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Operational challenges for astronomical instrumentation in Antarctica. Results from 5-years of environmental monitoring of AMICA at Dome C.

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ABSTRACT

The Antarctic Plateau is one of the best observing sites on Earth, especially for infrared astronomy. The extremely low temperatures (down to -80 C), the low pressure (around 650 mbar) and the very dry atmosphere (PWV less than 1 mm) allow for a very clear and dark sky, as well as for a very low instrumental background. These unique properties, however, make it also very difficult to install and operate astronomical instrumentation. AMICA (Antarctic Multiband Infrared CAmera) is an instrument especially designed for Antarctic operation, whose installation at Dome C has been completed in 2013. Since then it has been continuously working over the last five years, monitoring and controlling in particular the environmental and operating conditions through a dedicated application, its Environmental Control System (ECS). The recorded behavior of AMICA highlighted a set of peculiar aspects of the site that are hard to consider *a priori*. Although mechanical and electronic COTS components can reliably work in thermally insulated and controlled boxes, simple insulation causes their overheating because of the air dryness and rarefaction which make the heat transfer extremely inefficient. Heat removal is also a real problem when managing heavy-duty devices like cryocoolers, whose excess power removal needs to be fast and efficient. Finally, the lack of an electrical ground generates a wide variety of transient electrical and electromagnetic phenomena which often make electronic instrumentation very unstable. A list of new recommendations is therefore presented, as a guideline for future astronomical instruments operating in Antarctica.

Keywords: Antarctica, Environmental conditions, Astronomical instrumentation, Infrared camera

1. INTRODUCTION

Over the last twenty years an increasing number of experiments and devoted measurements have been revealing the great potential of Antarctic high plateau sites for astronomy, especially at infrared wavelengths[1][2][3]. Thanks to the low temperatures, indeed, thermal background emission from both the atmosphere and the instrumentation is substantially reduced. Low pressure and extreme air dryness increase the overall atmospheric transmission at infrared wavelengths and make it extremely stable[4], with new atmospheric windows that are opened, in particular beyond 15 μm, while the transmission and width of the existing ones is much higher than at temperate sites – for example, the high wavelength tail of the K-band.

Site testing campaigns have been carried out at several sites during the last years: South Pole and Dome C [75°06 S, 123°23 E, 3250 m][5][6][7] are now recognized as excellent infrared astronomical sites[4][8] and very promising for the future installation of large telescopes[9]; Dome A [80°22 S, 77°21 E, 4084 m] is still being extensively studied[10][11] although first astronomical optical observations are reported there[12]; Dome F [77°19 S, 39°42 E, 3810 m] has been studied for the installation of a medium-size telescope[13]; and finally, Ridge A (about 90 miles far from Dome A, at an elevation of 4050 m), defined as "the coldest, driest, calmest place on Earth", is claimed as the possible best astronomical site on the terrestrial surface[14].

On the other hand, the same climatic conditions responsible for the astronomical excellence of these sites also represent a serious drawback on human activities and instrumental endurance. In fact, the excellent features of Antarctic high plateau sites for infrared astronomy can be exploited only with *winterized* and *automatic* instrumentation. The need for a correspondingly adequate logistic support puts serious constraints on the sites were astronomical facilities could be currently developed: out of the above-mentioned sites, indeed, only South Pole and Dome C are provided with permanent and well-developed Bases, while Dome A is provided with a basic logistical installation only.

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The Concordia Base has been established at Dome C starting from 1996, and opened for winterover in 2005. It ensures the availability of a large number of facilities for the permanence of the personnel, the visiting researchers and the hosted scientific experiments and can provide a total electrical supply of 200 kW (shared among all scientific and logistic needs).

Basing upon this situation, the Project to install and operate an infrared telescope at Dome C has been developed at the beginning of 2000s[15][16], and named ITM (Infrared Telescope "Maffei"). It is a 80 cm aperture Cassegrain telescope that, according to the theoretical models, is expected to have the same sensitivity of a 3-m class telescope located in a temperate site[17]. AMICA (Antarctic Multiband Infrared Camera) is the camera for near- and mid-infrared astronomical imaging (2 – 28 μm) which has been mounted at the Nasmyth A focus of ITM at the end of 2012[18,19,20]. A view of the ITM telescope and its control building, with Concordia Base main buildings on the background are shown in Figure 1.

Commissioning of AMICA has been carried during the three years following its installation, revealing difficulties and problems which are peculiar of the Antarctic site.

In this paper a brief overview of the AMICA instrument is provided, with particular reference to its local management system, able to provide an extensive set of operational and environmental monitoring data. Results of this monitoring activity over the last five years (i.e. starting well before the final installation of the instrument) are discussed with a general presentation of the major issues encountered. A list of "lessons learned" is finally presented, with the aim to provide important hints for the design, construction, installation and operation of future Antarctic instrumentation.

Figure 1 – The Infrared Telescope Maffei (ITM), hosting AMICA at its Nasmyth A focus, and its control building at Dome C, Antarctica. On the background, the two main buildings ("noisy" and "silent" tower) of the Concordia Base are visible.

2. THE ANTARCTIC ENVIRONMENT

Antarctica is widely acknowledged as an *extreme environment*. Inner sites like Dome C, Dome A, Vostok lie on the large, flat top of the polar ice cap, at elevations above 3000 m (for this reason they are usually called high-plateau sites). Local temperatures are extremely low, normally ranging between a maximum around –25 °C in summer and a minimum that normally reaches –75 °C but sometimes goes down to –85 °C. At these temperatures, the effect of wind chill (which is present for both human operators and instrumentation) is dramatic, normally lowering the "felt" temperature by at least 10 degrees. Some exceptional episodes have been recorded, like the one of winter 2012, when the physical temperature was –76 °C but, due to a wind speed of 15 m/s, the sensed temperature was around –105 °C.

Thermal differences on instruments can be much higher than the date reported above. During summer and in the absence of wind, sunshine can heat surfaces to temperatures close to the ice-water equilibrium one, that is even a few positive Celsius degrees. Instrumentation can therefore undergo thermal excursion up to 100 °C during the year.

The low air temperature, together with the terrestrial shape at the poles, is also responsible for an additional drop of the atmospheric pressure which, for example, is around 630 mbar at Dome C, for an equivalent elevation of ~3900 m. The atmosphere is extremely dry, because of the condensation of most of the water vapor, with the relative humidity (RH) that can be as low as 15%.

All these features have important consequences on both instruments and operators. The average temperature during the long Antarctic winter is well below the minimum recommended temperature for operation and storage of the majority of commercial devices. On the other hand, the very reduced heat transfer by convection and conduction leads electrically powered instrumentation enclosed in thermally insulated boxes to surprisingly overheat and to creation of strong thermal vertical gradients in the absence of forced air circulation (see next section). Also, the extreme air dryness implies the serious risk of damages to instrumentation (and injury to operators) caused by static discharges[21], while the air rarefaction corresponds to a non-negligible reduction of oxygen, which has effects on operators efficiency.
Finally, because of the high-latitude, near-pole location of these sites, they are inaccessible for the majority of the year (~9 months) and geostationary telecommunication satellites are visible there only at very low altitudes (a few degrees) above the horizon. This has important consequences on maintenance procedures and efficiency of satellite data transfer in time and speed, that is the efficiency of remote control actions.

From the astronomical point of view, the advantages of Antarctic sites for infrared astronomy (thanks to the very low water vapor content, the very efficient passive cooling of the instrumentation and the reduced thermal background of the atmosphere) have already been highlighted in the previous section. An additional advantage is offered by the high latitude that makes a large portion of the sky circumpolar (declinations below $\delta = -15°$ from Dome C and $\delta = -10°$ from Dome A). Finally, the presence of a quasi-permanent area of high pressure on the inner regions of Antarctica makes the skies clear for a very large portion of the year. The resulting duty cycle for astronomical observations is very high at all wavelengths, with the relevant result to reach in principle a 100% yearly duty cycle at infrared wavelengths, especially at $\lambda > 4$ µm.

3. AMICA AND ITS ENVIRONMENTAL CONTROL SYSTEM

AMICA[18] is a double-armed camera designed to perform photometric imaging in the 2 − 28 µm spectral range (K, L, M, N and Q bands) by using two distinct detectors, a 256 × 256 InSb array for the 2 – 5 µm band (NIR) and a 128 × 128 BIB Si:As array for the 5 – 25 µm band (MIR). A single optical system alternatively feeds the two detectors, with diffraction-limited performance. Plate scales of 0.538 arcsec/pix and 1.345 arcsec/pix, with FOVs of 2.29 × 2.29 arcmin^2 and 2.89 × 2.89 arcmin^2 are achieved onto the NIR and MIR detectors, respectively. Optical system and detectors are placed inside a cryostat that also hosts two high-vacuum, cryogenic stepper motors needed to move a filter wheel and a switching mirror. Cryogenic conditions are ensured by a pumping system and a closed cycle cryocooler, which allows to reach ultimate temperatures of 29.68 K and 5.08 K on the MIR and NIR array, under Antarctic conditions (T –70 °C) outside the cryostat. The power consumption of the cryocooler is 6 kW at start-up and only 4.9 kW in steady state. These data are crucial for operations in Antarctica, were the power supply constraints put by the logistics are somewhat striking. In particular the excess power is removed by a glycol-based closed-cycle system, provided with a liquid de-rotator installed around the ITM azimuth axis. It has been designed and built together the CAMISTIC bolometer array, the other ITM far-infrared instrument mounted at the Nasmyth B focus of the telescope[22].

The unique features of AMICA are its *winterization* and *automation*. With respect to an infrared camera for a mid-latitude site, that is usually provided with control and readout electronics and additional devices for controlling several parameters like the vacuum level, the temperature of the detectors and other cryogenic devices, the position of a filter wheel and so on, AMICA has an additional system that, in turn, controls and manages the operating conditions of the above-mentioned controllers. These are indeed all placed inside thermally insulated and controlled racks (Figure 2), with the exception of very few passive components, able to work at external temperatures, and the cryostat which is kept outdoor in order to minimize the thermal input on the cryogenic chamber. This choice for the design of AMICA allowed to refer to commercial devices only by taking into account their long-period reliability, their connectivity with both the data network and the power supply network, and their size and mass, so making the overall volume as small and light as possible, optimizing the power needed to keep its operating conditions and significantly reducing the construction and maintenance cost with respect, e.g., to space-qualified components.

Figure 2 –AMICA mounted at the Nasmyth A focus of ITM. The cryostat (red box) is kept outdoor in such a way the thermal input is extremely reduced and the benefits of the Antarctic environment for infrared observation are fully exploited. All other sensitive devices are hosted inside thermally insulated and controlled racks: a main rack (the white box at the bottom) hosting all the control subsystems, plus three small boxes (covered with a reflecting thermal insulator in the figure) hosting the cold-head, the cryostat vacuum valve and the proximity modules of the readout electronics system.

An active control system, called AMICA ECS (Environmental Control System) has proven necessary because of the continuously changing conditions around AMICA. In spite of its thermal insulation, indeed, the rack hosting the AMICA subsystems cannot keep the operating conditions even with an internal dissipation of 750 W naturally due to the powering of the hosted devices. The AMICA ECS is based on an extended set of PT100 temperature sensors, one relative-humidity gauge, various heaters and fans, all handled by a local control cPCI computer and by a Programmable Logic Controller (PLC). The aim of ECS is to monitor and stabilize the operating conditions inside the cryostat and in each thermally controlled rack. In case of vacuum failures, or when the temperature or humidity in the racks approach critical values for even only one component, appropriate correcting actions are undertaken.

The main rack is shown in Figure 3. It was originally moved to Antarctica in December 2010 and installed in a container for testing during the 2011 winter campaign[23] (see next section).

The general electrical board powers all the devices and automatically switches them on or off. It receives a 380 V 3-phase power that is partly used for the cryocooler. The remaining power is split in three 220 V single-phase lines and distributed to the devices. The most relevant components of this board for ECS operations are the PLC and its expansions, that read all environmental, cryogenic, vacuum and management data, and a MTME digital multimeter used to read all the electrical parameters of interest.

Beyond the electrical board are all hosted devices, including readout electronics, central PC, vacuum and cryogenic control systems, network communication devices. Each component is provided with at least one PT100 temperature probe and at least one 50 W heating strip.

Possible overheating situations are faced by means of couple of pipes connected to the external environment. Each pipe is provided with two opposite fans that work alternatively, thus allowing each fan to inlet cold air or outlet hot air, and also to self-cleaning from undesired snow. Moreover, the two pipes in each couple always work in opposite directions, so one pipe enters external air while the other pushes out the internal one.

The central zone of the main rack is provided with environmental heaters devoted to keep the system in safe conditions when all the devices are turned off and to eventually support local heaters in case of excessive cooling. These environmental heaters are 100 W heating strips placed mainly on the floor, in specific points.

Finally, the air dryness and low pressure and the subsequent poor heat exchange in such a large size zone are responsible for the generation of a strong vertical temperature gradient (up to more than 40 °C across 1 m height). This is damped to a few degrees by means of forced air mixing, provided by a set of fans placed in specific points determined upon design considerations and then confirmed by laboratory tests in a climatic chamber. These fans are of always working, even when the devices are turned off and only the environmental heaters are going.

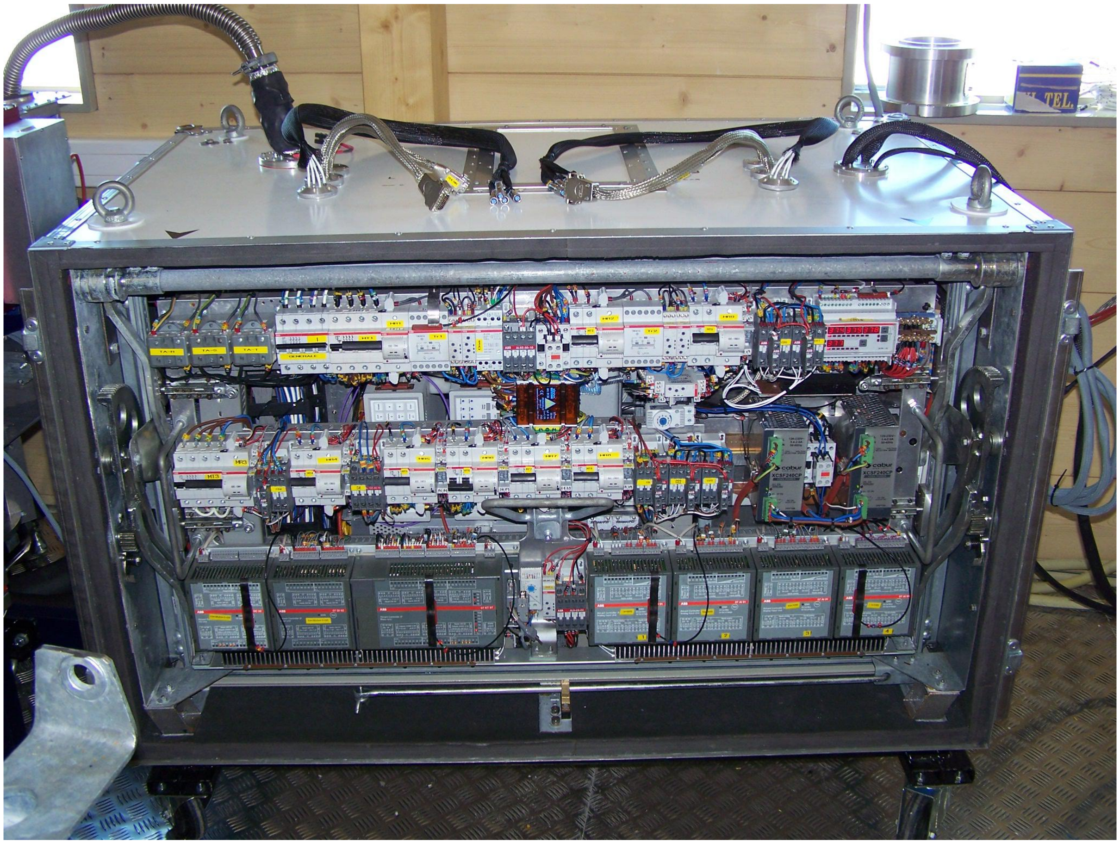

Figure 3 – The AMICA main rack, hosting the Environmental Control System (ECS). This is based on a PLC, aimed at monitoring and controlling the environmental conditions inside the rack plus the operating conditions inside the cryostat (cryogenic temperatures and vacuum level), plus a digital MTME multimeter aimed at recording all the electrical relevant parameters. They are mounted on the electrical board visible in the figure. It can be moved apart to allow easy access to the AMICA subsystems beyond it. These are all the sensitive devices aimed at managing the detectors readout, the cryogenic and vacuum conditions, as well as the general network communication both inside the rack and with external operators.

The Environmental Control Software (ECSW) manages the PLC, provided with an independent firmware, and the central PC hosting the main environmental control software. The evaluation of the environmental conditions which allow a safe boot of the system is previously assured by the PLC initialization procedure. Once the operating parameters are within the safety boot condition, the PC is turned on and the environmental control software is started. This module periodically checks the environmental conditions by sending a query via a RS232 port to the PLC, which monitors the electrical parameters, reads the PT100 sensors and controls fans and heaters inside the rack. The module also controls the full camera operating conditions, including the temperatures inside the cryostat, the status of the two detector heaters, the position of the filter wheel and the switching mirror, the vacuum level and some status parameters of the vacuum system, and finally a set of parameters concerning the cryocooler, especially the temperature of the compressor and the coldhead, the conditions of the oil compressor and the helium pressure, the temperatures of inlet and outlet refrigerating glycol.

Nr	Description	Sampling	Output file (.dat)
10	Cryogenic temperatures inside the cryostat	10 sec	ECScryo*YYYYMMDD*
2	Power dissipated by the detector heaters inside the cryostat	10 sec	
2	Vacuum pressures in the cryostat (redundant gauges)	10 sec	
8	Vacuum system status parameters	30 sec	ECSpump*YYYYMMDD*
1	Safety electromagnetic vacuum valve status	30 sec	
2	Cryogenic motors status parameters	30 sec	
31	Electrical parameters as read by digital multimeter	60 sec	ECSmtme*YYYYMMDD*
33	Environmental temperatures on the AMICA subsystems	30 sec	ECSenvi*YYYYMMDD*
16	Heaters status for the AMICA subsystems	30 sec	
56	Digital inputs status	30 sec	
56	Digital outputs status	30 sec	

Table 1 – Parameters monitored and controlled by ECS. The sampling times are different according to both the typical change time of the parameters and the reaction time in case of failures. The fastest sampling is for vacuum and cryogenic parameters in the cryostat, in order to reduce the risk of damages in case of vacuum failure at cryogenic conditions.

A total of 217 parameters are monitored at least once per minute, as specified in Table 1. The data are written in four separate output data files, named *ECScryo* (for the cryostat parameters), *ECSpump* (for the vacuum parameters), *ECSmtme* (for the electrical parameters, read by a MTME digital multimeter) and *ECSenvi* (for the environmental parameters) and newly created once per day. Within the same date, new data are simply appended to the corresponding, already existing file.

It appears from the last two rows of Table 1 that the set of recorded telemetries refers to environmental and operational monitoring data, as well as to every change occurred in the overall configuration of the system as a consequence of an automatic action. It provides therefore a detailed history of both the monitoring and the automatic control performed onto the system.

4. ECS MONITORING IN 2011-2015. REAL ANTARCTIC BEHAVIOR

Five test runs were performed during 2011, starting at the completion of the installation (2010-2011 summer campaign) and finishing at the end of the winter campaign. Telemetry data were acquired for 120 days, mostly under 100% duty cycle (24h/day). Since many devices were still to be installed and connected, the telemetries included only 192 parameters continuously recorded plus an additional vacuum pressure recorded only during some pump activation tests. More than 250000 samplings were performed, for a total of more than 55 million engineering data recorded. A detailed analysis of them is reported by Dolci[23].

The system was kept under maintenance conditions (i.e. without active control) during the 2012 winter campaign. After the complete installation of AMICA at ITM, the system was finally operating at full regime since January 2013 to December 2015. Only a few corrective maintenance actions were recorded during this period, none of them being of relevant importance. In particular, no vacuum problems were reported for the cryostat (which has never been opened in the period) or for the cryogenic performance.

Relevant upgrades were made, however, during the 2013-14 and the 2014-15 summer campaigns. In the first case, in particular, a second PC was installed to be completely devoted to run the ECS software only, while the original PC was left to manage the detector readout system only. This allowed to greatly improve the ECS performance, by almost completely suppressing the system crashes that had been mostly caused by the concurrent activities of the two control systems on the same PC. Results of environmental monitoring data for these years do not differ from those presented in 2012[23] and will not be discussed here in detail. The only important aspect to mention is the improved time coverage for telemetries recording by ECS, which has never been lower than 98 % in this period.

In general, although ECS showed a very good behavior of both itself and the system "winterized" design, it has been possible to observe a series of general "new" problems essentially related to the site, in particular from the electrical, electromagnetic and thermal point of view.

Table 2 shows a summary of the most relevant problems observed. For each of them, a generic "occurrence frequency" and a more detailed explanation are provided. These are based on the direct experience on site. The most important common causes derived from these observations seem to be the large thermal gradients over all time scales and the absence of an electrical ground (due to the 3000 m thick ice layer on the Antarctic Plateau) which prevents natural dampening of electrical and electromagnetic disturbances on the power and communication lines.

Observed problem	**Occurrence Frequency**	**Explanation notes**
Strong noise on power supply network	Almost continuous	The noise seems to be produced by the General Power Supplies in the Base, and not naturally disappearing because of the lack of electrical ground.
Structured electrical disturbances on power supply	Very frequent	The disturbances are injected locally by ITM motors, CAMISTIC cryocooler and other AMICA devices, and remotely by "spiky events" (e.g. start-up of a heavy-duty device) by other experiments at Concordia.
Voltage spikes, electrical shocks, general shutdown	Rare	Related to the Power Supply Units in the Base and the lack of electrical ground.
Network connections down	Poorly frequent	The problem seems related to peculiar environmental and electrical conditions in the Base.
Radio-frequency disturbances	Frequent	RFI have been observed in some cases. They seem produced by electrical and electronic devices in the Base. Influence from Earth's Magnetosphere effects has been evaluated and seems too low to be important at the observed levels.
Cryogenic system hangs	Increasing with time	The cryogenic performance (final temperatures and cooldown times) has been constant over the period. The hangs seemed all related to problems in the refrigerating liquid (glycol) circulation system, that was devoted to several systems and provided with a de-rotator based on moving parts. These problems have been impacting operations since restoring operations have sometimes been long and difficult.
Environmental parameters scarcely remain within acceptable range	Rare	Related to the high variability of the external conditions. In summer, sometimes it has been observed an overheating of devices difficult to mitigate, followed after a few hours by excessive cooling of the same devices, as soon as the system was no longer heated by sunshine or some wind got up.

Table 2 – A summary of general problems encountered during the AMICA operations at Dome C in the period 2012-2015. Foe each problem category the occurrence frequency is indicated and explanatory notes are given, mainly based on the direct experience on site.

5. LESSONS LEARNED FOR FUTURE EXPERIMENTS

The overall experience gained during the management of AMICA at Dome C in the period 2011-2015 allowed to outline a series of lessons learned that could be very useful for the design of future astronomical instruments and their operation in Antarctic sites. Eight general recommendations, to be added to what is already known about Antarctica, are reported as follows.

1) *Commercial versus Devoted Technology*. Special devices and components, in particular space-qualified ones, are not strictly necessary. Local temperate conditions, properly controlled, together with ad hoc design solutions allow to operate commercial components with high reliability and availability, with advantages on both procurement, costing and maintenance.
2) *Maintenance*. This is the real challenging aspect. Maintenance must have a central role in the design and the corresponding requirements (especially maintainability) should not be derived at system level, but as top-level requirements. A maintenance-oriented design should ideally foresee only simple LRUs or, in any case, the minimum possible number of composite LRUs. On the other side, maintenance procedures must be optimized for Antarctica by taking into account simple and fast operations.

3) *Common- and single points of failure*. Considering the need for simple and fast maintenance operations, the design should avoid (or minimize as much as possible) common points of failure and be based on single points of failure only.
4) *Stability of environmental conditions*. Although the AMICA experience has proven the technological maturity of the solutions adopted, configurations where the external temperature remains constant (or exhibits small variations) appear better to manage. To this respect, trying to keep instrumentation separated by the external air and wind appears a somewhat surprising result. However, it appears that a system where the instrumentation is separated by the telescope and kept inside the snow (Figure 4) can be a suitable solution for future instruments. Such a telescope should have a Coudé optical path, getting light below the azimuth axis at about 5 m depth into the ice, where the temperature remains nearly constant over the time and around –55 °C. Such an "instrument room" should not be insulated by the external ice and should therefore benefit of the reduced thermal input on instrumentation. Other "rooms" should be devoted to "services" (e.g. heat exchange for cryocooler refrigeration liquids) and "control" and could be thermally insulated and in case properly heated. All these rooms could be easily obtained from ISO9001 containers, as already done for other experiments in Concordia.

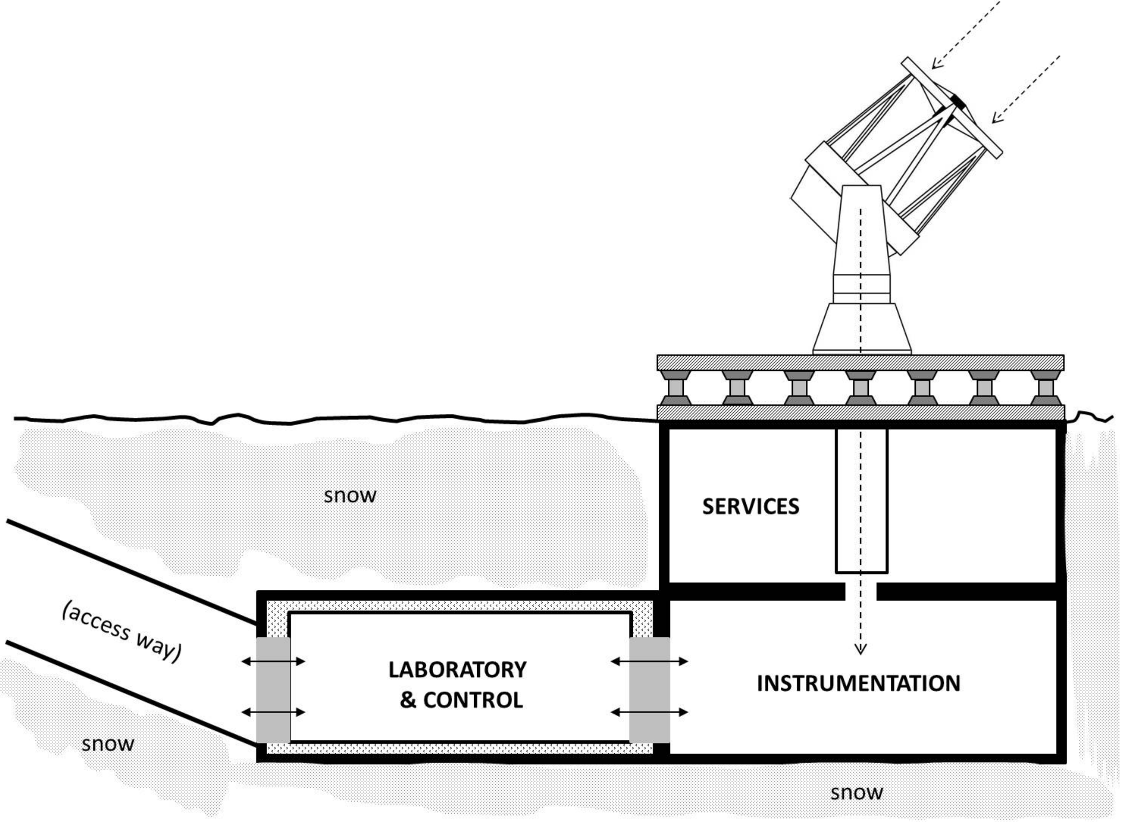

Figure 4 – A schematic view of the installation for a future astronomical telescope and instrumentation in Antarctica. While the telescope is outside, the instruments are placed in an appropriate volume (e.g. an ISO9001 container) embedded into the ice at a depth of 5 m. At this depth, indeed, the temperature remains nearly constant over all the time, keeping a value around –55 °C. The telescope should have a Coudé configuration, getting light along the azimuth axis down to the "instrumentation room" which of course should not be thermally insulated from the external ice. A "services room", placed above the instrumentation room, should be devoted to general services, like for example the circulation and heat exchange from refrigeration liquids used for cryocooler. Finally a "laboratory and control room" could be useful for fast maintenance operations and general control. Although the services and control rooms can be thermally insulated and in case heated, the permanent presence of human operators should not be foreseen. The instrumentation should anyway be automatic, with remote control and management.

5) *Lack of electrical ground*. This problem must be carefully considered during the design phase because it produces both electrical disturbances and electromagnetic interferences (EMI). In particular:
    a) disturbances that propagate on power lines can be suppressed with known devices (isolation transformers, filter banks, etc.) but taking into account the technical feasibility of production, installation and maintenance. As an example, such a UPS for a 3-phase, 50 kW line can be built but its volume, weight and thermal dissipation are very hard to manage. Rather, UPS devoted to specific single-phase lines (for example the most sensitive ones) must be used, provided they are not mutually interfering.
    b) To this respect, the infrastructure design should clearly separate (i.e. isolate) the single-phase lines devoted to sensitive devices from the lines devoted to heavy-duty devices.
    c) Such a separation should however include also a proper shielding from EMI, which should involve not only the infrastructure but also any device used in the field.
6) *Moving parts*. Given the low temperatures, moving parts should be reduced as much as possible. Alternative solutions could for example be provided for refrigerating liquid de-rotators, which should avoid liquid exchange between the moving and the fixed part. In case moving parts cannot be avoided (as in the case of a telescope), lubricants should be reduced or possibly replaced by technological solutions based on self-lubrication systems (like ceramic bearings).
7) *Personnel*. Personnel in the Base should be involved for extraordinary maintenance and daily checks only. Any other operation, for both science (astronomical data acquisition) and engineering (monitoring and control) should be remotely performed, through satellite link, by operators in the involved countries.
8) *Training*. Training of personnel, especially for maintenance operations, must take into account the unique features of the Antarctic sites, in particular the reduced oxygen content, the long isolation (9 months) and the duration of the Antarctic night (more than 3 months in Dome C). All these factors affect the psychophysical parameters, in particular lowering the capability to concentrate, to remember complex sequences of operations and to pay attention to too many details.

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