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Telescope and instrument robotization at Dome C

K.G. Strassmeier[1,⋆], **K. Agabi**[2], **L. Agnoletto**[3], **A. Allan**[4], **M. I. Andersen**[1], **W. Ansorge**[5], **F. Bortoletto**[6], **R. Briguglio**[7], **J.-T. Buey**[8], **S. Castellini**[9], **V. Coudé du Foresto**[8], **L. Damé**[10,8], **H. J. Deeg**[11], **C. Eiroa**[12], **G. Durand**[13], **D. Fappani**[14], **M. Frezzotti**[15], **T. Granzer**[1], **A. Gröschke**[16], **H. J. Kärcher**[17], **R. Lenzen**[18], **A. Mancini**[9], **C. Montanari**[3], **A. Mora**[12], **A. Pierre**[19], **O. Pirnay**[20], **F. Roncella**[9], **F.-X. Schmider**[2], **I. Steele**[21], **J. W. V. Storey**[22], **N. F. H. Tothill**[4], **T. Travouillon**[23], **L. Vittuari**[24], and **M. Weber**[1]

1 Astrophysikalisches Institut Potsdam (AIP), An der Sternwarte 16, D-14482 Potsdam, Germany
2 Laboratoire Universitaire d'Astrophysique de Nice (LUAN), Université de Nice-Sophia-Antipolis, Nice, France
3 Italian National Program for Research in Antarctica (PNRA) S.C.r.l., C.O.ENEA, Casaccia Research Ctr., Rome, Italy
4 School of Physics, University of Exeter, Stocker Road, Exeter, EX 4 4 QL, U.K.
5 RAMS-CON Management Consultants, D-85617 Assling, Germany
6 INAF-Osservatorio Astronomico di Padua, I-35122 Padua, Italy
7 Dipartimento di Fisica, Università di Roma La Sapienza, Roma, Italy
8 Observatoire de Paris/LESIA, F-92190 Meudon, France
9 Dipartimento di Fisica, Università di Perugia, Perugia, Italy
10 Service d'Aéronomie du CNRS, F-91371 Verrières-le-Buisson, France
11 Instituto de Astrofisica de Canarias (IAC), La Laguna, Tenerife, Spain
12 Departamento de Física Teórica C-XI. Universidad Autónoma de Madrid, 28049 Madrid, Spain
13 Service d'Astrophysique, DAPNIA, CEA Saclay, F-91191 Gif-sur-Yvette, France
14 Société Européenne de Systémes Optiques (SESO), Aix-en-Provence, France
15 Ente per le Nuove Tecnologie, l'Energia e l'Ambiente, Roma, Italy
16 Alfred-Wegener-Institute for Polar and Marine Research (AWI), Bremerhaven, Germany
17 MT Mechatronics GmbH, Mainz, Germany
18 Max-Planck Institut für Astronomie (MPIA), Heidelberg, Germany
19 Institut Polaire Francais Paul Emile Victore (IPEV), Brest, France
20 AMOS S.A., Liege, Belgium
21 Liverpool John Moores University, Liverpool, U.K.
22 The University of New South Wales, Sydney, Australia
23 California Institute of Technology (Caltech), Pasadena, U.S.A.
24 DISTART, University of Bologna, I-40136 Bologna, Italy

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This article reviews the situation for robotization of telescopes and instruments at the Antarctic station *Concordia* on Dome C. A brain-storming meeting was held in Tenerife in March 2007 from which this review emerged. We describe and summarize the challenges for night-time operations of various astronomical experiments at conditions "between Earth and Space" and conclude that robotization is likely a prerequisite for continuous astronomical data taking during the 2000-hour night at Dome C.

1 Introduction

Dome C on the east Antarctic plateau is among the most remote places on Earth. It is 1100 km from the coast at a height of 3233 m above sea surrounded by thousands of kilometers of solid ice and an average winter temperature of beyond –60°C. With mostly katabatic winds of less than 20 m/s (median 3 m/s), almost no absolute humidity, no light or air pollution, no seismic activity, very low atmospheric turbulence and an inversion layer reaching up to just 30–50 m above ground, the location is by all means outstanding (see, e.g., Fossat 2005a and the proceedings edited by Giard et al. 2005).

Dome C was originally selected for glaciological reasons and was one of the two sites of the EPICA ice-core drilling project that reached solid ground at a depth of 3270 m in December 2004 (EPICA 2004). However, one of the key drivers for a year-round operation on the plateau was astronomy. Out of it had developed the French-Italian sta-

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[⋆] Corresponding author: kstrassmeier@aip.de

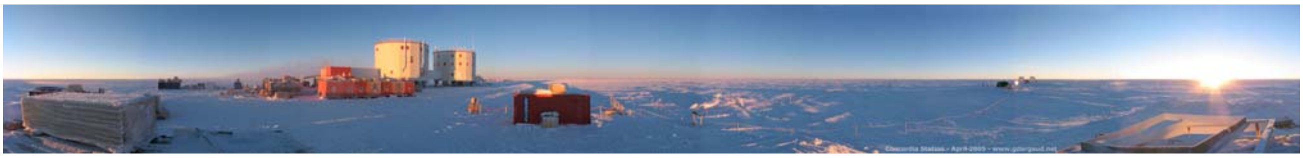

Fig. 1 360-degree view of the *Concordia* station on the east Antarctic plateau at 3233 m above sea. The French-Italian station is now populated also over winter (= night) with up to 16 desperados. The site's astronomical conditions are astounding at almost any wavelength and it is called a place between "Earth and Space". Image courtesy G. Dargaud, www.gdargaud.net.

tion *Concordia*[1] (Fig. 1) that, since its full opening in 2005, is experiencing its third over-wintering season now. First astronomical site testings were done by Valenziano & Dall 'Oglio (1999). The station had received world-wide attention from the night-time astronomical community when it became known that the seeing conditions on the east Antarctic plateau are likely the best on the entire planet with a median seeing of 0.3″ and occasionally even below 0.1″ at a height of approximately 30 m above ground (Lawrence et al. 2004; Agabi et al. 2006).

Astronomical site testing was undertaken by the *Concordiastro* consortium (Aristidi et al. 2003, 2005a) as well as the Australian AASTINO team (Lawrence et al. 2004). Now complemented by numerous experiments and embedded and extended by a large program on atmospheric and meteorological research (e.g. Geissler & Masciadri 2006), efforts will soon converge on a full astronomical site characterization (see http://arena.unice.fr). Dome C is located inside the polar vortex where the ozone hole can be detected in the Austral spring. The environmental conditions during winter time may be best described as "between Earth and Space" and do not allow humans to easily conduct extended physical or mental work although principal accessibility is retained. Fully automated systems, and even robots, are likely a mandatory requisite for astronomical night-time operation. Generally, "Robotic Astronomy" and "e-science" has received significant attention in the past years and has a bright future due to initiatives like, e.g., GRID computing or the Virtual Observatory. A number of proceedings on various subtopics of robotic astronomy were published and we refer to these for further details (e.g. Paczynski et al. 2001; Strassmeier et al. 2001; Strassmeier & Hessman 2004; Nayor et al. 2006).

In order to address the technology and logistics needed to face the construction and operation of robotic telescopes and instruments in the harsh environment of the Antarctic, a workshop was jointly organized by the Astrophysical Institute Potsdam (AIP) and the Instituto de Astrophysica de Canarias (IAC) under the auspices of the ARENA[2] EU network in March 2007. This workshop joined together the *Concordia* station operators, European, Australian and U.S. research institutes, and industries for a brainstorming discussion about expected problems at Dome C and possible solutions. Its key issues are presented in this paper.

2 Prerequisites for successful robotization at Dome C

Robotization is an integral systems engineering approach. While systems engineering combines optics, mechanics, electronics and software, successful robotization must furthermore have precise predictive knowledge of the environmental conditions under which a telescope or instrument is supposed to operate. It must ensure the endurability of new technologies at cold temperatures, the calibration procedures of an instrument must be known ahead and well defined to be automated, the data handling and its telemetry guaranteed until final data reduction and analysis can be performed. All these cornerstone issues must be embedded within a realistic operations and maintenance plan which itself is a question of what logistics are available at the site. Therefore, a great deal must be spent on the issue of local infrastructure.

2.1 Logistic aspects at Concordia

The station can accommodate 16 persons during the winter and up to ≈40 people during the summer season. Logistically, summer is defined as the access time from early November through early February, the rest is winter. The sky is dark from May till August.

2.1.1 Physical and electronic accessibility

Most of the cargo is moved to Dome C by traverse from the Dumont d'Urville (DDU) station, covering 1200 km in 7 to 12 days, while personnel and fragile cargo arrive by Twin Otter aircraft from the Mario Zucchelli station (also 1200 km away). From DDU, situated on an island, materials are transferred to Cap Prud'Homme station (CPH), a site on the Antarctic continent from which the French traverse (RAID) departs. Each RAID is made up of a certain number of tractors and trailers, to transport either standard shipping containers or unpacked materials. Because of the DDU's site shape, the *Astrolabe* ship can not arrive directly to CPH, so that materials have to be transferred from DDU to CPH

- during the summer by helicopter;

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[1] http://www.concordiabase.eu

[2] ARENA "Antarctic Research: a Network for Astronomy" is a FP-6 financed networking activity between 20 European partner institutes led by the University of Nice and compromises institutes from France, Italy, Germany, Spain, Belgium, Australia and ESO.

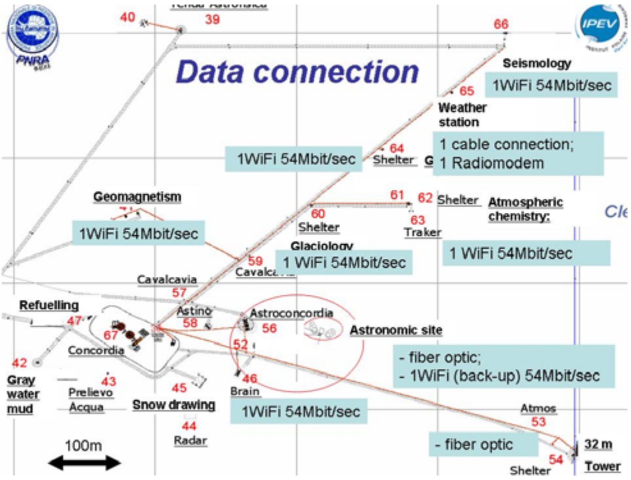

Fig. 2 Aerial view around the *Concordia* station and its electronic accessibility. The site with astronomical experiments is encircled. The two cylinders at the lower left side represent the *Concordia* station.

- in January there is the possibility to use a barge, but this opportunity depends on the marine ice and meteorological conditions;
- during the winter it is hauled on ice.

The accessibility of DDU itself is also a function of weather conditions.

To enable phone and data connection on an on-demand basis, *Concordia* has Iridium and Inmarsat satellite systems allowing a bandwidth of 64 kbps at the cost of 6.5 Euro/min, or a data-packet connection with a cost of about 7 Euro for each Mbit transferred. One Inmarsat "Standard B" and one Inmarsat "Fleet" antenna are installed on the roof of the station as well as inside the station. Inside the station the local area network is made up by a physical part (the plugs in each room connected to a rack for each station level) and an active part (a switch at each level connected by fiber optics to the main switch in the radio room). This connection runs at 1 Gbps.

An aerial view of existing data connections is shown in Fig. 2. Electric power is delivered there by silicone cables on wooden sticks while data connection is provided by WiFi or fiber-optics connections. All around the station up to about 1 km, some warmed containers host equipment to support the research programs in the field.

Dome C is still in the line of sight of existing geostationary satellites. The future AUSSAT communication satellite, accidentally at the same longitude as Dome C, may provide one way for fast data transmission.

2.1.2 The Concordia power system

The *Concordia* power station is made up of 3 Diesel generators adapted to the particular conditions of the air at Dome C. For safety reasons, there is also an emergency Diesel generator inside the noisy building. Each generator can deliver 125 kW at full load. The average power request was in total 85 kW during the 2006/7 summer campaign and required 610 liters of Diesel per day. 35 kW were needed for scientific activities outside the station. As a rule of thumb, the annual costs per kW is 7100 Euros.

2.1.3 Environmental and atmospheric data distribution

Existing instruments of astronomical interest are the three Automatic Weather Stations (AWS Concordia, Davis and AW11), a radio-sounding station and a BSRN station. These devices provide measurements of the following parameters, respectively:

- Temperature (T), wind, wind chill, relative humidity (RH), dew-point temperature, and pressure (p), all during the whole year from Concordia AWS. During summer, data are collected by Davis and AW11 stations too, but the availability and the quality of its data is not guaranteed because these are operational non-scientific instruments only.
- Vertical profiles of standard parameters (T, p, RH, wind) during the daily balloon ascent at 12:00 UTC.
- Short and long, diffuse, global, and direct solar radiation and optical thickness.

Furthermore, a 12 m tower with wind, temperature, relative humidity at standard levels, pressure and a solar radiation sensor, and a 30 m tower with four sonic anemometers (SONICS) are being operated around the clock. Real-time data from AWS-Concordia and from radiosoundings are disseminated through the *Concordia* station's intranet. A software procedure, monitoring the Concordia AWS, runs continuously in the background at the "Physics of the Atmosphere Lab" and is accessible on the Intranet from every PC connected to the net. Daily files are generated from the BSRN station. Average daily, weekly and monthly values of standard meteorological parameters are also available (see Table 1). All real-time and near-real time data are preliminary raw data that need to be validated. Taking into account the extreme meteorological conditions, we can make the following assumptions and considerations about the uncertainty of the measurements. Temperature: $\pm 0.5°$C; relative humidity: the measurement of relative humidity is more critical, data should be used very carefully; pressure: ± 0.3 hPa; wind speed: ± 1 knts with warning (the warning concerns essentially the behavior of the wind sensors below $-50°$C). Also, the wind speeds from our heated cup anemometer are underestimated during the winter due the snow accumulation on the cups of the sensor. Solar radiation: 3 W/m^2 raw data. The target accuracy of the BSRN is the highest of 1 W/m^2 or 2%. The measurements available to the scientific community are summarized in Table 1.

All data are provided after a simple request to the responsible for the "Physics of the Atmosphere" project during the summer and winter campaigns. Non-real time data can be obtained via a central web server[3] where the rou-

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[3] http://www.climantartide.it

Table 1 Atmospheric data from Dome C available to the community. T temperature, p pressure, RH relative humidity.

Availability	Source	Parameters	Sampling
Real time	Concordia AWS	T, p, RH, Wind, Wind Chill, Dew Point Temp	1 min and 30 min
Real time (at 12:00 UTC)	Sounding System	T, p, RH, Wind	2 sec and standard levels
Daily	BSRN Station	Short and long, diffuse, global, direct solar radiation and optical thickness	1 min (average from 1 Hz sampling)
Daily	Concordia AWS	Mean values of the standard parameters	Average daily values
Weekly	Concordia AWS	Mean values of the standard parameters	Average weekly values
Monthly	Concordia AWS	Mean values of the standard parameters	Average monthly values
Monthly	Concordia AWS	T, p, RH, Wind (daily files of the past month)	1 hour

tine meteorological observations are constantly published. Data and information uploaded to the web site has already passed the quality survey. Data from specific projects, e.g. located on the two towers (12 m and 30 m), are available from the respective P.I. on demand. In conclusion, a wide range of on-going and planned scientific activities in the Dome C area are producing and/or requiring atmospheric observations of mutual interest. Therefore, it has been suggested to establish a "COmmon Concordia Observatory of the Atmosphere" (COCOA) that would assure coordination between a number of existing and planned atmospheric and atmosphere-related routine observations including meteorology, atmospheric chemistry, glaciology and astronomy (Argentini et al. 2006). The main task of this project is to obtain continuous data on temperature, pressure, humidity, wind and related parameters from 30m up to the stratosphere, with very high resolution in the boundary layer near the surface (tower data), and radio-sounding data above.

2.2 Engineering aspects

The following subsections constitute a top-down priority listing of telescope robotization prerequisites.

2.2.1 Un-interrupted and clean power supply

A 230 V/50 Hz power grid from one of three 125 kW Diesel generators is available. Scientific experiments run lowest priority in the power distribution after life support and station support. Field experiments must be equipped with their own voltage filters and uninterrupted power supplies to deal with voltage browning and power interruptions. Standard lead-acid battery banks must be heated if located in the field. NiMH is another possible technology. Lead-acid batteries are heavy and therefore expensive to transport to Dome C but their advantages are that it is proven technology and that they can be reloaded during summer with solar panels. Lithium batteries are an (expensive) option for power needs of smaller than, say, 1 kW for 30 minutes and are frequently used in space technology. New developments are currently underway in the auto industry. Ultimately, a full bank of re-fuelable liquid hydrogen cells could provide 1 kW for the entire winter, but not without a well developed safety protocol (but remember, the technology is already used in cars on the street).

2.2.2 System-status knowledge at any time

A robotic system must be controlled electronically to a larger extend as a system that has an operator on site. Two principal levels exist. Firstly, near real-time status messages must be piped from the actual sensors to a local control computer or network server and then screened by an internal prioritization algorithm ("watchdog"). Secondly, left over from that screening procedure, important warnings and fatal failure messages are to be forwarded immediately to the operator's home computer somewhere in Europe. While the first level usually is based on high-speed local ethernet, the second level requires an outside connection to Dome C. Fortunately, a few kbps bandwidth is sufficient for such messages and an Iridium phone is a viable option. Such a solution has been implemented for automatic site testing facilities like, e.g. AASTINO (Lawrence et al. 2005), and is in the planning for PLATO at Dome A (Sect. 5.10).

2.2.3 System re-start procedures and hardware safe mode

Such a prerequisite is a standard item in space technology and every spacecraft is equipped with at least one boot system. That boot system is kept completely separated from every client and has nothing else to do than watching and commanding the central computer and its operating software (read-only disk on flash basis). It can force the system's main computer to perform an orderly shutdown, or at least order it to go into a safe mode. Reboot or ping switches are an alternative. Additionally, it could store all set-ups for all subcomponents.

Especially prone to a rebooting failure are computers when a peripheral component has been disconnected due to a power failure or is broken and does not reply in due time or, even worse, has some sort of intermittence error, e.g. due to fluctuating voltage or left-over erroneous status messages from a previous power incitant. A flush-process command shall be implemented and frequently used. Ashley et al. (2004) added that simply a cool down of the CPU to ambient temperature may be enough to prevent a restart.

If all goes wrong, only a human can help. Thus, ground-based robotic systems shall afford an engineer's console or at least provide the standard interface for it. It is important for designers to think about a system's physical accessibility, especially with thick gloves at −60°C.

2.2.4 Environmental-status knowledge at any time

A robotic telescope system at a temperate site is (better) always a slave of a weather station (Granzer et al. 2001). Otherwise one runs the danger to damage the system from, e.g. condensed air on critical optical surfaces or in electronics. At Antarctica, we face actually a different situation that is in many respects simpler than at a temperate site, see e.g. the list in Ashley et al. (2004). One of the most important concerns is the build up of ice crystals. Due to the proportionally higher radiative losses at temperatures around −60°C, any outdoor structure like a telescope and its optics will be soon cooler than ambient and therefore is prone to icing (see Sect. 4.5). One way around is to simply build in a heater or use special radiating paints or Mylar-like foils to cover up.

Another environmental threat is the horizontal and top-down ice-crystal flow once the wind tops a certain speed, location and height. This "diamond dust" is the most common form of precipitation in Antarctica (see Sect. 2.3.2). A classical dome is probably the best protection. However, to securely detect and measure such a flow one needs a proper sensor and must know the local wind speed and temperature in nearly real time (see Sect. 2.3).

2.2.5 Reliable intra-networking between active components

No watchdog is of any use if the intra networking between system components does not perform properly. High-speed ethernet with either twisted pair or fiber cables and parallel RS232 or RS485 are the basis. Serial ports all use today the same cables and connectors (RJ-45, cable standard Cat5e or Cat6 according TIA/EIA-568-B). The twisted pair ethernet has the advantage to be also useable as a low-power cord. "Power over ethernet" has become a standard IEEE feature[4] for remote sensing technologies and represents an option for various low-power (approx. 50 W per cable) components like, e.g., webcams or IP phones.

2.2.6 Data flow from detector to storage computer

Besides the permanent exchange of control messages, the real bandwidth requirements come from the scientific data flow. One must assure that both the computer hard disk and its cabling to the detector controller can handle the income from its detector in due time. With today's large CCD frames, and mosaics thereof, coupled with high-speed read-out controller electronics, one can even top the limit of a 100Base TX ethernet link. Although not an issue at a temperate site with GBit cards, fiber cables and frequent soft- and hardware updates done by dedicated IT staff, it is an issue at a remote site like Dome C.

2.2.7 Data transfer to local mass-storage medium

Additionally to cable-bandwidth limitations, as emphasized in the previous sections, comes the finite speed of writing data to tape. Let's take an example from Sect. 5. ICE-T is designed to generate 450 MB per 16.4-sec interval, i.e. 27 MB/s. Two-times lossless compression lowers this to 14 MB/s. A today's HP Storageworks Ultrium 960 SCSI tape robot can write at a speed of 80 MB/s on 400-GB SDLTs, thus leaving a significant time margin for overhead needed by the file server. However, if tape writing fails or if one chooses the safer verification-write mode, i.e. writing on tape and then reading it and comparing the two, one has a new bottleneck in the system. In case of ICE-T, its 5-TB RAID would be filled after approximately 90 hours of continuous observing and then the system must be shut down. Therefore, at least for some experiments, a parallel data-preprocessing chain seems essential.

2.2.8 Data pre-processing; also a back-up facility

The storage of preliminary reduced data can be viewed as a level-2 data backup in case full-frame raw-data storage had failed. If the level-2 data rate is of order kB/s one could even transfer it by satellite for on-line quality control in Europe. For medium data rates, say 10 kB/s, one could still use (expensive) fast flash disks and just occasionally transfer some bits and bytes. For data rates above a few tens of kB/s no other choice than taping in a temperate environment exists.

2.2.9 Data reduction pipeline and transfer to analysis computer

The last item in the chain of prerequisites for successful robotization is the timely data reduction and analysis. Because if raw data must be retrieved physically during the summer visit, then brought back to the host institution by air freight, the total amount of time viewing and judging the data becomes too short so that no feedback for the next observing season could be implemented. However, it will depend on the science case whether this is fatal or does not matter at all.

2.3 Atmospheric and environmental aspects

2.3.1 The atmospheric ground layer

One of the most important characteristics of the Dome C atmosphere is the decoupling between the free atmosphere and the lower part of the atmosphere commonly referred to as ground layer (GL). The stability of the free atmosphere, which translates to very low high altitude turbulence, has

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[4] http://standards.ieee.org/getieee802/802.3.html

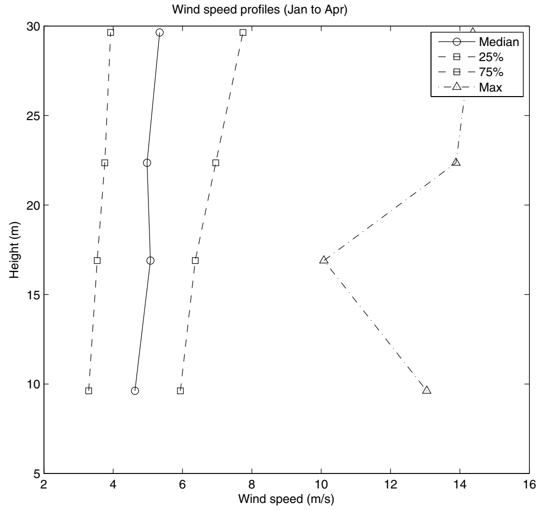

Fig. 3 Wind speed profiles. 25%, Median, 75%, and maximum wind speed profiles taken at Dome C between January and April 2006.

been measured independently by Lawrence et al. (2004) and Agabi et al. (2006). The GL, however, is far less forgiving.

As shown in Aristidi et al. (2005a), the temperature profile of the first 100 m shows a very large temperature inversion. In summer, when the Sun oscillates above the horizon, the ground heats enough to swing the inversion to a positive gradient. This daily oscillation, detailed in Fig. 10 of Aristidi et al. (2005a), causes the temperature profile to become totally flat between 3 pm and 5 pm LT. During this time, the seeing falls to an average of 0.4″ (Aristidi et al. 2005b), making Dome C excellent for solar astronomy.

During night however, the inversion remains stable and is, to our knowledge, the sharpest so far measured on Earth. The ground is 10°C cooler than the air at 30 m and 20°C cooler than the top of the inversion approximately located at 100 m. This gradient of 0.2°C/m in the GL has very negative consequences for astronomical observations.

In the first 30 m, this large temperature gradient is mixed by a wind shear making this part of the atmosphere very turbulent. High temporal resolution profiles obtained by four ultra-sonic anemometers located evenly on a 30 m tower were taken from January to April 2006. The results shown in Fig. 3 illustrate the continuous increase of wind speed with height. At 30 m, the median wind speed is 60% higher than at the ground. On the other end, we see that extreme wind conditions do not exist at Dome C. The maximum wind speed that was recorded at 30 m over this period was 14.3 m/s which is close to the all time maximum wind speed ever recorded at the ground at Dome C (20 m/s). This is a tremendous advantage for telescope design since the wind load is an engineering issue. The turbulence profiles measured by Aristidi et al. (2005b) show that the turbulence above 30 m dies very quickly, a result also found by the lower resolution measurements made by Lawrence et al. (2004).

Two questions of importance remain however when one wants to solve the problem of the GL seeing. The first concerns the fact that the temperature gradient is still strong above 30 m and remains so until 100 m. Putting a telescope on a 30 m tower may indeed get rid of the turbulence below it. However, exposing the structure to the laminar flow may disturb it and create additional turbulence. The second question concerns the variation of the elevation of the GL. Based on our current results we know it is close to the 30 m mark. However, there are not enough measurements to assert its variation. The statistical distribution of the elevation of the GL is a critical parameter that is needed to determine the GL turbulence. A year's worth of turbulence profiles measured by the sonic anemometers will give us an acceptable answer to this question.

2.3.2 Glaciological characteristics of Dome C

The *Concordia* station (75° 06′ 04″ S, 123° 20′ 52″ E, 3233 m WGS84), is about 1.4 km west of the Dome C summit. Dome C, the Earth's fourth highest ice dome (3233 m), is about 1200 km from the Southern Ocean. The Dome C areal has an elliptical shape, with a minor axis (NW-SE) about 70% shorter than the major one (Rémy & Tabacco 2000). The elongation direction of the dome is parallel to the prevalent wind direction SW-NE (Frezzotti et al. 2004). The very low slope of the surface (less than one decimeter per km) and its morphology, e.g. sastrugi, makes it difficult to determine the dome's summit. Accumulation results from precipitation in the form of snow, which is then modified by surface sublimation, erosion/deposition due to divergence/convergence of snowdrift transport and the sublimation of drifting snow particles. Sublimation (wind-driven and surface) removes mass from the surface, while erosion/deposition transports snow from one place to another. Solid atmospheric precipitation occurs at Dome C as snowfall (snowflakes that fall from clouds) and under clear-sky conditions (diamond dust); 50–70% of the solid precipitation occurs as diamond dust. Diamond dust is observed practically every day throughout the year in the inner part of the plateau (Ekaykin et al. 2004). Backward air parcel paths reveal that the resulting snowfall trajectories come mainly from the north (Reijmer et al. 2002).

Snow accumulation measurements taken at Dome C (stake, firn core, snow radar) show a variability in time and space from 25–32 mm water equivalent (we) yr^{-1} comparable to 120–150 mm of snow (Frezzotti et al. 2005). Spatial variability of snow accumulation is driven by snowfall trajectory and topography. Snow accumulation rates increase by about 0.02±0.01 mm we yr^{-1} per km from south to *Concordia* station and by about 0.08±0.01mm we yr^{-1} per km from *Concordia* to the north. At Dome C a significant temporal increase in accumulation has been observed since the 1990s (25.3 mm we yr^{-1} 1816–1998 AD; 28.3 mm we yr^{-1} 1965–2000 AD; 30mm we yr^{-1} 2004–2006 AD), which could be correlated with a changed snow accumulation pattern reflecting a change in the snowfall trajectory. Snow

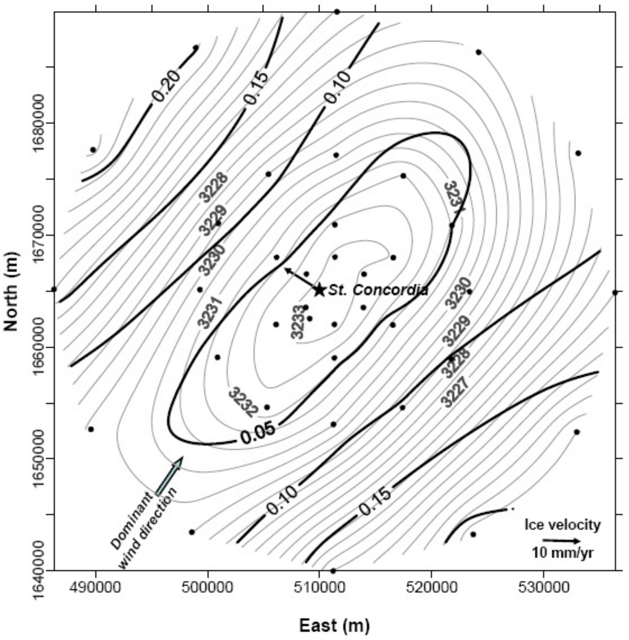

Fig. 4 Surface ice velocity (in m yr^{-1}, thick lines) and topographic map of Dome C (thin lines, in meters). Dots indicate the GPS poles. Elevations are above the ellipsoid, while the mapping projection is UTM-WGS84. The central asterisk is the location of the *Concordia* station. The arrow pointing away from *Concordia* indicates the direction of its local ice-flow.

transportation by saltation starts less than 30 cm in elevation at wind speeds >2 m s^{-1}, whereas snow erosion and transportation by suspension starts at winds >5 m s^{-1} (elevation up to tens of meters). Due to opposite direction of prevalent wind (from SW to NE) and prevalent snowfall event (North to South), blowing snow accumulation close to obstacle occurs along a SW-NE direction with higher accumulation in NE direction. Hoar frost ice deposits on solid surfaces in contact with the air are chilled below the deposition via reverse sublimations. The growing rate could reach 10-20 mm per day and reach dimensions of several centimeters (50–100 mm) around structure, with prevalent growing on downwind direction (NE). Snowfall density is typically very light from 50 to 150 kg m^{-3}. The snow density increases over time due to snow metamorphism. At Dome C the snow density of the first meter is around 350 kg m^{-3}. Density ρ increases with depth d, reaching about 500 kg m^{-3} at around 20 m depth and 700 kg m^{-3} at around 60 m, following the polynomial function in Eq. (1),

$$\rho = -0.0341\, d^2 + 8.2417\, d + 344\,. \tag{1}$$

Ice velocity is a complex function of slope, ice thickness/bedrock conditions as well as the distribution of the snow-accumulation rate. Within 25 km from Dome C the bedrock topography changes with amplitudes up to ±400 m with higher ice thickness in the northern part and thinner in the southern one (Forieri et al. 2003). GPS measurements indicate that poles closest to the Dome C summit move up to a few mm yr^{-1}, while poles located 25 km from the summit move up to 211 mm yr^{-1} (Vittuari et al. 2004). The direction of the ice movement correlates well with the direction of maximum surface gradient within a 25 km radius of the dome (Fig. 4).

The average velocities along each axis are proportional to the distance from the summit. The velocity in the SW-NE direction is three times lower than that in the NW-SE direction. The comparison between elevation and ice velocity contours reveals symmetrically higher velocities along the minor axis of the dome (steeper portion, see Fig. 4). Non-symmetric velocities are present in the NNW area along the major axis of the dome. One year of continuous GPS measurements on the *Concordia* station allow to measure an absolute velocity of the station of 11±0.6 mm yr^{-1} with azimuth 302°. The vertical velocity due to glaciological processes is 153±1.3 mm yr^{-1}. The change in elevation at GPS poles shows an average value of 90 mm yr^{-1} during the 1996–1999 period, with a snow accumulation value of 120 mm yr^{-1} (30 mm we yr^{-1}). The higher vertical velocity (about 60 mm yr^{-1}) of *Concordia* allows the hypothesis of higher compaction phenomena due to the station structure.

3 Robotic operations at temperate sites: lessons learned

This section aims to summarize the operational experiences with robotic telescopes at temperate sites. Although a very incomplete attempt, it should emphasize some of the lessons learned. We strongly suggest to consult other experience reports, e.g. from HST data management (Albrecht 2004) or SDSS data management (Ivezić et al. 2004).

3.1 SOFIA telescope manufacturing

SOFIA, the Stratospheric Observatory for Infrared Astronomy, is a joint 80/20% enterprise between NASA, U.S.A. and DLR, Germany. SOFIA operates a 2.7 m telescope on a Boeing-747SP aircraft at great height. But SOFIA is not a robotic telescope. Main features of the SOFIA observatory are flights with different science instruments and with access to those instruments during flight (Krabbe & Kärcher 2004). The optics of the telescope is exposed to a very harsh environment in an open port of the aircraft and has to withstand large temperature changes from ambient to −50°C, low air pressures and aero-acoustic excitations. The science instrument and the telescope mechanics are located inside the aircraft cabin, and the telescope structure has to penetrate the hull of the aircraft (Kärcher 2000, 2003). The conditions are much worse than that for earth-bound or space-based telescopes, e.g., pointing has a different meaning (Wandner & Kärcher 2000), but only the mainly passive optical system has to be qualified for the low outside temperatures. The main mirror system is made of lightweight monolithic glass ceramics on a thermal stable structure made of carbon-fiber composites. The mechanics are located in the warm cabin environment.

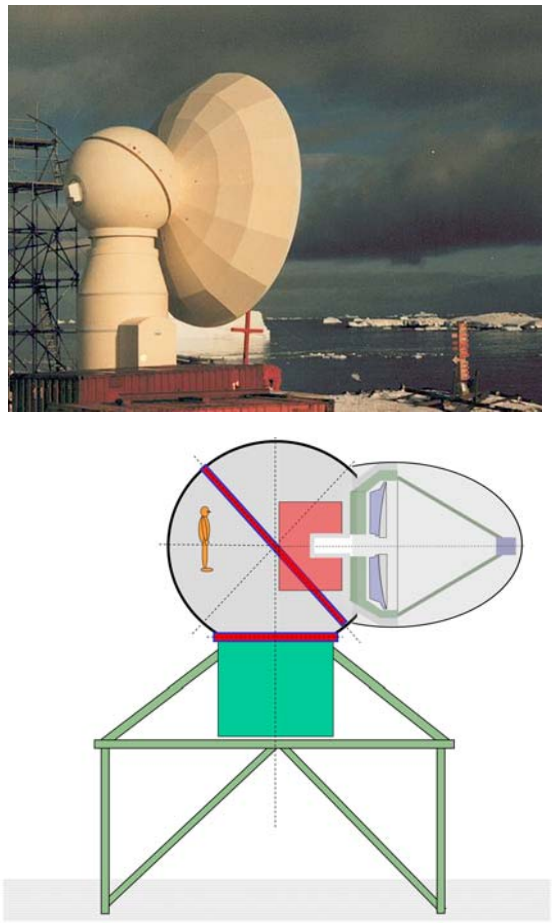

Fig. 5 The "penguin" concept for a 3m-class telescope (c/o H. J. Kärcher). *Top:* the O'Higgins pedestal; a 9 m telecommunication dish near Dumond d'Urville, Antarctica. *Bottom:* strawman design of a walkable telescope combining the O'Higgins pedestal and the SOFIA approach. All sensitive subsystems are in the "warm" inside; the telescope is in the cold outside.

The design concept of SOFIA – putting the optics into the cold, but the mechanics into the warm – may be an attractive alternative for larger optical telescopes in Antarctica. Hints could be gotten also from another telescope project built in 1996 for DLR/ESA on the Antarctica Peninsula. The design of the telescope follows the "penguin" strategy. The outside of the telescope is minimized as far as the required functions allow; all sensitive subsystems and components are in the warm inside; all outside surfaces are protected by a thermal insulation. Minimizing the outside surfaces is achieved by the "slant-axes mount". For an Antarctic telescope a combination of the SOFIA optics with the O'Higgins pedestal may be adequate (Fig. 5). In this design concept the optics is in the outside environment during observation but during severe weather protected by a retractable mirror cover. All mechanical and electronic equipment is inside in the warm environment. The science instrument is accessible during observation. Obviously, the penguin concept would not work for smaller telescope, where a design with full exposure to the cold (also of the mechanical components) may be the only alternative. But such a concept will need qualification to the low temperatures of all its subsystems, and the efforts for this in a reliable and service-free way may be as high as the efforts for the airworthiness verification in SOFIA.

3.2 The Liverpool robotic telescope experience

The Liverpool Telescope (LT) is a 2.0 m fully robotic telescope located in La Palma in the Canary Islands that has been in operation since 2004 (Steele et al. 2004). The site is temperate, with nighttime temperatures of between -5 and $+20$°C. The telescope is unmanned and unsupervised during night time operations (either locally or remotely). The telescope Acquisition & Guidance (A&G) unit can host up to five instruments with the beam able to be directed to one of four side ports via a folding mirror, or, with the folding mirror removed from the beam, to a straight through port. Instrument change time is less than 30 seconds. The telescope is operated as a national common-user facility, and supports both survey and time variable (including rapid reaction) science programmes. There are typically around 30 different programmes executed on the telescope at any one time, selected by a dispatch scheduling (Fraser & Steele 2004).

A number of important lessons have been learnt during the construction and operation of the LT regarding the delivery of reliable instrumentation. Key to these are the avoidance of moving parts where possible, and where not possible, the avoidance of precision mechanisms by using approaches such as the Geneva Mechanism to provide repeatable positioning without the need for servo control. Power conditioning is also key, but is difficult to achieve robustly even using commercial UPS systems, as the switching currents involved will often trip circuit-breakers even if the UPS remains on line. Software design is also critical. On the LT we have made full use of object oriented design techniques to construct robust and reliable systems, with knowledge of individual systems devolved to the lowest possible levels, thereby allowing higher level systems to continue function even if the lower level systems are changed. As an example of this our generic instrument command set (Mottram et al. 2004) means that a new instrument can be added to the LT without the need for changes to the robotic control software apart from a simple configuration change to make the robotic system aware of the new instruments existence.

The most important lesson learnt from LT however is that the effort required to operate a common-user facility both in terms of development and operations staffing is much larger than that for a PI-led single experiment. It is important to note this effort is in *addition* to the required maintenance and nightly operation of the facility itself. Management of the full science data flow, from proposal, through time allocation, observation specification, data quality control, data reduction, data distribution and archiving requires a large amount of effort both from scientists and software specialists. It is important to avoid the trap in developing a new facility to concentrate on delivering the performance

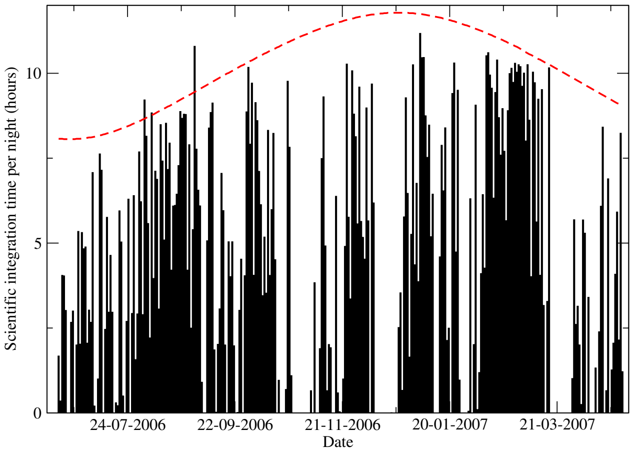

Fig. 6 STELLA/SES shutter-open time. The vertical bars represent the sum of science exposure times per night since beginning of robotic operations. The dashed line represents the nightly dark time. Note that some calibration exposures are done during nautical twilight.

of the telescope and its associated instrumentation. Without early planning for the science data flow, once operations begin, this task will quickly absorb *all* the effort of both developers and operations staff. In the case of the LT, we seriously underestimated the effort required to deliver it. Our initial estimate was that these systems would require ≈ 5 staff years to develop and ≈ 1 staff-year per year to operate. In fact we have found that such systems took a total of ≈ 15 staff-years of effort to develop, and to operate them takes ≈ 3 staff-years per year.

3.3 STELLA & RoboTel: a robotic telescope network

The STELLA telescope network[5] (Strassmeier et al. 2005) is dedicated to stellar activity research and consists of currently three telescopes: two with 1.2 m aperture on Tenerife (STELLA-I and II), and one with 0.8 m aperture in Potsdam (RoboTel). The one telescope equipped with a high resolution spectrograph is currently in commissioning and science verification mode, while the two telescopes dedicated to wide-field imaging photometry are under construction.

What follows is a list of lessons learned from experience gained in the first year of operation of the first STELLA telescope together with the SES (STELLA Echelle Spectrograph). Many of the problems are solved now, but could have been prevented by more careful planning, as needed at Dome C.

Software updates: After initial problems the system ran very stable with a high number of observations only interrupted by phases of bad weather and maintenance periods (Fig. 6). But after the latest maintenance run in March 2007, the performance has degraded, which is due to unexpected problems with a new version of the telescope control system. This upgrade was done to improve reliability, but many of the problems of the old system were already being worked around in the robotics software. A new problem introduced with the software upgrade took several observing nights to solve.

Setup changes: The instrument setup should be done once before shipping, and then one more time at commissioning. Alignment problems should be dealt with at home, and the necessary tools and changes implemented and tested before shipping. In our case, the spectrograph was not fully tested in the laboratory, and was fully aligned for the first time on site. Problems with the alignment (in our case the telescope side of the fiber injection) were not discovered before data analysis showed a not explainable photon loss. The alignment was done and all components were measured for efficiency on site. This solved the problems, but also brought up hitherto unknown mechanical stability problems. These were solved later, but no new alignment of the spectrograph was done due to this seemingly minor change.

The lesson learned is to test the complete system if possible. If not, one should at least try to simulate the part that was not tested. Necessary alignments need to be easy to do and to redo, which is even more important on a site like Dome C.

Computers: Computers hang, and one needs a strategy to meet this problem. One can use watchdogs and power switches (see Sect. 2.2), but one has to carefully plan what can and will happen. The following problems have occurred in the last years (yes, computer problems have plagued us even before robotic observations started):

- Boot order. When a device reboots, e.g. a guiding camera, it tries to get an IP-address. At that time the `dhcp` server needs to be running. If both are on the same power line, a computer will come up slower than an embedded device.
- Serial console. Use server computers that support a serial console for the BIOS setup or at least have the boot manager listen to the serial port by default. Sometimes computers jump into the BIOS setup screen during booting or the filesystem could be corrupt and asks for user confirmation.

Error recovery: A plan needs to be made for graceful error recovery. A prerequisite for this is proper error detection:

- Limit situations. Motors sometimes end up in positions they are not meant to be in. To be able to move out of such positions is mandatory.
- Clearing errors. Priorities must be assigned to error messages. Some errors can stop the system but the majority of errors are "normal" and must therefore dealt with automatically. The STELLA telescopes only know one priority level, i.e. "fatal errors", which prevents unreasoned down time but makes error recovery impossible.

Electronics: Electronics can be very sensitive to temperature, humidity and cable length, among others. Make sure you test your electronics under realistic conditions and in the final configuration. One should also galvanically isolate the signal lines by bridging long distances with fiber

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[5] http://www.aip.de/stella

trains (works well for serial and ethernet communication). Grounding should be carried out in a pedantic way, and great care should be taken when connecting cable shields in order not to produce loops: in doubt it is safer to connect only one end of a shielded cable.

Fuzzy logic: A robot is very strict about its rules. Even if the priority of one target is ten times higher than the next available target, it will not be picked if one condition is not met, even if this condition is only missed by a small margin.

3.4 The future: intelligent agent architectures

Loosely an agent is a computational entity which: acts on behalf of another entity in an autonomous fashion, performs its actions with some level of proactivity and/or responsiveness and exhibits some level of the key attributes of learning, co-operation and mobility. Those in search of a good introductory text on multi-agent architectures are directed to Wooldridge (2002).

The eSTAR project: The eSTAR Project[6] is an intelligent telescope network implemented using a peer-to-peer agent based architecture, cutting across traditional notions that a "master scheduler" is needed to run a network of telescopes. Effectively, eSTAR can be viewed as a collaborative agent system which schedules a collection of geographically distributed telescopes using a multi-agent contract model. In such an architecture both the software controlling the science programme, and the software embedded at the telescope acting as a high-level interface to the native telescope control software, are thought of as agents. A negotiation takes place between these agents in which each of the telescopes bids to carry out the work, with the user's agent scheduling the work with the agent embedded at the telescope that promises to return the best result.

This architectural distinction of viewing both sides of the negotiation as agents, and as equals, is crucial. Importantly this preserves the autonomy of individual telescope operators to implement scheduling of observations at their facility as they see fit, and offers adaptability in the face of asynchronously arriving data. For instance an agent working autonomously of the user can change, reschedule, or cancel queries, workflows or follow-up observations based on new information received.

The eSTAR architecture represents a "turn-key" system for autonomous observations of transient events. A more detailed discussion of the project and its architecture can be found in Allan et al. (2006a, 2006b).

Heterogeneous networks: The scientific need for a standard protocol permitting the exchange of generic observing services is rapidly escalating as more observatories adopt service observing as a standard operating mode and as more remote or robotic telescopes are brought on-line. To respond to this need, the Heterogeneous Telescope Networks (HTN) consortium[7] has drafted a protocol (Allan et al. 2006) designed to be independent of the specific instrumentation and software that controls the remote and/or robotic telescopes, allowing these telescopes to appear to the user with a unified interface despite any underlying architectural differences.

While this standard is primarily intended for use by remote robotic telescopes, it is equally applicable to non-robotic service facilities (e.g. Economou et al. 2006) and to databases of observations (Allan, Naylor & Saunders 2006b) as the standard can be seen as a dialogue between the user (whether that user is human or a piece of autonomous software) and a resource providing some service.

Event networking: The evolution of the IVOA's VOEvent[8] standard (see Williams & Seaman 2006; White et al. 2006) can be seen as a parallel strand to the standards proposed by the HTN. The proposed VOEvent standard has been designed to transport timely information concerning transient events, where as the proposed HTN standard has been designed to allow the recipient of an event message to negotiate for, and obtain, follow-up observations to these reported events from a heterogeneous collection of networked telescopes.

Advantages for Dome C: The intelligent agent architectures implemented inside the eSTAR project could provide crucial autonomous decision making in software, allowing us to build systems which will learn and adapt to the local conditions. More local autonomy also offers to significantly reduce the bandwidth needed for real time operations at Dome C, while the peer-to-peer architecture of the system provides a robustness to various possible failure modes.

4 Design issues at Concordia

4.1 Winterizing a telescope

Winterizing a telescope is making it compatible with the unusual conditions encountered during its lifetime in Antarctica. The design driver constraints identified up to now are the low temperature and huge temperature range, the inverted temperature layer, the icing effect on cold surfaces, the high altitude, the long term ice stability and the remoteness of the site. Fig. 7 is an attempt to summarize the efforts involved.

The conceptual phase will determine the need for robotization, a high tower, adaptive optics and an enclosure. The optical configuration shall be determined at that time. This can be achieved only if the environmental conditions are well known (see Sect. 2.3). In the engineering phase of the project, the major issues arising from the above constraints are the power management, the data transfer, the thermal management of the structure and the electronics, the mechanical structure design (especially for towers on an ice-based station) and the opto-mechanical design. The deploy-

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[6] http://www.estar.org.uk/

[7] http://www.telescope-networks.org/

[8] http://www.voevent.org/

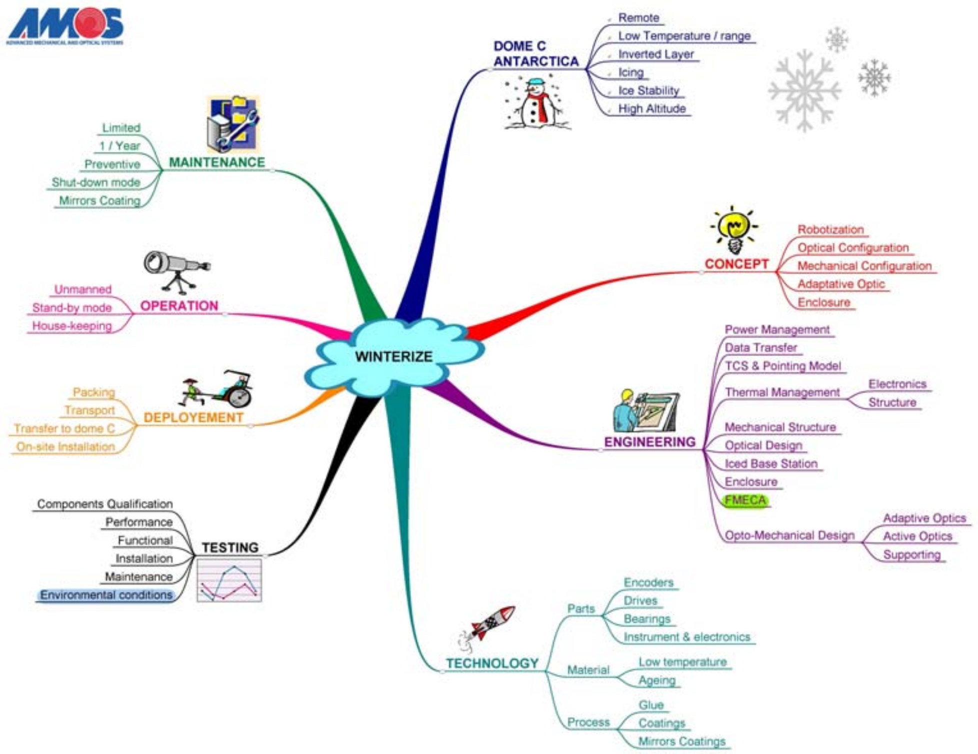

Fig. 7 Winterizing a telescope and an instrument is an integral engineering approach. The design constraints are the low temperature and the huge temperature range, the inverted temperature layer in which the telescope possibly operates, the icing effect on cold surfaces, the high altitude, the long term ice stability and the remoteness of the site. The figure summarizes the various efforts, from quantification of the environmental conditions to conceptual and engineering issues until operations and maintenance.

ment, operation and maintenance constraints are also driving the design from the beginning.

A proper development requires a system engineering approach that handles all these issues and manages the risks during development. The selection of parts, material and processes will require specific qualification but one can take advantage of the proven experience in space cryogenic applications (see also Sect. 4.2).

Experience shows that testing in factory is considerably reducing the risk during the on-site installation. The condition of performance testing shall be determined early on since it could have some impact on the engineering. The functional tests shall be done at low temperature. Some installation and maintenance testing shall be carefully prepared for on-site installation and maintenance within very short time.

The deployment constraints require to reduce the number of pieces to assemble on-site, but also to keep the weight and size of the pieces compatible with the available ships and traverses. A deployment plan shall be drawn up early since the interaction with the design is high.

The unmanned operation of a telescope requires a high level of safety and reliability. A “failure-mode effect and criticality analysis” (FMECA) shall discover efficiently a possible degraded mode of operation, but also define the stand-by and shut-down modes and how to recover to the safest mode when failures occur. The reliability and maintainability shall be considered at the system level since all subsystems are affected.

In conclusion, the development of medium or large projects for Dome C requires to minimize the development and operation risk because a lack of quality will cost more than anywhere else on Earth. This calls for a system-engineering approach together with an efficient risk and quality management.

4.2 Optics and coating for –80°C

A lot of projects using optics and coatings for low temperature have been successfully achieved all around the world, either for astronomy or space programs, but most of them were basically designed for use in vacuum (i.e. cryogenic conditions with stabilized temperature, so without spatial and/or temporal gradients). One of the major issues for optics and coatings for Dome C is the fact that there will be such spatial and temporal gradients.

For large optics (mainly mirrors), and in case the use is for uniform temperature (possibly varying but slowly), materials such as low expansion Zerodur could appear as being the best candidate in terms of specifications and price compared to, e.g., Silicone Carbide (SiC) mirrors or low quality aluminium ones. As an example, the WFCAM experiment for the UK-Infrared Telescope (UKATC) includes a 820 mm

Zerodur mirror from SESO which procures excellent performance from ambient to $-150°$C by using appropriate INVAR flexures to attach the mirror to the aluminium mount of the cryostat in a stress-free way. Nevertheless, due to the very poor thermal conductivity of Zerodur (and because the CTE is not strictly zero), this can induce more or less variable mirror deformations if the temperature varies with time and/or with location. For that reason, highly conductive SiC mirrors could be a solution, with important impact on the price. In case the temperature varies quickly but remains always uniform, aluminium mirrors could possibly be kept as an alternative low-cost solution. As a conclusion, the major recommendation before choosing the mirror material is to specify the environmental conditions of temperature all around the optics.

Regarding reflective coatings on mirrors, all kind of traditional protected coatings can be used at $-80°$C, e.g. protected aluminium, protected silver, protected gold. Among all, the protected aluminium is anyway the best one concerning environmental behavior and life duration (including cleaning). One of the major issue to consider for Dome C is the effect of freezing (directly onto the coatings) which will for sure limit its life duration.

For optics using lenses, different possible problems are:

- For large diameter optics, one must take care of the relative thermal dilatation from ambient (temperature of integration) to $-80°$C between the lenses and the barrel, which are generally of different CTE. Risks are, as a minimum, linked to lens de-centering because of variable diameters and, as a maximum, linked to lens breakage if thermal constraints are exceeding the limits of the glasses.
- For large optics too, one must avoid the use of thermal sensitive glasses such as CaF2 or BaF2. These glasses can operate at low temperature but will suffer (major risk is breakage) from large spatial thermal gradients and/or quick temperature changes.
- For optical cementing of doublets, triplets etc., there are optical glues that can accept a wide range of temperature. However, these need to be assessed for each case individually because it depends of many parameters (sizes of the optics, CTEs of the glasses to cement, a.s.o.).

Regarding anti-reflective coatings on lenses, all kind of existing single layer or broad-band coatings can be used at $-80°$C but, as for the reflective coatings, one of the major issue to consider for Dome C is the effect of freezing directly onto the coating. Again, this will for sure limit its life time. Preliminary coating qualifications with samples will appear necessary as soon as exact conditions of freezing are known.

4.3 Absolute encoders and motors for –80°C

This chapter deals with the IRAIT motor and encoder experience. Its design is based on commercial off-the-shelf products and materials, with some additional in-house working and an extensive testing program.

4.3.1 Encoders

Having chosen a position-feedback system for IRAIT, a precise angular position readout directly at the end of the 1:1440-ratio kinematic chain was adopted. This takes care of backlash issues due to, e.g. mechanics and grease. No encoders are on the motor axes. The choice of encoder has been the RCN-700 series absolute encoders from *Heidenhain*. This encoder has a 29-bit resolution, i.e. 536 870 912 positions per revolution, i.e. 414 counts per arc-second on the sky. These encoders perform precise optical scanning of a Diadur graduated disk. The graduations are extremely hard chromium lines applied to a carrier substrate of glass using a photolithographic process. This process offers a grating period of 10 μm. The readout is performed by a PCI IK200 interface card, using an EnDat 2.2 protocol. In the IRAIT case, the card is hosted by a dedicated VIA Epia computer, with a custom Linux-based operating system. There is no mass storage on board. All operations are done in RAM, loading the operating system at boot from the network. Telescope axes positions are provided to applications over LAN via a simple protocol over TCP. In this way, the system is very robust and the main control software can run on whatever computer on the IRAIT local network.

The encoder has a large hollow shaft with a diameter of 100 mm. On the azimuth axis, it is used to run power and signal cables and optical fibers to the telescope. On the elevation axis, it is used to feed the optical beam to one Nasmyth focus. The EN60529 protection is IP64. RCN-700 series encoders come from factory without specific thermal tests below 0°C. *Heidenhain* suggested a series of tests via the electric signals coming from the encoder, with a particular attention to the incremental signal in order to check for a signal degradation at very low temperatures. Climatic chamber tests from 0° to $-45°$C were performed at Perugia University, checking the system behavior in working conditions at various temperatures. Although the tests did not cover the full range of expected temperatures at Dome C, the incorporated self-heating of the device will keep it over the minimum value tested.

4.3.2 Motors

The choice for the IRAIT telescope were the stepper motors ZSH87 from *Phytron*. This company is well known for its catalogue of vacuum and cryo-stepper motors. A stepper motor moves among particular reproducible step angles due to defined wiring and triggering of windings. With a control electronic that triggers the phases, a quasi-continuous rotation is achieved. The smallest possible resolution of position depends on the motor as well as on the type of drive. An usual value for the resolution of commercial stepper motors is 200 steps per revolution, as for IRAIT. However, resolution can be considerably increased by electronic micro-

Table 2 List of large IR arrays for astronomical application.

Company/type	Name	Pixel pitch (μm)	Pixel number	Wavelength range (μm)	Temp. (K)
Teledyne	Hawaii I	18	1024×1024	0.9– 2.6	77
Teledyne	Hawaii I RG	18	2048×2048	0.9–2.6	77
Teledyne	Hawaii II RG	18	2048×2048	0.9–2.6	77
Teledyne	Hawaii II RG	18	2048×2048	0.9–5.0	40
Raytheon (SBRC)	Aladdin III InSb	27	1024×1024	0.9–5.4	30
Raytheon (SBRC)	ORION InSb	25	2048×2048	0.9–5.4	23
Raytheon (SBRC)	Si:As IBC	50	320×240	2–28	4
DRS	Si:AS BIB	18	1024×1024	5–28	3
Raytheon (SBRC) Si:As IBC	Aquarius	30 (tent.)	1024×1024	5–28	8

stepping. For IRAIT, 64× micro-stepping is used. With the right design of bearings and windings, a stepper motor is able to work in extreme environmental conditions. This leads to several advantages. Firstly, the availability of very high torque at low speeds, e.g. during tracking. Secondly, there is no need for an encoder on the motor axis to get reproducible positioning. Obviously, a loss of steps, typically due to a bad design and/or a bad tuning of the driving system in the presence of irregular loads, must be absolutely avoided. In case it still happens, IRAIT still relies on the absolute encoders on the telescope axes, enabling monitoring of the proper operation of the drive system.

Good smoothness of motion is achieved using PAB 93-70 Micro 256 power stages, again from *Phytron*. Climatic chamber tests from 0° to −80°C, planned with the supplier in Italy, *Micos Italia GmbH*, were performed in Germany by *Phytron*. System behavior in working conditions at various temperature values were tested. Especially low speeds, motion smoothness, and resolution and speed uniformity at low temperature. Finally, the system was calibrated at −30°C. With lower temperatures there will be no damage but the specs are not guaranteed anymore. In the IRAIT case, power supply to the motors will lead to a motor temperature warmer than −30°C. At that point the telescope is ready for slewing. Also, a considerable derating had been applied to take into account the effect of low-pressure values. Redundancy is provided by using a pair of motors for each axis. The telescope normally moves using only the primary motor, but the backup motor can be automatically activated any time. All moving parts use the special grease Fomblin PFPE from *Solvay Solexis*. It has the broadest temperature application range of all classes of lubricants, extending down to −90°C. It was tested and characterized in a climatic chamber in Perugia, and is now already in use at Dome C on the sIRAIT telescope (see Sect. 5.1).

4.4 Stability of IR-arrays for robotized observations at Dome C

Due to low ambient and atmospheric temperatures as well as low atmospheric turbulence (at least above the ground layer), Dome C is an excellent place for NIR and MIR wide field imaging: Diffraction limited imaging resolution can be achieved over large FOVs and the thermal background limiting the sensitivity at these wavelengths is reduced by a factor of up to 100 compared to the best temperate astronomical sites like Paranal or Mauna Kea. In addition, the reduced thermal background should allow for longer integration times at MIR wavelengths.

Worldwide there is only a small number of companies providing large infrared arrays for the NIR, TIR and MIR wavelength region. The NIR/TIR region is dominated by Teledyne (Rockwell) and Raytheon (SBRC), while the ground based MIR astronomy is mainly using the 320x240 Si:As array offered by Raytheon. A summary of the most interesting IR arrays is given in Table 2. The development of a 1024×1024 MIR array for ground based (large background) application similar to the ORION type detector for space application has been started by Raytheon, but such detectors are not yet available. All recently developed large IR arrays are at least 2-side buttable, thus, they are suitable to built up 2k×2k array facilities with small gaps.

These IR arrays in general are designed to be operated under controlled cryogenic environment, thus, at a first glance no special provisions are required using them under ambient conditions typical for Dome C. However, special constrains like continuous operation over years, cold ambient temperature, no maintenance in situ at winter time, icing problems, must be taken into account regarding the opto-mechanical and electronic layout. Cooling must be provided by puls-tube closed cycle coolers running at high frequencies, specified for low ambient external temperatures. To minimize flat field and gain variations, the readout electronics and the detector array temperatures must be carefully stabilized down to an accuracy of 0.02 K and 0.005 K, respectively, temperature stabilities that are already common for current carefully designed ground-based instrumentations. The dominating effect influencing long time stability of NIR to MIR array instrumentations are not the aging effects of the arrays themselves (storage aging and aging by thermo-cycling are negligible for modern arrays over decades and hundreds of cycles, respectively), the

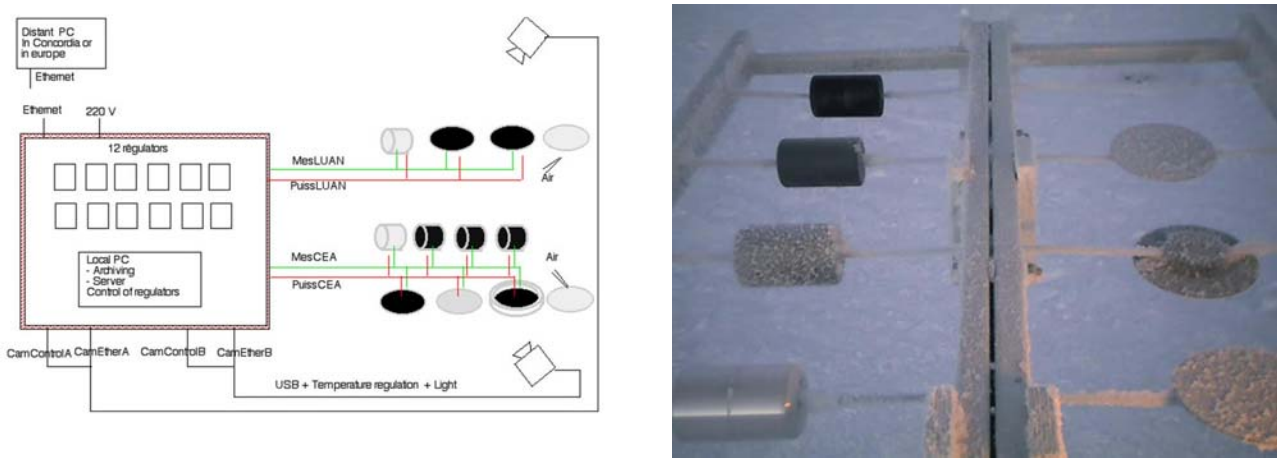

Fig. 8 The icing experiment GIVRE. *Left:* Schematic set up and read-out scheme. The test cells are a series of black and shiny cylinders and disks. These are observed during night with two webcams. *Right:* Typical icing one day after cleaning. Cylinders (from bottom to top): shiny aluminium cylinder; black cylinder without heating; black cylinder kept at air temperature; black cylinder kept 5°C above ambient. Disks without heating and one side black, other side aluminium (from bottom to top): aluminium-side facing sky; black-paint side facing sky; again aluminium facing sky; and disk with teflon both sides.

dominating contributions come from contamination effects within the cryostat. Unexpected ventilation of the cryostat with contaminated air (power failure), humidity entering the cryostat (maintenance failure) and contamination due to abrasion at cryogenic drive systems or blackened environment are influencing long time efficiency of optical surfaces and the detector array. Beside continuous monitoring of the optical quality, special care should be taken in designing and planning the maintenance of IR instruments at Dome C to optimize long time stability.

4.5 The infamous icing problem

Which temperature does a black body reach during polar night and at which temperature should we keep a black body to avoid frost formation? These two critical questions are addressed by the GIVRE experiment headed by G. Durand, Saclay. Its set up is such that reference polished aluminium cylinders will sense the air temperature while black cylinders (for total flux) and disks (to discriminate sky versus snow flux), equipped with heaters and sensors, are used to measure

- the equilibrium temperature of the cells with no power added,
- the heat flow to be added to keep the cells above freezing temperature,
- the warm up needed to remove diamond dust or accumulated frost. Webcams are used to control the frost accumulation.

In order to provide remote control either from *Concordia* station or from Europe, an industrial static PC acting as a server is installed near the experiment at *Concordiastro*. Fig. 8 shows the layout of its control system. This PC is archiving all logic data, physical data and images from the web cams. The access to this server is via a java program that allows the remote user to control the experiment through a graphic interface and to edit curves. Through this server it is possible to update the sequencer parameters and to maintain the software remotely. At the present time, no direct access from Europe is possible due to the lack of a stable network. Direct ethernet connection to the experiment would be very useful to avoid data transfer through e-mail (with a lot of work from the over-wintering personnel). The ANIBUS/FBI server program running in GIVRE is also used in many other astronomical and cryogenic experiments at the CEA-DAPNIA labs, e.g. it will be used to control the future CAMISTIC camera and its cryogeny at 0.3 K on the IRAIT telescope.

First preliminary measurements were obtained at the Nacelle platform (at height 2 m and 7 m) in April 2007 and indicate that the equilibrium temperature is 1.8°C below the ambient air temperature during a clear night. Fig. 8, right panel, shows some of the results. The power to keep a black cylinder of length 110 mm and diameter of 65 mm at ambient is about 0.2 W in absence of wind. Frost builds up in a few hours on polished aluminium. Quantitative numbers will be made available at the end of the winter 2007 to help in the design of anti-icing systems.

4.6 Aligning telescopes during daytime

The difficult working environment during winter night time and a very limited infrastructure does pose some challenges for aligning and maintenance of alignment of an astronomical telescope. It should be assumed that any regular engineering work, such as aligning the optics of a telescope, must be conducted during the summer season (early November to early February). Therefore, commissioning with initial alignment must be completed in full daylight, when the temperature is 30–40°C above the typical night time temperature. In the following, we consider how alignment could be achieved for two different larger projects currently being considered for Dome C.

4.6.1 Aligning ICE-T

ICE-T is a double 60 cm wide-field Schmidt telescope for detecting transiting planets, stellar activity and other variable phenomena (Strassmeier 2007, see Sect. 5.5). In order to avoid saturation of relatively bright stars, ICE-T will be de-focused, with image diameters of about $20''$. Even though the PSF is very far from diffraction limited, the uniformity and stability of the PSF is crucial for achieving Poisson-noise limited photometry.

The day sky has a brightness of about $V = 5\,\mathrm{mag/sqr''}$, from which it is clear that direct observations in daytime would not be feasible. The most obvious way for alignment of ICE-T would be an auto-collimation test, using a large, but not necessarily full, aperture plane mirror, in combination with a point source in the focal plane. This would allow for a good but not perfect alignment. There is additionally the possibility of mounting a Mylar or glass solar filter in front of the telescopes. With an attenuation of 12 magnitudes, a bright star such as Sirius can be observed as a 10th magnitude star against a sky background that is comparable to full Moon conditions, allowing on-sky verification of the alignment achieved. The remaining issue is to maintain this alignment when the temperature drops to -60 or -80°C. A controllable 3-point "active optics" adjustment of the mirror (focus and tip/tilt) is almost certainly required for optimal operation across the wide temperature range encountered at Dome C.

4.6.2 Aligning PILOT

PILOT is foreseen to be a classical two-mirror 2m-class telescope with RC optics, a Cassegrain focus and two Nasmyth foci (Storey et al. 2007, see Sect. 5.8). Provided that the mirror figures are nearly concentric with the circumference/central hole of the blanks, such a telescope can be approximately aligned in all nine degrees of freedom using quite simple tools, without the need of any on-sky work. Specifically, using the Cassegrain focus de-rotator axis as a reference, M1 can be centered through mechanical measurements of the central hole, M2 can be centered using a pupil imager and the tilt of M2 can also be adjusted by viewing M1 through M2 with the pupil imager. Left is the tilt of M1, which is approximately adjusted through auto collimation, using a large undersized flat mirror. Finally, spherical aberration, which is the result of an error in the spacing of M1 and M2, can be eliminated through the well known pentaprism test. Fine tuning of the alignment can then be done on the sky in the near-IR, where the contrast between a star and the daytime sky is sufficient for allowing for detailed wavefront sensing on bright stars.

The real challenge is to maintain alignment at a level which allows the science instrument to utilize the exceptional seeing above Dome C, which occasionally is below $0.1''$. This is almost certainly only possible through active or adaptive optics, or a combination thereof. This issue requires detailed studies during the design phase to ensure that an implementation is identified that allows for an autonomous robotic operation of the telescope-optics subsystem.

4.7 Automatic pointing models and their quality control

Fully robotic or remote-control telescope operation is only possible if the active pointing model is either reasonably stable or can be redone remotely. Although the environmental conditions in Antarctica are expected to be more stable than at temperate sites, the implementation of an automatic telescope pointing procedure and its quality control is a central issue for any robotic telescope. At Dome C we would want to do this even automatically.

We used the alt-az STELLA-II telescope (see Sect. 3.3), located at the Izaña observatory, Tenerife, Spain to automatically derive pointing models via commands from Potsdam, Germany (Granzer 2007). STELLA-II was not carrying a scientific instrument at that time, so the 15 cm refracting guiding telescope was used to measure celestial positions. The main goal was to establish methods to measure the quality of the pointing models derived and to study their thermal and temporal dependency. We concentrated on the well-understood classical pointing model (e.g. Greve et al. 1996 and references therein)

$$\begin{aligned}\Delta A &= A_{\mathrm{offset}} - B_{\mathrm{NP}}\sec E + N_{\mathrm{PAE}}\tan E\\ &\quad + A_{\mathrm{N}}\cos A\tan E + A_{\mathrm{E}}\sin A\tan E\,,\\ \Delta E &= E_{\mathrm{offset}} - A_{\mathrm{N}}\sin A + A_{\mathrm{E}}\cos A + T_{\mathrm{F}}\cos E\,, \qquad (2)\end{aligned}$$

where A represents the displacement in azimuth, E the displacement in elevation, N the non-perpendicularity angle between azimuth and elevation axes, B the (optical) beam non perpendicularity and T the tube flexure. There are a few caveats in the classic model and its derivatives leading to quality constraints if unchecked and, most importantly, if there is a correlation

- between N_{PAE} and B_{NP} in Eq. (2) due to $\sec E = \pm\sqrt{1+\tan^2 E} \approx \tan E, E \to 90°$, and/or
- between the constant terms A_{offset} and E_{offset} with coefficients to terms that have a non-vanishing integral over the hemisphere. This can be avoided by normalizing the appropriate terms to their means.

Using the RMS of the derived pointing model to deduce the quality of the pointing is dangerous, as the RMS will decrease with the number of fitted parameters. In the extreme case, where one fits as many parameters as measurements available, the RMS could be zero. There are two good indicators for the quality of a pointing model. Firstly, one can use bootstrapping methods to get confidence limits on the model-parameter errors. We used 1000 different bootstrapping sets for each pointing model to get to the confidence limits on the measured parameters. Except for

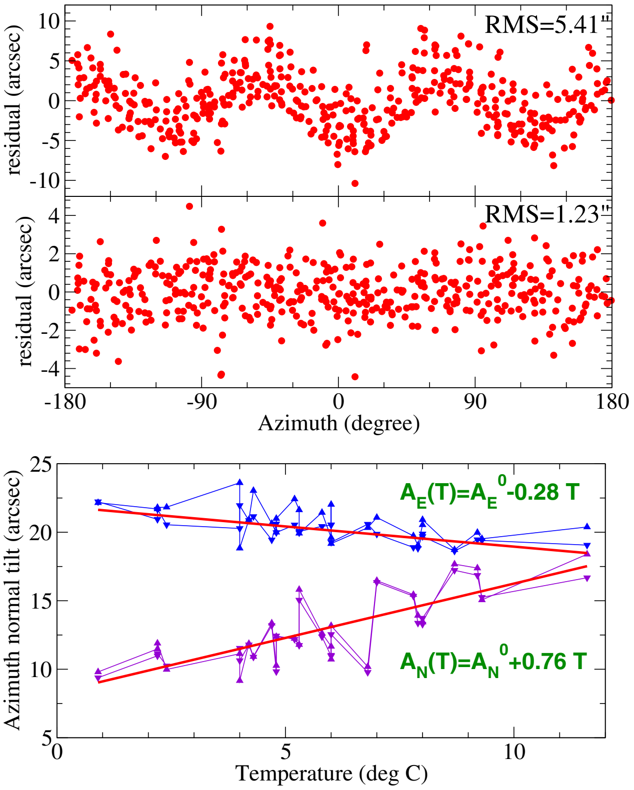

Fig. 9 *Top:* Residuals of the STELLA altitude model in arc seconds as a function of azimuth A in degrees. The top panel shows the residuals of a pure classic model with a clear $3A$ wave, while the lower panel shows the fit after including three empirical terms (see text). *Bottom:* Dependence of the azimuth axis alignment parameters $A_{\rm N}$ and $A_{\rm E}$ on the ambient temperature T along with the corresponding fits. Shown is again the case of the STELLA-II telescope. The effect is below $1''$ per $^\circ$C.

the highly correlated parameters $N_{\rm PAE}$ and $B_{\rm NP}$, the confidence limit decreases with the number of measurements taken. Secondly, the correlation between $N_{\rm PAE}$ and $B_{\rm NP}$ can be used to estimate the quality of the model because the correlation coefficient between these two parameters drops strictly as a function of number of measurements.

Non-classic terms that might be present in the pointing model can be spotted if the residuals of the classic model are plotted similar to Fig. 9 (top), where the residuals of the classic model in altitude is plotted against azimuth. A clear correlation of the residuals with a period of $3\pi/2$, i.e. $3A$, is visible (top subpanel). As a matter of fact, STELLA-II has three "legs" supporting the azimuth structure, the reminiscence of this design is visible as a $3A$ wave. Care must be taken in not over-parameterizing the model, so at least the correlation of any term additionally introduced against the already present ones should be observed. For our data sets, we only included a $\sin(3A)$, $\cos(3A)$ and spherical harmonics $Y_{1,1}$ and $Y_{1,-1}$ to Eq. (2). This allows to lower the RMS in the altitude model down to $1''$, while the azimuth model remained at an RMS of $\approx 3''$ (see Fig. 9 (top), lower subpanel for the residuals to the extended model).

An important question for Dome C is the thermal and temporal dependence of the parameters. This was partly already investigated e.g. for the MERLIN radio telescope by Bayley et al. (1993). Studying pure temporal evolution of the model parameters, no relevant correlation is found. However, analysis of the thermal evolution of the model parameters revealed a relevant dependence of the tilt of the telescope-azimuth normal, described by parameters $A_{\rm N}$ and $A_{\rm E}$ in Eq. (2), on temperature. For STELLA-II this is shown in Fig. 9 (bottom). The remaining effect is below $1''$ per $^\circ$C, which will still amount to a net effect of $\approx 30''$ during an Antarctic night if the linearity prevails also for higher temperature differences.

4.8 Systems engineering in Antarctic robotic telescopes and instrumentation projects

As all successful technical projects, also Antarctic robotic telescopes and instrumentation projects have to follow certain basic systems engineering principles in order to save the available funding for the scientific work rather than wasting it for the technical realization. The total life cycle of Antarctic robotic telescopes and instrumentation should be broken down into controllable time units, e.g. into individual project phases each ending with a dedicated design review (Fig. 10). Of the six project phases from Fig. 10, we discuss here the first two.

Project Phase 1 is the most important phase in the complete life cycle of any project. The real scientific needs are identified together with the financial, technical and operational boundary conditions. Concerning the ARENA road map this phase includes:

1. The demonstration of the scientific needs and justifications;
2. the transformation of the scientific needs into telescope and instrumentation requirements collected in a "System Requirement Specification";
3. the outline of an operation, maintenance, and logistic support concept for the entire operational life cycle stage of the system. This concept should be based on a realistic life cycle cost estimation;
4. the collection of all functional, physical and operational interfaces to the *Concordia* station and the logistic support system;
5. the identification of the on-site and transport environmental conditions.

Project Phase 2 is destined for the identification of the most economic solution for the needs and requirements defined in Phase 1. The term "most economic" is not only related to the operational stage of the telescope and instruments, but includes also the technical financial and schedule risks, i.e. the realization risks during the development, the manufacturing, and the installation and commissioning phases. The typical Phase 2 activities in the framework of the ARENA road map are:

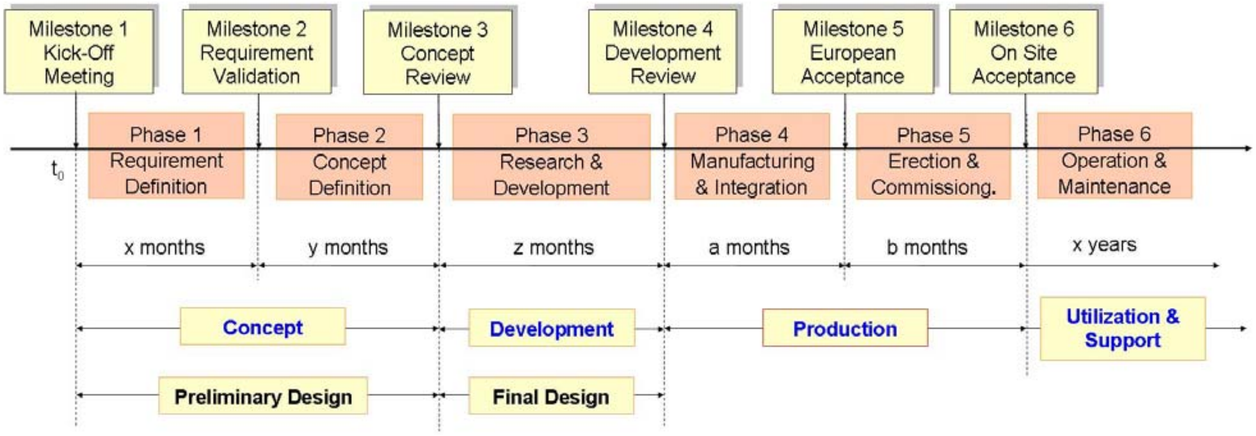

Fig. 10 The first two project phases "Requirement Definition" and "Concept Definition" (Phases 1 and 2) could serve as activities for the remaining time of the ARENA network, i.e. as main parts of an "ARENA Road Map for Telescopes and Instruments at Dome C".

1. Elaboration of alternative telescope and instrumentation concepts all capable to meet the specified requirements. This may include the assessment of existing telescope designs with respect to the ability to meet the environmental conditions and the operational and maintenance requirements, and/or the identification of the necessary design modifications;
2. evaluation and comparison of the alternative concepts with the goal to be able to select the most promising concept(s) for realization;
3. validation of selected concept(s);
4. definition of the programmatic, technical, financial and schedule requirements for the subsequent project phases. These requirements could form the basis for a FP7 Infrastructure proposal.

Project Phase 2 should end with the Preliminary Design Review (PDR).

5 Detailed robotization issues of projects for Dome C

5.1 sIRAIT: small IRAIT

Small-IRAIT is a precursor for the 80-cm IR Antarctic telescope IRAIT (Tosti et al. 2006). It has been designed to accomplish similar tasks and to experience the same difficulties, with the goal of performing a period of full tests on a smaller scale but in the same operative conditions foreseen for the main project. It is a 25-cm Cassegrain optical telescope with an equatorial mount of 15-degree inclination. It is equipped with a guiding refractor placed along the optical tube. It is moved by two very compact stepper motors, originally designed for vacuum and suitable for temperatures down to -60°C. The most remarkable feature of these motors is that they are neither supposed to be heated nor insulated (see also Sect. 4.3). Therefore they can work properly in an open space configuration even in extreme environments. The correct motion of azimuth and elevation axis at the site temperature is granted by a special grease, originally intended for aeronautic applications. This grease is fully operating without performance degradation down to -90°C.

All devices not able to operate at such temperatures are embedded in a box, mounted on the rear of the mirror cell, called the APU (astronomical portable unit). The APU contains the CCD camera, the filter wheel, two heaters, two fans, thermocouples and Pt100 probes, the mirror adjustment device and other electronics. It is insulated by a thin layer of foam and it is internally heated by two resistance-heaters. Temperature control is implemented through a PID filter performed by a software. A second box with the motor drivers is on the foot of the telescope. It is heated as well, but with a lower precision system. The reason is its lower sensitivity to temperature oscillations than the CCD camera and other devices present in the APU. The achieved precision is about 0.1°C in the CCD box, and 5°C in the motor-drivers box.

The computer that runs the temperature control software, the "navigator", is hosted in an ISO20 container, 10 m away from the telescope. The main computer, or the "pilot", runs the telescope control software and the motor control software. This computer is in the container as well. Entering object coordinates or object name, according to the catalogue in the database, results in the telescope automatically pointing and then tracking the desired position on the sky. Manual controls for telescope motion and power control are also present in the container. Besides, there is a third computer inside the *Concordia* station. These computers are connected with an Ethernet wireless link. The computer in the station can perform some raw operations, like on and off switching for the heaters or all-system powering-up and down. Data acquisition is constantly accomplished by instrumentation in the APU. Images and parameters like voltage, temperature, error messages a.s.o., are sent to the "navigator" computer and then transferred to the base computer via Ethernet, where they are stored in a database.

The telescope has been shipped to Dome C in January 2007 and is operative during winter 2007. The major problem during the early months of work was, and sometimes still is, icing. Diamond dust can enter even the narrowest spots, especially in two zones: main mirror and gears. Ice has been often found both over and under the mirror. Luckily it is dusty ice, easily removable since it does not stick to the mirror. Occasionally, it can melt and then re-freezes as a compact block. In that situation, forcing it to evaporate by blowing warm air is essential to avoid mirror scratching. However, the optical tube is not quick to open: it is completely closed and there are a lot of screws. Ice in the gears is even more difficult to remove, since it often requires to open the gear box. Nevertheless, a solution was found filling all the system with grease, to avoid the presence of empty spaces. It was mandatory to fill even the narrowest groove. Another problem was cable insulation. The plastic coating normally used in temperate sites is excluded, and also silicone cables present degradation after days of use, although they are rather reliable if not moved or bent, which is infrequent in our appliance. The best solution was using Teflon cables with a metal mesh envelope (see also Ashley et al. 2004).

Of major importance for the system safety was the availability of LEDs on the telescope, indicating on/off and master error states. They are suitable for visual inspection by means of field glasses from inside the base. Since managing an emergency or an unexpected situation cannot be done immediately (6 minutes at least under optimal circumstances are needed to reach the telescope), the visual inspection capability and computer in the base have been of great help during the initial stage. The presence of a computer in the base, of both manual and automatic control of several means of inspection and alarm, are all features based on a redundancy philosophy.

sIRAIT was designed by the IRAIT team at the University of Perugia, built by the *Marcon* telescope factory of San Donà di Piave, equipped with electronics and installed at Dome C by one of the coauthors (R. Briguglio). The CCD, the filter wheel, and the focusing unit were provided by the Astrophysical Institute Potsdam, Germany. The Osservatorio Astronomico of Teramo provided the motors and the driver.

5.2 IRAIT – the International Robotic Antarctic Infrared Telescope

The IRAIT telescope is a 80cm robotic telescope to be installed and operated at the *Concordia* station in 2007/8. It is provided with a wobbling secondary mirror to perform focusing, dithering (for near-infrared observations) and fast chopping (for mid-infrared observations). A plane tertiary mirror can alternatively feed the two Nasmyth foci. One of the Nasmyth focal stations is equipped with AMICA (Antarctic Multiband Infrared Camera), a NIR/MIR double armed camera operating in the near- and mid-infrared spectral regions, the other focus is tentatively foreseen for the CAMISTIC bolometer.

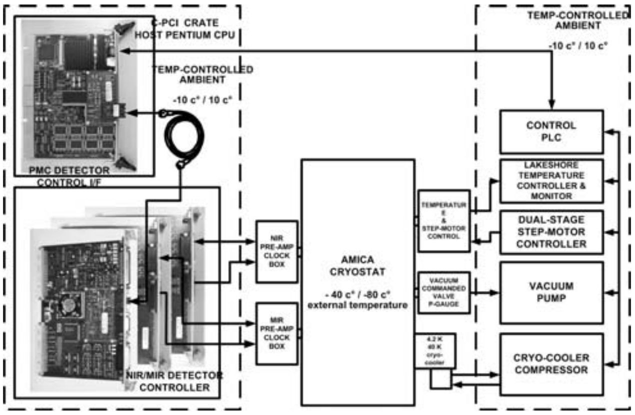

Fig. 11 The overall AMICA control system subdivided in cold and warm ambients. See text.

The NIR and MIR wavelength regions of AMICA are covered by a Raytheon CRC-463 InSb 256×256 array and a DRS Technologies MF-128 Si:As 128×128 array, respectively. Array readout is performed via a couple of independent video-sampling boards, each one handling four video channels. Video boards are handled by a SKYTECH PMC control I/F (Bortoletto et al. 2006) and supervised by a CPCI Pentium host.

Taking advantage from the large difference of pixel size between the NIR and MIR detectors a single TMA (three mirror anastigmatic) system with fixed magnification has been designed to feed the selected detector. Sampling scales are 0.54″/pixel for the short wavelength region and 1.34″/pixel for the long wavelength region with critical sampling at 4.5 μm and 8 μm, respectively. Detector selection is commanded by a simple step-motor driven flat flip mirror. A second advantage of this simple optical system is that it requires a single step-motor-driven filter wheel placed in the re-imaged pupil to switch between filters for both channels.

A scheme of the overall control system is shown in Fig. 11. The low ambient temperature and the difficulty to dissipate heat from electrical components due to air rarefaction place severe constraints on the system configuration. Two basic solutions were envisaged for AMICA: all the control electronics (CPCI computer, detector controller, PLC master control system) and the cryo-mechanisms (vacuum pump, cryo-cooler compressor and temperature controllers) shall be placed in a temperature controlled rack, while ambient temperature critical parts (the cryo-cooler head) will be protected and modified in order to properly operate.

The CPCI host provides high level system control I.E.: system ON/OFF cycles, vacuum and cryo-cooling cycles, temperature monitoring (inside and outside dewar), rack temperature control and cryo-motors control through a dedicated PLC.

Communication with the camera (commanding, telemetry and data), is implemented on an ftp protocol base, allowing to control the camera both from any remote computer in the network and from the CPCI as well. To support tests an IDL-atv based user interface is available, allowing to send commands, retrieve feedback and telemetry and read the detector data. The usual atv functionalities allow data quick look.

5.3 A-STEP

A-STEP is a 40 cm Newton telescope equipped with a commercial CCD camera of 4k×4k pixels. It will cover a field of 1 square degree, containing between 3000 and 6000 stars brighter than 16 mag. High declination fields are preferred for almost continuous visibility for the whole polar night from May to August (Mosser & Aristidi 2007). The expected precision for photometric measurement is 10^{-3}, at least for the brightest part of the sampling, and a relative precision better than a few 10^{-5} for periods shorter than 20 minutes. Such a precision requires good stability of the optics despite the external temperature variations.

The A-STEP instrument will use already validated technology, e.g., the telescope mount from *Astro-Physics, Inc.*. It will also include some new devices like an open Serrurier structure. This is presently under study. Different solutions to solve the icing problem on the telescope structure and optics will be tested through temperature control and proper use of different external treatments (see Sect. 4.5).

The first scientific campaign is foreseen during the year 2009, with the monitoring of a single field for the full winter. The following year, the instrument automatic capability will be improved, so it could be operated with a reduced maintenance, and an almost automatic data reduction procedure. It is envisioned to observe several fields simultaneously, and also to place the instrument on a higher platform in order to reduce the sensibility to the seeing variations, if this parameter proves to be a limitation.

For at least the first two years, A-STEP will require human intervention for winter operation and maintenance. A daily procedure will be necessary to ensure proper work. Each "day", the cables have to be unwrapped. Although this could be fully automatized, our experience has shown that the mechanical constraints of such a procedure are quite stringent and occasionally hazardous. It is therefore preferred to operate under the supervision of the winter operator. At the same time, the optics can be cleaned from snow and frost if necessary. The objective is to keep the necessary operation time to less than half an hour every day.

For safety reasons, the telescope will be able to operate for 48 hours without maintenance, but will stop automatically if it is not attended after this period. The astronomer will be able to operate the dome enclosure and to stop the telescope from the *Concordia* station in case of bad weather or mechanical failure. At the station, the astronomer will have access to several of its health parameters. Every day, pre-processed partial data will be sent to Europe through e-mail so that the proper operation and the data quality can be monitored. Due to reduced data transfer capability, final data will be archived on site and recovered after one year. After validation, a fully automatic data reduction procedure will be implemented for the second year of observation.

5.4 TAVERN-SP

The TAVERN[9] "Star Photometer" (SP) is a project to measure aerosol densities on the Antarctic plateau by means of stellar spectrophotometry. This is done differentially between two stars, one high in the sky, the other close to the horizon for a total of 16 bandpasses from 420–1040 nm, each 8 nm wide. During a first stage, SP provides optical depths and information on stratospheric clouds and tropospheric ice crystal events. During a second stage, ICE-T (Sect. 5.5) replaces the mount for the SP telescope and then acts as a wide-field photometry machine with the goal to retrieve the spatial distribution of the aerosol optical depth across the ICE-T FOV. SP will continue to operate "piggy-back" on the ICE-T mount.

SP uses a modified equatorial GM2000 mount from *10Micron* in alt-az position. Its load capacity is up to 50 kg with a positioning precision of $\pm 3'$ and a periodic tracking error of $\pm 3''$. Integrated encoders and homing sensors (both axes) will enable semi-autonomous operation. A local operator must initially start the observing sequence. It will automatically stop the system after sequence completion and closes the dome. The SP will be located at the new *Concordia* astronomy section in its own 4.5 m *Baader-Planetarium* all-sky dome. First operation is foreseen for the polar night 2009.

5.5 ICE-T – the International Concordia Explorer Telescope

The case for optical photometry from Dome C was highlighted by several authors, most recently by Strassmeier (2007), Kenyon et al. (2006), Pont & Bouchy (2005), Fossat (2005b), Deeg et al. (2005), but see also the Vulcan-South web site[10], the COROT pages[11], and the previous sections on SP and A-STEP. The envisioned observing strategy of ICE-T is to look at one field in the sky for the entire polar night; one of the unique advantages why we would want to deploy to the Antarctic at Dome C.

ICE-T consists of two 60 cm, f/1.1 ultra-wide-field Schmidt telescopes optimized for Sloan g (402–552 nm) and Sloan i (691–818 nm), respectively (an earlier version was based on a single 80/120 cm reflective Schmidt; Strassmeier et al. 2004). The technical goal is to perform time-series photometry of a million stars between 9–19th mag. A photometric precision of up to 200 micro-mag for the brightest 1 000 stars is envisioned. Such ultra-high precision for stars brighter than 12th mag is possible because the

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[9] "Tropospheric Aerosol and Thin Clouds Variability including the Radiation Budget over the East Antarctic Plateau"

[10] http://www.polartransits.org/index.html

[11] http://smsc.cnes.fr/COROT/index.htm

site has 3.6-times reduced scintillation (Kenyon et al. 2006) which makes a 60 cm telescope in the Antarctic equivalent to a global network of 1.5 m telescopes at temperate sites. Nominal time resolution would be between 10 s and 600 s, depending upon the choice of co-adding and the on-site disk space, thus even enabling asteroseismology. The two parallel-mounted 60/80 cm telescopes each feed a monolithic 10.3k × 10.3k thinned, back-illuminated 9-micron CCD, operated either in frame-transfer mode or in shutter mode. Its total field of view (FOV) would be 12° diameter, of which 65 square degrees would be seen by each CCD ($8.1^\circ \times 8.1^\circ$). The image scale is $3''$ per pixel with a nominal defocus to 6–8 pixels (18–$24''$) for optimal point-spread-function sampling.

Opposite to many other highly automated wide-field surveys, e.g. SDSS (Ivezić et al. 2004) or Pan-STARRS (Hodapp et al. 2004), ICE-T would operate in a truly robotic mode, i.e. with no human attendance at all. It is thus more like a space mission than an advanced queue-scheduled observatory. A master weather station and an internal clock are the keys for the start/stop of the system. The internal clock gives the first approval to start operation once a certain distance of the Sun below the horizon is reached (possibly 5° or less). A sky-brightness sensor provides the second input approval.

The main robotization problem for ICE-T is its high data rate. We consider only full-frame operation for the CCD, i.e. no pre-windowing like for space missions. With the two large 10k-chips without binning (a total of 225 million pixels), and 16 bit integer per pixel, a single exposure from both telescopes amounts to 450 MB (the 50 kB of metadata per frame are neglected here). An exceptional 100-day observing night and an optimistic 20% bad-weather/technical loss results in roughly 8 million useable seconds. For an integration time of 10 s per telescope in frame-transfer mode, the "nightly" data rate would be 360 TB. Combining always 30 of the 10-s frames reduces this to 12 TB. For the case with a shutter or in drift-scan mode with a read-out-time of also 10 s, the "nightly" data rate would be halved. A factor two lossless compression would lower this to approximately 6.5 TB for the frame-transfer case and again half of that for the shutter case. The bulk of data would be handled by an automated band station and produce a total of 200 512-GB SDLT tapes that must be carried back to Europe. Possibly, the metadata could be transferred via satellite.

5.6 SIAMOIS

Siamois is a Fourier-Transform interferometer dedicated to asteroseismology. It could observe up to two stars at the same time during long duration, up to several weeks with a duty cycle of 80%. It is foreseen to be ready for the 2011 winter. The instrument is made of several components: a telescope with a dedicated "bonnette" to track the star and collect the flux, an interferometer based on a scaled mirror concept without any moving element, and an optical fiber from the telescope. The command/control system allows to manage the instrument, the data flow, and to automate standard operations. One major issue is to minimize the human intervention during the observations and also during the set up of the instrument. The architecture is based on a command/control system (CCS) which acts as the main software receiving and sending information to specific stand alone sub-systems. Its functions are to control the different elements (camera, thermal-control system, telescope mounting motors a.s.o.), to store the data (spectra from the camera, temperature probe, motion of the telescope), to process the data, to send data and ensure the remote control. It is sustained by an embedded PC with an UPS control and a RAID disk system for maximum robustness of the system. Remote control is done by a distant PC in the main building via an ethernet link.

The CCS has very few different modes, two for the setup and specific calibration (co-alignment of the different optical axes, focus set up, optimization of the data processing, a.s.o.) and one for the main observation mode (the data are processed, stored locally, some data are sent to the remote control, the different control loops are actives, quick-look is available). The first two modes may be used with human intervention. A default configuration file may be used at the beginning of the set up, then a specific configuration file will be built corresponding to the current set up and will be stored with the data. The last mode (that runs during weeks) is a fully automatic mode with only human monitoring. A quick-look analysis shows the current status of the instrument over many image acquisitions by average or comparable. The data sent to Europe will show the state of the instrument at a given time, as an accurate estimator of the health of the instrument.

5.7 A-FOURMI: Antarctica FOUR Meter Interferometer

A-FOURMI is a solar 4 m-class diffraction limited robotized facility for high resolution solar imaging, 3D spectropolarimetry and coronagraphy from the visible to the IR at 28 μm. It is a compact co-phasing interferometer made of 9 telescopes (3 triplets of 3×70 cm off-axis telescopes), capable of $0.025''$ at 0.4 μm and still $0.25''$ at 4 μm. It optimizes real-time permanent high angular resolution thanks to a fast 60-element adaptive optics (AO) system at the level of the small elementary telescope and co-phasing of the telescopes and triplets by interferometry (a spatial filtering double synchronous detection scheme adapted to the extended solar object case). The combination of AO and interferometry also results in reduced mass and dimensions, much easier heat control, smaller relay optics and definite alignment and tolerance advantages.

A-FOURMI is the ground counterpart (visible, IR) of the HIRISE/SOLARNET solar physics space mission proposed to ESA's Cosmic Vision new missions cycle (Damé 2006), based on advanced technology readiness demonstrations carried for the space programme. As such it uses the same automatized (robotized) control-command and data acquisition approaches than its space counterpart. Furthermore, and since solar observing is performed during daytime (and with Sun shining), the Dome C system proposed is powered by solar cells and entirely autonomous (as a space mission is).

Excellent seeing, coronal conditions, and very low IR thermal background allow unique observing capabilities, e.g., an IR sensitivity equivalent of a 16 m telescope in the prime coronal lines of Mg VIII 3.027 μm and Si IX 3.935 μm. Even the feasibility demonstrator of A-FOURMI, with its 3×70 cm telescopes on a 1.9 m baseline – readily possible as a pathfinder-precursor at Dome C for Solar Astrophysics and tower technologies – would already achieve better performances (0.06″ spatial resolution) than a 4 m Solar telescope anywhere else on Earth. Compact and light with an open-telescope structure, this system is perfectly suited for an open-frame tower and an open dome, particularly appropriate for Dome C with its moderate wind speeds. While the system could be used in several good sites on Earth, only in Dome C can it access IR lines for coronagraphy and direct coronal magnetic field measurement with seeing better than 0.5″ during several hours. And, in the IR, even the already moderate AO system might not be necessary to phase the small 70 cm individual telescopes.

5.8 PILOT – the Pathfinder for an International Large Optical Telescope at Dome C

5.8.1 A 2 m telescope and its operations model

PILOT is a proposed 1.8–2.5 m optical/IR telescope (Storey et al. 2007). It would be placed on a 30 m tower to get above the majority of the turbulent boundary layer, and from there will enjoy the lowest infrared backgrounds and best seeing conditions of any telescope on Earth. PILOT was initially proposed in 2004 by a consortium of countries that included Australia, France, Italy, Germany, the UK and the US. The project is currently moving forward as a joint Australian-European project, with the objective of 50% financial and in-kind support from each side, and a 50% share of the observing time. The science case for PILOT has been published by Burton et al. (2005).

Although not fully robotic, PILOT must be designed for maximum reliability and minimum operator intervention. The telescope will be provided with a computer controlled Telescope Control System. Control (opening up, slewing to a field, acquiring a guide-star, offsetting, data-taking, closing up) must be possible in three modes: (1) by an operator, (2) remotely from outside Antarctica, (3) under computer control via a predetermined script. In each case interlocks (e.g. snow alarm, zenith limits, turnkey access to telescope) must prevent unsafe operation. It is also highly desirable for PILOT to be able to respond autonomously to automatic alerts, generated, for example via the eSTAR project (Sect. 3.4).

Sufficient computing facilities will be provided to allow: (1) Data taking at the expected maximum rate ($\approx$2 MB/s); (2) This data to be pipeline processed, including mosaicing and dithering, into reduced image frames and image catalogues, in real time; (3) An entire winter's worth of data ($\approx$20 TB) to be stored online; (4) There will be a separate system for data reduction; (5) There will be a backup system to allow all raw, reduced and extracted data to be automatically backed up to two copies of removable physical media in real time; (6) Provision will be made to store the two copies in different buildings.

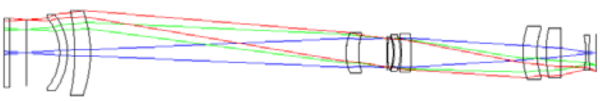

Fig. 12 Preliminary optical design for a wide field NIR camera for a 2 m-class telescope at Dome C. The system is based on nine spherical lenses that provide diffraction limited performance over the wavelength range 0.85–5.5 μm. The system's length is 950 mm.

The design study currently underway will examine the communications bandwidth necessary for reliable operation of PILOT and, in particular, the trade-off between wideband satellite communications and a more full robotic operations model.

5.8.2 Instrument concepts for a 2 m-class telescope

Several astronomers from European institutions (UAM, UGR and LAEFF-INTA from Spain and IASF-INAF from Italy) have started the exploration of two alternative concepts of NIR instruments for a 2 m-class telescope at Dome C: a wide-field camera and a camera spectrograph. Scientific drives are in the star formation and very low mass objects research field. The wavelength range would be 0.85–5.5 μm, with a possible extension up to 30 μm. The instrument performance would be optimized for the K, L and M bands, where gains in sensitivity are large compared to other temperate sites (Burton et al. 2005). After the completion of the conceptual design phase, both alternatives will be evaluated in terms of their scientific return and technical feasibility. The best concept will be selected for a preliminary design phase-A study.

The first option considered is a wide-field camera. It would be based on a monolithic or mosaic array of $4\text{k}\times4\text{k}$ pixels (see Table 2), with a plate scale of 0.25″/pixel and a field of view of $17'\times17'$, operating in the 0.85–5.5 μm wavelength range. The images would be Nyquist sampled in L and M. Full spatial resolution in the $zJHK$ bands would be recovered via the Drizzle algorithm (Fruchter & Hooke 2002). Preliminary optical designs based on lenses (see Fig. 12) and mirrors have been developed. The mirror design could use an additional Si:As large format array, fed by a dichroic or a flip mirror, to further increase the wavelength coverage to the mid infrared.

The second option is a camera-spectrograph. It would be based on a $2\text{k}\times2\text{k}$ IR array, sensitive in the 0.85–5.5 μm wavelength range, with a plate scale of $0.11''$/pixel, giving a field of view of $3.75' \times 3.75'$ and appropriate sampling for high spatial resolution imaging and high precision photometry. A preliminary optical design uses five spherical lenses and provides diffraction limited performance over the whole wavelength range. Spectroscopic limiting magnitude for the K, L and M bands at several spectral resolutions have been computed, for 2 m (PILOT) and 8m Antarctic telescopes, and an 8 m telescope located on Mauna Kea. It has been found that the advantage of Antarctica in terms of NIR photometric limiting magnitude (a 2 m telescope at Dome C is roughly equivalent to an 8 m at Mauna Kea) is identical for spectroscopy.

5.9 ALADDIN: a ground-based DARWIN pathfinder

ALADDIN (Antarctic L-band Astrophysics Discovery Demonstrator for Interferometric Nulling) is a pathfinder for the DARWIN space mission, whose purpose is the census of habitable planets around nearby solar-type stars, and the spectroscopic characterization of their atmosphere. The primary goal of ALADDIN is to pave the way for the DARWIN mission by measuring the amount of thermal light emitted by interplanetary dust within the habitable zone around potential targets. Like DARWIN, ALADDIN will be an interferometric nuller to cancel out on-axis stellar photons while transmitting off-axis light emitted in the stellar environment. The baseline concept calls for an instrument located between a pair of 1 m telescopes positioned on a 40 m rotating truss (Coudé du Foresto et al. 2006; Barillot et al. 2006). Thanks to the combined advantages provided by the low background, high photometric efficiency, and quiet atmosphere above the ground layer, the system will be more sensitive than a nulling instrument using a pair of 8 m telescopes in a temperate site such as Paranal (Absil et al. 2007).

Beyond the need for robotization, there are many similarities between the constraints which exist for a space mission and an Antarctic experiment (especially if it is planned to be operated during the winter): mass, volume, telemetry limits, deployment and commissioning considerations, operations, reliability issues and recovery modes. In these domains, the input and expertise of the space astronomy communities can be most useful for the development of heavy Antarctic instrumentation.

5.10 PLATO: a 3rd generation robotic site-testing observatory for Dome A

At 4100 m, Dome A is the highest point on the Antarctic plateau. It is therefore expected to be a superb astronomical site, possibly surpassing both the South Pole and Dome C for some kinds of observations. In January 2005, a Chinese expedition made a 30-day traverse to Dome A from the coastal station of Zhongshan to establish the first automated weather station there. This expedition will be followed by an even more ambitious one by the Polar Research Institute of China at the end of 2007. This expedition will deliver PLATO – the third generation of UNSW's robotic site testing observatories (Lawrence et al. 2006).

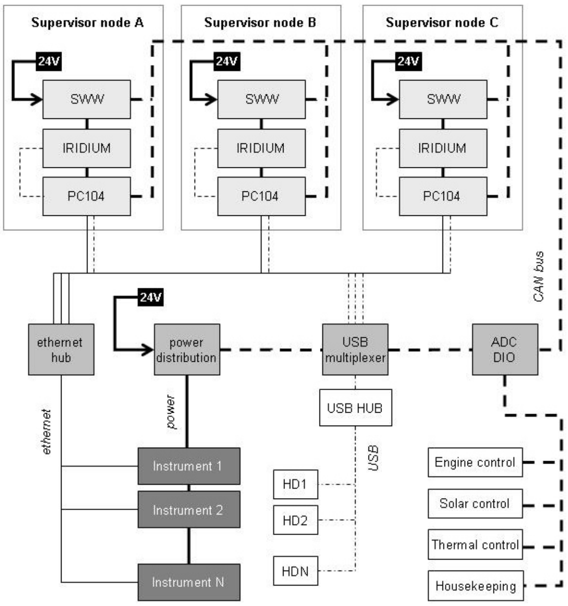

Fig. 13 Block diagram of the PLATO control system.

PLATO is designed to deliver over a kilowatt of electrical power from a combination of solar power and small diesel generators. To give plenty of redundancy and an ability to deliver additional power in mid-winter, six independent engines will be used. A system's overview is shown in Fig. 13.

At Dome C, the wind is predominantly from one direction. This greatly simplifies the problem of what to do with the exhaust gases from the engines. For example, the AASTINO was aligned with its long axis parallel to the prevailing wind, with the exhaust stack placed at the downwind end. This meant that all the instruments were upwind of the exhaust stack. At Dome A, however, models show that there is no preferred wind direction, and this is supported by preliminary data from the Automatic Weather Station placed there in January 2005. The problem of ensuring that the instruments do not observe through a plume of exhaust gas can only be solved by physically separating the power generation from the instruments. PLATO thus consists of two modules: a power module and an instrument module. These will be separated by some 20–30 m, with only electrical power and a CAN bus connecting the two modules.

This physical separation of the power and instrument modules also helps reduce the transmission of noise and vibration from the generators to the astronomical instruments. However, with none of the excess generator heat now being available for the instrument module, it must be kept warm solely by the waste heat from the instruments themselves. Extremely good thermal insulation is therefore required for the instrument module.

As with the AASTINO, two-way communication with PLATO will be via the Iridium satellite network. PLATO will use three independent ”Supervisor” computers, each with its own Iridium link. Independent watchdog timers will ensure that no single or double computer problem can cause a failure of the PLATO data acquisition system.

5.11 PreHEAT: a robotic sub-mm tipper at Dome A

PreHEAT is a 450 μm-wavelength tipper/telescope to be deployed in 2007 to Dome A on PLATO, to serve as a precursor to HEAT, a planned THz-frequency telescope for installation on PLATO by austral summer 2008/9. Chris Walker and Craig Kulesa lead the development of the (Pre)HEAT instruments at the University of Arizona. PreHEAT's aims are to monitor the sub-mm opacity of the atmosphere above Dome A, in order to assess the quality of the site for sub-mm/THz observations, and to map the Galactic plane in the J = 6–5 transition of ^{13}CO by drift-scanning. The 20 cm aperture of the tipper mirror will yield a $\approx 9'$ FWHM beam, comparable to that of the CO 1–0 surveys carried out by the 1.2 m Columbia mm-wave telescopes.

PLATO and PreHEAT are designed to operate without any human intervention after deployment. This requires not only that routine operation (observations, calibration etc.) be automated, but also all other tasks that might be carried out by a winterover at a crewed site. One particular concern is frost and snow management. A black surface at $\approx -70^\circ$C loses a few$\times$10 W m^{-2} purely by coupling to the cold sky. At this temperature, a heat flux of 10 W m^{-2} is equivalent to ice deposition of 0.3mm per day. In line with this estimate, frost is routinely observed at Dome C, but not at the South Pole. Since we expect conditions at Dome A to have more in common with Dome C than with the Pole, we expect frost management to be a problem.

A Goretex membrane is planned as a weather shield, and it is not clear whether this is likely to frost up (although the strong frosting observed on an upward-facing teflon disc by GIVRE – see Sect. 4.5 – is cause for concern.) Possible approaches to preventing or clearing frost include: ambient airflow over the surface; warming, either directly or by waste heat; and using an ambient-temperature baffle to reduce the radiative load.

Current plans call for a combined approach, with ambient-temperature baffles to restrict the area of sky seen by the tipper membrane to a narrow vertical strip, sufficient to allow the constant-azimuth observations for which the tipper is designed. But these baffles need not extend all the way down to the membrane: by leaving a space between the membrane surface and the baffle, an ambient airflow can be introduced over the surface of the membrane, perhaps by fans mounted between the baffles and the tipper structure. It may also be possible (depending on PLATO's thermal budget) to heat the membrane by allowing some (above ambient temperature) air from inside PLATO to bleed out, warming the membrane.

Pictures of the snow surface at Dome A show essentially no sastrugi, which suggests very little wind, so we might expect very little blowing snow, but there may be some precipitation. The membrane will prevent snow from getting into or onto the tipper mechanism, but it may be necessary to clean snow off the membrane itself. This will be accomplished by rotating the cylindrical tipper casing against a small, flexible brush.

6 Conclusions

Due to the harsh conditions, telescopes and instruments at Dome C should be able to perform without much human interaction, i.e. automatic or even robotic. Therefore, the quest for “robotization” is a quest for an integral system-engineering approach that links design and construction with operation and maintenance, and still is in compliance with the support that can be given by *Concordia*. The engineering challenges may approach those in space. However, they are performed on Earth, with the huge advantages of significantly lower costs, faster development cycles and the possibility of some human interaction.

As part of our quest for a scientific road map for astronomy at *Concordia*, the issues detailed in Sect. 2-5 suggest the following conclusions for successful robotization at Dome C:

- Temperate-site observatories have an extended infrastructure because it is needed! Eventually, a *Concordia* observatory at Dome C has the same needs.
- The management approach for a fully robotized telescope and instrument at Dome C appears more like that of a space experiment rather than a ground observatory.
- It always requires an integral, i.e. end-to-end, systems-engineering approach.
- The local infrastructure will decide upon the scientific operations success.

These conclusions are equally valid for day-time and night-time astronomy. A unique site always requires unique experiments. Currently, the instruments that have been, or shortly will be, placed at *Concordia* are the 0.8 m near and mid-IR telescope IRAIT (Tosti et al. 2006) and the sub-mm dish COCHISE (Dall'Oglio et al. 2003). Several smaller instruments like sIRAIT (Sect. 5.1, see Tosti et al. 2006) or PAIX (see Chadid-Vernin et al. 2007) are already on site as pathfinders along with the cosmic micro-wave background polarization experiment BRAIN (Masi et al. 2005). All of these and several others are prototypes or pilot projects for larger (optical/IR/sub-mm) instruments.

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