suggest that the spectral response measurements were performed 2 K warmer than the in-orbit temperatures[6]. Although this would give a small spectral shift of the order of 10 nm, the magnitude is too small to explain completely the observed anomaly but may be a contributing factor.

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[5] PO-RAL-0023/98

[6] Issues affecting 12 μm Radiometric Calibration – PO-TN-RAL-AT-0562

7. RETAINED HYPOTHESIS AND RATIONALE

7.1 Relationship Between Optical Throughput and Non-Linearity Correction

The AATSR instrument automatically adjusts on-board amplifier gains to compensate for variations in optical throughput. Immediate post-launch gains were a maximum of 2 % higher than pre-launch. Within the first year the gain in the 12 µm channel increased by a maximum of 8.2 % of its pre-launch value as compared to 1.9 % for the 11 µm channel and 3.5 % for 3.7 µm[7]. In fact, there were variations in gain throughout the mission varying from 2 % to 8.2 %. Most of this variation is due to the build-up of water ice that was reduced to background levels by periodic decontamination.

An analysis using the pre-launch calibration test results shows that change in optical throughput would affect the non-linearity in a manner that is consistent with results from sensor inter-comparisons, particularly at low scene temperatures, Figure 6. However, the bias in the range from 250 K to 300 K, which is of concern for SST observations, is < 0.05 K so does not fully explain the observed 0.2 K discrepancy.

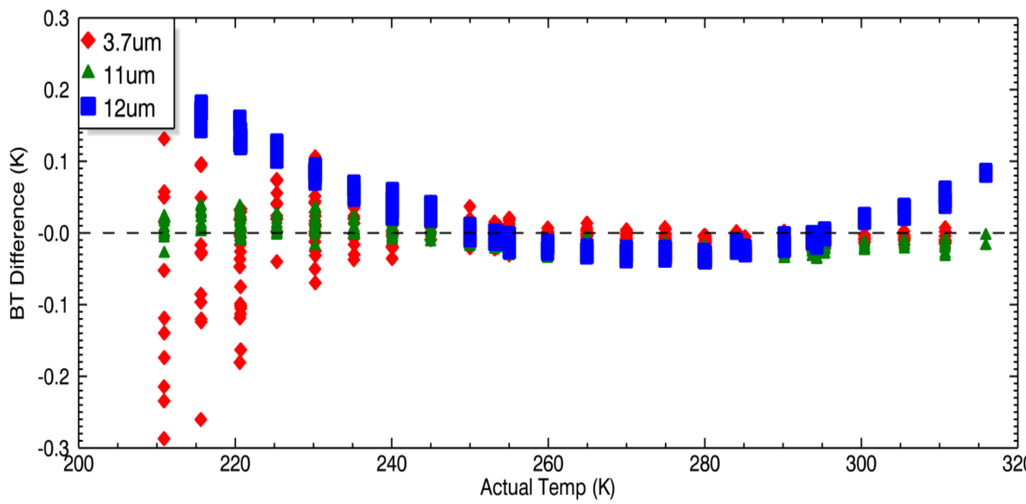

Figure 6: Calibration errors for 3.7 µm (red diamonds), 11 µm (green triangles) and 12 µm (blue squares) adjusted to account for observed change in optical throughput from pre-launch calibration to on-orbit operations.

It is concluded that the reduction in radiometric response due to degradation of the optics (reduction in throughput) affects the non-linearity correction and is a contributing factor to the observed anomaly. For AATSR, the non-linearity is more pronounced at 12 µm than at 11 µm; this does not apply to ATSR-1 and ATSR-2, Figure 7.

Non-linearity is an expected characteristic of the conductive MCT detectors for the 11 µm and 12 µm channels. Essentially, the electron-hole recombination rate increases as the number of carriers (electrons and holes); the result is a fall-off in the detector's response as the photon-flux increases. The non-linearity of the response was characterised as a function of scene radiance for all ATSR sensors during pre-flight calibration [Appendix A.03] to provide a correction.

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[7] *Issues Affecting 12um Radiometric Calibration – PO-TN-RAL-AT-0562*

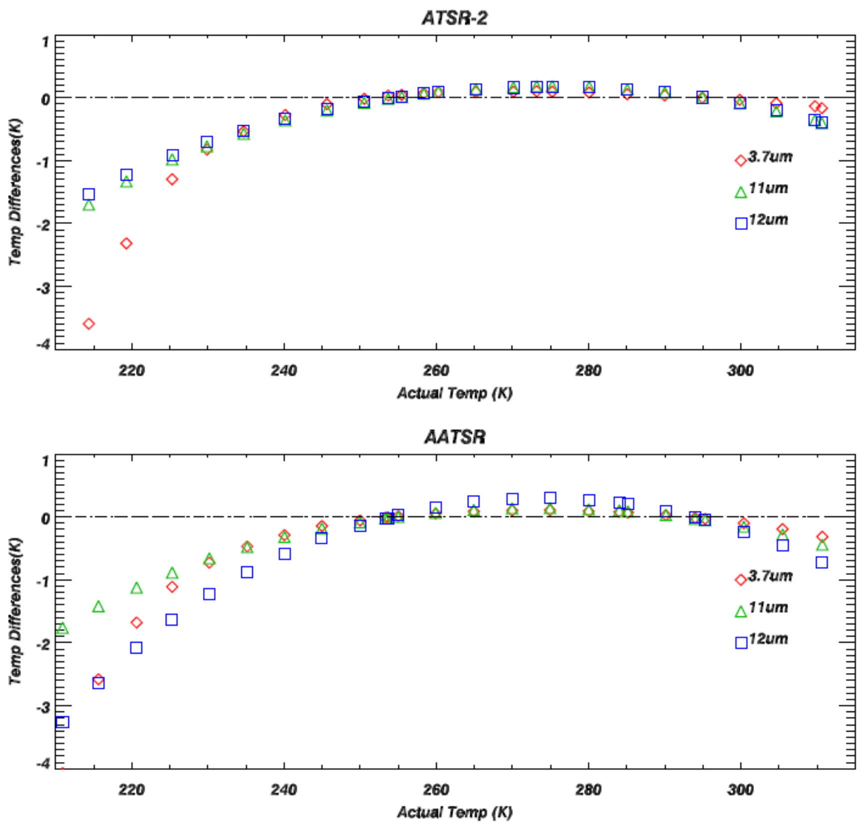


Figure 7: ATSR-2 and AATSR radiometric calibration results without correction for non-linearity.

The non-linearity is more pronounced at 12 µm than at 11 µm, and will have a stronger effect at temperatures lower than the cold BB. In fact, the shape of the difference due to a change in the non-linearity correction (Figure 6) matches the offset seen with the analysis using IASI data (see Appendix E.05).

To evaluate the effect of an incorrect non-linearity correction, the following analyses were carried out:

1. Comparison of AATSR vs. IASI BTs with an additional non-linearity adjustment factor
2. Comparison of AATSR vs. ATSR-2 simulated BTs from IASI radiances with an additional non-linearity adjustment factor
3. Comparison of AATSR minus ATSR-2 BTs vs. radiative transfer model BTs to ascertain the TCWV dependence with an additional non-linearity adjustment factor

Results from the three sets of analyses are presented in Appendix F.02; details on the provided non-linearity adjustment factors are in Appendix F.01.

In summary, the addition of a non-linearity adjustment factor reduces the temperature dependence of the differences between AATSR and IASI and between AATSR and ATSR-2 at low scene temperatures. In this simplified analysis, the comparisons show that an adjustment factor to AATSR of between 9-12 % provides the best agreement with IASI and ATSR-2.

The adjustment factors used for this simplified analysis do not take into account the effects of the actual in-orbit BB temperatures compared with those during on-ground calibration. The ARB expects that when this is taken into account there will be further improvements.

7.2 Error in Pre-Launch Wavelength Calibration

A strong candidate for discrepancies in the AATSR 12 µm brightness temperatures is differences between the in-flight spectral response and that reported by Auspace following on-ground calibration. Since it is not possible to measure the spectral response in flight, it is only possible to infer any likely errors based on the brightness temperature comparisons and an assessment of the likely causes.

The spectral responses for AATSR were measured by Auspace using a 0.25 m focal length monochromator, with commercially available gratings, that was originally used for ATSR-1 and ATSR-2 [Roberts and Petkovic 1993]. The measured signals are a combination of the instrument spectral response function R(λ) and the monochromator spectral radiance L(λ). To obtain the instrument response, the monochromator signal must be characterised using a detector whose spectral response is 'flat' but more importantly is known. For the (A)ATSR spectral calibration a pyroelectric detector was used for the source measurements. The wavelength calibration of the spectrometer was performed using a 'feature filter' with known spectral lines.

Auspace applied a wavelength adjustment to their calibrated spectral response function to account for the particular characteristics of their apparatus. Examination of the data provided by Auspace shows, for example, an adjustment at the peak of the response of the 12 µm detector of + 27 nm for the flight detector (FM-02) and of - 160 nm for the flight spare (FM-01). These measurements were made over a relatively short period of time (from Jan 1996 – Jan 1997[8]). These differences are *prima facie* evidence that the apparatus was not stable.

The spectral response function of the flight spare was recently re-measured by RAL who found that the SRF was shifted by - 50 nm with respect to the calibration reported by Auspace. A physical change is ruled out by the ARB because of the good environmental conditions of storage.

To evaluate the effect of a spectral shift three the following analyses were carried out:

1. Comparison of AATSR vs. IASI BTs with various spectral shifts;

2. Comparison of AATSR vs. ATSR-2 simulated BTs using IASI radiances with various spectral shifts;

3. Comparison of AATSR minus ATSR-2 BTs vs. radiative transfer model BTs to ascertain the TCWV dependence with various spectral shifts.

Results from the three sets of analyses are presented in Appendix D.02 and Appendix D.03 (reference also the input documentation in Appendices C.03-C.06).

In summary, a wavelength shift of the SRF of around 50 nm was able to provide a good representation of the observed TCWV dependence over clear sky ocean scenes for the nadir view, with a small residual remaining at low TCWV amounts for the forward view.

[8] *References: PO-TR-AUS-AT-1014 and PO-TR-AUS-AT-1004*

7.3 Combination of Non-Linearity and Wavelength Calibration Effects

The observed differences between AATSR & IASI and AATSR & ATSR-2 BTs can be reproduced with a high confidence with a combination of corrections for the two effects. This is shown in Figure 8.

Figure 8a shows the measured differences between collocated AATSR and IASI BTs as a function of scene temperature. Figure 8b shows the effect of subtracting a 12 % non-linearity adjustment factor from the measured AATSR BTs and shifting the AATSR 12 micron SRF by 0.048 nm to longer wavelengths before integrating over the IASI radiances. The strong dependence on scene temperature observed in Figure 8a has been significantly reduced in Figure 8b by correcting for both factors.

Figure 8c shows the measured and simulated BT differences between collocated AATSR and ATSR-2 BTs as a function of TCWV. Figure 8d shows the effect of applying the same 12% non-linearity adjustment factor to the AATSR BTs and shifting the AATSR 12 micron SRF prior to running the simulations. The notable disagreement between measurements and simulations observed in Figure 8c has been significantly reduced in Figure 8d by correcting for both factors.

The non-linearity adjustment factors evaluated here act against the effect of the spectral shift. Additional work is necessary to ascertain the optimal combination of non-linearity correction and SRF spectral shift to reproduce the measurements.

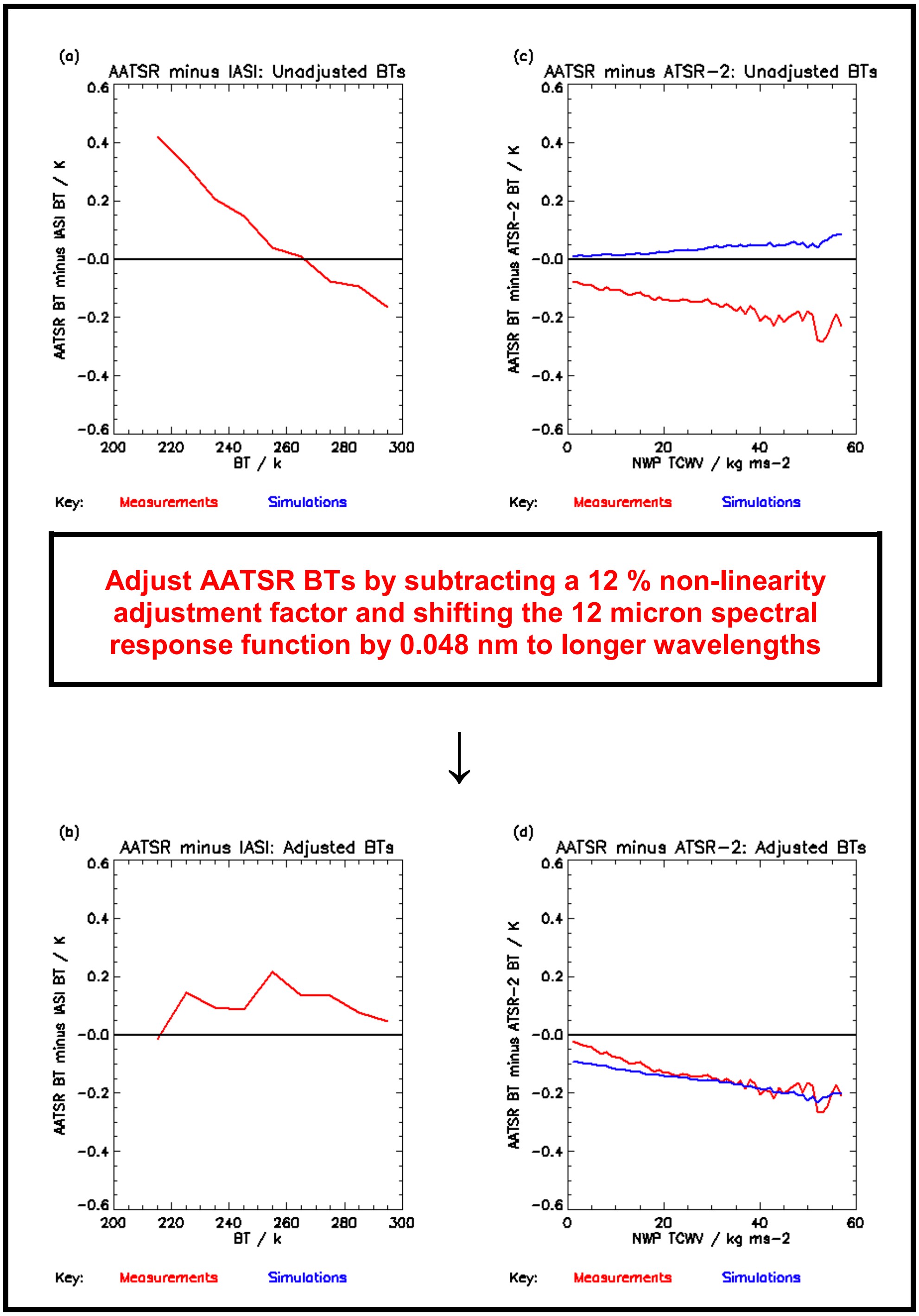


Figure 8: Result of adjusting AATSR BTs to account for the two factors suspected of causing the unexplained discrepancy in measured AATSR 12 microns BTs. See main text for a more detailed description of the figure.

8. RECOMMENDATIONS FOR REPROCESSING AATSR

The ARB has identified that an improved non-linearity correction is needed for the L1b radiometric calibration to reduce the residual errors at low scene temperatures caused by the changes in optical throughput, and if possible to provide a more robust method of correction.

Errors in the spectral response calibration affect the interpretation of the L1 scene brightness temperatures and hence the processing to higher level products. The current L2P products already account for the errors by implementing an empirical adjustment factor to the 12 µm BT values within the processor. For subsequent reprocessing, retrieval coefficients based on the ‘corrected’ spectral response should be considered.

Before implementing any changes to the processing chain, further analysis is needed to:

- Establish the magnitude of the non-linearity incl. possible time variations
- Establish the magnitude of the spectral shift
- Confirm results on a statistically more robust set of data
- Identify the corrections necessary to LUTs and/or algorithms
- Incorporate these corrections into AATSR processing

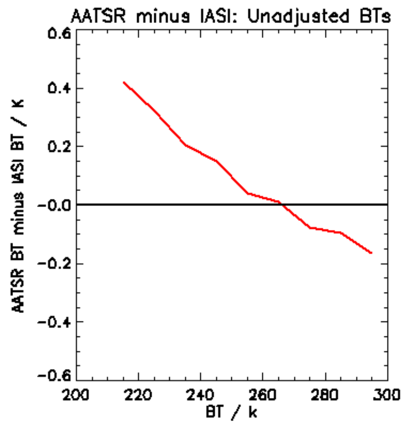
9. RECOMMENDATIONS FOR SLSTR

The significance of non-linearity to optimum performance of the AATSR has been demonstrated to the ARB. Clearly, accurate characterisation and adequate correction in the SLSTR processor is important.

The ARB has not been able adequately to understand the detailed SRF calibration carried out for the AATSR, and as a result is unable positively to confirm the hypothesis of an error in wavelength calibration. This situation should be avoided for SLSTR; the final test report for the SLSTR spectral response calibration should contain sufficient detail to demonstrate the traceability of the flight spectral response profiles. All documents related to the test (as run procedures, descriptions of test setups, description of data analysis methods, instrument configurations, test logs, data sources, calibration certificates etc…) and data acquired during the test, including ancillary data, should be preserved to allow a future reanalysis.

10. RECOMMENDATIONS FOR USERS

Users of AATSR data should be aware that there is evidence of a small temperature-dependent discrepancy in AATSR 12 µm BT measurements. A comparison between AATSR and IASI is shown below.



The discrepancy has been rigorously investigated by a specially convened Anomaly Review Board, which identified the most likely causes and has made specific recommendations for reprocessing to take into account these anomalies (*IDEAS-VEG-OQC-REP-1274*).

As an interim solution, users should take this into account as follows:

1. **If using AATSR Level 1B data (TOA files):**
   a) Adjust the 12 µm brightness temperatures by subtracting the values provided in the Technical Note "Empirical Nonlinearity Correction" (PO-TN-RAL-AT-0562)
   b) For subsequent processing, use the current AATSR 12 µm spectral response function but shifted by 50 nm towards longer wavelengths
2. **If using AATSR level 2 data (NR and AR files):** No direct correction is possible; for highest accuracy SST we recommend the use of the L2P products.

   For users of the NR SST products the effect has been minimised for data produced as part of the V2.1 reprocessing; for earlier versions it is estimated to be between 0.05 K - 0.15 K depending on the extract retrieval used.

   For users of the NR LST it is estimated to be between 0.02 K - 0.35 K depending on the pixel biome classification and scene temperature.
3. **If using the current L2P products:** An empirical adjustment factor to the 12 µm BT values has already been incorporated into the processor

In the future it is expected that the AATSR processor will be modified to take full account of the discrepancies as identified by the ARB.

11. CONCLUSIONS

The ARB has considered the available evidence for discrepancies in radiometric measurements between AATSR and ATSR-2 for the 12 µm channels. The ARB is convinced of the existence of these discrepancies and that they are due to AATSR.

The ARB has compared brightness temperatures measured by AATSR and IASI at 12 microns over a wide range of temperatures and for a statistically significant set of data. There are temperature-dependent differences which vary from + 0.4 K for cold scenes to - 0.2 K for hot scenes. The ARB is convinced that these differences are due to bias in the AATSR data.

The ARB has focused on the 12 µm channel but has also considered data from the 3.7 µm and 11 µm channels and has not observed such large discrepancies at these wavelengths.

The ARB has considered the possible reasons for a reported temperature measurement anomaly with the 12 µm channel of the AATSR on-board Envisat.

The Board was unable to be absolutely conclusive about the cause of the anomaly but considers that the most likely explanation is a combination of two factors:

1. **Changes after launch rendering the non-linearity corrections to the data inappropriate.** This effect produces biases that are more pronounced at low scene temperatures. The non-linearity for the AATSR 12 µm channel is more significant than for the 11 µm channel and for ATSR-1 and ATSR-2. Therefore this channel is more sensitive to errors in the non-linearity correction. The ARB found that for AATSR, optical throughput variations and uncertainties in the spectral response both contribute to non-linearity error.
2. **An apparent error in the wavelength calibration of the 12 µm channel.** This is of the order of 50 nm. This effect produces biases that are more pronounced at higher scene temperatures. The spectral response of the flight model and flight spare FPAs were calibrated by Auspace who applied a wavelength adjustment to their calibrated spectral response function. These adjustments differed widely between flight model and flight spare, suggesting instability in the measurement system. Subsequent re-calibration of the flight spare at RAL shows a wavelength calibration discrepancy with the Auspace measurements. The ARB notes that small wavelength discrepancies particularly at 12 microns produce significant temperature anomalies.

The ARB has processed a limited amount of data to demonstrate the effect of correcting these two factors on the 12 µm Brightness Temperature discrepancies. Observed dependences on scene BT and Total Column Water Vapour show a significant improvement in comparisons of AATSR's 12 µm channel with IASI and ATSR-2.

The ARB recommends to improve AATSR data taking into account the non-linearity and the wavelength calibration error, and to reprocess a statistically significant quantity of data. The results should be compared with IASI and ATSR-2. Provided they confirm the expected improvement in measurements, all AATSR data should then be reprocessed.

The ARB also recommends that all available ATSR-2 data be processed, so that results from the end of the mission, after failure of the on-board recording, are not lost. There are also recommendations in the report regarding calibration for future missions.

Finally the ARB proposes that its results are provided to the AATSR user community together with a timetable for implementing the recommendations.

12. GLOSSARY

The following acronyms and abbreviations have been used in this report.

AATSR	Advanced Along Track Scanning Radiometer
AEB	AATSR Exploitation Board
ARB	Anomaly Review Board
BB	BlackBody
BT	Brightness Temperature
DECC	Department of Energy and Climate Change
FPA	Focal Plane Assembly
QWG	Quality Working Group
SLSTR	Sea and Land Surface Temperature Radiometer
SRF	Spectral Response Function
SST	Sea Surface Temperature
TCWV	Total Column Water Vapour

ANNEX A LIST OF APPENDICES

The Appendices to accompany the report have been grouped into the following sections:

- Appendix A : Documents provided as inputs for the first meeting
- Appendix B : Presentations given at the first meeting
- Appendix C : Documents provided as inputs for the second meeting
- Appendix D : Presentations given at the second meeting
- Appendix E : Presentations given at the third meeting
- Appendix F : Presentations given at the fourth meeting
- Appendix G : Minutes of the meetings

Appendix A - Input documents for 1st ARB meeting

Appendix A.01: Executive Summary: Overview from the AATSR Principal Investigator Team (J. Remedios)

Appendix A.02: IR Radiometric Calibration: AATSR Infra-Red Radiometric Calibration Report (D. Smith)

Appendix A.03: ATSR Calibration and Performance - As published: ATSR infrared radiometric calibration and in-orbit performance (D. Smith et al.)

Appendix A.04: Comparison report: AATSR Algorithm Verification: Comparison of AATSR and ATSR-2 Data (T. Nightingale and A. Birks)

Appendix A.05: ARB Evidence from validation: Evidence of AATSR 12 micron Spectral Response Error from Validation Results (G. Corlett)

Appendix A.06: AATSR 12um Differences TN: Effect of long wavelength response in AATSR filters on brightness temperature measurements (D. Smith)

Appendix A.07: AATSR FPA Spectral Characterisation Report: AATSR FPA Spectral Response Recharacterisation using MSF spectrometer (H. Mortimer)

Appendix A.08: AATSR-ARB-UoE: University of Edinburgh submission to AATSR ARB (C. Merchant and O. Embury)

Appendix A.09: AATSR_ARB-UoE-SRF: Additional contribution to ARB (C. Merchant and S. MacCallum)

Appendix A.10: Intercomparison of AATSR and IASI thermal infra-red brightness temperatures (J. Remedios)

Appendix A.11: ARB_submission_SST overlap analysis: Results from an analysis of ATSR SSTs during the instrument overlap periods (K. Veal and J. Remedios)

Appendix A.12: Radiometric Calibration Checks on Operational and Prototype processors (D. Smith)

Appendix B - Presentations from 1st ARB meeting

Appendix B.01: AATSR 12um Anomaly - Initial Investigations.pdf (D. Smith)

Appendix B.02: ATSR_ARB_Corlett.pdf (G. Corlett)

Appendix B.03: OE_ARC_homogenisation.pdf (O. Embury)

Appendix B.04: SST Impact ARB JJR Final.pdf (J. Remedios)

Appendix B.05: 12um Anomaly - Possible Causes.pdf (D. Smith)

Appendix B.06: AATSR IR Calibration.pdf (D. Smith)

Appendix B.07: AATSR Spectral Response Analysis.pdf (H. Mortimer)

Appendix B.08: ATSR 12um ARB Input.pdf (M. Fletcher)

Appendix C - Input documents for 2nd ARB meeting

Appendix C.01: overlap analysis.pdf (G. Corlett)

Appendix C.02: solid angle limitations.pdf (G. Hawkins)

Appendix C.03: AATSR-ARB-UoE-3 TCWV SRF analysis.pdf (O. Embury)

Appendix C.04: ARB_submission_iasi_atsr_spectsens.pdf (J. Remedios)

Appendix C.05: ARB_submission_IASI_AATSR_mittaz.pdf (J. Remedios)

Appendix C.06: eumetsat_bali_mittaz.pdf (M. Bali, J. Mittaz)

Appendix C.07: AATSR IR Channel Comparisons over Dome-C.pdf (D. Smith)

Appendix C.08: Summary results from ARB Action 4 LUTs.pdf (S. O'Hara)

Appendix C.09: molecular contaminants.pdf (J. Frerick)

Appendix C.10: Issues affecting 12um radiometric calibration.pdf (D. Smith)

Appendix D - Presentations from 2nd ARB meeting

Appendix D.01: ATSR ARB Action 1.pdf (G. Corlett)

Appendix D.02: Investigation of solid angle limitations.pdf (G. Hawkins)

Appendix D.03: ATSR ARB Action 3.1.pdf (O. Embury, S. MacCallum)

Appendix D.04: ATSR ARB Action 3.2.pdf (J. Remedios et al.)

Appendix D.05: AATSR IR Channel Comparisons over Dome-C.pdf (D. Smith)

Appendix D.06: Determine Variation of in-flight gains.pdf (D. Smith)

Appendix D.07: Impact of loss of throughput on non-linearity.pdf (D. Smith)

Appendix D.08: Blackbody Emissivity Issues.pdf (D. Smith)

Appendix D.09: FPA Temperature Calibration Issues.pdf (D. Smith)

Appendix E – Presentations from the 3rd ARB Meeting

Appendix E.01: Spectral Response Modifications.pdf (D. Smith)

Appendix E.02: UoE_longwave.pdf (O. Embury)

Appendix E.03: UoL_longwave.pdf (G. Corlett)

Appendix E.04: UoL_tilt.pdf (G. Corlett)

Appendix E.05: AATSR-IASI_sea_finesplit_200709_ARB.pdf (J. Remedios)

Appendix F – Presentations from the 4th ARB Meeting

Appendix F.01: Non-Linearity Modifications.pdf (D. Smith)

Appendix F.02: ARB3_Actions_2to5.pdf (G. Corlett)

Appendix F.03: Auspace FPA Documents.zip (D.Smith)

Appendix G – Minutes of the ARB Meetings

Appendix G.01: Minutes of the 1st ARB meeting (IDEAS-VEG-OQC-MIN-0992)

Appendix G.02: Minutes of the 2nd ARB meeting (IDEAS-VEG-OQC-MIN-1192)

Appendix G.03: Minutes of the 3rd ARB meeting (IDEAS-VEG-OQC-MIN-1254)

Appendix G.04: Minutes of the 4th ARB meeting (IDEAS-VEG-OQC-MIN-1282)

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