Status of the ArTeMiS camera to be installed on APEX

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ABSTRACT

The ArTeMiS submillimetric camera will observe simultaneously the sky at 450, 350 and 200 µm using 3 different focal planes made of 2304, 2304 and 1152 bolometric pixels respectively. This camera will be mounted in the Cassegrain cabin of APEX, a 12 m antenna located on the Chajnantor plateau, Chile.

To realize the bolometric arrays, we have adapted the Silicon processing technology used for the Herschel-PACS photometer to account for higher incident fluxes and longer wavelengths from the ground. In addition, an autonomous cryogenic system has been designed to cool the 3 focal planes down to 300 mK. Preliminary performances obtained in laboratory with the first of 3 focal planes are presented.

Latest results obtained in 2009 with the P-ArTeMiS prototype camera are also discussed, including massive protostellar cores and several star forming regions that have been clearly identified and mapped.

Keyword list : Cryogenic bolometer array, sub-millimetre wavelength, stellar formation, circumstellar disks

1) CAMERA OVERVIEW

The ArTeMiS camera is presently under construction. Its basic design has already been presented (Talvard et al, 2008). This camera aims at achieving large field of view mapping of the southern sky at 3 wavelengths simultaneously: 200, 350, and 450 µm. The 3 focal planes are made of thousands of pixels sampling completely the field of view by using the same technology processes than those used for the Herschel-PACS imager. We recall that the 3 focal planes are made of MIS (Metal Insulator Semiconductor) bolometers whose concept has been previously detailed (Billot et al, 2006, Reveret et al, 2006).

Architecture of the various sub-systems is now definitive. We present in the following the status of each sub-system and detail the performances of preliminary laboratory set ups.
The Proto-ArTeMiS camera (256 pixels at 450 µm) has been operated one more time in 2009 during the development phase of ArTeMiS. Some new results are presented to illustrate the potential interest of the future camera.

The past two years have been spent to study the camera design at system level but also to define in more details all the main sub-systems. System study has been essential mainly for two reasons: first to optimize the camera and second to consolidate interfaces with the telescope. Camera optimization follows several axes such as:

- Optical compactness and imaging quality
- Stray light reduction
- Thermal performances
- Mechanical distortion reduction
- Coupling and alignment with telescope
- Control command
- Data transfers

All those parameters have been taken into account in order to make a camera as efficient as possible. Even though the particular cryostat shape, mainly due to the available room in the Cassegrain cabin, all blocking points are now solved and detail design is fully achieved. Figure 1 and 2 give an overview of the ArTeMiS camera architecture with its main components.

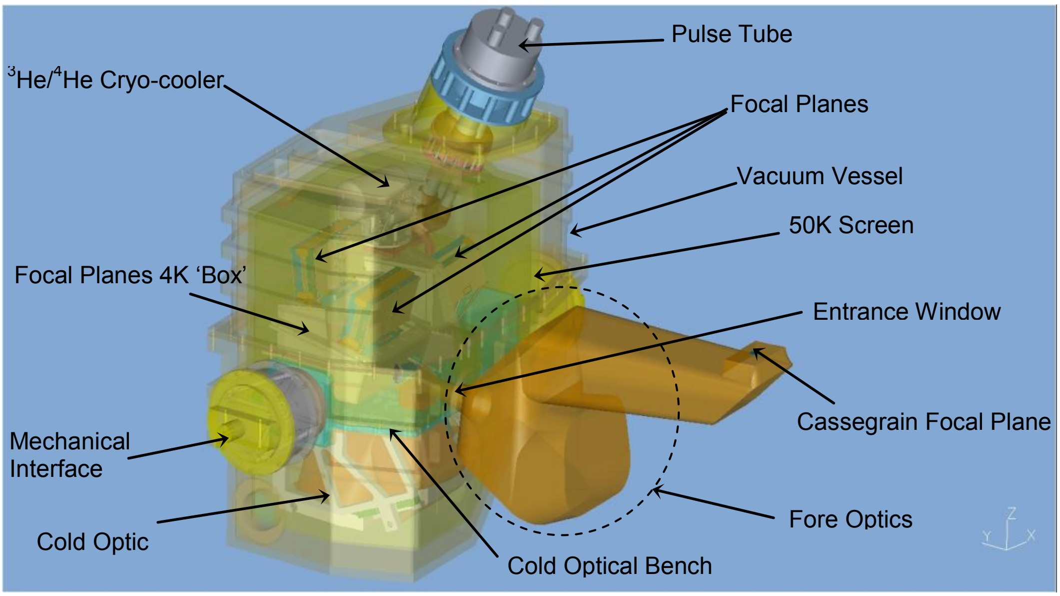


Figure 1: Overall architecture of the ArTeMiS camera

The entire camera is built around the Cold Optical Bench which acts as a reference plate. This optical bench makes also a very efficient frontier between the 50 K and the 4 K environment to stop potential parasitic flux on detectors.

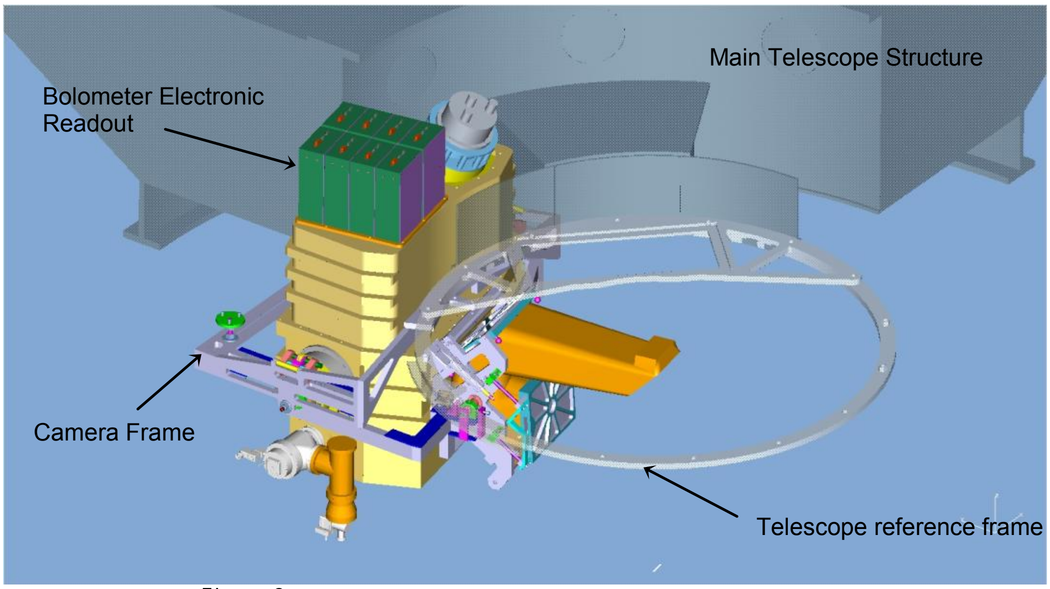


Figure 2: ArTeMiS camera installed in the APEX Cassegrain cabin

As it will be developed on section 2 for the vacuum vessel, special care has been taken regarding the camera global stiffness and distortion during telescope operation. The overall mechanical chain from which all the optical component positions depend has been designed as stiff and as close as possible regarding the telescope mechanical interface. The total camera distortion budget during normal operation has been managed in order to be less than 150 µm. In addition of these 'dynamic' distortions, the internal design of the camera was done to be compliant with all thermal contractions: 'static' distortions induced during the cryostat cool down phase. Even the fact that most of the parts are made in the same aluminium alloy, differential contractions between sub-assemblies has been anticipated in order to keep the good optical properties at cold temperature.

2) CRYOSTAT

The cryostat is made with an aluminium vacuum vessel split in 2 parts for manufacture reasons. Internal stiffeners (hexapods) have been designed to increase mechanical rigidity. This vacuum vessel is supported by a frame attached to the structure of the Cassegrain cabin of the telescope. Numerical simulations have been performed to optimize the engineering design of the cryostat. We could check the mechanical stress level and displacement of both the vacuum tank and the hexapods. Figure 3 shows the mechanical stresses due to atmospheric pressure on the vaccum vessel and due to 40 kg load on the hexapods. The resulting stresses are much lower than the elasticity limit of this metal which is perfectly convenient.

Inside the vacuum tank, the internal components such as plates and screens are made of 6063 Aluminium grade. This grade has been chosen for its excellent thermal conductivity performances. An aluminium plate named ''reference plate'' is supported by 2 hexapods including a rail allowing the free mechanical contraction of the plate. A screen (also split in 2 parts) is fixed on top of the plate and thermalized by the 1st stage of a PT415 pulse tube through a copper braid link. At the bottom of the plate, a dedicated structure supports the internal optics. The average temperature of this set-up will be a function of the operational thermal loads. Taking into account an incident power of 40 W spread upon the 1st screens of the cryostat, the temperature of this screen is expected around 55 K (see the thermal gradients on figure 4).

Inside this first screen, there is a second screen called ''4K screen''; it is supported by three tripods, fixed on the plate, and made of carbon fibers in order to limit the thermal load. This 4K screen is composed of a 6063 aluminium box, cooled by the second stage of the PT415 through a cooper braid link; this box includes:

- the He4-He3 sorption cooler
- 3 focal planes with their cold front-end electronics, the ''NABU'' (which stands for New ArTeMiS Buffer Unit) modules.

The NABU modules are cooled by the second stage of the PT415. Part of the focal planes is cooled by the 2K stage of the sorption cooler. The three focal planes are also linked to the 300 mK cryo-cooler. Two additional screens lock this cryo-system. The expected temperature on the screen is around 4.9 K, based on 0.5 W thermal load spread upon the surface (see figure 5).

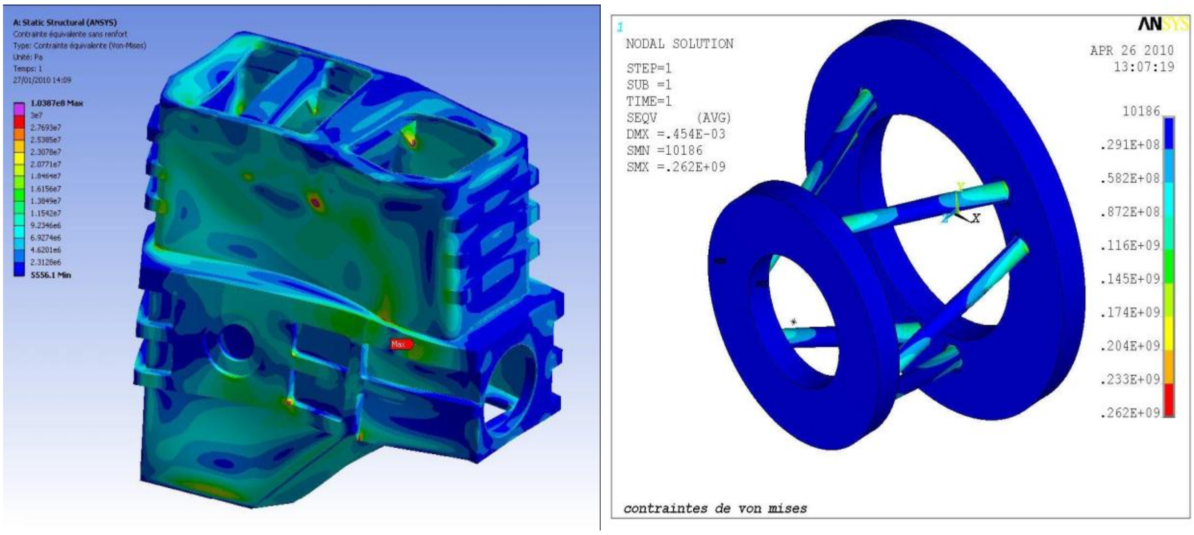


Figure 3: Mechanical stresses of the vacuum vessel and the hexapod.

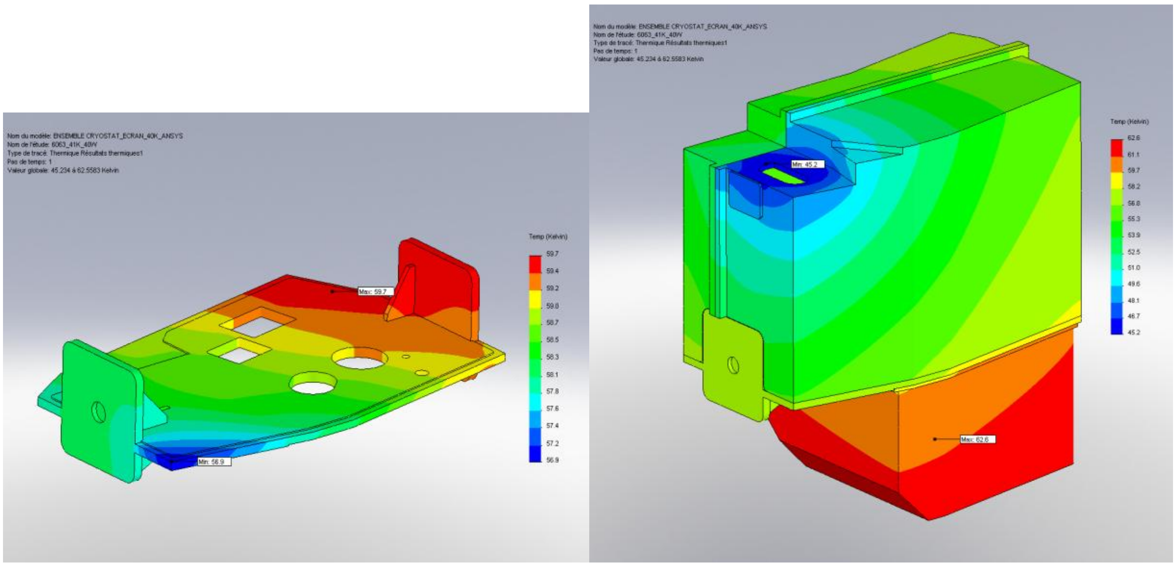


Figure 4: Thermal Gradients in the Reference plate and the first screen

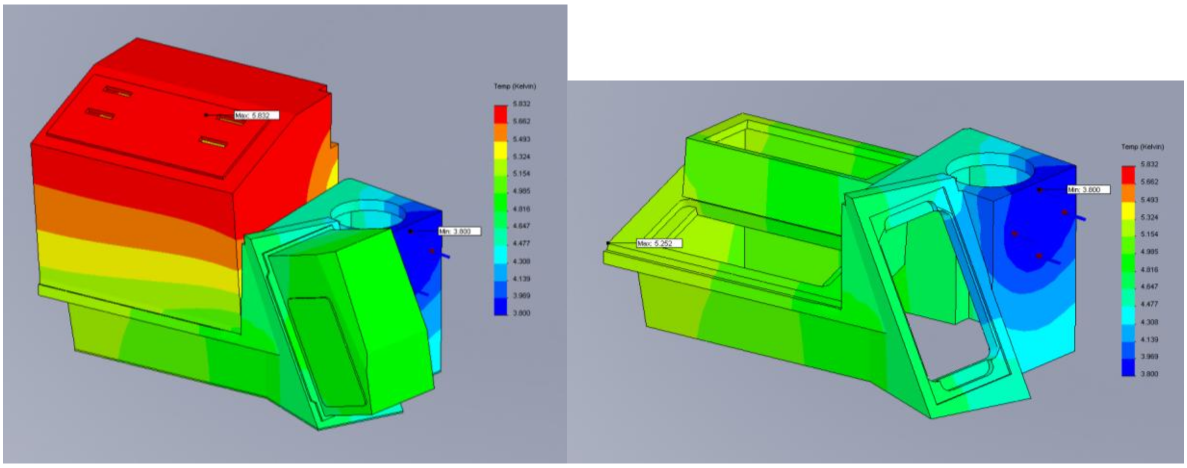


Figure 5: Thermal Gradients in the 4K screen

3) CRYOGENICS

After having been tested in a cryostat with liquid He bath, the He4-He3 sorption cooler, intended to cool the focal plane detectors, has been placed in a cryostat called Cryolic which is equipped with a PT 415 Cryomech pulse tube (see figure 6). The PT 415 cools a cooper plane which in turn thermalizes the condenser of the refrigerator.

By applying respectively 1 mW power on the He4 stage and 20 µW on the He3 stage of the cryo-cooler, the temperature of the He3 stage reached 290 mK to be compared with 288 mK obtained with the cryostat with liquid He bath. This good result was obtained by putting super insulation on evaporators. Autonomy tests were made. Results showed that the autonomy degrades drastically from 17.5 hours to 7.5 hours when the condensation of the cryo-cooler is made with a cold plane respectively at 4.2 K and 4.8 K. In the later case, the temperature of the He3 stage increases by about 10 K. This strongly points out the need to maintain the cold plane at a temperature as close as 4.2 K as possible, thus using a powerful pulse tube.

Influence of the pitch angle on the pulse tube and the cryo-cooler was also measured. Angles in the range [-45°; +45°] with 20° steps have been applied. The temperature of the cold plane and of the He3 stage increased by 0.2 K and 2 mK respectively (see figure 7); This is acceptable for both. This good result is due to the use of a particular foam, named ''Procelit'' which maintains the liquid in contact with evaporators during tilting.

Figure 6: Cryo-cooler inside the Cryolic cryostat.

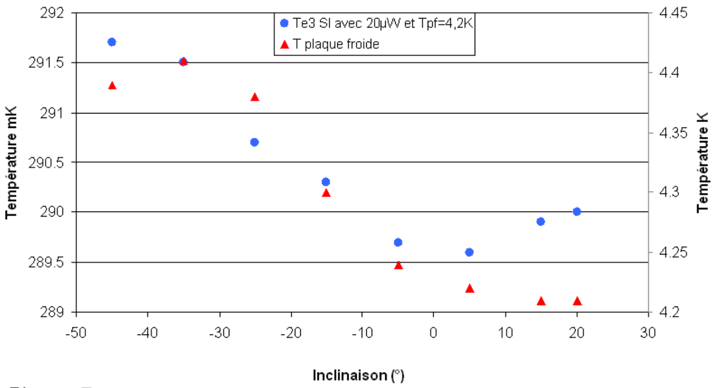


Figure 7: Pitch angle effect on He3 stage temperature (circles, left scale) and cold plane temperature (triangles, right scale)

4) OPTICS

Optical design of ArTeMiS has been conducted using 2 basic principles:
1) The optimization of the ArTeMiS sensitivity requires minimization of stray light which can be achieved by limiting the useful beam ''etendue'' with cold diaphragms. To achieve this, the optical design has to produce an intermediate image plane and an image of the telescope pupil inside the cryostat, both of good quality.
2) The high constraints on the ArTeMiS room allocation lead to use biconic toroidal mirrors in the optical design.
Aiming at achieving diffraction limited images with a uniform PSF within the whole FOV (see **Table 1**), and with low distortion rates, ArTeMiS now includes:

- A folding mirror F3 linked to the Cassegrain cabin. This retractable mirror is adjustable in tilt, through 2 mechanisms, to match the optical axis of the telescope and the ArTeMiS camera.
- A Fore Optics working at room temperature. It is composed of one additional folding mirror and 2 toroidal

mirrors. The Fore Optics provides a diffraction limited image of the focal plane in an intermediate image plane inside the cryostat. The Fore Optic is considered as a rigid subset adjustable, in laboratory, with respect to the ArTeMiS cryostat with 6 degrees of freedom.

- A cryostat including the cold optic, mainly 2 sets of 3 toroidal mirrors with additional folding mirrors for the 200 µm channel, and the set of filters. The cold optic provides 2 images of the telescope pupil to locate cold stops. Inside the cryostat two dichroic plates, DP1 and DP2, are required to separate the 3 channels. The optical paths at 200µm and (350µm & 450µm) are split by the first dichroic plate DP1 working at 40 K. The 200µm beam is transmitted while the 350µm & 450µm beams are reflected. Then the 350µm beam is reflected, and the 450µm transmitted, by the second dichroic plate DP2 working at 4K.

See **figure 8** for the 450µm optical path and **figure 9** for the set of filters in the case of the 350 µm/450µm beams. For sake of clarity, the 200µm channel is not represented in these pictures. The principle is the same as for the 450 µm one. Two additional folding mirrors, located just after the DP1 dichroic, bring the cold 200 µm optical path, in a parallel plane, beside the figure. At least a third folding mirror folds the beam roughly perpendicular to the figure till the 200µm array.

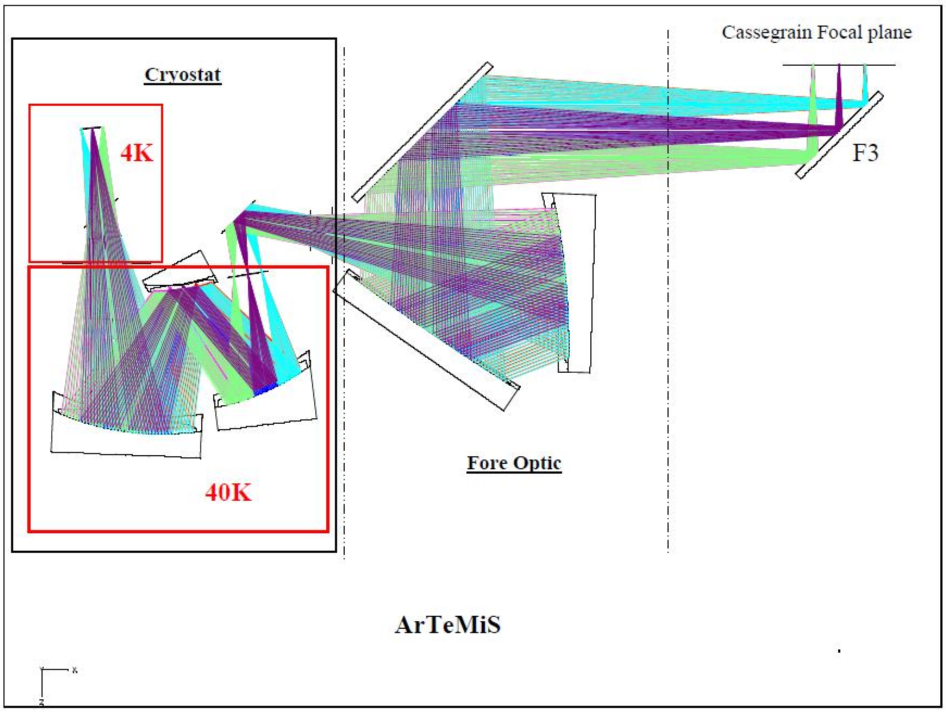


Figure 8: ArTeMiS optical layout for the 450µm beam

▫	PFOV Arcsec²	FOV Arcmin²	Array
450 µm	(3.87) ²	2.58 x 4.72	2 x 4
350 µm	(3.87) ²	2.58 x 4.72	2 x 4
200 µm	(1.72) ²	1.146 x 1.05	2 x 2

Table 1.

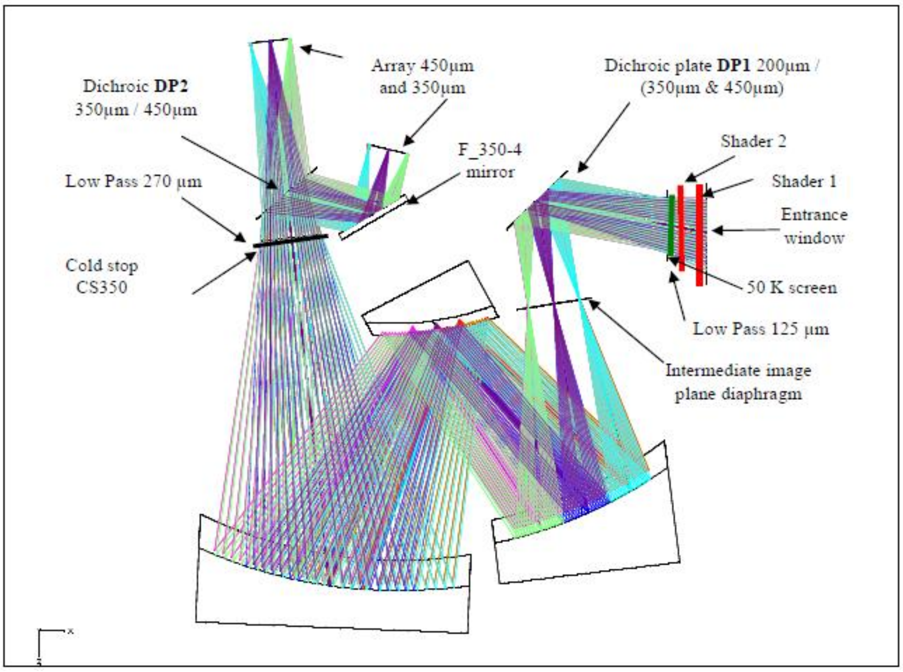


Figure 9: View of the cold optical path for the 350μm/450μm beam inside the cryostat

Inside the cryostat, 2 alignment tools are implemented: a lens alignment at the CS350 (350μm/450μm cold stop) location and a specific diaphragm located at the intermediate image focal plane. These components require a dedicated cold mechanism to remove them during observations. They are required to align the cold optic optical axis with the Fore Optics optical axis during alignment test in laboratory, and to check ArTeMiS with the optical axis of the telescope.
All the components, mirrors and optical bench, will be realized in aluminum alloy to provide a shrinking, during cooling down, as much homogenous as possible. At sub millimeter wavelengths, the mechanically accuracy is large enough that no settings are required for the mirrors.

A stray light analysis is under progress to define the location of baffles, if required, especially for the 350 μm beam.

Before delivery at the APEX telescope, many tests will be performed in laboratory:

- Pre alignment, in real temperature conditions between the Fore Optics and the cold optic of the cryostat.
- With the help of a telescope simulator, the image optical quality will be checked as well as the stray light level.
- The shift of the image of a fixed point source due to the cryostat deformations, as a function of the tilt with respect to a virtual elevation axis, will be measured. These measurements will be used as a corrective term during observation on telescope.

5) BOLOMETERS

While the delivery of the first ArTeMis bolometer arrays is scheduled for the end of 2010, preliminary measurements have been performed on similar arrays developed for the PILOT balloon-borne project. Indeed, the detectors for the PILOT short wavelength channel will work in the same wavelength range (240 microns) and flux range (20-40 pW/pixel) than the ArTeMiS detectors.

Figure 10 shows the responsivity of one PILOT detector for an incident power of 20 pW/pixel at 350 microns. The error bars in the figure shows the standard deviation of responsivities among the 256 pixels of the array.

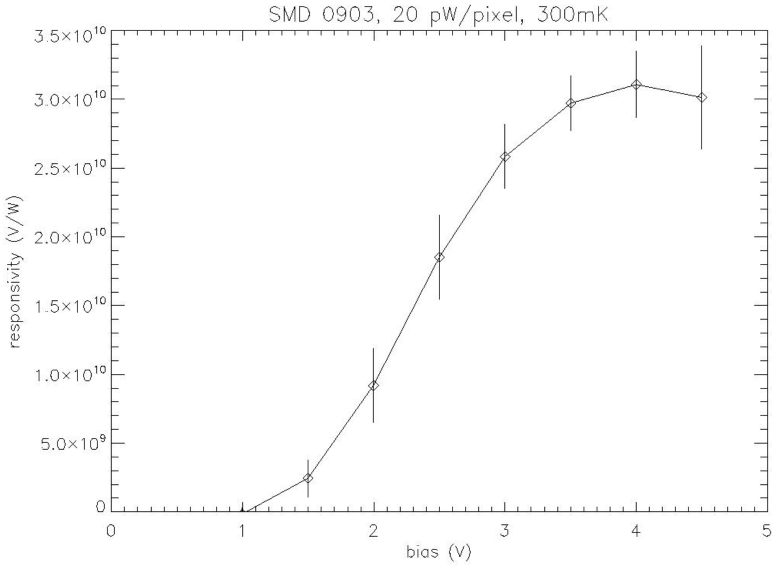


Figure 10: Responsivity of a PILOT type bolometer array at 350 microns

Compared to Herschel/PACS in space conditions, the PILOT and ArTeMiS bolometers have higher impedances to cope with the higher incident fluxes from atmosphere. In parallel, the bolometer pixels are using thicker indium bumps to make a deeper absorption cavity to cope for the longer wavelength. It is noticeable that the responsivities obtained on figure 10 are very close to those measured for Herschel/PACS bolometers.

On-going measurements are performed to measure the noise and NEP, as well as the bandwidth. More quantitative results will be given as soon as new arrays are received.

6) ELECTRONICS AND SOFTWARE

The development of electronics for ArTeMiS is almost completed. We are presently manufacturing and integrating hardware.
The cold front end electronic NABU (New ArTeMiS Buffer Unit architecture, based on CMOS technology) has been validated in a 4 K environment. We have changed the mechanical and thermal coupling between the silicon chip and the interface board and we are presently validating these changes before moving to production.
The warm electronic acquisition part: BOLERO (for Bolometer electronic readout box) has been validated in real conditions of observation during the Proto-ArTeMiS 2009 campaign. All features are functional (sequencing and detector biasing, analog acquisition and data transfer to the computer). The noise of acquisition chains is consistent with specifications ($<1\,\mu V/\sqrt{Hz}$ noise).
Other electronic boards BAB (Bolometer acquisition board) and BIAS (Bolometer biases and clock) of BOLERO are now available. We have started the testing phase. The whole acquisition electronics of the camera will have consisted in 60 electronic cards.
Design of the mechanical packaging of BOLERO has been done so that we should start soon the final integration (see **figure 11**).

The software development for the camera is still under progress. During the 2009 Proto-ArTeMiS run on APEX, the new BEAR software mounted on a Linux PC was used with 1 BOLERO through USB link. The setting of the detector and the images acquisition have worked very satisfactorily. Some unexpected synchronization problems with the APEX software have convinced us to use a GPS dating of the ArTeMiS frames thanks to an IRIG-B signal available on APEX. Indeed, the APEX telescope uses an IRIG-B format for absolute dating of all telescope instruments. On BOLERO, all the digital part (MISE board) which manages commands, sequencing detectors phases, acquisition of ADC and packaging data for transmission to the computer is implemented in two Xilinx Spartan (**figure 11**). Then, we had to develop a VHDL IP for decoding IRIG-B signal so that we flag now all image packets with this new dating reference.

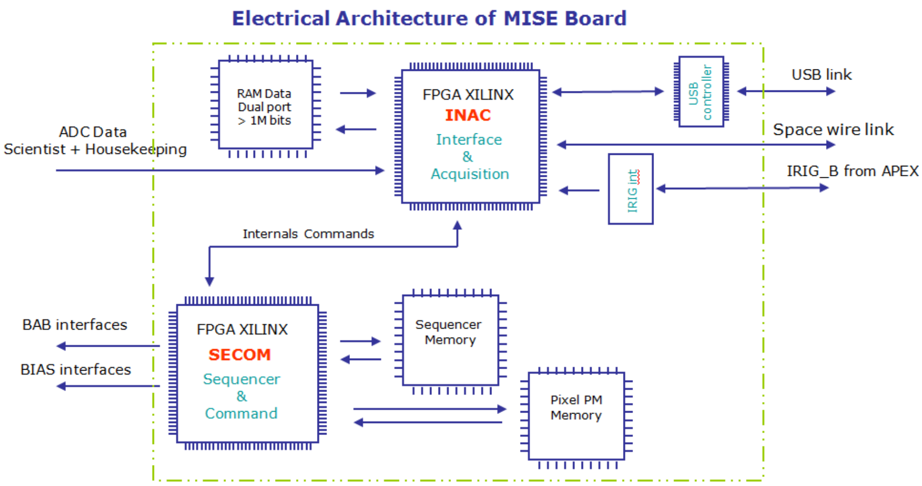
The new following functionalities have already been added:

- Communication with BOLERO through Space Wire link.
- Software functions to handle data fluxes from 10 BOLEROs and to build the images corresponding to the 3 focal planes.
- Use of threads to handle the UDP and TCP links with the APEX software within the C++ task
- New on-line display of the focal plane images for monitoring purpose.

The following items will be included soon:

- Handling of a start flag in the data to synchronize the frames coming from the different BOLEROs.
- Decoding of the IRIG-B dating.
- Getting housekeeping data from the cryogenic control-command software.
- Handling of focal plane housekeeping data from COYOTE box.
- Image offset compensation in BOLEROs.

Finally, the choice of an industrial PC with SSD hard disk will be done.



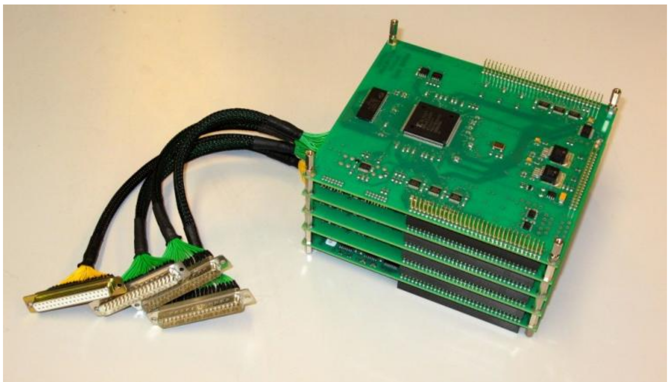


Figure 11: Final BOLERO electronic arrangement

7) COMMAND CONTROL

The global architecture of the command control of the camera (see figure 12) is based on a standalone programmable Logic Controller (PLC) that controls the cryogenic equipment with high robustness, and an industrial PC that performs archiving and communication tasks. This PLC verifies communication status of probes and sub-units ; controls out-gazing of the cryostat ; controls cooling down to 4K (or warming) according to specified procedures (including vacuum, pulse-tube and cryocooler control, temperature measurements…).

The industrial PC (Cryostat control and measurement PC) is a fan-less computer and low power consumption. The industrial PC provides one industrial compact flash memory where are stored Operating System (OS) and datas. The OS is Windows embedded standard.

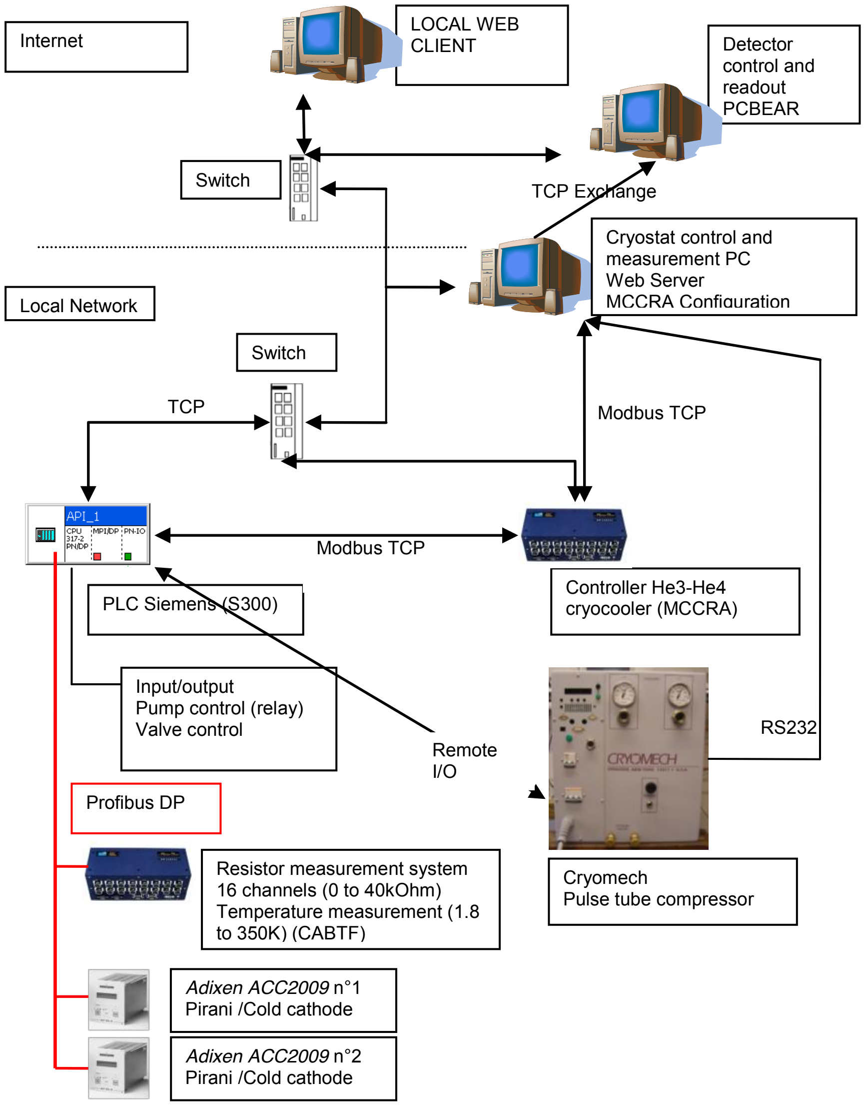


Figure 12: Global architecture and interface diagram of Command – Control

8) LATEST RESULTS OBTAINED IN 2009 WITH Proto-ARTEMIS

The first results obtained with Proto-ArTeMiS during the 2007 run on APEX have been published (André et al, 2008). They illustrate the ability of the camera to reveal embedded sites of high-mass star formation in the Galaxy. In particular, seven massive protostellar sources have been clearly separated along the NGC 3576 filament. These include four very young (class 0) protostars with estimated final masses M* ~15-20 M_{sun}. Proto-ArTeMiS also revealed ten massive cores in another region (G327.3-0.6). It has been proposed that these were the result of a shock between two expanding HII regions (Minier et al, 2009).

Ongoing wide-field surveys with the Herschel Space Observatory are revealing a profusion of filaments in Galactic molecular clouds (André et al. 2010, Men'shchikov et al. 2010, Molinari et al. 2010). The future ArTeMiS camera will help to map the internal structure of the densest filaments in detail. For example, during the 2009 observation run (Program ESO 083.C-0996 by P. André et al.), such a region, G305.2 located at ~ 3.3 kpc (Hill et al. 2005) has been mapped with proto-ArTeMiS. The resulting image shows several candidates of massive protostars (**figure 13**).

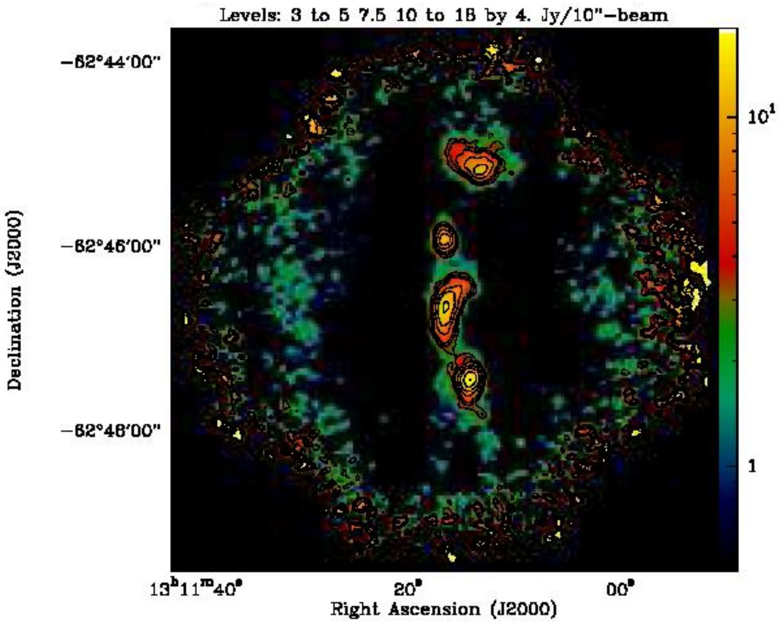


Figure 13: Total-power 450 µm dust continuum map of the massive, filamentary star-forming region G305.2 observed with Proto-ArTeMiS.

The Circinus molecular cloud located at d ~ 0.7 kpc (Reipurth et al. 1996) has also been observed with Proto-ArTeMiS during 2009 (Program ESO 083.C-0996 by P. Andre et al). The Proto-ArTeMiS map resolves a group of at least 7 protostars in this region of low- to intermediate-mass star formation (**figure 14**).

Outside our own Galaxy, during the same observational run (Program ESO 083.C-0994 by S. Hony et al), we could observe the N159 star-forming complex in the Large Magellanic Cloud located at d ~ 50 kpc (**figure 15**).

The scientific exploitation of these various results from the 2009 run is still in progress.

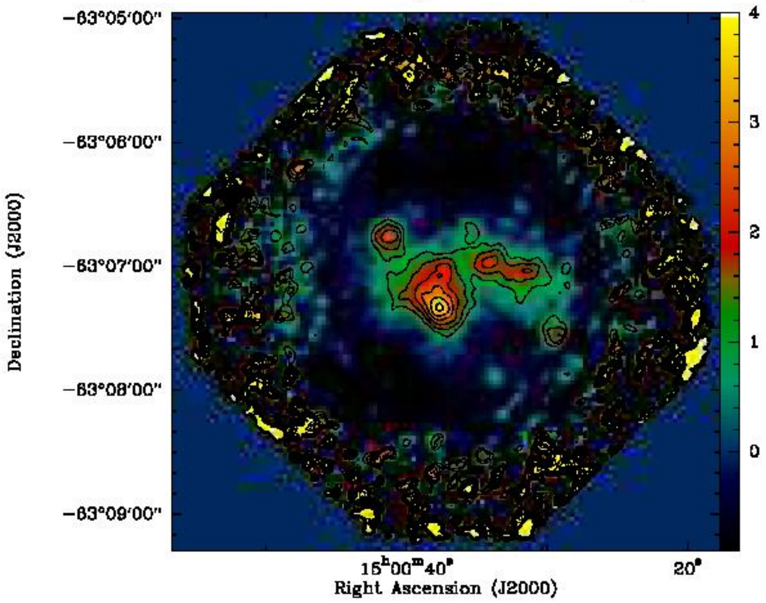


Figure 14: Total-power 450 µm dust continuum map of a dense core in CirMMS1.

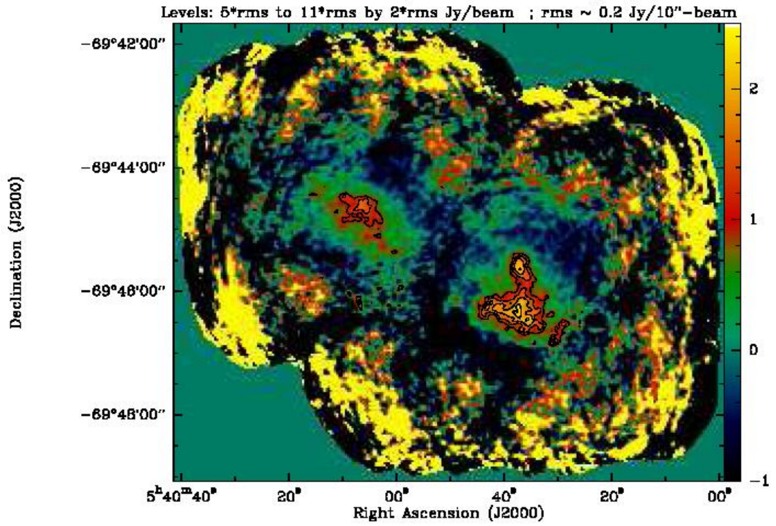


Figure 15: Total-power 450 µm dust continuum map of N159 in the Large Magellanic Cloud

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