2007-01-3162

The AMS Star Tracker thermal qualification overview

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ABSTRACT

Four different thermal-vacuum tests were performed on AMICA Star Tracker (AST) in the period March-July 2006 in the space simulator of the SERMS laboratory in Terni-Italy. Each of these tests was designed to verify different AST camera design features. The *Thermal Balance* test was conceived to validate the thermo-elastic model of the instrument and the active and passive thermal control subsystems. The *Thermal Vacuum Cycling* test was conceived to validate the AST electronics operative and survival temperature limits under vacuum conditions. The worst hot and cold operative and survival limits of the lens and filters in the AST optical system were assessed by means of the *"Sun in the lens"* and *Lens Cold* tests.

INTRODUCTION

The Alpha Magnetic Spectrometer AMS-02 is a particle physics detector that will be installed on the International Space Station (ISS). AST developed by CARSO and INFN Roma1, will provide real-time the source direction of the particles detected by the silicon tracker detector. The high accuracy requested for star tracker measurements imposes demanding specifications on the system design. The temperature, the mechanical and the thermo-elastic behaviour were predicted by analysis performed at INFN Rome and validated by tests. In *Thermal Vacuum Cycling* test the AST electronics and the CCD (mounted on an Aluminum alloy fixture) were subjected to eight thermal cycles between the worst hot (85°C) and cold (-45°C) temperature limits during ~ 10 days. The CCD was oriented toward a transparent window in order to point to a light spot used for functional tests. In *Thermal Balance* test all the QM AST (structure and electronics) was exposed to the worst hot (76°C) and cold (-40°C) thermal environments foreseen during the AMS-02 flight. The stability of the lens axis orientation was verified by means of a dedicated Alignment Monitoring Equipment. In the *"Sun in the lens"* test all the QM AST (structure and electronics) was exposed to the same worst hot (76°C) thermal environments of Thermal Balance, but with a QTH lamp in addition simulating the Sun directly in the lens. In the *Lens Cold* test, the lens and the filter of AST were subjected to a constant temperature of -40°C. Details on the test design and conduction will be reported, as well as main results in what concerns the AST thermal properties.

AMS-02 AND AST

AMS-02

The AMS-01 flew in space in June of 1998 aboard the Space Shuttle Discovery. AMS-02 [1] is a complete particle detector to be flown for at least three years on-board the ISS that is led by Nobel laureate Samuel Ting of the Massachusetts Institute of Technology (MIT). The launch is scheduled on the Utilization Flight #4.1 (UF4.1) of the Space Shuttle to the ISS. The 6900 kg AMS-02 payload is designed and constructed by an international team of over 450 physicists and engineers from over 50 institutions and companies in 16 countries. A picture of all the AMS-02 detectors (without mechanical support structure) can be seen in Fig. 1. This unique scientific mission of exploration seeks to understand fundamental issues shared by physics, astrophysics and cosmology on the origin and structure of the Universe. The AMS-02 physics program [2] includes Antimatter search with unprecedented sensitivity, a quantitative analysis of the galactic Cosmic Rays, Dark Matter indirect searches and Gamma-Ray astrophysics. The Gamma Ray physics domain will be probed by AMS-02 using two different and complementary approaches [3]:

- by measuring converted e_{+}/e_{-} pairs in the Silicon Tracker (conversion mode)
- as single photons in the imaging Electromagnetic Calorimeter (single-photon mode)

The photons interacting directly in the Electromagnetic Calorimeter (single-photon mode) are traced back to the original direction with a poor angular resolution of the order of 1–3 deg. On the other hand, taking advantage of the excellent Silicon Tracker intrinsic resolution, in conversion mode the single gamma photon is much better reconstructed. More precisely, the angular resolution improves with increasing $E\gamma$. For $E\gamma > 30$GeV the angular uncertainty vs. energy curve reaches a plateau at the “astronomical significant” value of 1–2 arcmin (0.3-0.6 mrad). It is important to point out that this is the angular uncertainty associated to a single photon; the final source localization box size will depend on the brightness/spectrum combination and will be smaller. About half of the overall AMS-02 gamma throughput for $E\gamma > 1$GeV (~1000 $cm^2 \times sr$) is related to the high angular resolution conversion mode. Please refer to [3,4] for a more detailed description of AMS-02 as a gamma-ray telescope.

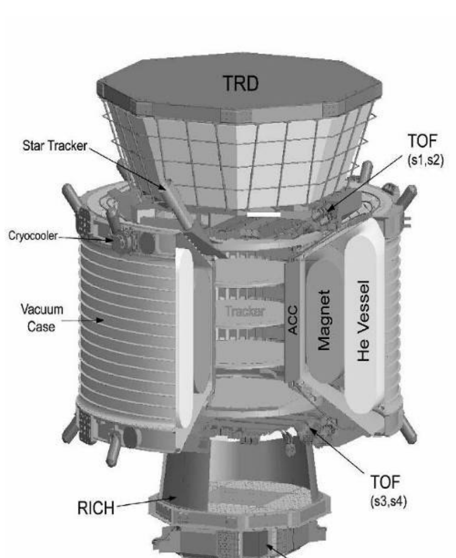

Fig. 1: AMS-02 detectors

AST: AMICA STAR TRACKER

The AMS-02 subsystem considered in this paper is the AMICA (Astro Mapper for Instrument Check of Attitude) Star Tracker (AST). The aim of the AST is to provide a precise (< 20 arcsec), real-time 3D transformation of the AMS-02 mechanical x-y-z frame to sky coordinates regardless of the large uncertainties introduced by the ISS attitude behaviour and structural elasticity. That transformation error, if uncorrected, would definitely dominate the intrinsic Silicon Tracker (SiT) one even on a single photon basis and destroy the source identification capabilities. In other words, it is the combination star-mapper and Silicon Tracker that guarantees a real, sky-projected, angular resolution in the astronomical range of interest. The AMS-g exposure/resolution performances will allow clean studies of the known galactic (e.g. Pulsars) and extra-galactic (e.g. Blazars and AGNs in general) sources, as well as the potential discovery of new multi-GeV emitters. Particularly interesting are the Gamma Ray Bursts (GRBs), and among them the still mysterious short/hard population. Provided the persevering large electromagnetic spectrum coverage of GRBs phenomena, the source compactness and the explosive nature of the event, observation in the multi-GeV domain would end-up in a precise estimate of potential photon speed energy dependence [5]. Two different AST will be mounted on AMS-02 (Fig. 2): ASTC0 (AMS-x-positive), ASTC1 (AMS-x-negative).

WHAT IS A STAR-MAPPER?

AST will work on AMS-02 as a star-mapper, i.e. a smart optical instrument pointed to the sky with sufficient field-of-view and sensitivity to actually see a certain number of stars per exposure. The observed point sources are then optimally matched with an on-board astrometric/photometric catalogue. The final result is a determination of the instantaneous orientation with respect to an inertial reference frame. The real mapping system complexity strongly depends on the required performances (duty cycle, astrometric error, mapping frequency) and on the operational environment (day/night, background sources, thermal, radiation, electronic interface etc.).

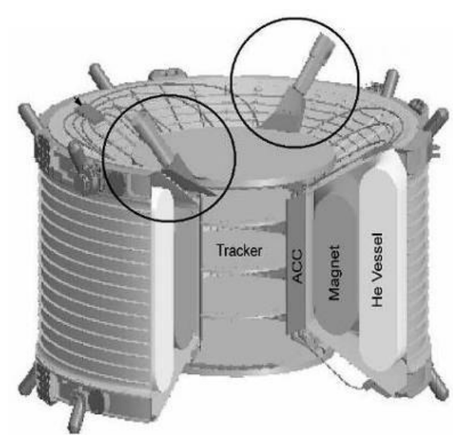

Fig. 2: AST0 and AST1 on AMS-02 Tracker

According to the system requirements for AST [7] on AMS-02, the performances are:

1. high day/night duty cycle
2. no moving parts
3. residual pointing error: few arcsec intrinsic [6]. A comparable, additional contribution is then introduced by the long supports finite stiffness and by the thermal deformations
4. maximum attitude determination rate: 15 Hz
5. dedicated interface with the AMS Universal Slow Control Module
6. on-board ms clock periodically synchronized by the external GPS unit with ms precision
7. total mass: 8 kg including cables and supports
8. power budget: 18 W
9. complicate geometrical and pointing constrains

AST DESIGN

The AST consists of a control unit based on DSP processor and two cameras (Fig. 3). Each camera is based on:

- optical system: AST Camera (ASTC)
- mechanical support: AST Support (ASTS) with AST thermal control system: (ASTT)
- baffle: AST Baffle (ASTB) with a mechanical interface: AST baffle support (ASTBS)

The ASTC and ASTB are developed CARSO in Trieste (Italy). The design of the ASTS, the ASTT and the ASTBS were performed by INFN Roma1.

AST CAMERA (ASTC)

The ASTC consists of: *lens and optical filters system; CCD and front-end electronics boards; baffle.* The baffle function is to limit the direct light or light reflected from the ISS entering into the lens system.

AST SUPPORT (ASTS)

The ASTC components, except for the baffle which has its own support, are supported by a CFRP (Carbon Fiber Reinforced Plastic) structure (ASTS) that attaches to the upper portion of the Silicon Tracker (SiT) sub-detector. Both the Star Tracker (ASTC0 and ASTC1) are supported to AMS-02 by an ASTS attached to the SiT. The ASTS consists of two parts, screwed together: *ASTS Upper* (attached to SiT Plane1); *ASTS Lower* (attached to SiT conical flange). The ASTS Upper is a light boxed structure with an irregular shape that develops among the nearby sub-detectors (Upper-Tof, Tracker, and Vacuum Case). One side of the box is open to allow the ASTC components installation. A flat wall screwed at periphery closes the lateral opening. The box houses the main electronics board and the thermal circuit that controls CCD temperature. Lens is fixed at the front of the ASTS Upper by a collar fastened to the structure through a back-collar. The CCD is mounted at the back of the lens, directly fixed to the collar. The ASTS Upper is fastened at one side to the Si Tracker Plane1 by screws. The fixation of the Star Tracker to the Si Tracker is stiffened by a bracket (the ASTS Lower) that connects the ASTS Upper to the Tracker Conical Flange. Support structure has to guarantee a deviation of the lens axis not larger than 20 arcsec.

AST THERMAL CONTROL SYSTEM (ASTT)

The AST thermal control system (Fig. 4) consists of: *ASTS Thermal Connectors; ASTS Thermal Blocks; Electronic Board Thermal Link; Thermal Bridge; CCD Thermal Link.* CCD and electronics board are connected to two copper blocks (ASTS Thermal Blocks) by a copper strip (Thermal Bridge) running at the floor of the ASTS Upper and thermally insulated from it. The CCD is connected to the thermal bridge by a flexible copper strip (CCD Thermal Link).

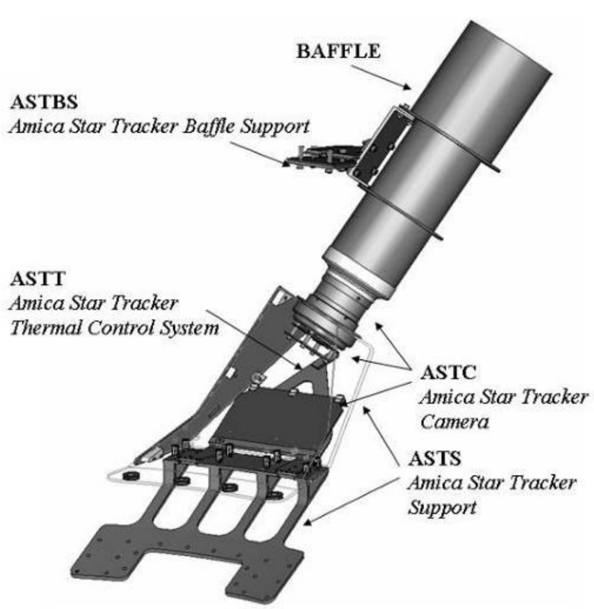

Fig. 3: AMICA Star Tracker Camera

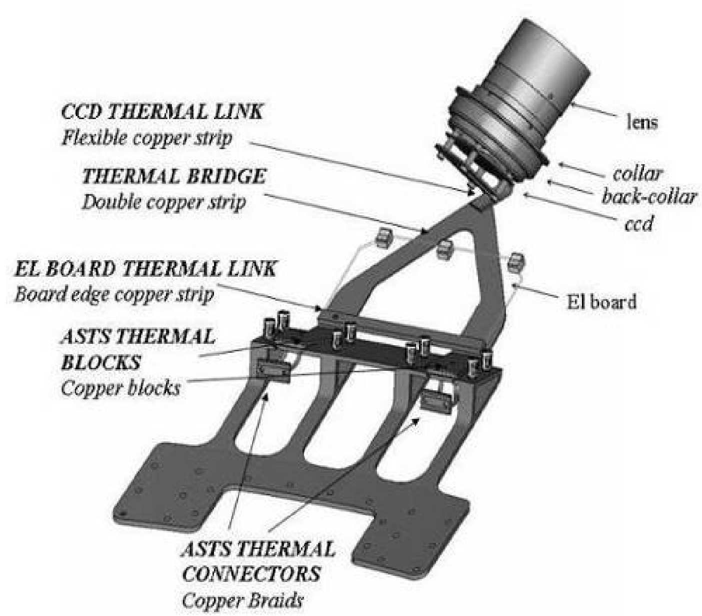

Fig. 4: AMICA Star Tracker Thermal Control System (ASTT)

Electronics board, located over the thermal bridge, is in thermal contact with it at one side where a copper ply covers the board edge (Electronic Board Thermal Link). Each ASTS Thermal Block at the end of the copper strip is connected to an evaporator block of the mechanically pumped TTCS (Tracker Thermal Control System) by two copper braids (ASTS Thermal Connector). The AMS-02 TTCS is a two-phase CO_2 based heat transport system [8] developed at NLR and NIKHEF for the Si Tracker. ASTT controls only the temperatures of the CCD and the electronics, therefore conductive interfaces between ASTT and composite structure are protected by insulating material.

AST BAFFLE SUPPORT (ASTBS)

The baffle is attached to the TRD M-Structure by a bracket ASTBS (AMICA Star Tracker Baffle Support) and it is not mechanically connected to the ASTS (there is no contact between baffle and lens plus filter system).

AST COMPONENTS TEMPERATURE RANGE AND POWER DISSIPATION

AST components can survive within the range of non operative temperatures, but they can work within the range of operative temperatures (Tab. 1).

		T_{min}	T_{max}
CCD	operative	-30℃	55℃*
	non operative	-40℃	80℃
Electronics board of CCD	operative	-20℃	55℃
	non operative	-40℃	80℃
Electronics board	operative	-20℃	55℃
	non operative	-40℃	80℃
Lens and filters	operative	-20℃	55℃
	non operative	-40℃	60℃

Tab. 1: AST components temperature range
(* The maximum indicated operative temperature is related to the CCD noise and to the ability of the system to recognize the faint star (6-7th magnitude) and therefore to give the pointing direction. The CCD could be operational at 55℃ but over 35℃/40℃ the system will not be able to extract pointing direction from this camera.)

The power dissipated from CCD, electronics front board of CCD and main electronics board (for each AST) is reported in Tab. 2. All this power is collected by the ASTT and then by TTCS of AMS-02.

	CCD	El board of CCD	Electronics board	TOTAL
Power	0.2 W	0.5 W	3 W	= 3.7 W

Tab. 2: AST components power dissipation

AST THERMAL INTERFACES

ASTS and ASTC

From thermal view point, ASTC is conductively coupled to the TTCS (Active Control System), while ASTS is conductively coupled (with mechanical connection) to the Si Tracker Plane1 and SiT Conical Flange. Moreover from thermal radiative coupling view point, ASTS is completely wrapped in MLI whose outer layer consists of Beta cloth (Fig. 5). This means that the AST is almost thermally insulated from outer space and thermally coupled with the SiT interface.

Baffle

The baffle is not in thermal conductive contact with the lens, because a nominal gap between the baffle and the lens is 10 mm. The baffle is supported by ASTBS (Al 7075 T7351) fixed to the TRD M-Structure, but the interface is conductively decoupled by insulation shimming plates. From thermal radiative coupling view point, the baffle (Al 6061) is internally black anodized ($\alpha = 0.88$; $\varepsilon = 0.78$) and externally is covered by silver tape ($\alpha = 0.135$; $\varepsilon = 0.63$) (passive control system, Fig. 5). It is also completely out of the MLI blanket that covers the nearby subdetectors in AMS-02 (Fig. 5). A dedicated MLI tubular collar allows the MLI cover being extended from the star tracker to the base of the baffle in order to protect the periphery of the lens exposure to outer space and also avoiding that light enters the baffle from the back. ASTBS is completely wrapped in MLI as well.

AST THERMAL MODELING

AST thermal modeling activities were an interactive effort between INFN Roma1, Carlo Gavazzi Space and CARSO.

- INFN Roma1 thermally modeled the AST and performed detailed thermal and thermo-elastic analysis
- CGS integrated AST model in AMS-02 overall model and produced to INFN Roma1 interface data for standard hot and cold cases and for special cases specified by CARSO

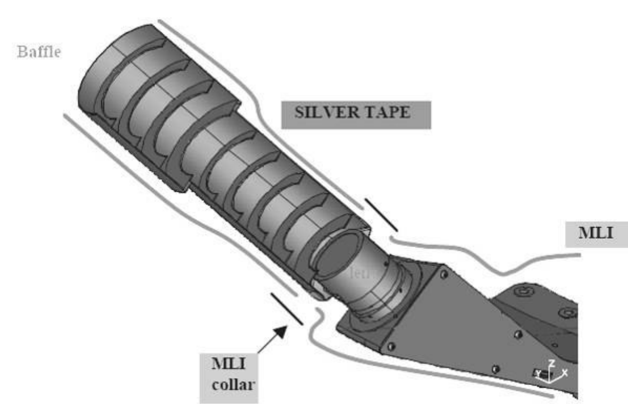

Fig. 5: MLI around AST

- CARSO performed AST visibility study and specified special cases to be thermally analyzed. These cases refer to orbital condition with low values for the sun angle (angle between lens axis and AST-sun direction)

THERMAL-VACUUM TESTS DESIGN

The activity consisted of four different tests that demonstrated the ability of the equipment to operate when exposed to extreme operational temperatures and vacuum environment (specific purposes of each test are described at the beginning of the following subchapters). The tests were performed in a Thermal Vacuum Chamber (TVC) with the test articles mounted on dedicated fixtures attached to the chamber coldplates. The tests were performed in the TVC of the SERMS [9] laboratory in Terni, Italy. This chamber is capable of reaching pressures below $5x10^{-5}$ mbar and imposing independently the shroud and the coldplates temperatures within a range of -70 to 125°C. The TVC dimensions are: *internal diameter: 2.1 m; internal length: 2.1 m*. The minimum temperature drift of the TVC shroud and coldplates is 1°C/min (in the range -20 to 50°C for the coldplates and -70 to 125°C for the shroud). The TVC door is in a clean room class 100000 that communicates with a clean room class 10000. The AST electronics were connected to the Electronic Ground Segment Equipment (EGSE) located outside of the TVC and supplied at nominal operating voltage by devoted feed-through.

THERMAL VACUUM CYCLING TEST

The Thermal Vacuum Cycling Test article was the AST Electronics QM: Electronic board and CCD. These parts were separately tested with respect to AST to verify their operative and non-operative limits of temperature and functionality under vacuum conditions through functional testing.

Thermal Vacuum Cycling test Fixture (TVCF)

The AST electronics board was fixed to the coldplate by the TVCF (Fig. 6).

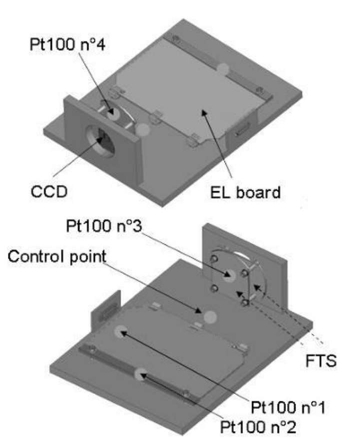

Fig. 6: Thermal Vacuum Cycling Test Fixture

The TVCF consisted of an Aluminum alloy plate with the electronics boards mounted at one side and fixed at the opposite side to the coldplate. CCD was oriented in order to point a light spot used for functional test. The electronics board was fixed to the TVCF reproducing the same interface connections that will be in flight configuration. A platinum resistance Pt100 thermometer was installed on the TVCF to control the coldplate temperature during test (Control Point in Fig. 6). Two CCD Flight Thermal Sensors (FTS) were integrated with four additional Test Temperature Sensors (Pt100) on both CCD and Electronics boards.

Thermal Cycle test profile

Thermal Cycle test profile followed during test is plotted in Fig. 7. As the procedure required, six intermediate cycles were performed, although Fig. 7 shows two intermediate cycles only. The cycle temperatures values are listed in Tab. 3. These values were used considering data-sheet AST components temperature ranges (Tab. 1). The hot bounds were increased by 5°C and cold bounds were decreased by 5°C.

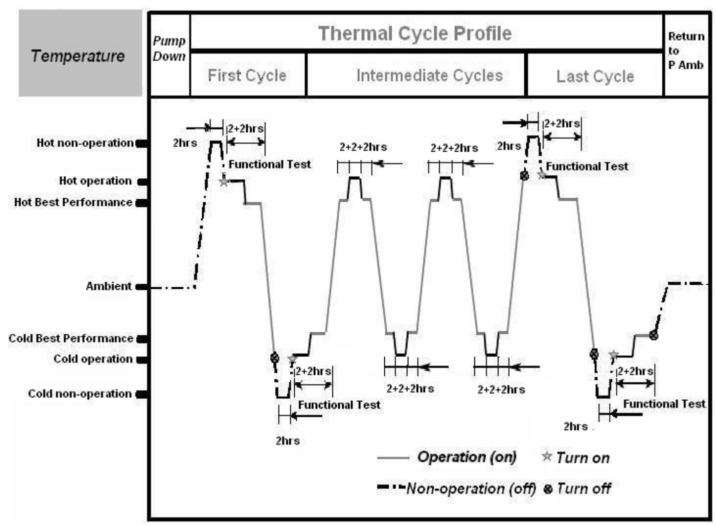

Fig. 7: Thermal Vacuum Cycling Test Profile

THERMAL BALANCE (TB) TEST

The device under Thermal Balance Test was AST, QM version with exception for the baffle (EM version). The EM baffle had thermo-optical properties like QM baffle, but different geometrical properties: EM was a cylindrical straight tube; QM and FM will be a tube with two cylindrical sections of different radius.

	Hot	Cold
non-operation	85°C	-45°C
operation	60°C	-35°C
best performance	40°C	-25°C

Tab. 3: TVC Temperatures

Final baffle bracket wasn't available (the verification of baffle bracket conductive thermal decoupling from the AMS-02 TRD M-structure will be carried out in a separate test). The AST was configured in its flight configuration, and it was tested under the extreme environments predicted for the life of the instrument. The purposes of this test were to:

- correlate thermal mathematical models
- validate the AST active (connection to TTCS) and passive (AST MLI blanket cover and Baffle silver tape) thermal control subsystems
- estimate the stability of the lens axis orientation (based on ASTS structure thermo-elastic behaviour)

AST camera was switched off during the Worst Case Cold and Worst Case Hot of TB test.

Thermal Balance test Fixture (TBF)

The AST electronics were fixed to the coldplate by the TBF (Fig. 8, Fig. 9). The TBF provided also the required thermal environment to simulate the Interfaces between ASTS (Upper and Lower) and Si Tracker. The fixture was constituted of Aluminum alloy plates and its geometry was such to align the lens and baffle axis to the TV chamber window. Baffle was mechanical fixed by a fixture to the intermediate coldplate. This fixture was made of Teflon and steel in order to ensure thermally decoupling.

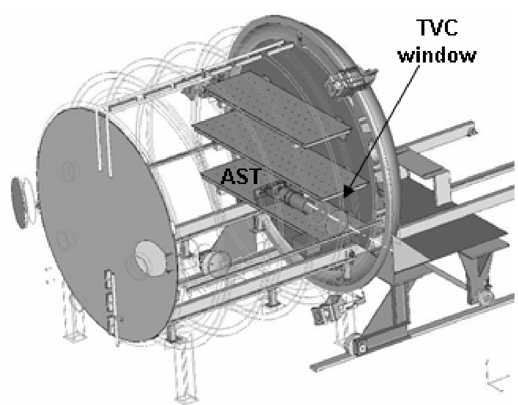

Fig. 8: AST inside SERMS Thermo Vacuum Chamber

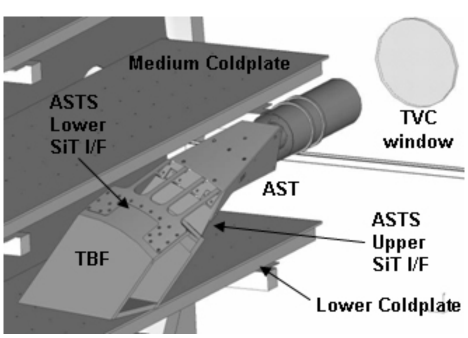

Fig. 9: AST mounted on TBF and fixed on a coldplate

Test Design

The lower face of TBF was in thermal contact with the surface of the coldplate. The target was to simulate by TBF the thermal environment given during flight by the mechanical connection to the AMS-02 **Si Tracker**. For this purpose, two test resistive heaters were installed on the TBF to control and monitor temperature variations during test (the dark rectangle on Fig. 10). Each heater temperature was monitored and controlled by one Pt100 installed on the TBF (CH2 on ASTS Upper interface, CH1 on ASTS Lower interface on Fig. 10). A two channels PID (Proportional Integrative Derivative) digital controller was used to read the temperatures of these Pt100 and to set independently the temperature of each heater. The conductive interface between ASTT (ASTS Thermal Connectors) and the AMS-02 **TTCS** was simulated by thermal connecting the two copper connectors of ASTT through a copper arm to the coldplate. The copper arm was equipped with a heater controlled and monitored by a Pt100 placed at the ASTT copper blocks location. The temperature of this heater was set with a PID digital controller by this Pt100 (CH3 on Fig. 10). The **coldplate temperature** was driven by the lowest temperature between TTCS and Tracker I/F; therefore the temperature of each interface (two for Tracker INTERFACE and one for TTCS INTERFACE) was risen by heaters and controlled by PID digital controllers, thus allowing a two-temperature sinking scheme.

The AST was radiatively coupled to the shroud. Therefore it was wrapped in MLI (20 layers) with the exception of the baffle whose external surface was covered by silver tape. Shroud temperature was driven by one of the two Pt100 placed on the baffle.

Sensors

23 platinum resistance Pt100 thermometers were installed on AST to monitor temperature:

- 17 located externally: 12 on ASTS, 1 on Aluminum alloy collar, 1 on lens, 1 on filters, 2 on the baffle (1 of them used as CTS, to drive the shroud of TVC)
- 6 located internally: 3 on ASTC, 3 on ASTT

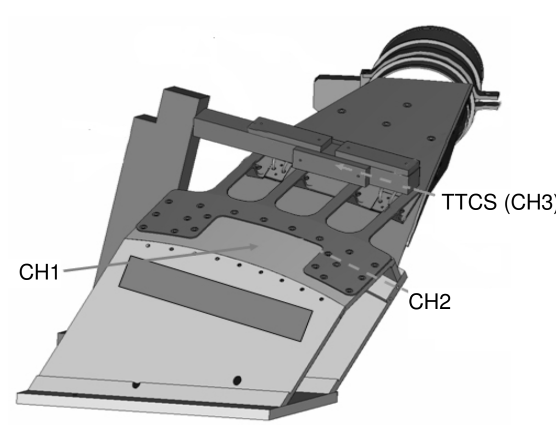

Fig. 10: Heaters on Copper Arm and TBF

15 strain gages were installed on ASTS to monitor local deformations of CFRP structure:

- 13 strain gage rosettes (biaxial, 0°/90°), quarter bridge configuration (1 SG = 2 channels). Thermal compensation was performed by Pt100 temperature sensors placed near strain gages
- 2 strain gage (uniaxial), half bridge configuration (2 SG = 1 channel), auto thermal compensated

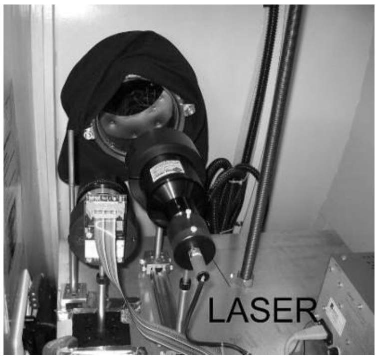

Fig. 11: Alignment Monitoring Equipment

An Alignment Monitoring Equipment (AME, Fig. 11) was located out of the TVC in front of the window at the chamber side to monitor lens axis deviation during the TB test. Considering the possibility to evaluate the position of defocused beam on the CCD with the centroid technique, angular resolutions of few arcsec were measured. A second laser (located into the TVC, fixed to the TBF) with independent camera was used for monitoring the TBF deformation.

Thermal Balance test profile

TB test profile followed during test is plotted in Fig. 12. According to thermal analysis prediction, the orbit leading to Worst Case Hot is when the ISS is flying at Beta angle= +75° and attitude Yaw=-15°, Pitch=-20° and Roll=-15° and the orbit leading to Worst Case Cold is Beta=+50°, Y/P/R=-15°/-20°/-15°. Based on this prediction the temperature of Conductive and Radiative interfaces was set at the values reported in Tab. 4.

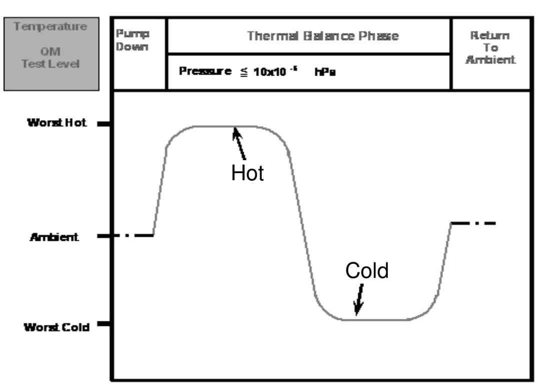

Fig. 12: Thermal Balance Test Profile

Condition		Worst Hot	Worst Cold
Star tracker Location in AMS-02		ASTS0 (X pos)	ASTS1 (X neg.)
Orbit		B+75-15-20-15	B+50-15-20-15
INTERFACE Temperature		Baffle = 76°C	Baffle = -65°C
		TTCS = 15°C	TTCS = -5°C
		Tracker = 28°C	Tracker = -10°C

Tab. 4: Interface temperature

SUN IN THE LENS TEST

The “Sun in the lens” Test article was the same used in Thermal Balance Test, with unchanged setup inside the TVC. The purpose of this test was to evaluate:

- the local heating effect on the CCD pixel due to lens focalization when sun rays have the same direction of the lens axis
- the ability of ASTT to carry out the additional power due to solar rays focused on the CCD

A Solar Simulation Equipment (SSE, Fig. 13), provided by a lamp located out of the TVC, completed the tests configuration. This was the basic difference between this test setup and Thermal Balance Test Setup and it was needed to simulate the sun. The correct intensity of the lamp was set through a calibration performed by a photodiode placed in the CCD position: the power flux corresponded to 0.056W/cm^2 (1.6W on 28.6 cm^2)

Sun in the Lens test profile

According to the thermal analysis prediction, the maximum time window extension for which the sun is in axis with the lens is 20 min. This occurs in the orbit Beta=+75°, Y/P/R=-15°/-20°/-15° (Worst Hot condition in Tab. 4). Based on this prediction the test “Sun in the lens” was performed stabilizing the Star Tracker INTERFACE at the temperatures defined in Tab. 4 for the “Worst Hot” condition; then the QTH lamp was switched on for 30 min. Therefore the “Sun in the lens” Test profile was like the first part (Worst Case Hot) of Thermal Balance Test Profile (Fig. 12).

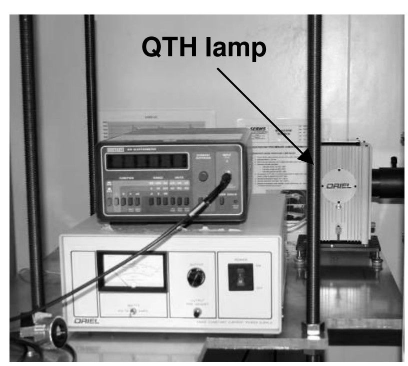

Fig. 13: Solar Simulation Equipment

LENS COLD TEST

The Lens Cold Test article was the AST lens and filters assembly QM. These parts were separately tested with respect to AST to verify that the worst cold temperature (foreseen to occur in cold orbits during an AMS-02 power outage of 16 hours) doesn't permanently compromise lens and filter functionality when back to best performance range.

Lens Case Fixture (LCF)

The AST lens and filter assembly were fixed to the coldplate by the LCF (Fig. 14).

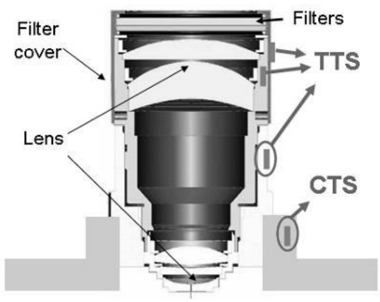

Fig. 14: Lens Cold Fixture: section

The LCF consisted of an Aluminum alloy part (the blocks in gray in Fig. 14) fixed to the coldplate and housing an M78x1 threaded hole for lens fixation. A platinum resistance Pt100 thermometer (Control Test Sensor, CTS in Fig. 14) was installed on the LCF to control the coldplate temperature during test. Three additional Pt100 (TTS, Test Temperature Sensors in Fig. 14) on lens body, filter cover and filters body were used to monitor lens temperatures.

Lens Cold test profile

Lens Cold test profile followed during test is plotted in Fig. 15. According to thermal analysis prediction, when AMS is on the ISS, in case of a power outage, the lens temperature after 16 hours stabilizes in the worst case at -35℃. Based on this prediction the lens was stabilized at -40℃ for 2 hours.

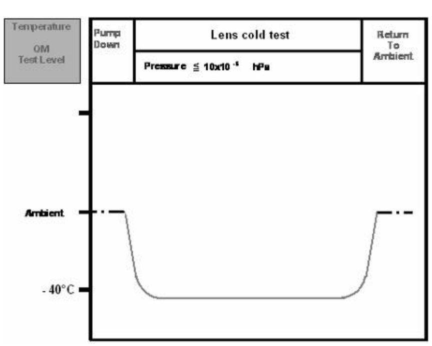

Fig. 15: Lens Cold Test Profile

THERMAL-VACUUM TESTS CONDUCTION

Tests were performed at SERMS [9] in TVC according to the periods listed in Tab. 5 (year 2006). Test setups are shown in the following pictures (Fig. 16 to Fig. 20). In order to avoid contamination of the optical parts, before the Thermal Balance test, the ASTS composite structure (without any optics and electronics) was subjected to a bake-out cycle at maximum non operative temperature (+85℃) for 24 hours. After the bake-out procedure the ASTS was taken out from the TVC and stored in the clean-room class 100000. The assembling of optics and electronics with the ASTS was performed in this clean room. Heater control was active during TB test to set the temperature of conductive interfaces. After TB test, inside the TVC the setup used for "Sun in the lens" Test was the same with respect to TB test, with except of the lens filters. Outside the TVC, the AME was replaced with SSE.

Test	Step	Start	End
Thermal Cycling	Setup + Test	March 14th	March 23rd
Thermal Balance	Setup	June 26th	July 7th
Thermal Balance	Test	July 7th	July 10th
Sun in the Lens	Test	July 10th	July 12th
Lens Cold	Setup + Test	July 14th	July 15th

Tab. 5: Test Periods

Fig. 16: Thermal Vacuum Cycling Test Setup

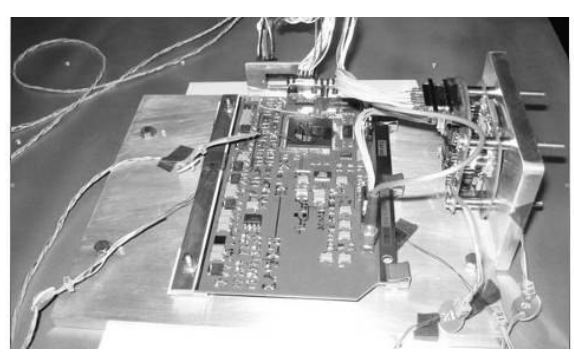

Fig. 17: Thermal Vacuum Cycling Test Setup, with Pt100

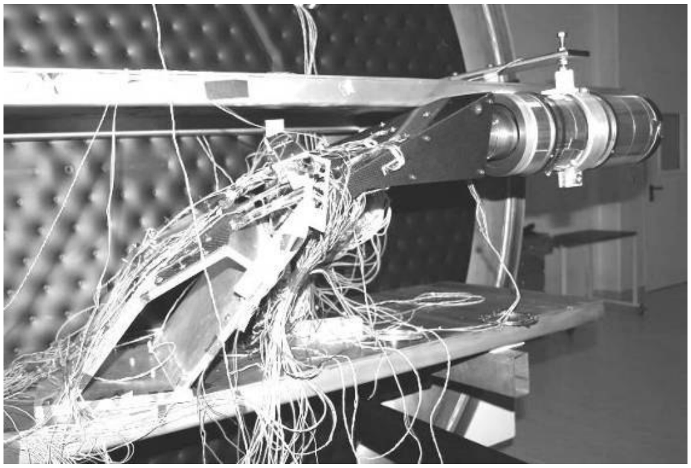

Fig. 18: Thermal Balance Test without MLI

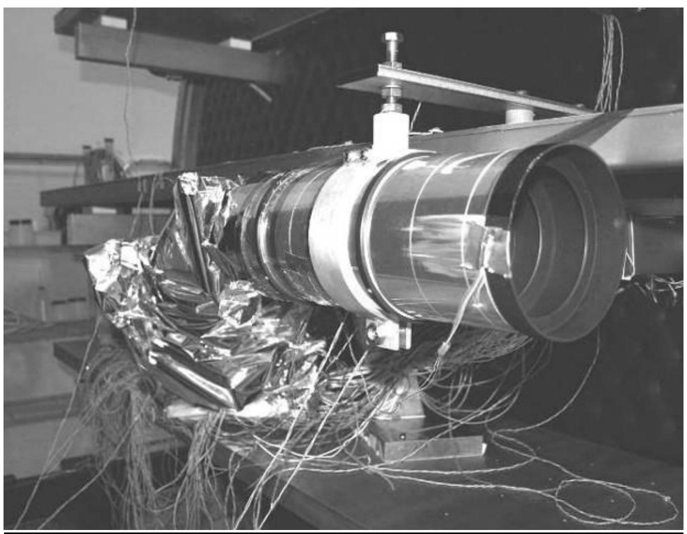

Fig. 19: Thermal Balance Test Setup with MLI

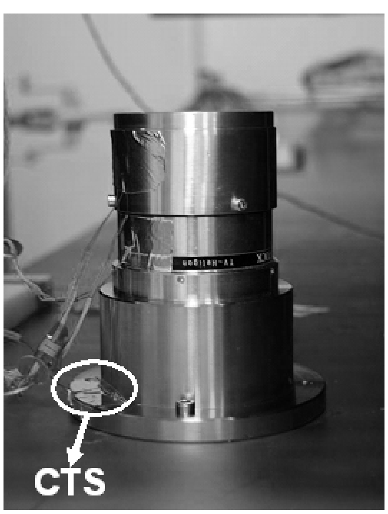

Fig. 20: Lens Cold Test Setup

FUNCTIONAL TESTS

Functional performance of the test item was checked before, during and after the test to reveal potential functional degradation or malfunction. CARSO experts attended the test and operated the AST electronics during the switch-on/switch-off and functional test phases. Except for Lens Cold test (final visual inspection only), functional tests were performed for every stabilization phase of temperature and they consisted of:

- register the current flow absorbed
- acquire a CCD image without light
- acquire a CCD image with light on (light spot from TVC Plexiglas window)

TEMPERATURE SENSORS

TVC parameters and AST electronics temperature values were continuously monitored and recorded in all the locations described in chapter 3 for each test. The tests were started and the data considered valid when the pressure value was less than $1*10^{-5}$ mbar. They were performed according to the thermal profiles shown in the chapter 3 of this paper, using temperature tolerances specified in Tab. 6. TVC Pt100 probes were used as temperature sensors for Thermal Cycling and Lens Cold tests. For other tests Pt100 temperature sensors were acquired by a SCXI National Instruments data acquisition system. For Thermal Cycling Test these Pt100 were installed using Kapton tape (for other tests they were fixed with Aluminum tape). A layer of thermal conductive material (Cho-Term) was placed between fixtures and coldplate to guarantee proper thermal connection between fixtures and coldplate.

Temperature	High	Low
-50°C<T<100°C	$T_{\max}{}^{+3}_{-0}$	$T_{\min}{}^{+0}_{-3}$
T<-50°C or T>100°C	$T_{\max}{}^{+4}_{-0}$	$T_{\min}{}^{+0}_{-4}$

Tab. 6: Test Tolerances

STABILIZATION CRITERIA

For Thermal Cycling and Lens Cold the accepted stabilization criteria were fixed according to the following condition: "$\Delta T/\Delta t \leq 1$°C/h (evaluated on a period of 10 minutes). Then the temperature was stabilized for at least 2 hours". For TB and "Sun in the lens" the stabilization criteria were: "the readings of all flight and test temperature sensors vary by no more than 0.5°C for 5 hours with a decreasing slope with a fixed electronics power profile and a stable environment. In addition, heaters power shall not vary by more than 5% over the last five hours".

THERMAL-VACUUM TESTS RESULTS

The graphs reported in this section summarize the temporal evolution of all measured quantities during the whole tests period. During the tests the pressure value remained most of the time below 10^{-5} mbar.

THERMAL VACUUM CYCLING TEST

Fig. 21 shows the resulting thermal profile: this confirms that the electronics can survive to temperature levels out of design range (-25℃ to 40℃) without damage. The images taken by the camera (Fig. 22) during the test show a level of background noise in the form of granularity of the image (especially at high temperature) which is some orders of magnitude larger than that of the CCD which is going to be installed on AST. This noise is function of the temperature. The test was considered successful for the absence of malfunction of electronics and CCD. In Fig. 23, the peaks of pressure correspond to the hot phase of each cycle.

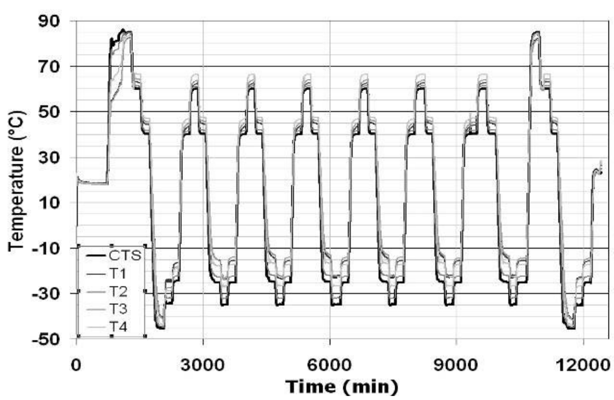

Fig. 21: Temperature (℃) vs. Time (min) during the test

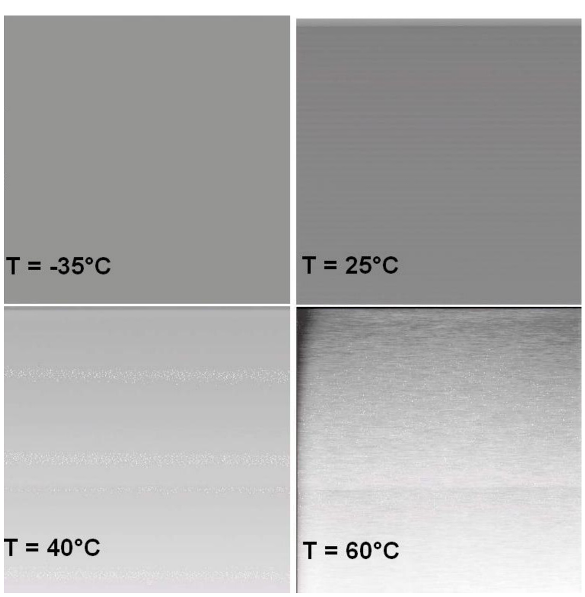

Fig. 22: CCD images of dark at various temperature

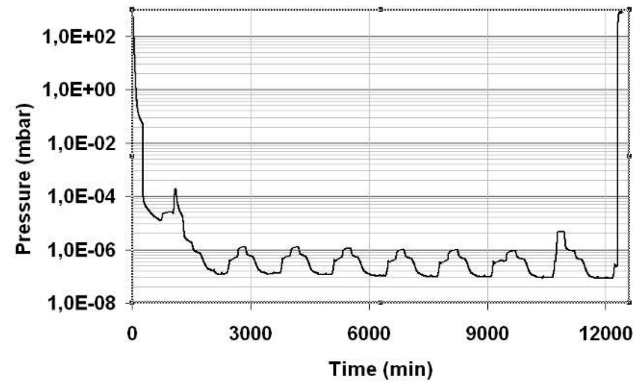

Fig. 23: Pressure (mbar) vs. Time (min) during the test

THERMAL BALANCE TEST

From the start of Worst Case Hot stabilization (Fig. 24) the pressure value remained below 10^{-5} mbar. Fig. 25 and Fig. 26 show temperature profile respectively at conductive and radiative interfaces. Fig. 27 and Fig. 28 show the difference between values obtained from thermal analysis prediction and test. Conductive interfaces temperature values were very close to the requested (max 1.5℃ of difference). This came from the exceptional stability of the control of temperature obtained with heaters and PID thermostats. Radiative interfaces were not so close to the requested temperature values, in particular for the Worst Case Cold: the requested value on the baffle (-65℃) was too near to the shroud low limit (-70℃), so the radiative thermal coupling allowed to reach only -58℃ (7℃ of difference). Considering this unexpected difficulty, the data obtained from test were near to the values predicted from analysis, especially for Worst Case Hot. This pictures (Fig. 27 and Fig. 28) shows only ASTT and ASTC, but also correlation of measured data with ASTS composite structure thermal model was good. This values of temperature were used also to thermal compensate the strain gage deformation values. Therefore correlation with thermal analytic models was good and AST active (especially the connection to TTCS) and passive (AST MLI blanket cover and Baffle silver tape) thermal control subsystems were validated.

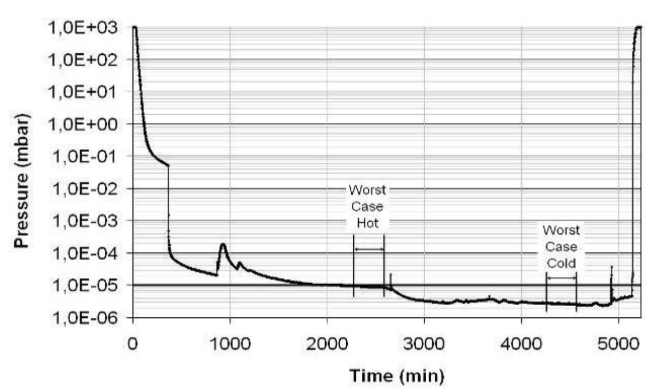

Fig. 24: Pressure (mbar) vs. Time (min) during the test

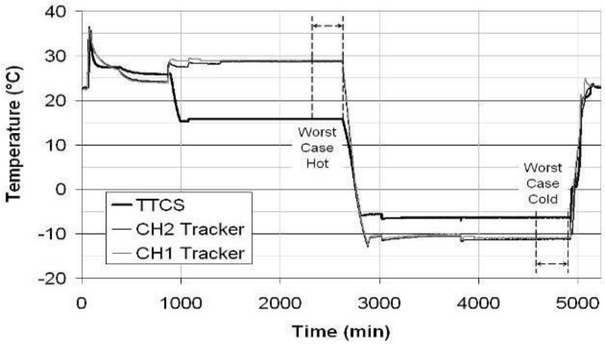

Fig. 25: Temperature (℃) of Cond. INTERFACE vs. Time (min)

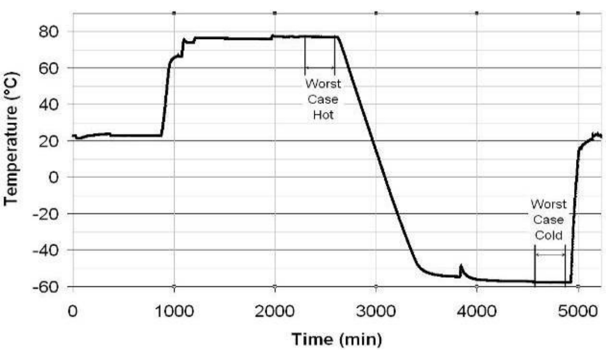

Fig. 26: Temperature (℃) of Baffle vs. Time (min) during the test

Strains obtained from strain gages were very little (close to the errors due to the data acquisition chain), in the order of 50-100 μm/m the entire temperature range, then local deformations were negligible: only thermal expansion was measured. Also macroscopic angular deformation monitored with the lasers was contained into the requirements. The test was considered successful because the required criteria (absence of malfunction of the electronics and CCD, lens axis deviation < 5 arcsec) were satisfied.

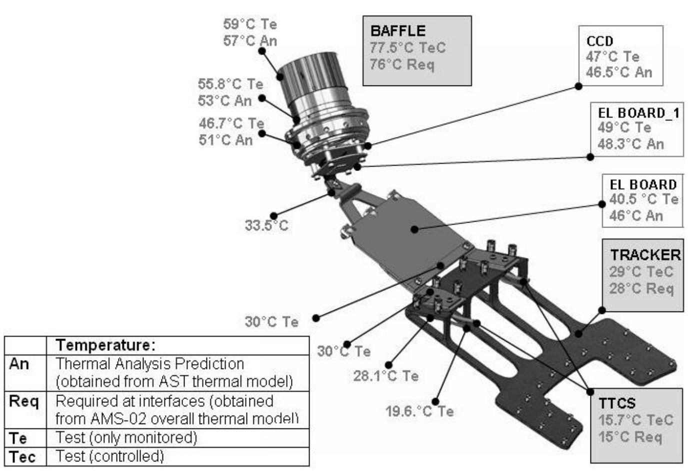

Fig. 27: Worst Case Hot temperature results

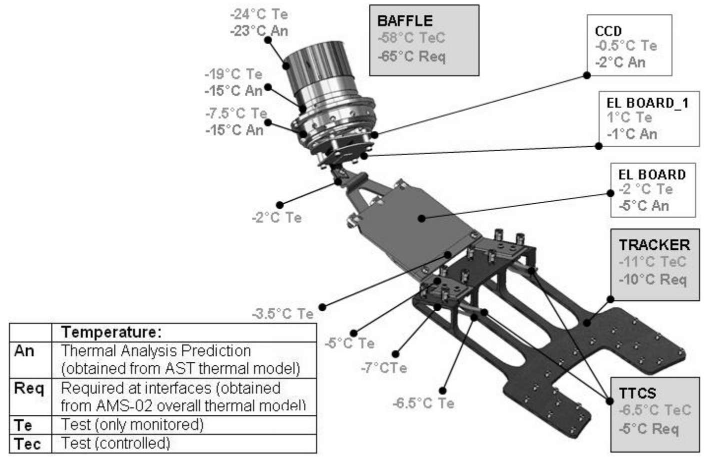

Fig. 28: Worst Case Cold temperature results

SUN IN THE LENS TEST

The pressure and thermal profiles were very similar to those obtained in Thermal Balance Test (during Worst Case Hot) and are not reported here. Therefore an important result was reproducibility: temperature values were very close to those obtained during Worst Case Hot of TB test (the boundary conditions at interfaces were the same). With the SSE turned on, the temperature drift of CCD was 1℃. Turning on AST camera and SSE together the drift was more consistent: 11℃. The CCD survived to this test, so the required criteria for test approval (absence of pixel damage and malfunction of the CCD) were fulfilled.

LENS COLD TEST

The pressure value remained below 10^{-5} mbar (Fig. 29) beginning from test start. The requested temperature profile was followed controlling the temperature of TVC coldplates (Fig. 30). Visual inspection of the lens was performed and no evident cracks or fault was registered. Also a spot light acquisition (Fig. 31) was performed after the test to verify the performance of the lens and this demonstrated that the lens and filters survived without any evident damage.

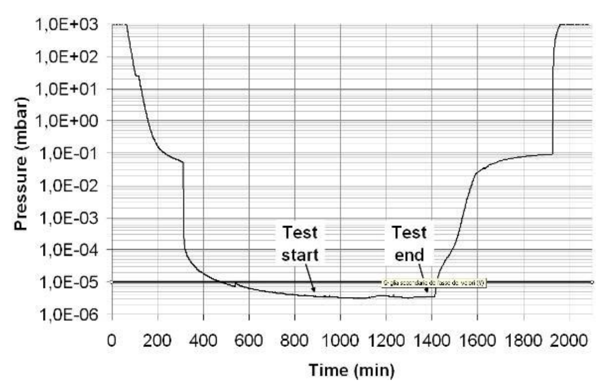

Fig. 29: Pressure (mbar) vs. Time (min) during the test

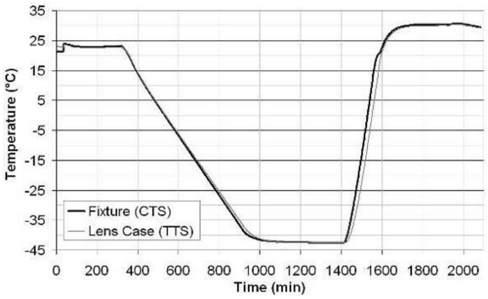

Fig. 30: Temperature (°C) vs. Time (min) during the test

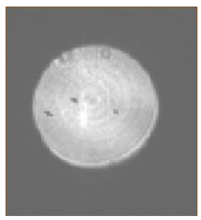

Fig. 31: spot acquired image after test

LESSONS LEARNED

TB Test was performed twice: the first time in April 2006, with poor results: the temperatures were far to those predicted by analyses. Some test design and setup improvements were attained for the second TB test.

Baffle fixture

Old baffle fixture was made of G10 (thermal insulant); it was massive and directly inserted into coldplate hollow support frame without fasteners (by friction). This caused a poor baffle thermal decoupling from intermediate coldplate support. This thermal insulation was needed because baffle and coldplate temperatures were very different. Another problem was baffle mechanical instability for alignment. For the second TB test the fixture was totally redesigned: it was a thin steel rod (Fig. 19), connected to the intermediate coldplate by two bolts plus two Teflon shims and to the baffle collar with a long bolt plus a Teflon cylinder. This resulted in a good thermal insulation and a stable alignment of the baffle.

Alignment Monitoring Equipment

During the first TB test two external lasers were used, with a mirror fixed on the TBF in order to reflect laser beam and monitor the TBF angular deformation. With this solution the localization of the mirror with the incident beam and the tracing of the reflected beam were difficult; the Plexiglas window was little compared to the optical obstacle given by the baffle: the reflected beam hit the TVC walls. For the second TB test an internal laser shortened the optical path, eliminating entering beam.

Pt100 fixing

Many Pt100 sensors were attached with Kapton tape, but TVC sensors were fixed with Aluminum tape during the first TB test. Kapton high emissivity and poor conduction through the Kapton foil, in combination with different temperatures between shroud and conductive interfaces resulted in radiatively heated or cooled Pt100. For example with the shroud at 96°C and a surface at 20°C, the value reported by the Pt100 covered with Kapton tape was 45°C, while TVC Pt100 mounted on the same surface, but covered with Aluminum tape (low emissivity and good conduction through the Al foil), measured the correct value (20° C). In the second TB test all Pt100 were fixed with Al tape. Thermal Cycling Test's sensors were fixed with Kapton, but shroud temperature was close to coldplate temperature, then the temperatures were very similar into the TVC in a certain moment, therefore the radiative effect on the Pt100 was negligible.

MLI baffle-lens

In the first TB test the baffle and AST were wrapped together in MLI, which was fixed with Kapton Tape on AST. This will not be the flight configuration, because baffle must be conductively decoupled from the AST. In the second TB test the MLI between baffle and AST was blocked with a dedicated fixture on lens collar with Teflon shims to reduce heat transfer between AST and baffle.

CONCLUSION

The challenging design of thermal and structural stability of AST system required a special effort for the testing and validation. The Thermal Vacuum Cycling, Thermal Balance, "Sun in the lens" and Lens cold tests were performed on AST at SERMS [9] from March 26th to July 15th 2006. Special effort was requested by the unique Thermal Balance and "Sun in the lens" Test setup:

- thermal design of a test with four different thermal interfaces (three conductive, one radiative) reproducing two flight extreme conditions, with a great temperature difference between radiative and conductive interfaces (~ 60°C)
- great number of sensors of different type
- control and stabilizing of different interfaces with strict temperature tolerances and drift criteria

ACKNOWLEDGMENTS

This work has been partially funded by ASI contract I/021/05/0

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

Cold best performance temperature: Minimum qualification temperature (lowest design temperature at which the equipment demonstrates full design ability)

Cold non-operation temperature: Minimum non operating temperature (lowest design temperature for the equipment to survive not powered)

Cold operation temperature: Minimum start up temperature (lowest design temperature of the equipment, at which the equipment can be switched on).

Hot best performance temperature: Maximum qualification temperature (highest design temperature at which the equipment demonstrates full design ability)

Hot non-operation temperature: Maximum non operating temperature (highest design temperature for the equipment to survive not powered)

Hot operation temperature: Maximum start up temperature (highest design temperature of the equipment, at which the equipment can be switched on).

AME: Alignment Monitoring Equipment

AMICA: Astro Mapper for Instrument Check of Attitude

AMS: Alpha Magnetic Spectroscope

AST: AMICA Star Tracker

ASTC: AMICA Star Tracker Camera

ASTBS: AMICA Star Tracker Baffle Support

ASTS: AMICA Star Tracker Support

ASTT: AMICA Star Tracker Thermal control system

CARSO: Center for Advanced Research in Space Optics

CFRP: Carbon Fiber Reinforced Plastic

CTS: Control Test Sensor

EGSE: Electronic Ground Segment Equipment

EM: Engineering Model

FM: Flight Model

FTS: Flight Temperature Sensor

GPS: Global Positioning System

INFN: Istituto Nazionale di Fisica Nucleare

ISS: International Space Station

LCF: Lens Case Fixture

MLI: Multi Layer Insulation

PID: Proportional Integrative Derivative

QM: Qualification Model

QTH: Quartz Tungsten Halogen

SERMS: laboratory for the Study of Radiation Effects on Materials for Space applications

SiT: Silicon Tracker

SSE: Solar Simulation Equipment

TB: Thermal Balance test

TBF: Thermal Balance test Fixture

TRD: Transition Radiation Detector

TTCS: Tracker Thermal Control System

TTS: Test Temperature Sensors

TVC: Thermal Vacuum Chamber

TVCF: Thermal Vacuum Cycling test Fixture