ABB Bomem inc.

ENVISAT-1 GROUND SEGMENT

Michelson Interferometer for Passive Atmospheric Sounding

Reviewed Gain Calibration Scenario

Document Number: **ENVI-BOM-TN-04-0003**

Issue: **1** **Revision:** A

Issue Date: **17 August 2004**

	Function	Name	Signature	Date
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DOCUMENT CHANGE RECORD

Issue	Rev.	Date	Chapter/Paragraph Number, Change Description (and Reasons)
Draft		22 April 2004	First draft
1	-	5 July 2004	Upgrade to consider the fixed OPD at 8.2 cm
1	A	17 Aug. 2004	Upgrade to mention the selected scenario

1. INTRODUCTION

1.1 PURPOSE OF DOCUMENT

The purpose of this note is to evaluate the modification to the gain calibration scenario to adjust it to the actual in-flight performance of MIPAS.

1.2 SCOPE

The document is performed under ESRIN contract no 17124/03/I-OL.

1.3 DOCUMENT OVERVIEW

This document contains description of the current gain calibration scenario with its rational based on RD1 and RD5.

The current situation in-flight is evaluated and modification to the calibration scenario to consider the in-flight operation and to preserve the initially predicted performance is derived and proposed.

The proposed modification to the operation mode (fixed MPD of 8.2 cm) is also evaluated and a new calibrations scenarios are also proposed for that operation mode.

Finally the impact of the offset is also evaluated for comparison with the gain error.

1.4 REFERENCE DOCUMENTS

No	Reference	Issue	Title
RD1	PO-RP-BOM-MP-0001	1C	Performance Analysis Report, 1993.
RD2			IF10 In-flight $NESR_0$ Verification, MIPAS QWG Meeting 3, March 2004.
RD3			MIPAS User Manual
RD4			Technical Note, A Kleinert & F. Friedl-Vallon, IMK, 29 April 2004
RD5	PO-PL-DAS-MP-0031	3-	In-Flight Calibration Plan, DASA, Nov. 1998.

1.5 ACRONYMS

CBB	On-board Calibration Black Body
DS	Deep Space
MIPAS	Michelson Interferometer for Passive Atmospheric Sounding
MPD	Maximum Path Difference
NESR	Noise Equivalent Spectral Radiance
OPD	Optical Path Difference
PDR	Preliminary Design Review
SNR	Signal-to-Noise Ratio
RD	Reference Document
RMS	Root Mean Squared
TBC	To Be Confirmed
TBD	To Be Determined
ZPD	Zero Path Difference

2. CALIBRATION GAIN ERROR

The equation that gives the radiometric gain of MIPAS is (RD3):

$$G = \frac{L_{CBB}}{S_{CBB} - S_{DS}} \qquad (1)$$

L_{CBB} is the theoretical radiance of the onboard calibration blackbody (CBB). S_{CBB} is the raw signal acquired while looking at the CBB. S_{DS} is the raw signal acquired while looking at the deep space (DS). The gain is thus affected by noise the in the CBB and in the DS measurements.

The relative RMS random error on the gain is thus:

$$\delta G_R = \frac{\delta G}{G} = \frac{\sqrt{\delta S_{CBB}^2 + \delta S_o^2}}{S_{CBB} - S_{DS}} \qquad (2)$$

Where δS_{CBB} is the noise in the CBB measurements and δS_o is the noise in the deep space measurement. These noises can be “calibrated” into NESR by applying the gain to them:

$$NESR = G\delta S \qquad (3)$$

The relative gain error can thus be rewritten as:

$$\delta G_R = \frac{\delta G}{G} = \frac{G\sqrt{\delta S_{CBB}^2 + \delta S_o^2}}{G(S_{CBB} - S_{DS})} = \frac{\sqrt{NESR_{CBB}^2 + NESR_o^2}}{L_{CBB}} \qquad (4)$$

Because the gain is multiplicative in the calibration equation, the contribution of the gain error on the total radiometric error is equal to the relative gain error.

2.1 SCENARIO PROPOSED AT PDR

The current calibration gain scenario is based on RD1. It is based on the predicted SNR at 2410 cm^{-1}. The expected SNR at a resolution of 0.025 cm^{-1} and at a wavenumber of 2410 cm^{-1} is 0.266. Resolution reduction and coadditions were called for to bring the SNR to 40 in order to achieve a a contribution due to the gain on the RMS radiometric accuracy of 2.5%. Resolution is degraded from 0.025 cm^{-1} to 4 cm^{-1} and the number of coadditions proposed (for CBB and DS) is 142. By this way, the SNR of a single calibration measurement is increased from 0.266 to 40:

$$SNR = 0.266 \times \sqrt{\frac{4}{0.025}} \times \sqrt{142} = 40$$

It was further realised that this number is not sufficient since the deep space measurements also contribute. It was also decided to add a little margin. In RD5, it was proposed to use 300 CBB and 300 DS measurements per direction to determine the radiometric calibration gain. With this number of coadditions, the initial SNR is increased from 0.266 to 58.3:

$$SNR = 0.266 \times \sqrt{\frac{4}{0.025}} \times \sqrt{300} = 58.3$$

The total contribution is the RSS of the DS and CBB contributions, supposed equal so that the total contribution to the radiometric error is:

$$\delta = \sqrt{\left(\frac{1}{58.3}\right)^2 + \left(\frac{1}{58.3}\right)^2} = 2.4\%$$

The total number of calibration measurements is 1200: 300 DS and 300 CBB per direction. The calibration data is acquired at a resolution of 0.25 cm^{-1} and the resolution is further degraded to 4 cm^{-1} by removing points in the interferograms.

At the time of redaction of RD1, the guaranteed $NESR_0$ was 3.5×10^{-9} W cm^{-2} sr^{-1} cm for a resolution of 0.025 cm^{-1} (RD1, Figure B3).

At time of redaction of RD1, the temperature of the CBB was 220 K.

2.2 CURRENT IN-FLIGHT SITUATION (MPD = 20 CM)

The $NESR_0$ at 2410 cm^{-1} measured in flight is 5.8×10^{-9} W cm^{-2} sr^{-1} cm at a resolution of 0.025 cm^{-1} (RD2).

We do not have an evaluation of the NESR when MIPAS is looking at the CBB but we can use $NESR_T$ as an approximation. The $NESR_T$ at 2410 cm^{-1} is 6×10^{-9} W cm^{-2} sr^{-1} cm at a resolution of 0.025 cm^{-1} (RD4).

The operational temperature of the CBB is close to 238 K.

The duration of a scan at a resolution of 0.25 cm^{-1} is 0.4 s. The turn around time is about 0.45 s. Acquiring 300 calibration DS and 300 CBB measurements at a resolution of 0.25 cm^{-1} thus takes about 510 seconds per direction for a total of 1020 seconds.

However, the proposition to reduce the resolution of the calibration data to 4 cm^{-1} by processing was forgotten along the way; it was not flow-downed to the ground segment and was never implemented. This omission means that the current impact of the noise in the calibration data on the radiometric accuracy is 4 time worst than expected if everything else remains as expected.

Considering that the actual $NESR_0$ and the temperature of the CBB are different from the predicted values at the time of the definition of the calibration scenario, and considering the fact that the resolution of the calibration data is not reduced as expected, the number of CBB and DS measurement must be recomputed.

The NESR is inversely proportional to the spectral resolution ($\Delta\sigma$) and the to the square root of the integration time (t) and number of coadditions (N). For a system with constant sweep velocity, the NESR is inversely proportional to the square root of the spectral resolution:

$$NESR \propto \frac{1}{\Delta\sigma\sqrt{N}\sqrt{t}} \propto \frac{\sqrt{\Delta\sigma}}{\sqrt{N}\,\Delta\sigma} \propto \frac{1}{\sqrt{N\,\Delta\sigma}} \qquad (5)$$

We can apply equation (5) into equation (4) and estimate the current relative error of the gain:

$$\delta G_R = \frac{\sqrt{\frac{\Delta\sigma_o \, NESR_{CBB}^2}{N_{CBB}\,\Delta\sigma} + \frac{\Delta\sigma_o \, NESR_o^2}{N_{DS}\,\Delta\sigma}}}{L_{CBB}} \qquad (6)$$

where:

$NESR_0$: in-flight $NESR_0$ at 2410 cm^{-1} (5.8 nW cm^{-2} sr^{-1} cm)

$NESR_{CBB}$: in-flight NESR at 2410 cm^{-1} while looking at the CBB (taken as $NESR_T$ = 6 nW cm^{-2} sr^{-1} cm)

L_{CBB}: in flight radiance of calibration target at 2410 cm^{-1} (7.8 nW cm^{-2} sr^{-1} cm)

$\Delta\sigma$: in-flight resolution of calibration measurements (0.25 cm^{-1})

$\Delta\sigma_o$: initial resolution of NESR acquisition (0.025 cm^{-1})

N_{CBB}: number of CBB acquisitions (300)

N_{DS}: number of DS acquisitions in gain (300)

Placing the above values into (6) gives an error of 1.95% at 2410 cm^{-1}, which is below the budgeted value. Using only 184 DS and 184 CBB measurements per direction is sufficient to makintain the relative RMS gain random error to 2.5%.

300 DS and 300 CBB measurements per direction are acquired for each gain set, for a total of 1200 interferograms per set. The interferograms are acquired at a resolution of 0.25 cm^{-1} and it takes about 0.4 s + 0.45 s of turn around per interferogram. The total time required to build a gain set is thus 1020 seconds.

2.3 NEW IN-FLIGHT MODE (MPD = 8.2 CM)

Considering the recent problems encountered by MIPAS, a solution that has been proposed is to reduce the total optical path difference of the instrument to 8.2 cm compared to the initial 20 cm. Furthermore, the OPD will be fixed and acquisition at reduced OPD for calibration will not be allowed. The integration time for a single acquisition becomes 1.64 seconds.

Assuming that $N_{DS} = N_{CBB}$ (a reasonable assumption since $NESR_T$ and $NESR_0$ are almost identical at 2410 cm^{-1}), we can invert equation (6) and find the required number of coadditions to achieve an error of 2.5% as initially budgeted:

$$N = \frac{\Delta\sigma_o \left(NESR_{CBB}^2 + NESR_o^2\right)}{\Delta\sigma \left(L_{CBB}\,\delta G_R\right)^2} \qquad (7)$$

We also suppose that the contribution of the offset has not changed in the new operation mode and that $NESR_T$ and $NESR_0$ can be scaled by the square root of the resolution. Note that this assumption is not true if the calibration scenario is not changed (see Section 3).

Using $\Delta\sigma$ = 0.061 cm^{-1} in equation (7), we find that N must be at least 751 per direction for DS and for CBB measurements. The total acquisition time for a gain set is thus 3214 seconds, including the turn around time.

In the initial mode, one gain set took 1020 seconds. Science acquisition took 4 seconds. One gain set was thus equivalent to 255 science acquisitions. Assuming that this proportion is still acceptable, the number of coadditions can be 63 per direction and per target. We can determine at which resolution the calibration data must be reduced, by isolating $\Delta\sigma$ in equation (7):

$$\Delta\sigma = \frac{\Delta\sigma_o \left(NESR_{CBB}^2 + NESR_o^2\right)}{N\left(L_{CBB}\,\delta G_R\right)^2} \tag{8}$$

By inserting the appropriate values, one finds that the resolution of the calibration measurements must not be finer than 0.73 cm^{-1} at 2410 cm^{-1}. Since the OPD is now fixed, the reduction of resolution can be achieved by removing points in the calibration interferograms. This resolution is equivalent to a MPD of 0.74 cm.

Another possibility, is to keep the total time allocated to the acquisition of the gain set to 1020 seconds as before. This time is equivalent to 488 calibration measurements, or 122 per target and direction. In that case the resolution of the calibration measurements must not be finer than 0.375 cm^{-1} at 2410 cm^{-1}.

IF16 showed that the channelling generates artefacts at 1 cm of OPD on both sides of the ZPD in all bands (see Figure 1). To preserve the channelling information in the calibration, the resolution of the calibration data should not be degraded to less than about 0.45 cm^{-1}. At this resolution, 101 measurements per target and per side are required to maintain the relative error to 2.5% at 2410 cm^{-1}. Repeating the characterization test IF11 will tell if this resolution is acceptable or not.

Other possibilities, include accepting more error at 2410 cm^{-1}, having gain resolution different for the various bands, etc. RD4 presented one such possibility.

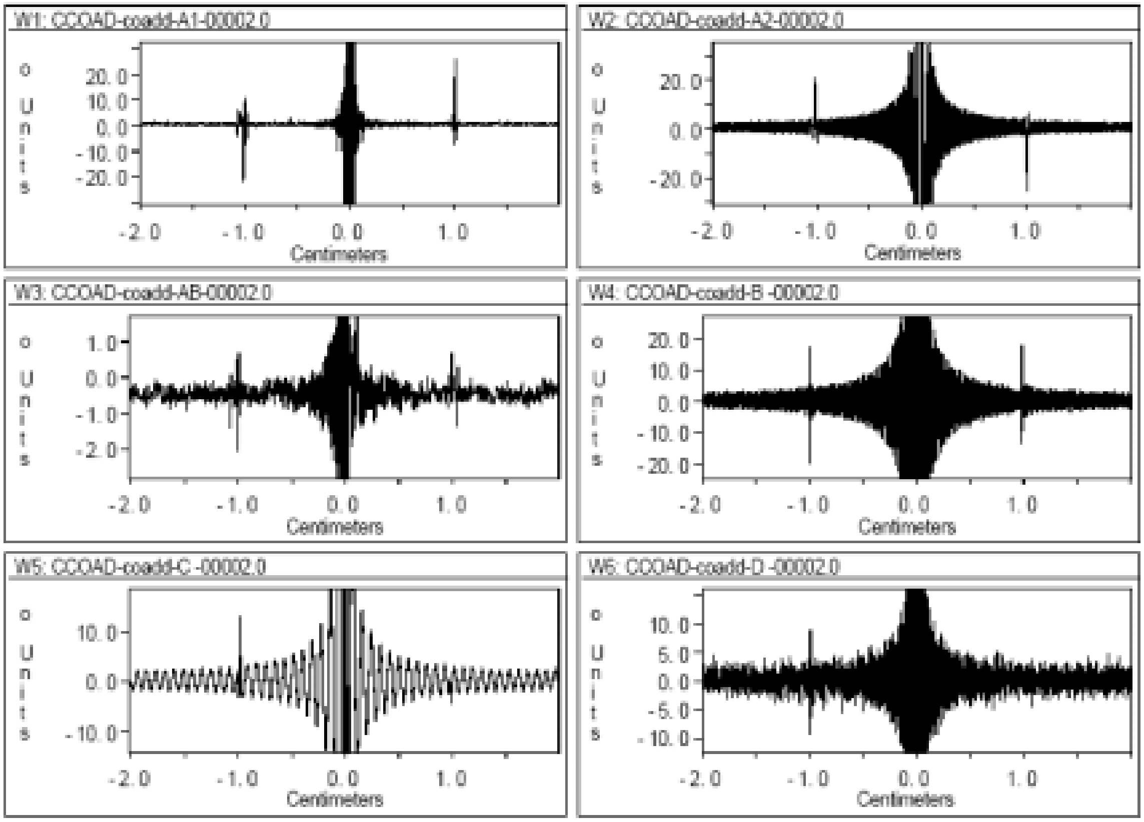

Figure 1: Results from IF16 showing channeling artifacts in interferograms

The required number of calibration measurements is driven by the short-wave end of band D. For the other wavenumbers, the radiometric error is much less as Figure 2 shows. For this figure, the value of $NESR_0$ given by IF10 (RD2) and the $NESR_T$ spectra given in RD4 were used (see Table 1). The figure shown is for the new operation mode (MPD=8.2 cm) with the resolution of the calibration data reduced to 0.45 cm^{-1}.

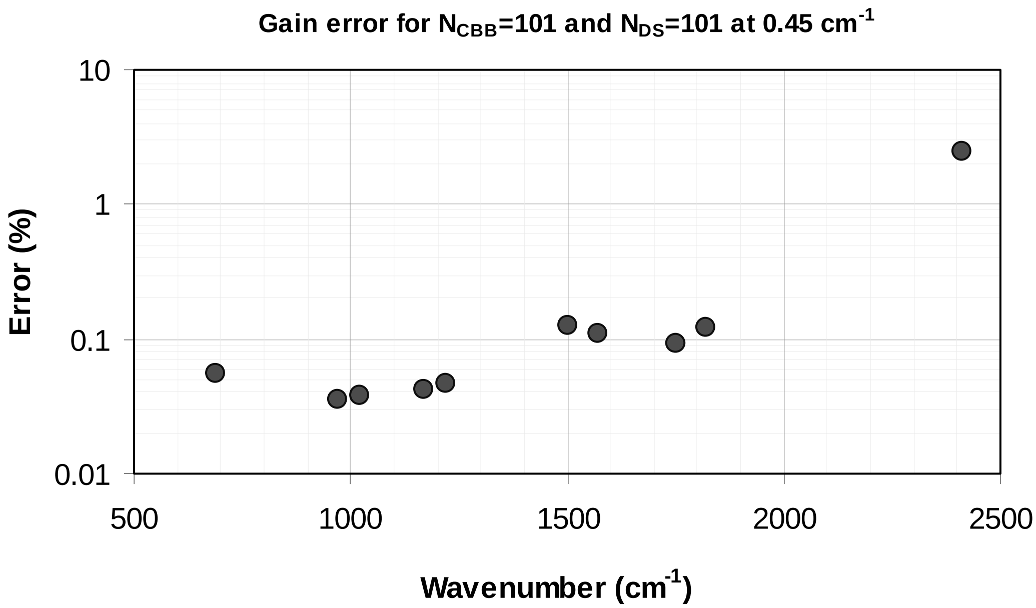

Figure 2: Radiometric error for the new operation mode and calibration data at 0.45 cm^{-1}

Table 1: NESR values at a resolution of 0.025 cm^{-1}

σ	$NESR_0$	$NESR_T$
cm-1	W m^{-2} sr^{-1} cm	W m^{-2} sr^{-1} cm
690	1.0×10^{-3}	1.0×10^{-3}
970	2.5×10^{-4}	4.0×10^{-4}
1020	1.5×10^{-4}	4.0×10^{-4}
1170	1.5×10^{-4}	2.5×10^{-4}
1220	1.2×10^{-4}	2.4×10^{-4}
1500	1.5×10^{-4}	2.0×10^{-4}
1570	3.0×10^{-5}	1.6×10^{-4}
1750	4.0×10^{-5}	5.0×10^{-5}
1820	4.0×10^{-5}	4.7×10^{-5}
2410	5.8×10^{-5}	6.0×10^{-5}

$NESR_0$ comes from RD2. $NESR_T$ comes from RD4. These values have been measured at a resolution of 0.025 cm^{-1}.

2.4 SUMMARY

The table below presents the cases studied. Three scenarios are proposed for the new in-flight operation mode. They represent but a few of the possibilities.

Table 2: Scenario for the acquisition of the calibration gain data

Parameter	**Expected at PDR (1993)**	**In-flight (2004)**	**New in-flight mode**	**New in-flight mode**	**New in-flight mode**	**New in-flight mode**	**New in-flight mode**
Science MPD	20 cm	20 cm	8.2 cm	8.2 cm	8.2 cm	8.2 cm	8.2 cm
CBB temperature	220 K	238 K	238 K	238 K	238 K	238 K	238 K
$NESR_{CBB}$ (nW cm^{-2} sr^{-1} cm)	?	6	3.8	3.8	3.8	3.8	3.8
$NESR_0$ (nW cm^{-2} sr^{-1} cm)	3.5	5.8	3.7	3.7	3.7	3.7	3.7
Resolution of acquired calibration data	0.25 cm^{-1}	0.25 cm^{-1}	0.061 cm^{-1}	0.061 cm^{-1}	0.061 cm^{-1}	0.061 cm^{-1}	0.061 cm^{-}
Downgraded resolution of calibration data	4 cm^{-1}	0.25 cm^{-1}	0.061 cm^{-1}	0.73 cm^{-1}	0.36 cm^{-1}	0.45 cm^{-1}	0.305 cm^{-1} 1.83 cm^{-1} for Band D
Other parameters affecting SNR	-	Assumed as PDR	Assumed as PDR	Assumed as PDR	Assumed as PDR	Assumed as PDR	Assumed as PDR
Number of CBB measurements required per direction	300	184	751	63	122	101	100
Number of DS measurements required per direction	300	184	751	63	122	101	100
Total number of calibration measurements	1200	736	1502	272	508	404	400
Total spent on one calibration set	1020 s	626 s	6278 s	526 s	1020 s	844 s	836 s
Notes	Original plan (obsolete)	To maintain accuracy with planned in-flight mode (obsolete)	No post-acquisition reduction of resolution	Same ratio of calibration time over science time as initially planned	Same calibration time as initially planned	Maximum resolution reduction to preserve channeling information	Scenario proposed by IMK. Gain error is 1.25% at 2410 cm^{-1}

3. CALIBRATION OFFSET ERROR

The calibration equation of MIPAS is:

$$L = G \times \left(S - S^{*}_{DS}\right) \qquad (9)$$

where S_{DS}* is the deep space measurement used to estimate the offset. Note that this DS measurement is different from the one used in the computation of the gain, equation (1); it does not contain the same number of coadditions and it is not measured at the same frequency.

The total noise in L will be:

$$NESR_T = G \times \sqrt{\delta S_T^2 + \left(\delta S^{*}_{DS}\right)^2} \qquad (10)$$

The contribution of the offset to the total noise will be greater when the instrument is looking at deep space. In that condition equation (10) can be re-written as:

$$NESR_o = G \times \sqrt{\left(\delta S_{DS}\right)^2 + \frac{\Delta\sigma\left(\delta S_{DS}\right)^2}{\Delta\sigma_{DS} N^{*}_{DS}}} \qquad (11)$$

Where δS_{DS} is the noise in a single deep space measurement. N_{DS}* is the number of coadded DS measurement in the offset. $\Delta\sigma_{DS}$ is the resolution of the DS measurement in the offset. $\Delta\sigma$ is the resolution of the science measurements. The left-side part of the equation under the square root of (10) is the noise in the scene; the right side part is the noise in the offset. The fraction of the noise added by the offset is:

$$\frac{\sqrt{\left(\delta S_{DS}\right)^2 + \frac{\Delta\sigma\left(\delta S_{DS}\right)^2}{\Delta\sigma_{DS} N^{*}_{DS}}} - \delta S_{DS}}{\delta S_{DS}} = \sqrt{1 + \frac{\Delta\sigma}{\Delta\sigma_{DS} N^{*}_{DS}}} - 1 \qquad (12)$$

In the original operation mode: N_{DS}* =3. $\Delta\sigma_{DS}$ =0.25 cm^{-1}. $\Delta\sigma$ = 0.025 cm^{-1}. Replacing these values in (12), we find that the contribution of the offset to the total noise is 1.65%.

In the operation mode with the MPD fixed at 8.2 cm, $\Delta\sigma_{DS}$ =0.061 cm^{-1} and $\Delta\sigma$ = 0.061 cm^{-1}. The contribution of the offset is 15.5%. To reduce the contribution of the offset back to 1.65% as originally planed, would require that 30 DS measurements be coadded to estimate the offset.

It is also possible to consider the contribution of the offset in terms of radiometric accuracy with respect to the scene (as for the gain) rather than with respect to the total NESR. This gives a better representation of the accuracy impact of the offset on the calibrated radiance. The relative radiometric error due to the offset is:

$$\frac{\delta L}{L} = \frac{\delta S^*_{DS}}{\left(S - S^*_{DS}\right)} = \frac{G}{G}\frac{\delta S^*_{DS}}{\left(S - S^*_{DS}\right)} = \frac{NESR_{DS}}{L} = \frac{NESR_o}{L\sqrt{N^*_{DS}}} \qquad (13)$$

where N_{DS}* is the number of coadded DS measurements to estimate the offset.

In the current plan, N_{DS}* is equal to three. In the proposed operation mode with MPD of 8.2 cm, $NESR_0$ will be approximately 3.7 nW cm^{-2} sr^{-1} cm at 2410 cm^{-1}. For a scene at 225 K, the radiance at 2410 cm^{-1} is 3.4 nW cm^{-2} sr^{-1} cm. The radiometric error due to the offset will thus be 63% (RMS). Obviously, the offset scenario will have to be reviewed also. By comparison, with the initial operation mode, the error due to the offset was 30% (RMS) with respect to a scene at 225 K.

In order to reduce the effect of the offset to about the same as the gain or 2.5%, about 1895 DS measurements at 0.061 cm^{-1} of resolution would be required. If the resolution of the DS measurements is reduced by the ground segment, the number of measurements will be proportionally less.

4. CONCLUSION AND SUMMARY

The calibration gain plan of MIPAS was updated to consider the in-flight performance. The new number of coadditions required to preserve the relative random gain error were computed.

With the initial operation mode with calibration data acquired at 0.25 cm^{-1}, the required number of DS and CBB measurements are 184 each per direction, to maintain the gain error to 2.5% (RMS).

With the new operation mode with calibration data acquired at 0.061 cm^{-1}, the required number of DS and CBB measurements are 751 each, per direction, to maintain the gain error to 2.5% (RMS).

If the resolution of the calibration data is reduced by the ground segment by truncating the interferograms, the number of conditions is reduced. For instance, if the resolution of the calibration data is reduced to, 0.23 cm^{-1}, just enough to preserve the first channelling artefact, only 200 DS and 200 CBB measurements per direction are required. This scenario is just one of the many possibilities.

The impact of the offset was briefly estimated. If the plan is not changed, it is estimated that the error due to the offset will be around 63% (RMS) at 2410 cm^{-1} with the new operation mode at 8.2 cm of OPD and with respect to a scene at 225 K. In comparison, the impact of the gain error is negligible.

As of August 2004, the retained scenario for the computation of the gain is 200 coadded gain measurements and 200 coadded deep space measurements. The resolution is further degraded to 0.305 cm^{-1} for bands A, AB, B and C and to 1.83 cm^{-1} for band D. This roughly preserves the initially planned performance except in band D where the error due to the gain is 1.25 % at 2410 cm^{-1}.

As of August 2004, the retained scenario for the offset computation is 6 coadded deep space measurements. The resolution is further degraded to 0.305 cm^{-1} for bands A, AB, B and C and to 1.83 cm^{-1} for band D. At a wavenumber of 2410 cm^{-1}, the impact of the offset is thus 0.3% of the total NESR or 8% of a scene radiance at 225 K.