A Vision

for European Astronomy and Astrophysics at the Antarctic station Concordia, Dome C

In the next decade 2010-2020

Prepared by the

ARENA *ANTARCTIC RESEARCH, A EUROPEAN NETWORK FOR ASTROPHYSICS*

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Silent with star-dust, yonder it lies -
The Winter Street, so fair and so white;
Winding along through the boundless skies,
Down heavenly vale, up heavenly height.
Faintly it gleams, like a summer road
When the light in the west is sinking low,
Silent with star-dust! By whose abode
Does the Winter Street in its windings go?
And who are they, all unheard and unseen -
O, who are they, whose blessed feet
Pass over that highway smooth and sheen?

What pilgrims travel the Winter Street?
Are they not those whom here we miss
In the ways and the days that are vacant below?
As the dust of that Street their footfalls kiss
Does it not brighter and brighter grow?
Steps of the children there may stray
Where the broad day shines to dark earth sleeps,
And there at peace in the light they play,
While some one below still wakes and weeps.

Miss Edith Matilda Thomas (1854-1925)

Table of contents

Executive Summary

This document, prepared with the contributions of more than 100 scientists and engineers from Europe and Australia involved in Antarctic astronomy, presents a roadmap for the development of European astronomy and astrophysics in the Antarctic continent, and more specifically, at the Concordia station (Dome C) in the coming decade (2010-2020). It is based on the work carried out during the period 2006-2009 within the framework of the ARENA network.

Astronomers have always sought the best possible observing conditions. The inner Antarctic continent is the wildest, coldest, and driest desert on earth, offering an almost pristine nature without human contamination, or even faunal or floral presence. It is therefore, in essence, an outstandingly appealing area to explore for the construction of major astronomical facilities of the future. Astronomers have for decades been attracted by this opportunity. Several pioneering attempts have been made to set up increasingly sophisticated instruments over the last 40 years encompassing a wide range of techniques and scientific goals. The only major astronomical facility so far established is at the US station Amundsen-Scott, right at the geographic South Pole station, and named the Martin A. Pomerantz Observatory in tribute to one of the most active astronomers in Antarctica over the last half century.

France and Italy have recently joined the effort: they have built and, since 2005, operate year-round a multidisciplinary station at Dome C called Concordia, one of the highest domes on the Antarctic Plateau, located about 1,200km from the sea coast at a latitude of about -75° and an elevation of 3,202m. Dome C is an extremely promising location for the establishment of the first European astronomical observatory in Antarctica, which eventually could become a major item of international research infrastructure.

To explore this opportunity in all its aspects, a network, ARENA, was created under the auspices of the European Commission. ARENA has had as a goal the investigation of the scientific prospects of and the possibility of implementing an astronomical observatory at Concordia, and to document a suite of instrumental projects that could benefit greatly from the conditions on the Antarctic plateau. ARENA created the impetus necessary to form international consortia in charge of preparing detailed studies (Phase A and B) of at least a couple of the proposed projects; consortia that could possibly undertake their construction before the end of the coming decade, 2010-2020.

Preliminary site assessments and atmospheric modelling by several expert teams, primarily from Australia, France, and Italy, have demonstrated that this region offers exceptional conditions for astronomy mainly thanks to the cold, dry, and calm atmosphere. The atmosphere above the highest spots of the Antarctic continent offers the best conditions on earth to investigate astronomical objects at high angular resolution in the near thermal IR and submillimetre-wave ranges. The high latitude location allows very long continuous night-time photometric observations, which are essential for the study of periodic variability of celestial objects. In several well-identified domains («*niches*») the Antarctic plateau may even compete with space missions, but at a much lower cost, and with the invaluable bonus of using the most advanced technologies.

The ARENA network has identified six particularly promising astrophysical areas with well-defined research programmes. Taking into account the constraints of logistics and environment, the network has been able to outline the top-level requirements for the instrumentation able to address these programmes.

They are, i) wide-field, extremely sensitive imaging and spectro-imaging in the near and thermal infrared (2.3-4µm) with a 2.5m-class telescope (the PLT project), ii) extremely sensitive submillimetre-wave imager with a collecting area equivalent to a 25m dish (project AST), iii) near IR interferometry for the detection of exoplanets and exozodiacal light (the ALADDIN project), iv) a set of smaller dedicated instruments (some of them already in the construction on-site) for planetary transits, stellar variability, asteroseismology, and infrared imaging photometry, v) cosmic microwave background experiments (the QUBIC project) and, vi) high angular resolution solar measurements (the AFSIIC project).

A series of recommendations have been drawn from the discussions held during the several workshops and conferences that took place during the last four years.

Site assessment

A large amount of data have been collected with the aim of quantifying the day and night-time astronomical observing conditions at Dome C. The available data show that the precipitable water vapour is usually below 0.7mm and drops to 0.3mm for 50% of the time, thus offering excellent conditions for submillimetre observations. The extreme cold of the atmosphere means that its thermal emission is greatly reduced. This, in turn, leads to significant savings in the time required to carry out large observing programmes at wavelengths longer than 2µm.

The absence of strong turbulence in the upper atmosphere results in low scintillation and creates favourable conditions for photometric programmes. The median free-atmosphere seeing in the visible is 0".36, but achieving this imaging accuracy in the optical is limited by the presence of a very strongly turbulent boundary layer which extends up to median altitudes of some 40m in winter and up to 400m in summer. The small outer scale of turbulence measured at Dome C, combined with a long coherence time and with the large isoplanatic angle is beneficial for high angular resolution techniques at this site. Detailed measurements of the vertical and temporal variation of the atmospheric parameters are now needed, in order to draw robust conclusions about short- and long-term stabilities and trends, and to constrain the specifications of instruments to be deployed at Dome C.

Near-infrared high angular resolution wide-field imaging

Various countries have for some time proposed the construction of a large optical/infrared telescope in Antarctica. The conditions on the Antarctic plateau particularly favour an exploitation of the spectral windows not easily accessible from the ground, *i.e.*, in the thermal IR beyond 2.3µm where observations are normally hampered by the strong thermal background emission of the sky from the ground. Thanks to the exceptional seeing conditions above the turbulent layer, Dome C is an ideal site to make large-scale, high angular resolution, extremely deep imaging surveys in this wavelength regime.

The **PLT** (Polar Large Telescope) project is the result of extensive discussions between Europeans and Australians to propose a realistic, albeit ambitious, project for such a telescope with a 2.5m aperture. A limited number of programmes will be performed aimed at surveying very distant galaxies, dusty SNIas, and extreme stellar populations in the local group, and at characterizing exoplanets by transit and microlensing milli-magnitude photometry. The project will be based on a European-Australian collaboration. A preliminary evaluation of the cost points toward a 11 M€ telescope and 5 M€ focal instrument with a Phase B study in 2010-2013 potentially funded by the FP7 and a first light before the end of the decade (hopefully 2018).

Submillimetre-wave astronomy

Performing ground-based astronomical observations in the submillimetre part of the electromagnetic spectrum requires, at a minimum, very dry conditions. The Antarctic plateau, a unique «desert» on Earth, is an obvious candidate site.

The atmospheric transmission in the submillimetre windows centred at *e.g.*, 200, 350, 450, and 850µm has been estimated by the team of CEA-IRFU/Saclay using measurements with a tipper instrument and the MOLIERE radiative transfer modelling code. The 200µm window opens up to better than 20% transmission for 25% of the time. Observations at 350 and 450µm would be possible all year. These values of transmission indicate that observing conditions at Dome C are superior to the known sites in Chile or Argentina. The estimated transmission values were used as filters to select science cases. The «Cosmic history of star formation, black holes and galaxies», «Origins of stellar masses», «Galactic engines», and «Galaxy clusters in the far Universe and dark energy» were selected as the four main topics of science cases for a submillimetre-wave telescope facility in Antarctica.

One of the functions of the thermal infrared telescope (the Italian IRAIT 80cm) can be as a pathfinding experiment for submillimetre astronomy. It will perform atmospheric and sky-noise measurements with a bolometer array, prepare a catalogue of source calibrators in the far-southern sky, and attempt several science observations of the Sun and of star formation.

Finally, this roadmap provides a vision for an Antarctic Submillimetre Telescope (**AST**) project. This could be a large telescope facility consisting of a 25m diameter class, single-dish at Dome C, or equivalent collective area achieved with a network of medium-size radio telescope antennas, operating at submillimetre wavelengths and offering unique science possibilities. Its perfomance at 200, 350 and 450µm would be superior to an equivalent telescope on any of the Andean sites in Chile and Argentina. Furthermore, a single-dish telescope could be used as a Very Long Baseline Interferometry station with the ALMA and other antennas in South America.

Optical and infrared interferometry

Studying the warm inner parts of debris disks, the extrasolar counterparts of the zodiacal dust cloud, is of prime importance to characterize the global architecture of planetary systems. Furthermore, the presence of large quantities of warm dust around nearby main sequence stars represents a possible obstacle for future space missions dedicated to the direct detection and characterization of Earth-like planets. The frequency of the occurrence of bright exozodiacal disks around solar-type stars is currently mostly unknown. As of today, exozodiacal disks have been directly resolved around a small number of main sequence stars, at a sensitivity level of about 1,000 times our Solar System zodiacal dust cloud. In this context, the Antarctic plateau could provide the optimal ground-based conditions for an infrared nulling interferometer dedicated to the direct detection of warm dust clouds around nearby main sequence stars.

Joint efforts between several European institutes within the ARENA consortium led to the definition of the **ALADDIN** concept. In order to achieve a significantly improved sensitivity with respect to existing instruments, the architecture of the system is specifically focussed and optimised for the purpose: ALADDIN implements the nulling interferometry technique at the focal plane of a two telescope interferometer mounted on a rotating beam structure. Thanks to the Antarctic environment, such a nulling interferometer coupled to a pair of 1m-class telescopes operated at thermal infrared wavelengths would perform significantly better than a similar instrument working on 8m-class telescopes in a temperate site (*e.g.*, at ESO Paranal).

Long time-series photometric observations

Time-series data are the result of astronomical observations of temporal phenomena; to be valuable such observations typically require one or more of the following conditions:

- Long observing duration coverage in stable conditions, particularly in combination with high duty cycles
- Very good seeing and/or low scintillation
- Observations in spectral ranges that have been little explored to date.

Contributing to all of these requirements, Dome C provides unique opportunities for ground-based observations. Because of the need for long and continuous time coverage, most such observations require a dedicated telescope, typically of sub-1m size. However, there are also scientific cases for which the use of significant time allocations on larger multi-purpose facilities is more appropriate. The major science cases for time-series at Dome C are: detection and characterization of extrasolar planets (transits), asteroseismology, and stellar activity studies. The panel reviewed several projects that were presented:

- **ASTEP 400,** a 40cm telescope for planet detection, received its first light in November 2009. It should provide scientific data rapidly (2010-2011) and thus ought to be strongly supported by the relevant agencies.
- Of projects in the development phase, **ICE-T** (International Concordia Explorer Telescope), a 2x60cm binocular telescope, is graded the top priority instrument for time-series photometry; it is expected to become the reference instrument for stellar activity studies. Its construction is funded, but site-access and operational issues need to be resolved as soon as possible for an anticipated deployment around 2013-2014.
- **SIAMOIS** (Seismic Interferometer Aiming to Measure Oscillations in the Interior of Stars) is the top priority instrument for advanced time-series spectroscopy, and is expected to become the reference in stellar Doppler velocity studies. Its deployment with two small-aperture telescopes is anticipated for 2013-2014. In a second phase, the scientific return can be enhanced to include specific faint targets by feeding the instrument from a 2m-class telescope.
- Finally, **PLT** (Polar Large Telescope) is considered critical for shorter time-series projects requiring a larger and flexible instrument, where open access for the scientific community will be important.

Cosmic Microwave Background

Cosmic Microwave Background (CMB) observations have been extensively developed since the discovery of this radiation in 1965 by Penzias and Wilson and it has been demonstrated that Antarctica is the best place on Earth to study its anisotropies in temperature and polarization. The US M.A. Pomerantz Observatory at the South Pole is essentially dedicated to this research with, today, the largest astrophysical instrument ever built on this continent, the South Pole Telescope (SPT), a 10m aperture millimetre-wave dish and the BICEP polarization experiment. The basic advantage of the polar environment for CMB research is the unique atmospheric stability, particularly of the Earth atmospheric molecular oxygen lines, and the fact that one can observe the same area of the sky over very long periods at almost constant elevation. Dome C appears to be even better because of a lower atmospheric optical depth and of lower wind speeds, and thus even better stability (with respect to the South Pole). Moreover, its location 14° in latitude away from the pole allows cross-linked scans and drift removal techniques.

Members of the CMB working group are currently implementing the **QUBIC** experiment through a collaboration between Italy, France, Ireland, UK and the USA. This instrument (formerly called BRAIN) will take advantage of the conditions at Dome C to mainly measure the B-mode of the CMB polarization with a bolometric interferometer combining the extreme sensitivity of bolometric detectors with the optical purity of interferometers. The project is supported by IN2P3 in France and PNRA in Italy and by the ARENA CMC.

The working group also supports a project for a single millimetre and submillimetre-wave large dish mainly for high angular resolution observations of intra-cluster structures and the study of the different populations of thermal and non-thermal electrons that produce distinct Sunyaev-Zel'dovitch effects (SZE) and that could provide new clues on Dark Matter candidates.

Solar astrophysics

The Concordia station also offers unique qualities for solar observations, combining excellent seeing, low coronal sky brightness, low water vapour content, continuity and an impressive duty cycle (four months, *i.e.,* three times more than at mid-latitudes sites, under excellent observing conditions). This allows both to perform very high angular resolution (<< 0".1) adaptive optics observations and access to the corona, thus providing data on the chromosphere-corona interface that is impossible to obtain from other sites (or indeed from space for many years). These data include direct measurements of the magnetic field in the chromosphere and corona made possible by exploiting the remarkable infrared atmospheric transmission on the Antarctic plateau. Accordingly, primary science cases were defined in both high angular resolution and 2D coronal spectroscopy and a mesoscale facility, has been designed to achieve them.

The project proposed the Antarctica Facility for Solar Interferometric Imaging and Coronagraphy (**AFSIIC**), a large (by solar astronomy standards) assembly of 3xØ500mm (preferably Ø700mm) off-axis SiC telescopes placed above the turbulent layer. With a baseline of 1.4-4m this solar interferometer with coronal capabilities would have a performance superior to any current or planned ground-based telescope, including the 4m-class ATST and EST. It features 2D spectro-imaging, spectropolarimetry, magnetoseismology, and chromospheric and coronal magnetometry to facilitate a magnetic investigation from the convection zone to the corona. Furthermore, it will be the only major solar observing facility in the southern hemisphere, observing when other (northern) telescopes will suffer from winter conditions.

ARENA roadmap

Considering the various propositions made by the working groups and on the basis of the present knowledge of the site assessment, the following statements and recommendations are made by the ARENA CMC. We recommend that a process be fostered to lead to the creation of an internationally managed astrophysical station at Dome C aimed at collecting unique data over a wide range of wavelengths from the visible to the millimetre. We strongly recommend continuation of the site quality characterization to confirm the promising results already obtained, and to study their variations with time. Atmospheric parameters that have thus far not been fully studied should be measured and monitored with some urgency. These include: the atmospheric opacity at all wavelengths, the photometric stability, the sky background emission (particularly in the near thermal infrared) the turbulence profile and the outer scale of turbulence. We strongly recommend making these data rapidly available to the community and implementing a regularly updated data-base to archive the data and provide long-term, easy access to them. We strongly recommend using, as far as possible, the same instruments, calibration, data processing in the different polar sites currently under investigation, to enable objective comparison.

We express our interest in the exploration of as yet undocumented sites (such as the Antarctic Ridges A and B).

We have identified a wide range of science cases, as detailed above, that would strongly benefit from the unique Antarctic conditions. A suite of appropriately designed instruments is identified; these can be classified into three main categories:
• *small instruments*, some of which are currently in the construction phase (IRAIT, COCHISE, BRAIN/QUBIC, TAVERN, ASTEP) or ready to be built (SIAMOIS, ICE-T). They all fit within the present logistics capabilities. Their cost is in the range of a few million euros. For obvious reasons of manpower capacity on site, and to leave room for more ambitious projects, their number should not increase without limit in the future. An international peer-reviewing process to select future projects based on their scientific excellence should be established,
• *mid-size facilities* (mesoscale projects, cost range of a few tens of millions euros, (such as PLT or a solar telescope/interferometer) that will need affordable upgrades of the logistics (power supply, transport, e-communication). They will require, however, a very large deployment of personnel to the site over several summer seasons for the construction,
• *large to extremely large projects* that, according to the conclusions of the dedicated ARENA activity NA4 would require a sufficiently large increase in the resources available for logistics that one could not expect to be deployed in the coming decade (such as ALADDIN, AST, AFSIIC and, a fortiori, KEOPS - the km-scale optical/infrared interferometer array).

For the coming decade and in consideration of the reflections of the different working groups the following recommendations of ARENA are made:

• to continue the site assessment
• to establish a major funding plan in order to run the currently on-going telescopes or instruments (**COCHISE, IRAIT, ASTEP, BRAIN**) and obtain as soon as possible high-quality science from them
• to make plans for the rapid implementation of **SIAMOIS** and **ICE-T**
• to start immediately, in 2010, a phase B study for **PLT** on the basis of the phase A studies made by the Australians for PILOT, for first light before the end of the decade.
• to commence phase A studies for:
 - a large submillimetre-wave telescope facility (AST) to exploit the extraordinary potential of the site in the THz regime,
 - a pathfinder for interferometry in the optical/NIR range (such as **ALADDIN**),
 - an instrument dedicated to high angular resolution astrophysical studies of the Sun (such as **AFSIIC**).

It is unlikely that all these actions will be funded in the next decade, but, after deliberation in the CMC, ARENA refrains from ranking these projects, leaving these strategic decisions to the national, european, and international agencies that are expressed, for instance, in the body of the ASTRONET recommendations.

However, we believe that the only project in the mid-size (cost) range that can effectively be carried out in the next decade is PLT. This project has the potential for a wide support from the community and will be made possible only if a strong and sustainable international collaboration is set up around it.

We point out that several studies that will be carried out for this project, such as the implementation of a Ground Layer Adaptative Optics (GLAO) device specific to polar conditions, the construction of a stiff tower and the mitigation of frosting, will also be useful for other projects, in particular future optical/IR interferometric and solar projects.

Fostering European and international collaborations and aggregating a critical mass of resources have been constantly emphasised during the ARENA meetings. Although ARENA has helped in initiating some successful common work, the present situation is far from being satisfactory. In particular there is clearly a deficit of collaborative programmes between institutes belonging to the two countries of Concordia. Additionally, there is little doubt that an emphasis on small projects does not encourage wide, long-term collaborations. The internationalisation of Concordia for astrophysics to the status of a European Research Infrastructure is essential, but it is strongly dependent on the decision to build at least one significant ambitious project, now, and to propose an ambitious vision beyond. Our conclusion is that, without vigorous support from the national and international agencies and agreements between them, the astronomical potential of the station will not develop even though it is located in the best astronomical site on Earth. This would constitute a major paradox precisely at the time when China is creating an Antarctic Astronomical Centre at Dome A.

In conclusion, we consider that the Concordia station at Dome C represents a real opportunity for Europe (and collaborators) to develop one of the best astronomical sites on the Earth, operated all year round. Concordia is, in principle, ready to implement, host, and operate a new generation of mesoscale astronomical instruments capable of major advances in several cutting-edge astrophysical areas during the next decades. The momentum created by ARENA should definitely be sustained through new vigorous actions, such as a better coordination of the site testing operations and data access, the establishment of consortia to submit excellent proposals to the relevant funding calls, and above all the Phase B study of mesoscale projects. This should be followed with firm decisions by the national agencies.

An accompanying public outreach programme is essential and should be set up. A culture of cooperation between the management of the different stations currently in operation is also highly desirable. Ultimately, we propose the creation of a *European Centre for Astrophysics in Antarctica* on the model of existing multinational organizations. ■

The ARENA CMC,
December 2009


Bird Island
0°
60° S
Signy (UK)
Orcadas (Argentina)
Neumayer (Germany)
SANAE IV (South Africa)
Troll
(Norway)
Dakshin Gangotri (India)
Maitri (India), Novolazarevskaya (Russia)
Tor
(Norway)
Asuka (Japan)
Syowa (Japan)
Aboa (Finland)
Wasa (Sweden)
Princess
Elisabeth
(Belgium)
Molodezhnaya
(Russia)
See inset
Kohnen
(Germany)
Mizuho
(Japan)
Brown (Argentina)
Gabriel González Videla (Chile)
Yelcho (Chile)
Vernadsky (Ukraine)
San Martín (Argentina)
Melchior
(Argentina)
Palmer
(USA)
Rothera (UK)
Luis Carvajal
(Chile)
Halley (UK)
Belgrano II
(Argentina)
Dome Fuji (Japan)
Mawson
(Australia)
RONNE
ICE SHELF
Sobral (Argentina)
Soyuz (Russia)
Druzhnaya 4 (Russia)
Law - Racovita (Australia/Romania)
Proposed station (India)
Davis
(Australia)
Progress 2 (Russia)
Kunlun (China)
Zhongshan (China)
Arturo Parodi (Chile)
Amundsen-Scott (USA)
– 90° W
90° E –
Mirny
(Russia)
Vostok (Russia)
Concordia
(France/Italy)
Casey
(Australia)
ROSS
ICE SHELF
Russkaya
(Russia)
Scott Base
(NZ)
McMurdo (USA)
Gondwana (Germany)
Mario Zucchelli (Italy)
Dumont d'Urville
(France)
Leningradskaya
(Russia)
Legend
Year-round station
Seasonal station
Closed station
Proposed station
180°
Macquarie Island
1,15
2
5,6,7,8
3,4,16
9,10,17
11,17,
18,26
19
20,21
22,23
Petrel
(Argentina)
13, 24
12
14
25
Primavera
(Argentina)
Matienzo
(Argentina)
Year-round stations
1 Comandante Ferraz (Brazil)
2 Arctowski (Poland)
3 Jubany (Argentina)
4 King Sejong (Korea)
5 Artigas (Uruguay)
6 Bellingshausen (Russia)
7 Eduardo Frei (Chile)
8 Julio Escudero (Chile)
9 Estación marítima Antártica (Chile)
10 Great Wall (China)
11 Arturo Prat (Chile)
12 Bernado O'Higgins (Chile)
13 Esperanza (Argentina)
14 Marambio (Argentina)
Seasonal stations
15 Macchu Picchu (Peru)
16 Dallman (Germany)
17 Julio Ripamonti (Chile)
18 Maldonado (Ecuador)
19 Guillermo Mann (Chile)
20 Juan Carlos I (Spain)
21 Ohridiski (Bulgaria)
22 Decepcíon (Argentina)
23 Gabriel de Castilla (Spain)
24 T/N Ruperto Elichiribehety (Uruguay)
25 Gregor Mendel (Czech Republic)
Closed station
26 Luis Risopatron (Chile)

1 Approach and Scope

1a Context

The Antarctic Plateau offers exceptional atmospheric and environmental conditions for astronomical observations over a wide range of wavelengths. The ARENA network has investigated the various scientific, technical and practical issues relevant to the creation of a world class international observatory in Antarctica.

Stations in Antarctica

Astronomers have consistently sought geographical locations that provide the best conditions for their observations: the largest fraction of time that the sky is clear, access to the broadest spectral range, the highest transparency, the best seeing and the lowest sky brightness, minimal contamination by dust, light, or aerosols. A powerful, but expensive and limited solution is to set up instruments above the lowest layers of the Earth atmosphere using balloons, airplanes, rockets or satellites.

However, space platforms have never replaced ground based astronomy. It is currently, and most likely will remain so for a long time to come, necessary to use ground-based facilities to achieve extremely large collecting areas and in particular to be able to use state-of-the-art instrumentation that can be upgraded on a regular basis. Interferometry, for instance, is unlikely to be performed from space in the next decade. The search for the best ground based site remains topical, although the Chilean Andes and Hawaii are currently viewed as the best facilities currently in use. There might be, however, even more attractive locations - for instance on the Antarctic continent.

The scope of the present document is to propose a decadal plan for the development of Antarctica as a platform for a new type of astronomy. It is the result of a common reflection and thorough investigations in different astrophysical areas of about one hundred experts: researchers and engineers in astrophysics, atmospheric physics, instrumentation and polar logistics.

The inner Antarctica is indeed the wildest, coldest and driest desert on Earth. It offers an almost virgin nature without human, faunal or floral contamination, and negligible seismic or volcanic activity. The nearest significant source of industrial pollution is more than 5,000km away and the pattern of atmospheric circulation is such that very little pollution is introduced into the atmosphere above the Antarctic plateau. It is therefore, in essence, an outstandingly appealing area to explore for the establishment of major astronomical facilities in the future. Astronomers have been attracted since decades by this opportunity and have made several pioneering attempts to set up increasingly sophisticated instruments during the last 40 years. Only one significant spot has been implemented at the US station Amundsen-Scott, right at the South Pole, so far, the Martin A. Pomerantz Observatory named in tribute to one of the most active astronomers in Antarctica since 1959. The recent opening all year long of the French-Italian Concordia station at Dome C is a major opportunity for Europe to participate in this challenging adventure.

Concordia plan: exploded view of the Concordia station

Winterover staff 2008

Winterover staff 2009

Ground based astronomy will clearly be dominated in the next decade by the construction of giant telescopes such as the European-ELT and the American TMT/for the optical/infrared range, and by ALMA for the millimetre/submillimetre wave range. These gigantic instruments will offer exceptional sensitivity and very high angular resolution allowing one to study the most distant galaxies (first light in the Universe), identify and characterize exo-Earths and possibly identify traces of life thereon. From space, the 6m James Webb Space Telescope will probe the Universe at an unprecedented level of sensitivity from the visible to the mid-infrared. All these instruments will be fully operational during the next decade and will undoubtedly yield major breakthroughs in the understanding of the evolution of the Universe since its very beginning to the possible emergence of life.

Besides these extremely large and costly instruments, smaller telescopes will continue to be essential tools for astronomers to investigate astrophysical phenomena that do not require extreme sensitivities or angular resolution. Among such essential astrophysical investigations are the multispectral mapping of large sky areas (surveys), high time resolution monitoring of variable objects, high angular resolution of the Sun and solar corona and CMB polarization measurements. These investigations do not necessarily require very large collecting areas, but rather, long observing time or extremely stable atmospheric conditions. Telescopes in the range spanning from 1 to a few meters diameter, provided they are suitably located, equipped with state-of-the art focal instruments and linked to powerful pipeline and archiving centres will still continue to provide essential data at relatively modest cost. Indeed, telescopes dedicated to surveys of the sky, such as the 2.5m Sloan telescope used for the Sloan Digital Sky Survey (SDSS), or the Canada-France-Hawaii Telescope (CFHT), routinely achieve very high publication and citation rates.

Although a number of 2-4m telescopes are in operation across the world, many of them are not suitable for "survey" observations, or do not operate from outstanding sites, or would require upgrading of their control system, focal equipment or data pipeline that their operators cannot afford. Several 2-4m class telescopes, such as the CFHT have been successfully moved into the "survey" dedicated mode, providing immense databases as "legacies".

Excellent site location is essential to the success of any telescope, in particular the spectral range in which it can be usefully operated strongly depends on the atmospheric transparency, which in turn is basically governed by its altitude above sea level and the absence of sky pollution of any origin, human or natural, above it. The best currently operated tropical sites in Hawaii (Mauna Kea) and the Chilean Andes (Cerro Paranal, Cerro Chajnantor) have long proven their excellence but, nevertheless, remain limited by their relatively low infrared/submillimetre transparency, by their infrared thermal sky background emission and by some undesirable molecular and radical emission lines (such as OH in the near infrared).

Improving the observing conditions and, thus, the resulting science value requires constructions of observatories at the highest, coldest, driest and most stable sites. The Antarctic plateau is high (3,000 to 4,000m), cold (-30 to -80°C), and the column density of atmospheric water vapour is extremely low (5 to 10 times less than the best currently exploited IR site at Mauna Kea). Under these conditions, new spectral windows open, and the usual ones become significantly broader or cleaner (free of undesirable absorption lines or molecular bands) allowing much more stable photometric conditions or the access to otherwise unobservable spectral lines or bands of major astrophy-

The Concordiastro towers (2006)

sical interest just at the edges of the usual atmospheric windows. Moreover, Antarctica has a unique political status on our planet:it is a continent exclusively dedicated to scientific research under the protection of international treaties (the Antarctic Treaty and the Madrid protocol) preserving the entire continent from all sorts of future undesirable human pollution. It is therefore, in essence, a model for international collaborations.

In addition, because of its high latitude range, the long duration of dark time allows long duty cycle observations particularly suited to a continuous photometric sampling of variable phenomena such as stellar pulsations (asteroseismology), or periodic events such as planetary transits.

Finally, the structure of the atmospheric turbulent layer is such that the "free" atmosphere begins relatively close to the ground, from a few to a few tens meters altitude. This particular behaviour of the boundary layer and of the key parameters that govern high angular resolution imaging in the optical and near infrared brings an additional incomparable advantage of Antarctica over conventional sites.

Creating an astronomical observatory in Antarctica has been dreamt of for decades in several countries and the USA have effectively established a major observatory at the geographical South Pole making use year-round of the Amundsen-Scott station. The M. A. Pomerantz Observatory is now mainly dedicated to millimetre wave astronomy - and in particular to CMB measurements. It is in continuous development and has recently received a new large millimetre wave instrument consisting of a 10m diameter dish (South Pole Telescope).

However, this station is not particularly suited to shorter wavelength astronomy because of the relatively small fraction of clear sky, and a relatively thick boundary layer resulting in poor seeing conditions. On the other hand, sites located on "Domes" that dominate the plateau and away from which flow the katabatic winds are much more appealing for optical, infrared and submillimetre observations.

It has been the purpose of the ARENA network to conduct studies and to produce documents covering all aspects relevant to the creation of this « Observatory of the Future» at the station Concordia in coordination with other roadmap exercises such as ASTRONET. ■

1b Brief historical overview

Nearly a century ago, in 1911, the Norwegian Roald Amundsen reached the South Pole. As early as 1912, the American polar explorer Robert E. Peary had the intuition that the privileged geographical position of the South Pole could be suitable for astronomical observations. Today many results covering a wide field of interests from star formation through solar physics to the analysis of the CMB have been obtained from Antarctica. Ambitious projects to create an observatory are under consideration at Dome C thanks to the successes obtained with earlier polar astronomical experiments developed during the previous half century.

Windows into geospace

In 1955, Antarctic astronomy started with non conventional telescopes when the Australians installed their cosmic ray observatory at the Mawson coastal station. The collisions between cosmic rays and atmospheric molecules create particle showers, especially muons and neutrons. This cosmic radiation also gives birth to many phenomena located in the upper atmosphere: auroras, ionization of the atmosphere, *etc.* Thus the polar regions constitute a unique place to observe the geomagnetic properties and the interactions between the Earth and the interplanetary medium. In the 1950s these geophysical issues pushed the ICSU (International Council of Scientific Unions) to launch an international cooperation programme, the International Geophysical Year (IGY).

IGY is a major milestone in the history of polar exploration and particularly in Antarctic research. Building up on the model of the previous polar years (in 1882-1883 and 1932-1933), the IGY lasted from July 1957 to December 1958. The IGY was not restricted to the polar regions and, by the end of 1958, 61 countries were finally involved in this worldwide collaboration. IGY stimulated unprecedented developments of polar logistics and the construction of about fifty bases inside the continent or along the Antarctic coast. As a consequence of IGY the Antarctic Treaty was written, then ratified by 12 countries in 1961. With this treaty, *"freedom of scientific investigation in Antarctica and cooperation toward that end, as applied during the International Geophysical Year, shall continue, subject to the provisions of the present Treaty"* and *"Antarctica shall be used for peaceful purposes only. There shall be prohibited, inter alia, any measure of a military nature, such as the establishment of military bases and fortifications, the carrying out of military manoeuvres, as well as the testing of any type of weapon"*. Moreover, in order to pursue the effective scientific coordination of IGY, the Scientific Committee on Antarctic Research (SCAR) is created in 1958.

In 1959, Americans began a cosmic ray programme research in Antarctica. They installed a neutron detector developed during the IGY at the McMurdo coastal station inside the Cosray building standing here in the middle of the picture.

This international cooperation was a real springboard for the cosmic ray measurements from Antarctica. In 1959, just after the IGY, the recently opened Office of Polar Programmes of the US National Science Foundation (NSF) puts Martin Pomerantz in charge of installing one of these detectors at the US McMurdo coastal base. In 1964, he installed neutron detectors at the South Pole too. These detectors, both in the Arctic and Antarctic allowed for the first time simultaneous measurements from the two hemispheres of solar cosmic rays and a very precise characterization of the heliosphere. Pomerantz's team also initiated balloon launches with instruments on board to detect X-rays above Antarctica from McMurdo. Thus, in 1969 and 1970, they discovered serendipitously the unique possibilities of long lifetime balloon-borne flights above Antarctica.

Every year since 1988, astronomers take advantage of the McMurdo coastal station to launch long flight balloons. Using the summer polar vortex, these balloons can fly during 10 days or more above Antarctica. Here, the famous BOOMERanG experiment launched in 1998 and which gave fundamental results in cosmology.

During the Antarctic summer, atmospheric thermal streams above the continent create a vortex that the balloon can follow throughout several days while remaining at the same latitude. Every summer since 1988, two flights have been launched from McMurdo. The famous BOOMERanG (Balloon Observations of Millimetric Extragalactic Radiations and Geomagnetics) experiment is one of them. In 1998, after a 10-days flight, this experiment carried out unique cosmological measurements, which showed that our universe is flat (see **Chapter 4e**).

First steps of photonic astronomy in Antarctica

Working in collaboration with a solar physicist, the Swedish astronomer Arne Wyller, Pomerantz noted that the South Pole would be also a unique place to carry out solar observations: a constant source elevation, a clear sky and cold temperatures. Observations made in 1968-1969 with a 5 inch telescope convinced Wyller to write a report to the committee for polar research of the US Academy of Sciences in 1970, advocating the unique potential of the South Pole for astronomy. This is the first time that the potential for astronomy in Antarctica was officially presented and published.

Eight years later, Pomerantz started a collaboration with two young French solar astronomers who proposed to carry out uninterrupted observations of the Sun over periods longer than 24 hours, Eric Fossat and Gérard Grec, from Nice. Their instrument was installed in summer 1978-1979 with American funding. They achieved their objective: six uninterrupted full days of observations of the Sun. These measurements enabled them to distinguish more than 80 resonance modes of the Sun. These observations marked the birth of a new discipline, helioseismology, and the beginning of photonic astronomy in Antarctica.

Following these historical results, networks such as IRIS (International Research of the Interior of the Sun) and GONG (Global Oscillations Network Group) were created and an instrument dedicated to helioseismology was on board of the solar space observatory SOHO (Solar and Heliospheric Observatory). The programme ended in 1994. There is no doubt that the success of solar observations deeply changed the perception of the astronomical community, mostly sceptical, about the extraordinary potential of Antarctic observations.

Other fields of astronomy could also benefit from the Antarctic conditions. The precipitable water vapour content (PWV), the main source of atmospheric opacity in the infrared and the millimetre-wave range, is extremely low there. This was confirmed by the first preliminary measurements of the PWV at the South Pole in 1975. Pomerantz called upon a reputable French team in the submillimetre-wave domain, the team of Jean-Loup Puget from Orsay. Their instrument, EMILIE (*Emission Millimétrique*), measured the galactic centre emission in the submillimetre-wave range during the 1984-1985 summer. The experiment was a success. At the South Pole, measurements were found to reach instrumental limits, whereas at Mauna Kea in Hawaii, they were limited by the atmospheric fluctuations. The superiority of the South Pole over Mauna Kea in this field was thus demonstrated. It is thus a double success for astronomy at the South Pole: it is an excellent millimetre-wave site and the logistics allows the supply of the liquid helium necessary to cool down the detectors.

Photonic astronomy in Antarctica started in January 1980 with solar observations. A French American collaboration observed the Sun continuously during 6 days at South Pole. This was the beginning of helioseismology. (From left to right: G. Grec, L.. Page, M. Pomerantz, E. Fossat).

This potential for millimetre-wave astronomy was immediately understood by the experts in CMB who were investigating the tiny temperature fluctuations in the cosmological background. In summer 1986-1987, a team from ATT Bell Labs lead by Anthony Stark, Mark Dragovan and Robert Pernic set up an instrument to carry out preliminary measurements.

A French-American collaboration took place in december 1984 at South Pole with the EMILIE experiment. This instrument demonstrated the potential of Antarctica high plateau for submillimetre-wave astronomy. (From upper right to upper left: J.L. Puget, R. Gispert, J.M. Lamarre, C. Maurel - behind the ladder -, J.C. Renault).

The accurate measurement of the cosmological background constitutes one of the themes of predilection of the South Pole observatory.

On their side, Italians also recognised the potential of Antarctica at their Terra Nova (now Mario Zucchelli) station by installing there since 1986 the submillimetre-wave antenna OASI (*Osservatorio Antartico Submillimetrico E Infrarosso*). This 2.60m-antenna was the first telescope to perform measurements during Antarctic winter. Meanwhile continuous observations were achieved by SPOT (the South Polar Optical Telescope), a small telescope of 8cm in the visible, which obtained, in 1986, 16 uninterrupted hours of observations of variable stars such as γ^2 Velorum. This was the first time that uninterrupted observations were made over such a long period from the ground.

Super seeing conditions on the Antarctic plateau

In the 1980s, the evaluation of the astronomical potential in Antarctica was based on meteorological data collected at the South Pole (called Amundsen-Scott base since 1975), at Vostok (located at an altitude of 3,500m) and at Dome C. These data allowed the community to get a realistic idea of the atmospheric conditions on the high plateau.

After the solar and millimetric observations at the South Pole, and the Italian initiative at Terra Nova, Australians showed their interest in the potential of an astronomical site located so close to their country. During the second half of the eighties, Peter Gillingham suggested that the extremely low temperatures and the atmosphere stability could lead to the unique potential for high angular resolution observations on the high plateau; he spoke about *"super seeing"*.

Following an initiative of Pomerantz, more than 100 astronomers interested in the astronomical potential of the high Antarctic plateau were invited to a conference at the Bartol Institute in June 1989, *"Astrophysics in Antarctica"*. This meeting leads to a real American scientific policy which durably influenced the "astrophysical" conquest of the highest spots of the plateau. During this meeting, the idea to create a Centre for Astrophysical Research in Antarctica (CARA) is put forward. This centre was officially founded in 1991, it is headquarted at the Yerkes Observatory (University of Chicago) and gathers several American universities. With an optimized logistic organisation for astrophysics, the goal of CARA is to achieve four main projects: SPIREX (South Pole Infrared Explorer), a 60cm telescope specially developed to probe the deep sky between 2 and 3µm and to assess the infrared potential of the site; AST/RO (Antarctic Submillimetre Telescopes and Remote Observatory), a 1.70m submillimetre-wave antenna to probe the carbon line around 600µm in our Galaxy and in the Magellanic Clouds; COBRA (Cosmic Background Radiation Anisotropy), a 0.75m telescope to detect the temperature fluctuations of the CMB up to angular scales of 20°; and finally ATP (Advanced Telescope Project), a collaboration between American and foreign institutions to evaluate the site quality for astronomy and to prepare a larger telescope in the infrared and in the submillimetre-wave for the end of the 1990s.

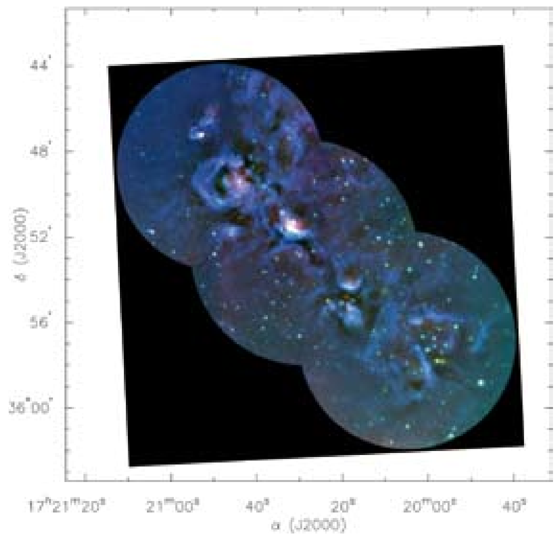
This conference also gave rise to a proposal of John Lynch, the NSF program manager for Aeronomy and Astrophysics, for the construction of an international station on top of the high plateau. This station would be a pathfinder for a lunar station, then under discussion in the space agencies. More precisely, this station would have a strong "astrophysical" colour and would be located at 4,000m above the sea level. At the end of the 1980s, the Antarctic domes are estimated to be the best ground sites for infrared, submillimetre and millimetre-wave astronomy as well as Earth-Sun interactions study, due to the proximity of the magnetic pole.

The Amundsen-Scott station has developed a large area entirely dedicated to astronomical observations (essentially cosmological background observations and neutrino detection) free from electromagnetic perturbations: the "dark sector". (In the upper left: SPT and BICEP; in the upper centre: the M. Pomerantz Observatory; in the middle: the IceCube laboratory; the red drills are the summer camp for icecubers).

The international astronomical community recognized the astronomical potential of the Antarctic plateau during the 21st IAU Assembly in Buenos Aires in 1991.
A session dedicated to Antarctic astronomy was organized and the IAU recognizes *"the fact that the extremely dry, cold and tenuous atmosphere above the Antarctic plateau provides the best observing conditions on Earth in the infrared wavelength, submillimetre and millimetre wavelength range"* and in particular resolves *"to create a working group to encourage international cooperation in site testing […]"*. Several meetings took place in France and in Australia between the site testing specialists of the University of Nice and the University of New South Wales. A collaboration was established in 1993 between Al Harper (CARA), Peter Gillingham (UNSW) and Jean Vernin (University of Nice).

Temperature measurements were carried out in 1994 at the South Pole with microthermal sensors installed on a 30m mast, then in 1995 with 15 balloons instrumented with microthermal probes.

These first measurements confirmed Gillingham predictions: the seeing in the visible is quite poor, but turbulence is essentially concentrated in a thin layer localized in the first 200m above the ground. On top of the plateau, where the winds are lower and temperatures colder, this turbulence layer may be even thinner. It is what is actually observed at Dome C (nearly 30m).



One of the major results of the infrared telescope SPIREX set at the South Pole is a survey of the NGC 6334 nebula in the near infrared range from 2.42 to 4.8µm taken in 1998. This wide-field survey (30') acknowledged infrared potential of Antarctica to study such star formation regions with high angular resolution.

Towards an observatory at Dome C

The construction of the French-Italian Concordia station is mentioned for the first time at the conference, "Polar Research: a strategy for the year 2000" held in the French *Académie des Sciences* in Paris in 1992. The selected site sets at Dome C, located about 40km away from the site where the glaciologist Claude Lorius and his team have extracted an ice core sample in 1978. Paleoclimatology is one of the main scientific drivers for the establishment of this 3rd permanent base on the inland, after Amundsen-Scott and Vostok.
This became in 2004 with the record extraction of a 3km long ice core giving information on climatic variations during the last 800,000 years (EPICA).

From 2000 to the first winterover in 2005, site testing observations could be led only during the summer campaigns (from December to February). Here in 2002, an astronomer observed atmospheric fluctuations in front of the half constructed Concordia station.

In February 2009, Chinese inaugurated the first building of the Kunlun station (the red and yellow one in the background on the left) at Dome A (4,040m above the sea level). They have already achieved two campaigns in 2005 and 2006 and they installed automated instruments to measure the atmospheric turbulence above Dome A.

Dome Fuji (3,810m above the sea level) is considered as one of the best sites for astronomy on the high plateau. Japan plans to begin site testing campaigns for astronomy in 2010.

OASI telescope is a 2.60m antenna in the submillimetre-wave range. It has been set in 1987 at Mario Zucchelli station and was the first Antarctic telescope to operate during winter. This antenna is still operational but the PNRA priority is currently the COCHISE antenna set at Dome C.

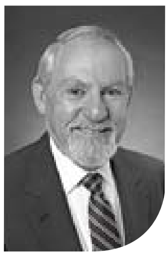
2007-2008 Summer Campaign

As soon as 1995, Jean Vernin's team launched balloons from Dome C to carry out the same type of measurements as those from the South Pole to characterize atmospheric turbulence in the visible. In 1995-1996, two Italians, Luca Valenziano (*INAF, Bologna*) and Giorgio Dall'Oglio (*Università La Sapienza*), using their experience with OASI at Terra Nova, evaluated the submillimetre-wave characteristics of Dome C by measuring the atmospheric precipitable water vapour content. From 1996 to 2000, the construction of Concordia was stopped because of logistics problems. In 2000, the Concordiastro programme lead by Eric Fossat *(Laboratoire Universitaire d'Astrophysique de Nice, LUAN)* consists in a systematic characterization of Dome C. Many instruments dedicated to this purpose are installed during summer missions from December to February each year. But as long as the construction of the station was not completed, these measurements could not be done during the polar night.

This is why in 2003 the Australian group lead by John Storey set at Concordia an automatic station to characterize the quality of the sky during the whole year: AASTINO (Automated Astrophysical Site Testing International Observatory). It is an improved version of AASTO (Automated Astrophysical Observatory for Antarctica) installed at the South Pole from 1997 to 2003.

MARTIN ARTHUR POMERANTZ 1916-2008

Considered as one of the leaders of the development of astronomy in Antarctica and mainly at the South Pole, Martin Arthur Pomerantz did all his scientific career at the Bartol Research Institute (University of Delaware). During the International Geophysical Year, the study of cosmic rays, his primary speciality, drove him to Thule, in the Arctic (Groenland). This first polar experience led him to McMurdo in 1959 then to the South Pole in 1964. Convinced that the South Pole is an ideal location for astronomy, he initiated several astrophysical collaborations in various domains: solar physics, cosmological microwave background, neutrino detection... In honour of this exceptional contribution, NSF inaugurated at the South Pole in 1995 one of the buildings dedicated to the CMB observations: MAPO (Martin A. Pomerantz Observatory). It was the last of his 26 missions at the South Pole.



In 1995, Giorgio Dall'Oglio (on the left in red) and Jean Vernin (the one who took the picture) were the two first astronomers to go to Dome C. It was the beginning of the site testing campaigns.

MARIO ZUCCHELLI 1944-2003

Mario Zucchelli was one of the main figures of the Italian Research programme in Antarctica. With an initial training as nuclear physicist, he was appointed director in 1975 of the most important Italian nuclear research center until 1987, the Brasimone Research Centre. Then he was appointed director of the Antarctica Italian programme for which he lead 15 expeditions until his death in 2003. During these 16 years, he initiated several international collaborations: for instance, the ice coring European programme EPICA or the French-Italian agreement signed in 1993 for the construction of the Concordia station. To honour him, PNRA decided in 2004 to give his name to the coastal station of Terra Nova, one of the stopping places towards Concordia.

These stations allow atmospheric characterization from the near UV to the submillimetre-wave range all year long. Since 2005, date of the first wintering at Concordia, the various site testing instruments are maintained during successive winterovers. The ground layer which concentrates the essential of the turbulence is now becoming precisely characterized thanks to the accumulation of such measurements.

In the frame of this race to the high plateau, the European network ARENA begins its activities in 2006. It brings together the European and Australian astronomers in order to define the basis of a future international observatory at Dome C, and at the end of 2009 it proposes the present roadmap. Besides, Chinese and Japanese teams are seeking to develop astronomy, at Dome A and Dome F, respectively. ■

1c How ARENA worked

The project to gather skills and resources of several European and Australian laboratories to implement an international astronomical observatory at the Concordia station Dome C came into existence in the early 2000s. It was basically motivated by the extensive site testing experiments made by various laboratories in France, Italy and Australia, the important involvement of the Italian community to set up an infrared telescope (IRAIT), and the desire to implement optical/IR interferometric arrays and to access new spectral windows in the thermal infrared and Terahertz ranges. The exceptional seeing conditions measured above a thin turbulent layer of a few tens of meters stimulated the high angular resolution and interferometric communities. The exceptional transparency of the earth atmosphere in the far infrared and in the submillimetre-wave range was another strong incentive to raise the interest of astrophysicists.

The primary role of the roadmap is to provide a comprehensive and consistent plan for the development of an optimised research infrastructure for European astronomy in Antarctica in the mid range (2010-2020) and to envision even more ambitious project(s) beyond 2020, if Antarctic astronomy turns out to be viable on the basis of the first results obtained with the "pathfinder generation". The roadmap aims at defining a number of scientific milestones and goals that can be reached as well as the facilities that are required to reach them. ARENA was not set up to "do science", nor was it a political tool supervised by agencies such as ASTRONET. It was basically a bottom up approach aimed at identifying the most compelling science programmes that can be proposed in the Antarctic conditions, to evaluate the polar and logistics constraints on instrumental devices and their feasibility in polar conditions and to set up a comprehensive synthesis of the atmospheric conditions based on statistically significant sets of data. The ARENA work programme was defined by the end of 2005 and as it necessarily happens in a rapidly evolving discipline, the management committee (Consortium Management Committee) and coordinator strived to adjust the work programme according to the most recent site testing results, and to welcome new expressions of interest to join the network. The original work programme was amended several times and after the Mid Term Review, in 2007, the contract was extended for one year (2009). Originally dedicated to optical and infrared astronomy, it moved toward a wider scope including cosmic microwave background experiments, millimetre wave astronomy and solar physics. ARENA encompassed most of the astronomical activities that are already, or could be, carried out in Antarctica, as well as some aspects of atmospheric physics directly linked to astronomy.

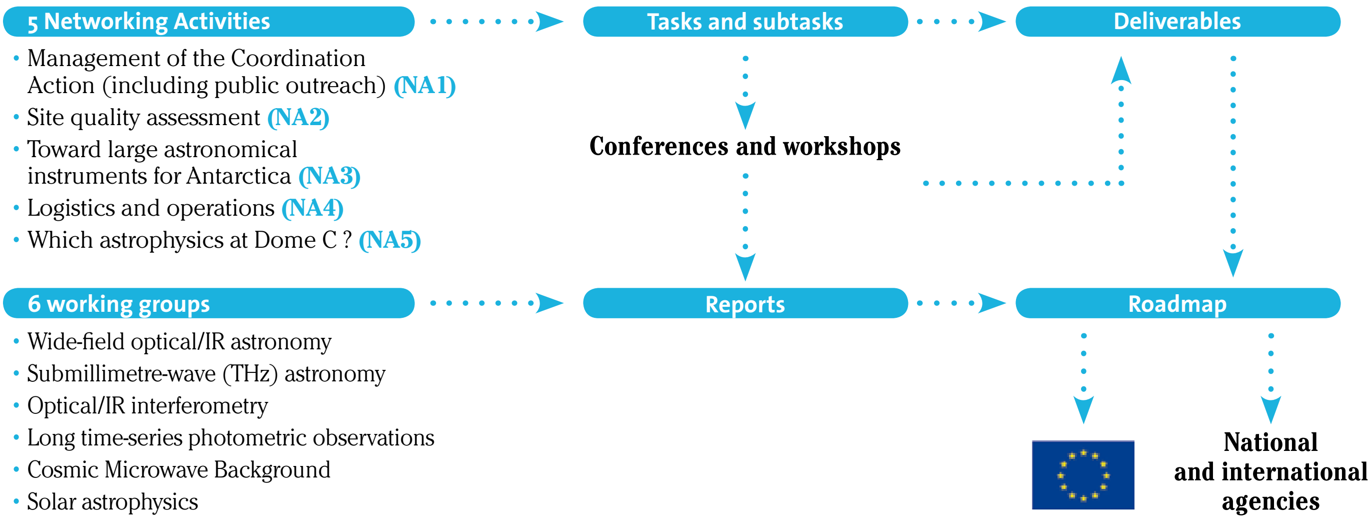
The ARENA work programme is split in five networking activities dedicated to:

- Management (including public outreach actions) (NA1),
- Site assessment and provision of an access to a dedicated database (NA2),
- Instrumentation in polar environment (NA3),
- Logistics (NA4),
- Astrophysical science cases (NA5).

Each of these activities are supervising a number of tasks (see **Table 1**).

ARENA organized 11 dedicated workshops and 3 plenary conferences (see **Table 2**) to foster close contact between researchers, engineers, industrial companies and directors of polar institutes. This permanent contact was essential to construct this roadmap. The proceedings of the conferences are published by *"Les Editions de Physique (EDP)"* in its EAS Series (volumes 25, 33, 40). Other more informal meetings were organized in parallel by the working groups. The presentation made at these workshops are available at the ARENA website. The website *(http://arena.unice.fr)* was opened at the University of Nice to provide the necessary information and news of the consortium. To complement the ARENA web portal, a special site dedicated to the public outreach was set up and is maintained at the University of Liège *(http://www.arena.ulg.ac.be)* (see **Chapter 6**). Each networking activity was subdivided into tasks chaired by expert leaders belonging to various partner's la-

How ARENA worked



boratory and coordinated by the NA leaders. There are 22 such tasks (see **Table 1**). Their leaders were in charge of producing the 28 deliverables due to the European Commission (see **Chapter 2**). They were produced according to a pre-established agenda and were attached to the 3 interim annual scientific reports (Reporting Period 1, 2, 3) and the final report (2010) They were eventually approved by the Project Officer. All these documents are available at the website. The task of developing the roadmap began in 2007. With the mandate and the approval of the ARENA CMC, 6 working groups (WG) were established at the 2nd Conference in Potsdam (2007) to document 6 most promising astrophysical areas and a plan of appropriate instrumental projects for the next decade (2010-2020) together with a long term vision. One chair and one co-chair per WG were appointed in October 2007, these were given the responsability to designate members or associates from the academic or industrial community, not necessarily belonging to the ARENA consortium. They worked independently, held specific workshops and contributed considerably to the final 3rd ARENA Conference in 2009 (see **Members' list of WG** in annex). Each WG was entrusted to elaborate its own roadmap by preparing a short report and to make their own selection of projects to be supported. The preparation was made in three iterations, a first version was presented to the CMC in December 2008, then a second one was prepared for the 3rd ARENA Conference held in Frascati in May 2009 (Spinoglio & Epchtein, 2010, EDP, EAS vol. 40) and the final version is basically the matter of **Chapter 4** of this roadmap. The second version was distributed to leading researchers in the relevant areas who were independent

of ARENA. These were also invited speakers at the Frascati conference who provided comments and feedback on the proposed roadmap, as well as participated in the various round tables held at the end of each session of the conference. The final version of the WG reports takes into account the comments and reflections made at this conference. The WGs made their own selection of projects to be supported. The ARENA CMC - although this was not unanimous - decided not to make any ranking of the projects proposed by the different working groups, recognizing that they deal with very different areas of astronomy and that ARENA was not the appropriate body to provide relative rankings, for instance CMB or solar projects. Moreover, it is the role of the national (and international) agencies - and their evaluation committees - as well as European ERA-NET such as ASTRONET to set up an overall policy of the discipline. One of the outcome of ARENA was basically to document as thoroughly as possible the projects that the WG supports and to submit their conclusions in the shape of a suite of recommendations to these organizations (see **Chapter 8**). It is also likely that the overall concept of European Astronomy in Antarctica will be "peer-reviewed" by the European Science Foundation (ESF).

For obvious reasons of funding and logistics, it is clear that only a fraction of the projects herewith proposed will eventually be funded and carried out all the way to completion. Only those which will prove their scientific excellence, their unambiguous support by a wide international community, their technical feasibility and that will match the present logistics capabilities – possibly slightly improved – provided by the polar agencies will have a chance to be materialized at least in the forthcoming decade. ■

Table 1 List of ARENA tasks

Task	Title	Task leader(s)
NA1	**MANAGEMENT OF THE COORDINATION ACTION**	**Coordinator : Nicolas Epchtein (CNRS - Fizeau, Nice, France)**
1.1	**Contractual management**	Marie-Laure Péronne (CNRS - Fizeau, Nice, France)
1.2	**Scientific management**	CMC members (cf. annexes)
1.3	**Information, communication and public outreach**	Cyrille Baudouin and Marie-Laure Péronne (CNRS - Fizeau, Nice, France), Anna Pospiezsalska- Surdej (*Université de Liège*)
1.4	**Technical management**	NA leaders
NA2	**SITE QUALITY ASSESSMENT**	**NA leader : Roland Gredel (MPIA, Heidelberg, Germany)**
2.1	**Parameters review**	Jean Vernin (CNRS - Fizeau, Nice, France)
2.2	**Synthesis of observations at Dome C**	Roland Gredel (MPIA, Heidelberg, Germany), Aziz Ziad (CNRS - Fizeau, Nice, France)
2.3	**Modelling the site properties for science optimisation**	*idem*
NA3	**TOWARD LARGE ASTRONOMICAL INSTRUMENTS FOR ANTARCTICA**	**NA leader : Jean-Pierre Swings (*Université de Liège*, Belgium)**
3.1	**Low emissivity optical configurations for infrared and high dynamical imaging for Antarctic conditions**	Carlos Eiroa (UAM, Madrid, Spain)
3.2	**Telescope and instrumentation robotization**	Klaus Strassmeier (AIP, Potsdam, Germany)
3.3	**Focal instrumentation for Antarctic telescopes**	Jean-Pierre Maillard (CNRS - IAP, Paris, France)
3.4	**The International Robotic Antarctic Infrared Telescope (IRAIT)**	Gino Tosti (*Università degli Studi di Perugia*, Italy)
3.5	**The IRAIT focal instrumentation**	Oscar Straniero (INAF, Teramo, Italy)
NA4	**LOGISTICS AND OPERATIONS AT DOME C**	**NA leader : Maurizio Candidi (INAF, Rome, Italy)**
4.1	**Logistics for the transportation of large astronomical instruments and implication for construction of astronomical equipments**	Patrice Godon (IPEV, Brest, France), Antonio Cucinotta (PNRA, Rome, Italy)
4.2	**Logistics for the construction of large buildings and enclosures for telescopes at Dome C**	*idem*
4.3	**Consumable needs and requests to the operators; power supply, fluids and communications**	Alain Pierre (IPEV, Brest, France), Chiara Montanari (PNRA, Rome, Italy)
4.4	**Human questions - Training of polar teams**	Claude Bachelard (IPEV, Brest, France)
4.5	**Environmental considerations**	Yves Frénot (IPEV, Brest, France), Sandro Torcini (PNRA, Rome, Italy)
4.6	**Telecommunications**	Dominique Fleury (IPEV, Brest, France), Marco Maggiore (PNRA, Rome, Italy)
NA5	**WHICH ASTROPHYSICS AT DOME C?**	**NA leader : Hans Zinnecker (AIP, Potsdam, Germany)**
5.1	**Wide-field imaging surveys in the thermal infrared**	Maurizio Busso (*Università degli Studi di Perugia*, Italy), Mark McCaughrean (University of Exeter, United Kingdom)
5.2	**New windows in the far infrared**	Pierre-Olivier Lagage (CEA/IRFU, Saclay, France)
5.3	**Time variability: new domains for ground based high precision and long duration time-series photometry and spectroscopy**	Heike Rauer (DLR, Berlin, Germany)
5.3.1	**Asteroseismology and helioseismology**	Eric Fossat (CNRS - Fizeau, Nice, France)
5.3.2	**Photometric search for extrasolar planets**	Hans Deeg (IAC, Tenerife, Spain)
5.3.3	**Solar-stellar connection**	Klaus Strassmeier (AIP, Potsdam, Germany)
5.4	**Obtaining the ultimate angular resolution**	Farrokh Vakili (CNRS - Fizeau/OCA, Nice, France)
5.5	**Spectroscopy and spectro-imagery**	Carlos Abia (*Universidad de Granada*, Spain)

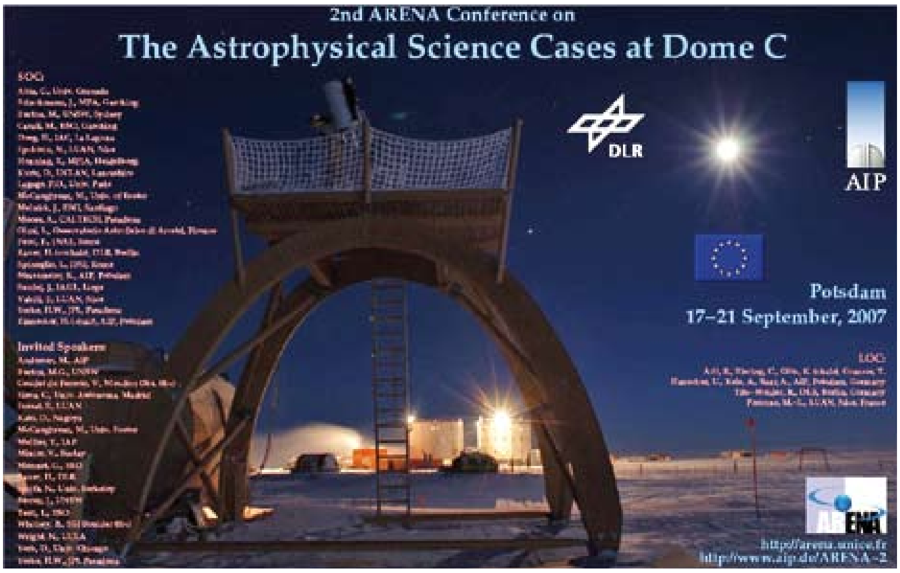
Table 2 ARENA meetings

Type	Title	Date	Venue
2006			
Workshop	Interferometry 1 (in collaboration with OPTICON JRA4)	May 10-12	Nice, France
Workshop	Wide-field imaging at Dome C	June 14-17	Paris, France
Workshop	Visit to IRAIT	September 12-13	Perugia, Italy
1st ARENA CONFERENCE	**Large Astronomical Infrastructures at CONCORDIA, prospects and constraints for Antarctic Optical/IR Astronomy** [1]	**October 16-19**	**Roscoff, France**
2007			
Workshop	Telescope and instrument robotization at Dome C	March 26-28	Puerto Santiago, Tenerife, Spain
Workshop	Site testing at Dome C	June 11-13	Rome, Italy
Workshop	Submillimetre astronomy at Dome C	June 25-27	Saclay, France
2nd ARENA CONFERENCE	**The Astrophysical Science Cases at Dome C** [2]	**September 17-21**	**Potsdam, Germany**
2008			
Workshop	Wide-field telescopes	March 26-27	Exeter, United Kingdom
Workshop	Spectroscopy	April 16-18	Granada, Spain
Workshop	Time-series observations from Dome C	September 17-19	Catania, Italy
Workshop	Interferometry 2	October 13-14	Garching-bei-München, Germany
2009			
3rd ARENA CONFERENCE	**An astronomical Observatory at CONCORDIA (Antarctica) for the next decade** [3]	**May 11-15**	**Frascati, Italy**
Workshop	Progress on site testing	December 10	Nice, France

1

Poster of the 1st ARENA Conference

2



Poster of the 2nd ARENA Conference

The Concordiastro towers

2nd ARENA Conference attendance in Potsdam

3

Poster of the 3rd ARENA Conference

2 ARENA deliverables

The ARENA network members have delivered about 30 documents, from technical concept studies to conference proceedings.
These documents were prepared by more than 100 experts from 8 countries with the aim of documenting in depth the project of an astronomical observatory at the Concordia station.

ARENA was committed to prepare periodically a set of contractual deliverables consisting of reports on instrumental studies, tools and data base providing access to site assessments, and publication of proceedings of conferences or summaries of workshops accessible through a web interface. These deliverables were prepared under the supervision of the networking activity leaders with contributions of the task leaders and annexed to the 4 annual scientific reports (RP) to the European Commission. The present roadmap document constitutes the final deliverable. The following tables (see **Table 3** to **Table 6**) summarize the titles of these deliverables and the main contractors involved in their preparation. All these documents are accessible through the ARENA website *(http://arena.unice.fr)* upon request to the coordinator.

Table 3 List of deliverables (2006, reporting period 1)

Activity NA	Deliverable No	Name	Workpackage Task No	Delivered by Contractor(s)	Issued in months
NA2	D2.1	Atmospheric turbulence parameters review	2.1	CNRS	6
NA3	D3.5	Six month reports on the IRAIT activity at Dome C	3.4/ 3.5	CNRS	6
NA5	D5.4	Presentations of the workshops (2006) (ARENA website/CD Rom)			

Table 4 List of deliverables (2007, reporting period 2)

Activity NA	Deliverable No	Name	Workpackage Task No	Delivered by Contractor(s)	Issued in months
NA2	D2.2	Analysis and archiving of Dome C site testing data	2.2	CNRS	12
NA2	D2.3	Update of site parameters in regards of science goals	2.1	MPIA	24
NA2	D2.4	Analysis and archiving of 1st Winter campaign data	2.3	CNRS	24
NA2	D2.5 D3.2	Implication of relevant parameters on science goals, ground-based instruments and site infrastructures	2.3	CNRS	24
NA3	D3.4	Proceedings of the workshop on focal instrumentation	3.3	CNRS	24
NA3	D3.5	Six months report on the IRAIT activity at Dome C	3.4/3.5	INAF/UNIPG	18
NA3	D3.5	Six months report on the IRAIT activity at Dome C	3.4/3.5	INAF/UNIPG	24
NA5	D5.2	Published Proceedings of Conference 1	All tasks	CNRS/INAF	18
NA2 NA3	D5.4	Presentations of the workshops (2007) (ARENA website/CD Rom)	All tasks	All	24

Table 5 List of deliverables (2008, reporting period 3)

Activity	Deliverable		Workpackage	Delivered by	Issued
NA	No	Name	Task No	Contractor(s)	in months
NA2	D2.6	Analysis and archiving of 2nd Winter campaign data	2.2	CNRS/INAF/ MPIA	36
NA2	D2.7	Update of the implication of relevant parameters on science goals, ground-based instruments and site infrastructures	2.2	CNRS/INAF/ MPIA	36
NA3	D3.1	A report on the general constraints linked to polar conditions on optical configuration and particularly on adaptative optics	3.1	CNRS	36
NA3	D3.4	Report on the workshops on wide-field telescope and focal instrumentation (Exeter, Granada)	3.3	CNRS/UGR	36
NA3	D3.5	Six month report on IRAIT and AMICA activity at Dome C	3.4/3.5	UNIPG/ INAF	36
NA5	D5.2	Published Proceedings of Conference 2	All tasks	AIP/DLR /CNRS	33
NA5	D5.4	Presentations of the workshops (2008) (ARENA website/CD Rom)	All tasks	All	36

Table 6 List of deliverables (2009, reporting period 4)

Activity	Deliverable		Workpackage	Delivered by	Issued
NA	No	Name	Task No	Contractor(s)	in months
NA2	D2.8	Book synthesizing the site qualification With conclusions on the opportunities	2.1, 2.2, 2.3	CNRS/MPIA	43
NA2	D2.9 abc	Annual workshop on progress of the site testing (workshop presentations)		CNRS/MPIA	43
NA3	D3.2	General guidelines on the design of large IR (adaptive) optics	3.1		42
NA4	D4.1	Report on the logistics of Dome C for large astronomical infrastructures	4.1	IPEV/PNRA	42
NA4	D4.2	Report on the construction of large buildings for astronomy at Dome C	4.2	IPEV/PNRA	42
NA4	D4.3	Report on consumables requirements for large astronomical infrastructures and proposed solutions	4.3	IPEV/PNRA	42
NA4	D4.4	Medical and psychological recommendations for astronomical activities at Dome C	4.4	IPEV/PNRA	42
NA4	D4.5	Report on impact study on the environment	4.5	IPEV/PNRA	42
NA4	D4.6	Report on telecommunications	4.6	IPEV/PNRA	42
NA5	D5.3	Published proceedings of Conference 3	All tasks	INAF/CNRS	46
NA5	D5.5	Roadmap (this book) and executive summary of recommendations to the national and international agencies (ESO-ESA) for an astrophysical programme at Dome C	All tasks	All	46


SBM
ASTEP 400
ASTEP SUD
PAIX
GSM
DIMM
MOSP
LUCAS

3 Site quality assessment

3a Available data

Site qualification is a prerequisite for proceeding with future, expensive astronomical developments in Antarctica. Measurement and assessment of relevant atmospheric parameters already gathered must be archived, calibrated and put at the disposal of scientists and decision makers. A major task of ARENA was to synthesize these data, provide easy access to them through Internet databases and to identify the as yet undocumented parameters for future investigations.

The release of site testing data to the community via an electronically accessible data bank was one of the main objectives of the ARENA contract. Their access is now available via the ARENA website (*http://arena.unice.fr*). The database includes the seeing and isoplanatic angle data taken during the summer and winter campaigns starting in December 2004, and the meteo-balloon data taken during the 2001-2004 period in the framework of the Concordiastro[1] programme. The site provides a link to the AASTINO database as well. Data taken during the PNRA campaigns are available via the web-accessible database at *www.climantartide.it.*

Precipitable water vapour (PWV)

Measurements of the precipitable water vapour (PWV) have been carried out during the last decade and relatively robust statements are possible as far as the absolute values are concerned. Monthly averages range from 0.72(±0.20)mm in December to 0.26 (±0.1)mm during the March/April period. Variations in the PWV by factors of 2-3 occur on a daily basis. A systematic monitoring of the short-term variations in PWV is in progress at the COCHISE submillimetre telescope. The 200µm bolometer camera CAMISTIC from CEA/Saclay, to be deployed at the second Nasmyth focus of IRAIT, will eventually sample small spatial fluctuations in the atmospheric emission that arise from small water clouds in the lower atmosphere, thus allowing to determine the stability of the sky noise at this frequency.

Measurements demonstrate that the 200µm window opens at a transmission level about 20% during 25% of the time. Detailed atmospheric transmission models (*e.g.*, MOLIERE) have then been used to estimate the PWV and show that observations at 350µm and 450µm are possible all year, compared to only 30% of the time on the Llano Chajnantor. The measurements and model calculations indicate that Dome C is probably the best site known on Earth for submillimetre astronomy.

A low atmospheric water vapour content results in higher transmission in the near- to mid-infrared windows and an extended wavelength coverage. The highest benefits for observations in the thermal infrared regime arise from the very low temperatures at Dome C, as discussed in the following section.

Sky brightness at infrared wavelengths

At wavelengths above 2.3µm, the dominant parameter that determines the brightness of the sky during day- and night time is the temperature of the atmosphere. In the thermal infrared, most of the observing programmes are background limited, and the integration time needed to reach a given signal to noise ratio is proportional to the sky background.

Data obtained at the South Pole demonstrate that compared to the mid-latitude observatories, the sky is darker by factors of 10-100. Daytime measurements of the infrared sky brightness at Dome C were obtained during the two summer seasons in 2003 and 2004.

Sky brightness measurements in the 2-28µm wavelength region will eventually be obtained with the AMICA camera on IRAIT,

[1] *Concordiastro is a scientific programme carried out by LUAN Laboratory (Université de Nice Sophia Antipolis), with contributions of Observatoire de la Côte d'Azur (OCA) and Osservatorio di Capodimonte at Napoli (OAC), and funded by the polar institutes IPEV (France) and PNRA (Italy).*

but given the similar temperatures, it is expected that Dome C is as dark as the South Pole. Dome C thus offers very considerable savings in the time needed to carry out large, deep mid-IR surveys, and consequently very significant cost savings, as well as the access to spectral windows otherwise not accessible from the ground.

Generalized seeing monitor (GSM)

Optical sky brightness, fraction of clear nights, and visual extinction

The sky brightness in the optical wavelength measured with the Gattini SBC camera shows that the sky is dark at a solar elevation of -12° already. The situation at Dome C is clearly different from mid-latitude sites, where multiple scattering by aerosols dominates the sky background until the sun is below an elevation of -18°. The fact that the sky is dark at solar elevations of -12° results in a total of 2,506 dark hours per year for Dome C. This number of dark hours per year is thus significantly larger than what is obtained from the limit where the sun is below an elevation of -18°, which is 1,767 hours.

The fraction of clear nights at Dome C has been determined from the Gattini all-sky camera and is of the order of 80-85% in the winter. First results obtained from PAIX show a rather high visual extinction up to 0.5 mag per airmass in the V-band, which is poor by all standards. Continued extinction measurements are needed to evaluate the magnitude of visual extinction over Dome C.

Temperature and wind profiles

The meteorological data obtained from the PNRA programmes demonstrate a quasi-periodic ground temperature oscillation during summer and winter months. The oscillation reaches the very large values of up to 30°C per week during the winter, and diurnal gradients that exceed dT/dt > 10°C/hour in summer. Temperature jumps in the winter exceeding 10°C in the matter of minutes have been reported. The large temperature variations pose a severe problem to the control of the thermal environment of an optical telescope and its enclosure, and very likely limit the image quality that can be reached in optical and near-infrared imaging altogether.

Wind conditions at Dome C are very favorable for astronomical observations, as wind speeds are very low indeed. Ground layer wind speed profiles do not show any strong diurnal variations, apart from a variation between summer and winter. An analysis of meteorological data obtained from satellites has been given.

Seeing ε_0

For seeing-limited observations, the signal to noise ratio S/N scales roughly inversely with the final image quality that is being obtained. The seeing is thus a fundamental parameter which determines the scientific production of an optical telescope. Data obtained with three DIMMs placed at 3m, 8m, and 20m height show that the seeing at 3m is mediocre and worse than 2" median. The median seeing measured at 8m height is 1."65 in winter and 0."57 in summer. The poor values are caused by a turbulent boundary layer with a mean height of 23m in winter.

The free atmosphere seeing above the boundary layer is very good indeed and of the order of 0."36. From the three DIMMs, the mean duration of the good seeing events, for seeing better than 0."5, are around 30min for elevations of 3m and 8m above the ice, and around 40min for heights of 20m above the ice.

The interpretation of DIMM data in terms of the image quality that can be reached with an optical telescope is not trivial. For medium-size, 2-4m class telescopes and for outer scales in the range of L_0 = 20-30m, the image quality obtained in the absence of local degradations equals the seeing ε_0. For larger telescopes, the image quality depends on the outer scale as well.

Outer scale L_0

The outer scale is an important parameter for the technical specification and the performance optimisation of high angular resolution techniques (HAR). For telescope diameters $D > L_0$, the lowest Zernike aberrations modes are largely reduced, thus minimizing the need to correct for *e.g.*, tip/tilt. The required stroke of deformable mirrors depends on L_0 as well, and the design of GLAO and MCAO systems depends critically on the vertical variation of $C_n^2(h)$ and the outer scale $L_0(h)$. The outer scale has implications for the design of fringe trackers for interferometric systems as well.

Using a campaign with the generalized seeing monitor (GSM), very small values of L_0<10m were measured. Values at mid-latitude sites range from L_0 = 20-30m. The low values of L_0 are beneficial for large telescopes and long baseline interferometers. There are indications that L_0 exhibits diurnal variations. The GSM campaign was carried out from the ground, with the instrument located at a height of 3.5m above the ice, and the significance of these values for a facility located on a tower is not obvious. Further measurements of L_0 will be obtained with MOSP.

Boundary layer and $C_n^2(h)$ profiles

Data obtained from the three DIMMs together with some 35 balloon flights during the winter of 2006 to infer the temporal and vertical variation in $C_n^2(h)$.

From those data, it is concluded that on a statistical average, the boundary layer originates some 2m above the ice, that it has a sharp upper boundary at a median height of 23m, and that the free atmospheric seeing above the boundary layer is 0."36.

The results obtained during the summer of 1999-2000 revealed a regular day-time variation in the height of the boundary layer, reaching up to an elevation of about 250-400m during high-summer.

Table 7 DIMM data

Elevation	3 m			8 m			20 m
	summer	winter	total	summer	winter	total	
Mean	1.06	2.51	1.83	0.69	1.72	1.23	1.10
Median	0.95	2.37	1.67	0.57	1.65	0.98	0.84
P_{75}	1.32	2.98	2.38	0.86	2.32	1.69	1.55
P_{25}	0.70	1.86	1.06	0.40	0.83	0.52	0.43
Max	4.76	9.26	9.78	7.63	9.09	15.05	8.20
Min	0.03	0.24	0.03	0.03	0.13	0.03	0.13

Global seeing statistics for the three available DIMM data (Aristidi et al. A&A 499, 955). P75 and P25 are the 75% and 25% percentiles. The data have been collected during 3 years and half (Dec. 2004 to April 2008) except for the DIMM installed at an elevation of 20m for which data are limited to the period from July to October 2005. The seeing is given in arcsec at λ = 0.5µm.

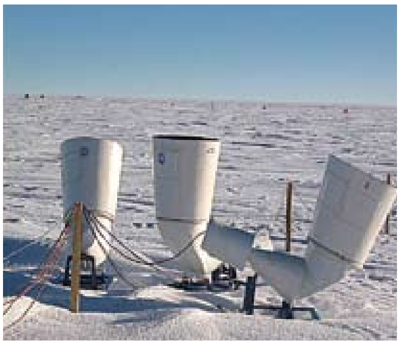
The absence of significant turbulence above the boundary layer results in a very low scintillation and offers improvements by factors of a few in the photometric accuracy that can be reached from the ground. The photometric ICE-T Explorer Telescope is designed to take full advantage of the improved photometric conditions, and once installed will obtain unique time-series observations of a single field during an entire polar night.

Our present knowledge of $C_n^2(h)$ is based on a rather limited amount of data. The methods that have been employed suffer from a relatively low vertical resolution, and, in the case of the balloon flights, from a very limited temporal coverage. The previous SODAR measurements obtained in the framework of the STABLEDC and AASTINO campaigns have a vertical resolution of 13m. In the future, a better temporal sampling of the boundary layer will become available from the SONICS experiment, which now runs six sonic anemometers on the extended 45m high meteo-mast.

From SODAR data obtained within the TMT site testing campaign, it becomes clear that a very strong contribution to the total seeing at potential astronomical sites in Chile, such as Tolonchar and Cerro Armazones, occurs below heights of 40m and 60m, respectively, and that the seeing on Armazones, Tolonchar, Mauna Kea, and San Pedro Martir above a height of 60m ranges from 0."4 to 0."6. The UNSW has developed and tested a SODAR which provides vertical and temporal resolutions of 1m and 1s, respectively. SODAR data obtained at Dome A show that variations in the height of the boundary layer by factors of a few occur on short timescales. Measurements on Dome C with high resolution optical profilers are urgently needed in order to fully characterize the temporal and vertical variations of $C_n^2(t,h)$. Calibration between optical profilers and other techniques (SODAR, SONICS) is necessary for site comparisons.

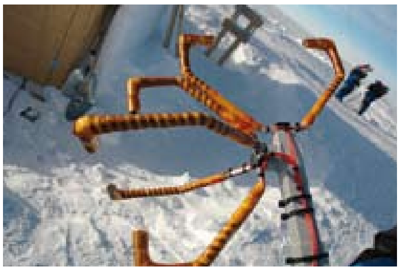
Coherence time τ_0 and the isoplanatic angle θ_0

The efficiency of adaptive optics and high angular resolution (HAR) techniques depends on the coherence time τ_0 and the isoplanatic angle θ_0. For Dome C, a median value of θ_0 = 3."9 is inferred, with values as large as 7" during summer. During winter, relatively low values of θ_0 have been measured, similar to values obtained at moderate, mid-latitude sites, and the South Pole, where θ_0 = 3."2 is estimated from in-situ radio soundings. The small values are probably due to the occurrence of strong high-altitude winds in winter, which introduce some high-altitude turbulence. The isoplanatic angle carries a $h^{5/3}$ term which leads to a higher influence of turbulence from high altitudes.



The SODAR instruments measures the wind speed height profile that determines the atmospheric turbulence.

AASTINO is an australian autonomous station that measured various atmospheric parameters above Dome C.



The SONICS measure the turbulence at different heights above the ice (7, 17, 22 and 30m).

A very limited number of balloon flights were used to obtain the coherence time τ_0. In general, the coherence times are very large and of the order of 5-11ms, caused by the absence of strong turbulence at high altitudes, yet significantly smaller values have been reported elsewhere. These findings confirm the need of continued and detailed measurements of $C_n^2(t,h)$, together with meteo-balloon flights in summer and in winter to acquire accurate wind profiles v(h,t).

Additional note concerning day-time observation conditions

On average, day-time seeing at Dome C is better than in the best other sites on Earth – even accounting for the relatively low elevation of the Sun, *e.g.*, Sac Peak (1."16) or Fuxian Lake (1."2). And — of importance for high resolution and interferometry — the isoplanatic angle also appears to be significantly better, up to 7", compared to ~3" at South Pole and even smaller at mid-latitude sites. Other measurements also point to exceptional coherence times *superior to 10ms*. These characteristics raise the possibility to implement a solar observatory with exceptional capabilities of high angular resolution over extended periods of time.

But not only: low water vapour content makes the site particularly suited for IR, millimetre and submillimetre observations. Dome C should display IR sensitivity gains relative to the South Pole, already one of the best sites on Earth, of up to a factor of 2, while in the mid- to far-infrared the gain over South Pole raises to a factor 100, and up to 3 orders of magnitude compared to the best mid-latitude sites.

Finally, meteorological studies and anecdotal evidence point to a low sky brightness, suitable for coronal observations. Preliminary analysis of data from an ongoing systematic study on the sky brightness during summer months indicate a sky brightness at least better (lower) than in the best mid-latitude sites by a factor 2.

In summary, these peculiarities could permit a versatile observing facility, with capabilities in many respects intermediate between a ground and space observatory, especially if taking advantage of the small size of the Turbulent Ground Layer (TGL) (instruments/telescopes on a 30m tower). ■

The DIMM on the ConcordiaAstro plateform

3b What is needed to finalize the site characterization at Dome C

Despite the large quantity of data available for Dome C, a number of measurements remain to be perfomed.

Modeling of the turbulence surface layer

Dome C is dominated by a surface layer (SL) which contributes some 95% of the total turbulence. As evidenced from measurements at Dome A, the surface layer is expected to vary on small temporal and spatial scales. Detailed measurements and models of the SL are needed to evaluate the potential degradation of optical and near- to mid-infrared observations.

Interaction between the SL and the telescope structure and towers

It is not clear whether the interaction of the telescope enclosure and tower with the incoming flow breaks the Kolmogorov turbulent cascade at larger scales.
Detailed models are needed to investigate the SL-telescope-tower interactions and to evaluate the impact of these interactions on the SL. The numerical simulations will be of assistance to specify and constrain the telescope and tower design.

$C_n^2(h)$ profile with high vertical resolution

It is to be expected that telescopes deployed at Dome C will make use of MCAO and GLAO systems. The optimization of these systems requires a detailed knowledge of the temporal and spatial variations in $C_n^2(t,h)$ and L_0. Different profilers as such as SCIDAR, MASS, and balloon flights have been used to infer $C_n^2(t,h)$, yet at very low spatial and temporal resolution. Profiles which provide a better spatial and temporal resolution are thus urgently needed.

Coherence time measurement for HAR techniques

The available data on the coherence time were obtained from a statistically insufficient number of balloon data. The coherence time is a crucial parameter for the specification and the optimization of the HAR techniques, and a comprehension of θ_0 is required.

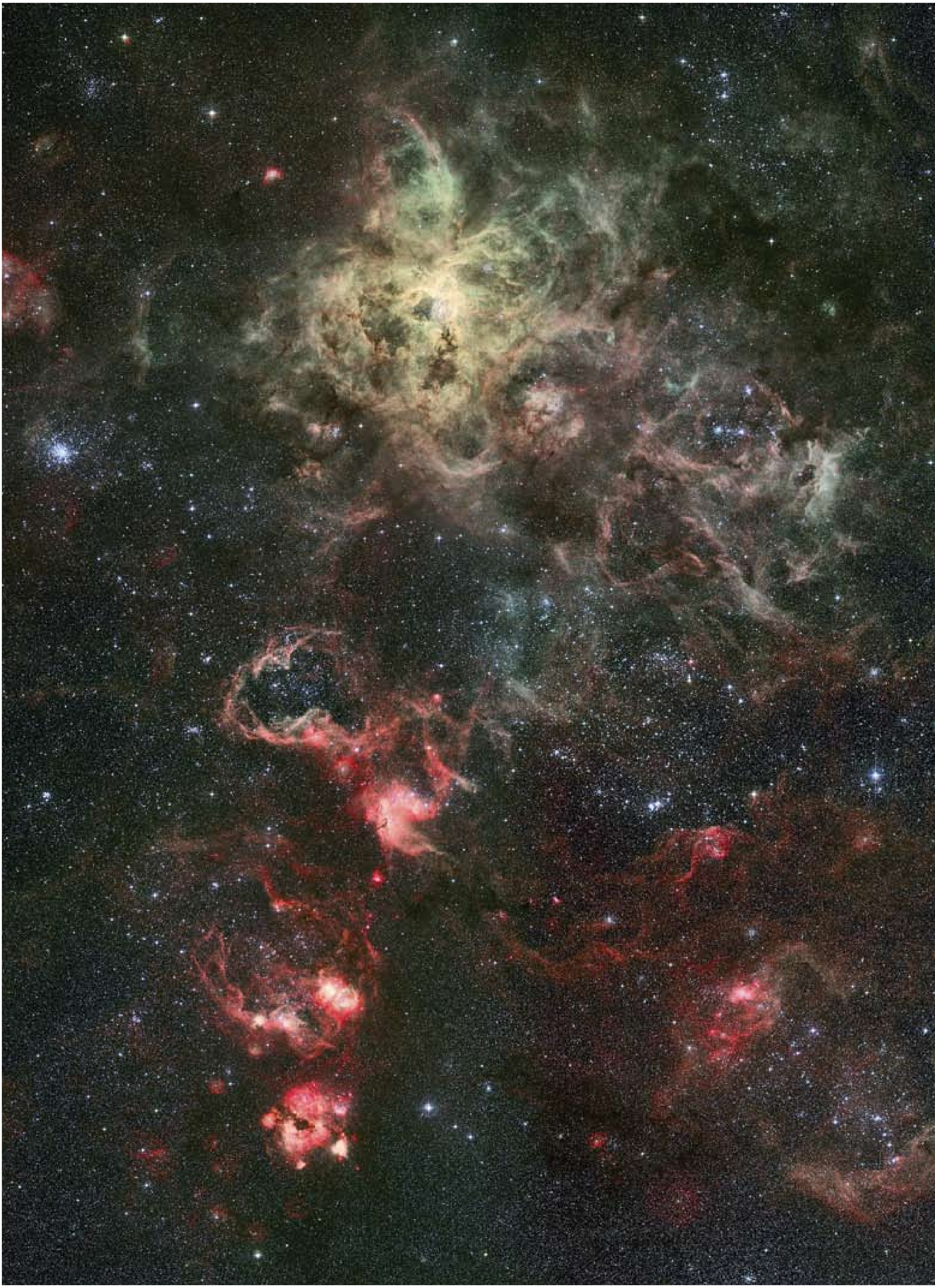
Monitoring of the transmission and thermal emission of the sky

from the visible to 40µm in winter (and in summer, in the infrared). Monitoring of the submillimetre-wave atmospheric transmission and stability. Accurate monitoring of the spectral opacity of the IR atmospheric windows should be made at moderate resolution, as well.

Measurement of the isopistonic angle

To reach a suitable limiting magnitude with a multi-aperture long-baseline interferometer, the co-phase of the different telescopes using a reference source needs to be known. The source should be located in the same isopistonic domain as the science source, which means that the differential atmospheric piston, within certain specifications, is the same in the direction of the two sources.

Model-dependent estimates of the isopistonic angle have been obtained using the GSM data. The isopistonic angle at Dome C is more than three times larger than at Paranal, which relaxes the interferometer cophasing in terms of sky coverage. Confirmation of these estimations from direct measurements are required for the specification of future interferometers to be deployed at Dome C. ■



4 Astrophysics at Dome C

Major astrophysical questions, ranging from the characterization of exoplanets to the polarization of the CMB, could greatly benefit from observations carried out in the Antarctic environment. ARENA has set up six working groups to investigate, in their fields of expertise, the most promising astrophysical breakthroughs and to carry out preliminary concept studies of the appropriate instruments-including their logistics impact and financial requirements.

The prerequisite for the development of major astronomical facilities in Antarctica is to demonstrate that as a result of the exceptional polar atmospheric environment one would gain orders of magnitude of improvement on essential parameters such as overall sensitivity, angular resolution, or duty cycle.

In a single sentence, these new facilities must provide essential data to solve major astrophysical problems that could not be obtained from any other place on Earth or, at an unrealistic cost, from space. A major activity and concern of ARENA members and, in particular NA5, was to identify these "scientific niches" and to propose instrumental concepts able to achieve them. To this purpose, six specialist working groups (see **Chapter 1c**) were set up to investigate their top-level science cases and requirements. These working groups produced reports that constitute the body of the present chapter. ■

The Butterly Nebula (composite of three exposures through broad-band blue, green and red filters, lasting a total of 25 minutes at the ESO VLT)

4a Wide-field optical and infrared astronomy

Working group activities

The ARENA Working Group 1 (WG1) was formed with the brief of considering the science drivers for a 2m-class optical/infrared telescope that might be built at Dome C, together with the principal issues that must be dealt with in order to do so. The WG1 was informed of the discussions and many presentations made at the various ARENA–sponsored meetings, in particular the science conferences held in Roscoff in 2006 and Potsdam in 2007. It also followed closely the preliminary design study undertaken for the PILOT telescope, completed in 2008. This design study involved an in-depth examination of several science cases, as well as the technical issues of building and operating a 2m-class optical/IR telescope in Antarctica. The results of the PILOT study have strongly influenced the deliberations of WG1, although the final conclusions differ in emphasis. WG1 conducted its discussions largely electronically, presenting a preliminary report at the Paris ARENA meeting in December 2008, and its final report at the 3rd ARENA Conference in May 2009.

Science and context

It is clear that the Antarctic plateau offers a range of exciting science opportunities for astronomy, from optical to radio wavelengths, and across the particle spectrum. The task of WG1 was to consider the optical and IR spectrum, as it might be studied using a single, 2m-class telescope located at Dome C. Motivating this was the knowledge of the environment of the Antarctic high plateau, the coldest, driest location on our planet, and its stable air flow. The cold reduces the background from both sky and telescope, thus, for instance, making a 2m-sized telescope in Antarctica the equivalent of an 8m-sized telescope on a good temperate site for extended source imaging in the thermal-IR. The dry conditions open up windows in the mid-IR for regular viewing, as well as improving the transmission through other IR windows used at temperate sites. As mentioned earlier, the stability of the air flow had first led Peter Gillingham in 1989 to propose that "super-seeing" might be obtained over the Antarctic plateau, above a narrow surface inversion layer, and hence the possibility of superior imaging quality in the optical than obtainable from temperate sites.

When the WG began its deliberations, site testing results from Dome C had recently suggested that superb optical seeing might be obtained above a ~30m high boundary layer. Hence interest in an optical telescope, capable of near-diffraction limited imaging, was high. While this still remains a desirable feature for an Antarctic telescope, as the WG continued its work it became apparent that the constraints this requirement places on the design and construction of an optical telescope are significantly greater than for an infrared-optimised facility. Moreover, moving to the infrared means that we can make use of a GLAO device to secure sharper data from a telescope much closer to the ground (about 10-20m to be studied during a phase B). The WG concluded that opportunities and prospects for the infrared provide the most feasible path forward for the first

2m-class telescope for Antarctica. Such a telescope also provides a range of exciting science programmes that are competitive with those that may be conducted from any other facility available to astronomers today. The report of WG1 follows.

Dome C potential

An optical/infrared telescope at Dome C would be supremely powerful for its size, enjoying not only a substantial advantage in both sensitivity and photometric accuracy over comparable ground-based facilities, but also having a wide-field, high-resolution, high-cadence imaging capability otherwise achievable only from space. This is a result of the improved background, transparency, stability and seeing conditions on the Antarctic plateau over temperate latitude sites. New and improved atmospheric windows are opened thanks to the extremely dry air. Low turbulence results in the free-air seeing being more than twice as good. Longer observing times are available due to clearer skies and more stable backgrounds.

Taking the combination of these gains, the primary wavelength range identified by this working group for an Antarctic telescope is in the infrared. This includes both the near-infrared (in particular, the bands of K_{dark} at 2.4µm, L' at 3.8µm and M at 4.7µm) and the mid-infrared (N' at 11.5µm, Q_N at 20µm and Q^+ at 30µm). Above 3µm, observations can be carried out during daylight periods and moonlight is not a limitation.

The near-infrared performance gains of an Antarctic telescope arise from the combination of the relatively high spatial resolution and the low thermal background. Comparing against future telescopes, the primary ELT role in the near-infrared will be for high spectral and/or spatial resolution observation. JWST will be diffraction limited and 10-500 times faster than any existing ground based telescope, as well as ~20 times faster than an Antarctic 2.5m. Both ELTs and JWST are observatory-class facilities, however, and neither is focussed on wide-field science. A complementary survey telescope is needed for the surveys discussed below, programmes that an Antarctic 2.5m-class telescope would be uniquely capable of undertaking.

The mid-infrared wavelength range falls in the large gaps between ground and space telescopes in terms of survey speed, and between large-aperture, small-field telescopes and small-aperture, wide-field telescopes in terms of resolution. An Antarctic telescope would be the only telescope capable of obtaining moderate spatial resolution photometry over very wide regions of sky, and thus an ideal complement to both the deep, narrow fields of JWST & ELTs and the wide area, low spatial resolution fields of Spitzer & WISE.

In the instrumental parameter space domain, this working group identifies several characteristics that should be included in the design of an infrared telescope in Antarctica:

- Wide-field is fundamental: the instantaneous field can be very large, up to ~ 1 square degree.
- High angular resolution (about 200 or 300 milli-arcsec) is essential, especially if combined with wide-field. Due to the stability of the atmosphere, high image quality can be homogeneously reached over the complete field using a ground layer adaptive optics system and/or a tower.
- Time monitoring is important because long observing periods are available with good, stable observing conditions.
- Spectroscopic capabilities should be included, in addition to those for continuum imaging.

To be competitive, the working group believes that such an Antarctic telescope must be larger than 2m. Although the science that could be attained with a 4m telescope or larger would simply be exceptional, we believe that a 2.5 diameter telescope is the next step in developing Antarctic optical/IR astronomy. It is capable of delivering unique and exciting science for relatively modest cost, while also demonstrating the future possibilities for larger Antarctic plateau telescopes (and possibly interferometers).

Science cases

A 2.5m diameter Dome C telescope could undertake a wide range of competitive science. However, the WG1 is conscious that due to the special conditions of Antarctica and the numerous other challenging instruments, only a selection of them will appear in the final roadmap. Three key programmes for such an infrared optimised facility are identified: (i) the distant universe, including first light in the universe and the equation of state of the universe, (ii) exoplanet science and (iii) galactic ecology. The order in which they appear and are described below is not a priority ranking. These key programs in turn define two initial instruments that will be required. A third one is also considered as a commissioning instrument. Other instruments are also identified for Phase 2 operations.

Key programme 1: The Distant Universe (Wide-field, near-infrared imager)

First light in the Universe

This key programme aims to measure the signatures of the final evolutionary stages of the first stars to form in the Universe, and the properties of the first galaxies. Pair-instability Supernovae (PISNe) are predicted to be extremely powerful explosions that occur in massive progenitor stars formed in low metallicity environments and should thus be numerous amongst the first Population III stars. A 2.5m Antarctic telescope should be capable of finding PISNe out to a maximum redshift in the range z = 7-10, via a dedicated search in the near-infrared. Together with JWST, these would be the only facilities capable of detecting such high-redshift objects, but each probes a different region of the PISNe parameter space.

Because of their high intrinsic luminosity, gamma ray bursts (GRBs) offer a powerful probe of the Universe at a range of cosmological distances. The highest redshift GRB so far detected is at z = 6.3; theories suggest that objects should be numerous at even higher red-shifts in the range z = 10-20. While current high-energy satellites find hundreds of GRBs per year, there is a paucity of uniform optical/infrared afterglow observations. A 2.5m telescope would be expected to find several z > 6 GRBs per season and at least one z > 10 GRB after a few years of monitoring.

Deep infrared imaging surveys
A large number of world-wide programmes and instruments on the ground (SDSS, 2MASS, DENIS, CFHT, UKIRT, SUBARU, VLT…) and in space (ISO, HST, SPITZER, AKARI…) are or have been devoted to extragalactic imaging surveys, driven by their cosmological interest. In the infrared, mid-latitude ground-based telescopes are hampered by the high thermal background. Future space telescopes like WISE and JWST will be devoted to deep infrared imaging. WISE just started to make an all-sky imaging survey in the 3.3 to 23µm range, at low angular resolution and JWST will offer an incomparable image resolution, but on medium size fields (~2'x2') and only in the 1 to 5µm domain (NIRCAM instrument). An Antarctic 2.5m telescope is a perfect complementary instrument able to undertake imaging surveys on much wider fields than JWST, and at a spatial resolution of ~0."3 in the near infrared and diffraction-limited in the mid-infrared, which is much better than WISE.

The 2 to 4µm range corresponds to the rest-frame optical range for galaxies at $2 < z < 5$. This telescope will be perfectly suited to extend the determination of the physical parameters, largely used today in the local universe, to the high-redshift universe. The Hα line is one of the main tracers of star formation at all redshifts. It lies in the K band for $z = 2$ to 3, the peak for star bursts in the evolution of galaxies. In the L' band the $z = 4$ to 5 range can be explored.

These two domains are crucial to achieving an understanding of the star formation history of the universe. The low sky thermal emission and the wide field of view would also allow a wide-area 2.4µm K_{dark} survey to find more distant galaxies at lower limiting masses than possible with other facilities.

The Equation of State of the Universe
Supernovae (SNe) are at the intersection of cosmology, galaxy evolution and stellar evolution. Type Ia SNe are standard candles with which the cosmic acceleration of the Universe can be probed. Their use is strongly constrained by the environment in which they explode. If these are dusty, uncertainties are introduced in the estimation of their distance and absolute brightness from the optical light curve, which in turn leads to errors in the derived Hubble diagram. SNe in this band at the depth which can be reached from Dome C should thus allow more accurate interpretation of SN light curves, so obtaining improved constraints on the cosmological parameters derived from them.

Key programme 2: Exoplanet Science: (Wide-field near-infrared and mid-infrared imagers)
Two techniques of detection and characterization of exoplanets can benefit from the unique properties of Dome C. These are the transit and micro-lensing techniques. Applying these in the near infrared can enable to reach a remarkable depth. Furthermore, the K and M stars have their maximum brightness in this spectral domain, allowing a systematic study of planets around these stars. Such a census is necessary for a full appraisal of the planet formation process. One should note that exoplanet science has also been given priority by WG 4 (Time-series observations, see **Section 4d**).

It must be stressed that the goal here is not to commence another programme of detection of exoplanets, as are already being conducted by several global networks, but to undertake observations only under alert. These typically would require no more than 20-40 hours of continuous observations.

Exoplanets by the transit technique
The observation of known transits, by selecting the brightest targets, is the only way to characterize the planetary atmospheres, through their composition (molecules, clouds, hazes) and temperature profiles, by recording the stellar spectrum at low resolution (few hundreds) during the event. From the difference between two spectra of the planet, one obtained in front of its star (primary transit) and the other off the star, one can derive the transmission spectrum of the planet. Observations in the 2 to 5µm range, where the emission is dominated by common molecules such as H_2O, CH_4, CO_2, are recommended. With measurement of the secondary transit (planet behind its star) as well, an emission spectrum of the planetary day-side can also be obtained. Dome C offers the unique capability of making it possible to follow both these types of transits from the same ground-based site.

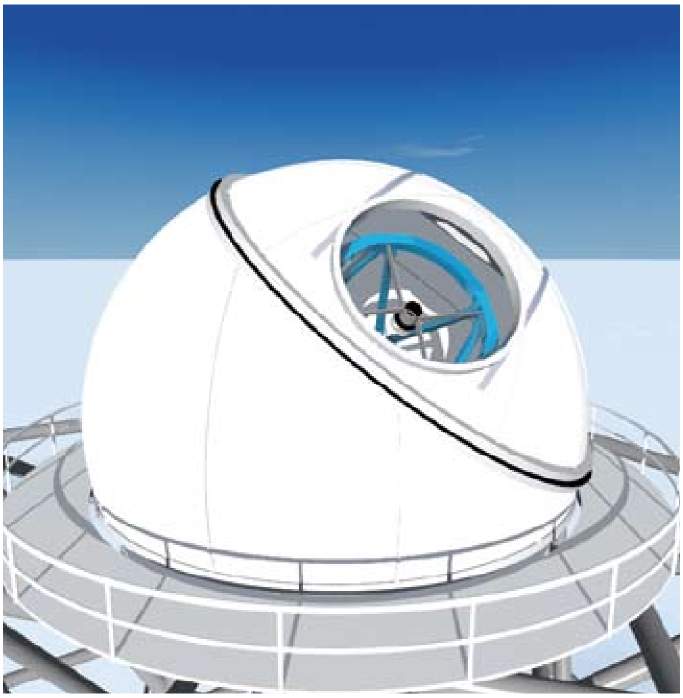
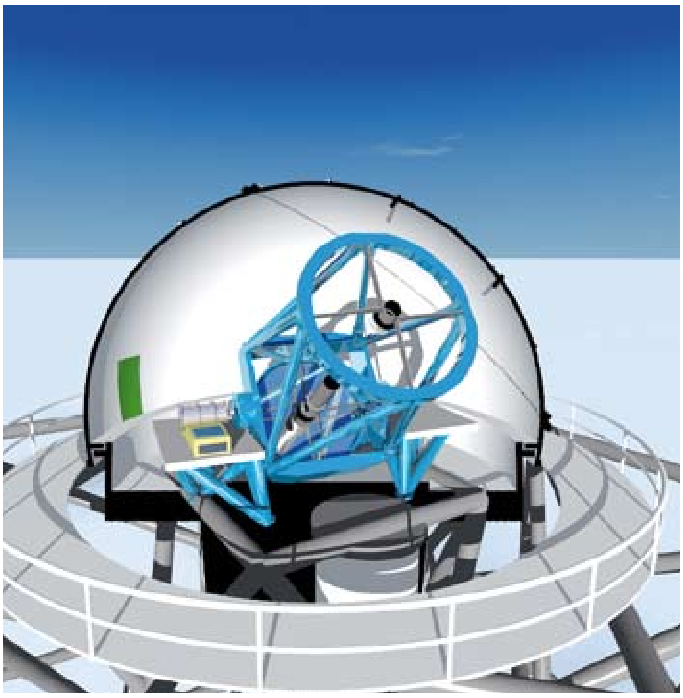



Fig. 1 CAD image of how a 2.5m IR telescope might look like at Dome C, mounted on top of a tower and inside a calotte-style dome. Image courtesy of Andrew McGrath (Anglo Australian Observatory), as designed for the PILOT Phase A study.

Table 8 Performance Characteristics of an Antarctic 2.5m Optical/IR Telescope

Expected resolution and sensitivity for an Antarctic 2.5m telescope. The resolution, over the full imaging field of view for each camera, is given as a function of wavelength, including tip-tilt to remove boundary-layer turbulence and tower wind-shake. For λ > 3µm near-diffraction limited performance is achieved. Point source and extended object limiting sensitivities (in AB magnitudes) are also given for a 5σ, 1hour integration, assuming that the sky background is summed over 4 times the FWHM disc (for point sources), the telescope is at 227K with 5% emissivity, the overall optical efficiency is 50% (including throughput, detector efficiencies, and secondary mirror obscuration). The proposed instruments are indicated in the final column, together with their pixel scales and fields of view. Columns 2 lists the priorities: in agreement with the text, the NIR camera has the highest priority.

Band	Priority	λ (µ)	R(λ/δλ)	FWHM (arcsec)	m_{AB}	m_{AB}/arsec²	Prospective Instrument
G	2	0.47	3.4	0.35	27.6	27.1	Visible Camera, 0.08" pixel scale, 40'x40' FOV
R	2	0.62	4.4	0.33	27.1	26.5	
I	2	0.76	5.1	0.32	26.6	26.0	
Z	2	0.91	6.5	0.31	25.8	25.1	
Y	2	1.04	5.1	0.30	25.5	24.8	
J	0	1.21	4.6	0.30	25.0	24.3	Near-IR camera 0.06" pixel, 4' FOV 0.15" pixel, 10' FOV or more
H	0	1.65	5.7	0.29	24.6	23.8	
K_{dark}	0	2.40	10	0.32	25.3	24.7	
L	0	3.76	5.8	0.40	21.2	20.8	Near-IR camera 0.15" pixel, 10' FOV
M	0	4,66	19	0.46	19.6	19.4	
N'	1	11.5	11	1.05	16.3	17.0	Mid-IR camera (blue arm) 0.8" pixel, 14' FOV
Q_N	1	20.1	20	1.80	14.6	15.8	
Q^+	1	30	20	2.7	13.4	15.1	(red arm) 1.3" pixel, 6' FOV

Exoplanets by the micro-lensing technique
The method is complementary to the transit technique, which is more sensitive to planets within 1 AU of the star. It requires, first, a search for amplification events by wide-field telescope networks pointed towards the Galactic Bulge (GB), to obtain the highest probability of alignment of a star belonging to the disk to act as a lens for a source in the GB. The full crossing of the Einstein circle can take up to 60 days, monitored by specialized networks (*e.g.*, OGLE and MOA). Then, the follow-up of the strongest light curves is undertaken by other telescopes organized in a network (*e.g.*, PLANET). For the best chance of detecting the perturbation of the light curve due to a planet, continuous monitoring is necessary during the ~two days around the light maximum. Photometry undertaken in the K band, rather than in the visible, significantly reduces the extinction toward the GB. The two Magellanic Clouds are also favourable targets for this programme. All these requirements are favoured by measurements made from Antarctica.

Key programme 3: Galactic Ecology (Wide-field, mid-infrared spectroscopic line imager)
This programme aims to investigate the molecular phase of the Galaxy. An Antarctic telescope should be able to map the mid-infrared emission from the pure rotational lines of H_2 at 12 and 17µm in the typical warm environment of molecular clouds at a spatial resolution of ~2" over a wide region of the Galactic plane. This could not be done from a temperate latitude site as a suitable telescope would not have sufficient sensitivity. This spatial resolution is more than an order of magnitude better than achievable with mapping surveys using millimetre-wave telescopes, and is nearly two orders of magnitude better than the current best southern Galactic plane molecular survey. It will enable the molecular medium to be viewed with a new clarity of vision. A central issue relating to our understanding of the Galactic ecology is what the turbulent energy distribution is, and how it relates to the contrasting pictures of local turbulence injection from the natal stellar content or whether it arises from external sources? Such questions can be addressed by unveiling the molecular galaxy, mapping directly the distribution of its principal tracer, the hydrogen molecule, on the arcsecond scale.

Other science programmes
There are many other frontline science programmes that such a 2.5m telescope in Antarctica could undertake. Some possibilities are listed below:
• *Dark energy and the evolution of structure:* observation of weak gravitationally-lensed galaxies; and a study of a sample of moderate-redshift galaxy clusters.
• *Stellar properties and populations:* a near-infrared survey of disk galaxies in the local group to study the processes of galaxy formation and evolution; a deep mid-infrared survey of the Large and Small Magellanic Clouds in order to understand star formation processes and extreme populations of AGB stars.
• *Star and planet formation:* a series of mid-infrared spectrophotometric surveys searching for signatures of embedded protostars, crystalline silicates, and circumstellar disks around young stellar objects and brown dwarfs. The infrared search for free-floating planets in nearby star forming regions.
• *Diffraction-limited imaging science:* a range of projects for high resolution imaging in the optical over small fields ("Hubble from the ground"), including solar system science and emission line mapping of galaxy centres.

Instrumental requirements
The baseline optical design comprises a 2.5m Ritchey-Chrétien telescope with f/1.5 primary and f/10 overall focal ratios, giving diffraction-limited performance at 1µm over a 1° field. Instruments are mounted on twin Nasmyth foci. The telescope is housed in a calotte-style dome at an altitude of about 10-20m (to be studied in Phase B) (see Fig. 1). The enclosure is temperature and humidity controlled, protecting the optical elements from large spatial and temporal thermal gradients, and preventing frost formation on optical surfaces, so allowing, with the use of a Ground Layer Adaptive Optics and/or a tip-tilt system to reach the superb natural seeing above the ground layer. The need for a tower is to overcome the steep vertical temperature gradient in the boundary layer (up to 20°C in ~30m), as well as frosting on exposed surfaces caused by the super-saturated water vapour in the intensely cold air[2] (see also the next section).

[2] *It should be noted that there is minimal effect on telescope sensitivity caused by placing it on a tower rather than on the ice surface, even though this is a warmer environment, if the telescope has sufficiently low emissivity so that sky emission still dominates over telescope thermal emission.*

The height of the tower, however, should be determined through Phase B studies. Further data on both the rate of variation of temperature within the boundary layer, and on the variability of the boundary layer height, are needed as input for such studies. The tower height needs to be chosen so that any surface layer turbulence above the telescope can be corrected, via either GLAO and/or tip-tilt, to a level much smaller than that caused by the free seeing.

Both GLAO and tip-tilt systems may be used to mitigate the effect of the surface layer at Dome C, and a full study needs to be undertaken during Phase B on their effectiveness. The narrow height of the surface boundary layer and the large values of the Fried parameter make both attractive options to consider, but their efficacy depends on a full understanding of the behaviour of the boundary layer, which we do not yet have (see **Chapter 3**).

The imaging specifications are that the telescope should be capable of taking diffraction-limited images at 1μm in the best conditions; and that the imaging over wide-fields, longwards of 0.4μm, in normal conditions should be limited by the median free (tip-tilt-corrected) seeing and/or diffraction, rather, than by imperfections in the telescope itself.

The gains in seeing, isokinetic angle and coherence time over existing sites collectively mean that, in terms of suitable guide stars per isokinetic patch, Dome C enjoys a 20-fold advantage over, *e.g.*, Mauna Kea. This means that there are enough guide stars at r and i-bands to map the entire atmospheric deflection field, at a level giving negligible anisokinetic error. This will ensure that the median image quality of ~0.″25 is achievable over arbitrarily large fields, using tip-tilt correction for high-level turbulence via orthogonal transfer CCDs.

• Performance specifications for such a telescope are given in **Table 8**. It would outperform a similar or somewhat larger telescope at a temperate latitude observatory for the following kinds of observations:

• Wide-field imaging in the visible and near-infrared with partial (tip-tilt and/or GLAO) correction of the residual boundary layer turbulence (resulting from the excellent free atmospheric seeing, the low height of the turbulent boundary layer, the wide isoplanatic angle and the long coherence time).
• High sensitivity in the near-infrared (arising from the low atmospheric thermal emission) and the mid-infrared (arising from a combination of the low atmospheric thermal emission and the high atmospheric transmission).
• High photometric precision in the optical (enabled by the low atmospheric scintillation) and the infrared (enabled by the stable atmospheric thermal emission).
• Continuous coverage (due to the high latitude of the Dome C site and the high cloud free fraction).

Consideration of these performance gains in turn leads to an initial suite of three instruments designed to take advantage of them:
• A wide-field, near-infrared camera, with ground layer tip-tilt / GLAO correction and adjustable pixel scales matched to the diffraction limit at short and long wavelengths.
• A wide-field, mid-infrared instrument, with a tuneable Fabry-Perot filter or a GRISM spectrometer, and two separate arms with short and long wavelength ranges.
• A fast optical camera for diffraction limited imaging over relatively small fields in the visible, which would also serve as a commissioning camera.

Further instruments might then be built as Phase 2 instruments, designed to exploit, for instance, the superb free-air optical seeing, or to enhance the spectroscopic capabilities. These might include:
• A wide-field, visible camera with ground layer tip-tilt correction.
• A wide-field, near-infrared imaging spectrometer, such as an FTS or integral field spectrometer.

Roadmap and funding

Unique operational aspects of an Antarctic observatory arise from its remoteness, the polar environment and the unusual observing cycle afforded by long periods of darkness and daylight. The telescope must be planned to be run with remote observing via satellite communications, and must overcome both limited physical access and data transfer.

Commissioning and lifetime operations must deal with extended logistics chains, continual wintertime darkness, extremely low temperatures and frost accumulation. A 100kW PV and wind power installation is envisaged for electricity generation.

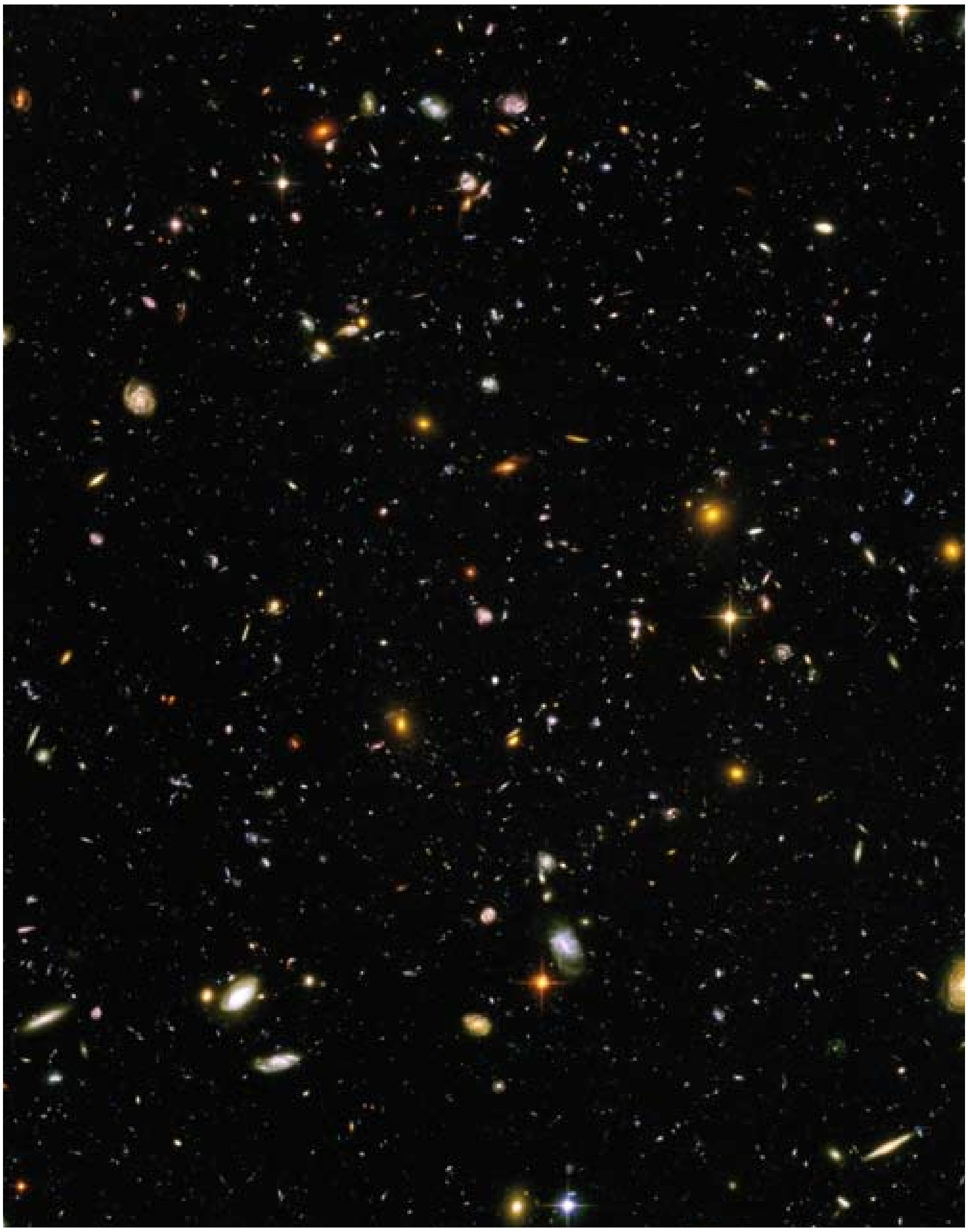
The design challenges caused by the extreme cold are dominated by the continued performance of lubricants; mechanical clearances that may change due to thermally induced dimensional changes; and the operation of electronics designed for room temperature operation. However, all of these are quite readily overcome with proper mechanical design, as long as the design takes account of the temperature requirements. The high rates of change of temperature can be more problematic, especially for components with high thermal mass and tight thermal equilibrium requirements - notably, the primary mirror. Active thermal control has been considered, and unconventional mirror substrates with low thermal mass (*e.g.*, silicon carbide), but current indications are that a relatively conventional light weighted zerodur primary mirror will have adequate thermal performance.

Apart from surface layer turbulence, the other major challenges specific to the acquisition of astronomical data at Dome C are the enormous vertical temperature gradient, (~1°C/m at surface level and ~0.15°C/m even at 30m), and the supersaturated humidity. To solve these problems, a temperature and humidity-controlled enclosure is proposed. This enclosure will be continuously flushed with sub-saturated air, matched in temperature to the external air at the dome aperture. This air is drawn from closer to the surface of the snow, and is heated using largely the waste heat from the instrumentation, resulting in its humidity falling below the saturation point. A further advantage of this scheme is the delivery of excellent dome seeing, as the temperatures can be closely matched and the external airflow suffers minimum disruption – as demonstrated by computational fluid dynamics (CFD) models.

One possible funding model sees an initial cash injection of 20 M€ for the cost of the telescope structure and optics. Project management, software development and support are funded through national observatories, and logistic support through national polar agencies. Contributions here provide return in terms of share of observing time on the facility. Instruments are funded and built by individual consortia made up from the partner countries. Each instrument is estimated to cost of order 5 M€.

Phase B studies are necessary to fully cost all the options, including the performance and science trade-offs that would result from any de-scoping. For instance, costs could be reduced if the telescope were to be designed only for operation at infrared and not optical wavelengths, as the specifications on image quality are then lower. Similarly, the fields of view might be reduced in order to lower costs. Investigation of the performance and operation of a GLAO system is an essential element in a Phase B study, as well as the possible integration of the telescope into an interferometric array. ■

The Milky Way, the Galactic centre and the Large Magellanic Cloud as seen from Concordia



Hubble ultra deep field black

4b Submillimetre-wave astronomy

Working group activities

The ARENA Working Group 2 for submillimetre astronomy (WG2) has focused on the following items during one year of activity.

- Analysis of site testing data.
- Atmospheric modelling.
- Selection of science cases.
- Telescope selection.
- Study of possible Concordia station upgrades.
- Preparation of a feasibility study by industries.
- Roadmap and funding.

This section aims to provide a summary of the status of the large submillimetre telescope project. It is a very new project for Antarctic astronomy. The necessary prerequisites for a future deployment of a large telescope infrastructure have been verified in the years 2007, 2008 and 2009. A knowledge of the atmospheric transmission, frost formation and temperature gradient are required before starting a feasibility study. The telescope specifications and requirements are currently being discussed with the industrial partners. An estimate of the cost of the necessary technology, the power supply, means of hardware transportation, and communication requirements, as well as good initial estimates of the annual running costs, are also under discussion.

Submillimetre astronomy: science and context

Far-infrared/submillimetre (hereinafter FIR/submillimetre - 100 to 1,000µm) astronomy is the prime technique to study the 'cold Universe' and unveil the birth and early evolution of planets, stars and galaxies. It is a relatively new branch of astronomy at the frontier between IR and radio astronomy. FIR/submillimetre continuum observations are particularly powerful to measure the luminosities, temperatures and masses of cold dust containing objects because dust - enshrouded star-forming regions emit the bulk of their energy between 60 and 500µm. The submillimetre/FIR range of the spectrum (or THz regime) is also rich in several atomic and molecular lines that are the only means to study the kinematical structure of the interstellar medium (ISM) of galaxies. These lines allow us to probe different physical and chemical regimes, *i.e.*, regions of widely different densities, temperatures and UV illumination, depending on their excitation levels and critical abundances. Observations at these wavelengths with a large telescope will primarily lead to breakthroughs in the study of star formation at all scales and to an understanding of its cosmic history back to the early Universe as well as that of galaxy evolution. Asteroids, debris disks, planet formation, dust origin in evolved stars, interstellar dust and polarisation of dust in the Universe are also potential science drivers for FIR/submillimetre astronomy.

What is the context today of submillimetre astronomy? The Herschel Space Observatory, a FIR/submillimetre (60-500µm) telescope in Space has successfully been launched by Ariane 5 on May 14, 2009. It is now performing science observations. ALMA, a ground-based mm-wave (350µm-7mm) interferometer on the Chajnantor plateau

COCHISE 2.5m dish in set up phase

in the northern Atacama Desert, will soon be available. Both facilities will have their specific niches. Herschel has the ability to carry out large-area imaging surveys of both the distant Universe and the nearby interstellar medium in our own Galaxy. ALMA will make possible ultra-deep searches for primordial galaxies, as well as detailed kinematical investigations of individual protostars. However, both Herschel and ALMA will have their own limitations. The Herschel telescope (3.5m) suffers from its only moderate angular resolution, implying a fairly high extragalactic confusion limit and preventing the study of individual protostars in all but the nearest star-forming clusters of our Galaxy. ALMA will suffer from a small field of view (10”) and limited observable conditions in the FIR/submillimetre, making extensive wide-field mapping impossible given the amount of time necessary to cover large star forming complexes and fields of primordial galaxies.

Besides these two major facilities, there are other submillimetre/FIR telescope projects in operation or under study, balloon-borne (*e.g.*, BLAST, OLIMPO, PILOTE, *etc.*), aboard an airplane (SOFIA), aboard satellites (*e.g.*, AKARI, SPICA) and on high-altitude sites (*e.g.*, APEX, CCAT).
Why consider potential science with a FIR/submillimetre telescope at Dome C?

Table 9 Limiting sensitivity

Performances for the observation of an astronomical point source located at 50° in elevation with the following assumptions: a bolometer array camera installed on a 25m single-dish telescope with a total optical transmission of 50% (optics & filters), with a bolometer absorption of 80%, with a noise equivalent power limited by the atmosphere under the 50% quartile of transmission. It is believed that these hypotheses are representative of realistic observations on Cerro de Chajnantor in Chile (CCAT site) and at Dome C in Antarctica.

Site	200 μm	350 μm
Dome C	1000 mJy/s/ beam **20 mJy in 1 h**	60 mJy/s/ beam **1 mJy in 1 h**
Chajnantor 5600m	24000 mJy/s/ beam	200 mJy/s/ beam **3.3 mJy in 1 h** **1 mJy in 11 h**

Besides Herschel and ALMA, there is a clear need for a large (>10m) single-dish telescope operating at 30-450μm and providing:
• better angular resolution than Herschel
• wider-field mapping capabilities than ALMA, making large-scale mapping with a relatively good angular resolution (~ 1”) possible and well matched with the thermal infrared space telescope (*e.g.*, Spitzer) and
• bringing zero-spacing baseline data for interferometry and/or long baseline for VLBI.
New sites are therefore intensively tested because the 200-350-450μm windows at Chajnantor open less than 30% of wintertime at an observable level, probably less than 5% at 200μm. The stability of the atmosphere is an equally important parameter when comparing the sites, and Dome C may stand out as being far more stable than Chilean sites. Equipped with FIR/submillimetre imagers and spectrometers, a European telescope at Dome C in Antarctica might be able to operate in all atmospheric windows between 200μm and 1mm, and very regularly at 350 and 450μm all year long.

Dome C potential and atmosphere transmission

A major obstacle to carrying out submillimetre observations below 500 μm from ground is the atmosphere as well as the harsh environment of the potential ground-based sites (high altitude deserts; Antarctica). Preliminary meteorological studies and atmospheric transmission models tend to demonstrate that Dome C could offer atmospheric conditions that open the 200μm windows. The SUMMIT08 submillimetre tipper (see **Fig.2**), a collaboration between CEA Saclay and UNSW/Sydney, has started operation in early 2008 to measure the sky opacity at 200μm. Using the MOLIERE model for atmospheric transmission, it is possible to estimate the transmission at 350μm (see **Fig.4**). These results confirm the transmission estimates using radiosounding data by *Valenziano et al.* With these two sets of independent measurements, one can now state that Dome C is currently the best accessible[3] site on Earth in terms of transmission in the FIR/submillimetre. The 200μm window opens at a level of better than 20% transmission during 25% of the time (see **Fig.3**). About 40 nights of observations at 200μm are expected with a sensitivity of 300mJy/s/beam for a 25m dish telescope under the assumptions described in the **Table 9**. Further analysis indicates that observations at 350 and 450μm are possible all year compared to only 30% of the time on ALMA site. A factor 11 in time is expected in favour of Dome C versus Cerro de Chajnantor when conducting observations of a source at 50° elevation with a current state-of-the-art bolometer camera. Comparisons with another site, Antarctic Dome A, have been possible for a short period of time based on a graph available

[3] *Accessible meaning that Dome C has a permanent station with winter-over operation.*

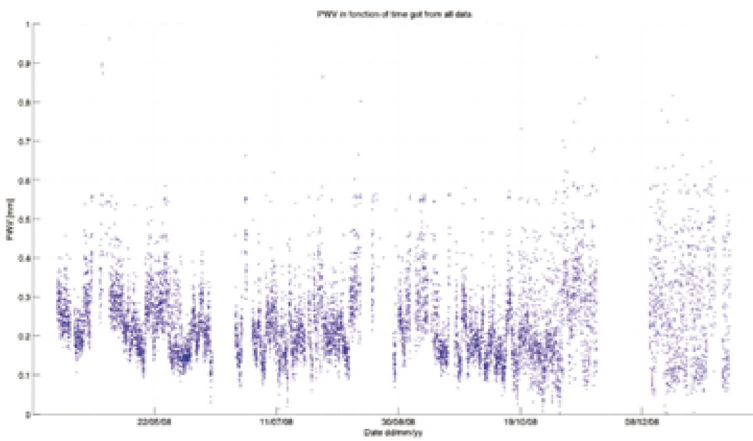


Fig. 2: Precipitable water vapour levels at Dome C from April to December 2008, converted from the transmission measurements with SUMMIT08 using MOLIERE atmospheric modelling.

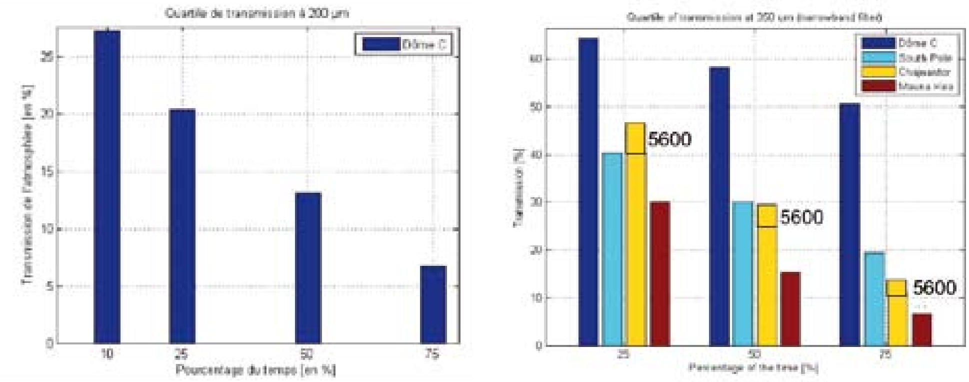


Fig. 3: Percentage of time the atmosphere has a certain transmission at 200µm (measurement) and at 350µm (extrapolated using modelled transmission vs. PWV). The extrapolated results at 350µm for Dome C are compared with other sites like the South Pole (Antarctica), Mauna Kea (Hawaii), and Chajnantor (Chile). Note that the Chajnantor yellow bars are divided in two: the lower parts are for the ALMA site at 5,100m; the upper boxes are for Cerro de Chajnantor (CCAT site) at 5,600m. The CCAT site values are based on discussion with Simon Radford, Frascati, 2009. Comparisons are mainly indicative. They should not be reproduced or taken as absolute comparisons.

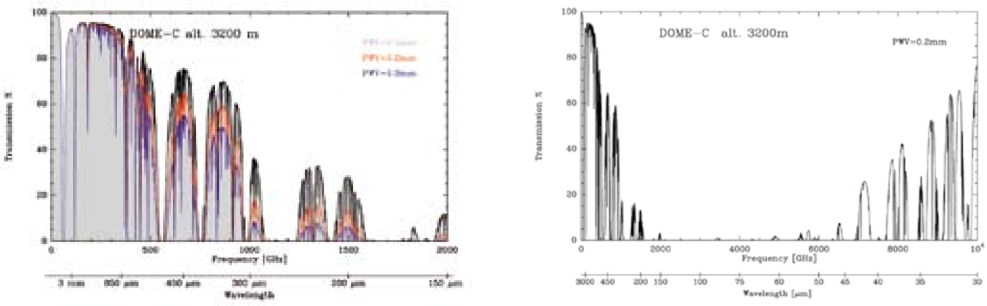


Fig.4: Modelled transmission at Dome C for several PWV values using the MOLIERE code. Left: the submillimetre range. Right: the mid- and far-infrared range.

on the pre-Heat webpage and for the whole period of time with the MHS NOAA satellite dataset (see **Fig.5**). We conclude that Dome A would be slightly better at 200µm, but no major gain is expected especially at 350 and 450µm. Atmospheric transmission stability will be assessed with the CAMISTIC bolometer array on the IRAIT telescope in the future (possibly in 2011-2012).

Science cases for submillimetre/ far-infrared astronomy at Dome C

Science case 1:
The cosmic history of star formation, black holes and galaxies

The immediate objective is the detection of more than 50% of the star formation rate density in the Universe, and to disentangle black holes from star-formation activity in galaxy evolution over z=1 to z=4. By measuring the galaxy bolometric luminosity from 30 to 450µm and by detecting starburst spectral lines (NeII, OIV, OH…) in the FIR and THz ranges, this objective should be reached with a telescope of 25m diameter (or equivalent collective area) that is equipped with spectro-imagers including a large format bolometer camera (FOV>>10 arcmin^2). Sky areas of a few deg^2 and hence large surveys are possible at 350µm all year long down to the confusion limit around 1mJy (in one hour of observation that is reached during 50% of the time). A 2-year project is sufficient to carry out this project.

Science case 2:
The origins of stellar masses

The immediate objective is the detection of the prestellar and protostellar core mass function down to sub-solar masses and throughout the Milky Way in order to construct a "core mass function" and compare it with the modelled and observed stellar initial mass function. By measuring core bolometric luminosity from 30 to 450µm, density profiles, temperatures and masses, the core mass function is determined as well as the position of the protostellar cores on a "luminosity *vs.* mass" evolutionary phase diagram. A 25m dish (or equivalent collecting area and resolution that is equipped with a large-format bolometer array (FOV>>10 arcmin2) and spectrometer in the mid-, far-infrared, and submillimetre is needed to cover completely giant molecular clouds (*e.g.*, Carina, Chamaeleon) in one year of operation.

Science case 3:
The galactic energetic engines

The immediate objective is the knowledge of the physical and chemical properties of the interstellar medium in our Galaxy down to prestellar cores, in the Magellanic Clouds and in nearby galaxies. By performing molecular line surveys in the THz regime and dust emission mapping in the FIR/submillimetre across these targets, a complete mapping of the LMC/SMC is achievable in 6 years with a 25m single dish telescope equipped with multi-beam heterodyne receiver (min. 14 beams) and a large format bolometer array (FOV>>10 arcmin^2).

Science case 4:
Galaxy clusters in the far Universe and dark energy

The immediate objective is the observation of Sunyaev-Zel'dovich effects, CMB temperature evolution and the dark energy equation of state (synergy with the CMB ARENA working group). Mapping in the submillimetre/millimetre (700µm to 2mm) with a 12m dish or with a 25m dish to achieve an improvement in angular resolution, equipped with a large format bolometer array (FOV>>10 arcmin^2) is recommended.

Telescope requirements

To fulfil the science case requirements, two telescope configurations were studied:

- A single-dish telescope with no diameter limitation up to a reasonable size, starting with the performance obtained with a 12m diameter dish such as the ALMA antenna.
- A network of three small telescopes, a FIR/submillimetre interferometer as a pathfinder for the FIRI space interferometer. The single dish telescope with a 25m diameter aperture, AST was selected. The interferometer configuration (three antennas only) has been dismissed for two reasons:
- Poor sensitivity at 200µm: the sensitivity after a reasonable amount of time (10 hours) at 200µm will not be sufficient to allow detection of faint objects within the small synthesized beam of the interferometer. This is mainly due to the narrow spectral width of the THz atmospheric windows (~10µm at 200µm), delivering about 10mJy in tens of hours on a single baseline. Science at 350 and 450µm will be achieved by ALMA.
- Extreme winter conditions for operating a pathfinder experiment of FIRI: it would require high level of maintenance and manpower during the best observing conditions in wintertime.

We note, however, that an array of many antennas (>>10) would be competitive and could offer an alternative to a large single dish. It would offer the same collecting area and better angular resolution, while preserving the field of view if bolometer interferometry were selected. Use of COCHISE as a first element of this array should be studied as well as the installation of one (or more) medium-size antenna(s) (6-12m), which might be adapted and built cost-effectively from already existing designs. Such antenna(s) would constitute a necessary technological testbed and pathfinder for a larger facility and would be able to achieve extremely interesting science results of their own. The AST-25m telescope would provide a large collecting aperture with high surface accuracy (<12µm) to operate at wavelengths as low as 200µm, providing deep, high angular resolution (< 2 arcsec) images. The combination of the atmospheric transparency at Dome C and the large aperture would make this the most sensitive submillimetre telescope ever planned. AST-25m would enable Europe to be at the forefront of astronomical research and would favour state-of-the-art instrumental development. AST could also be used as a VLBI antenna between ALMA and Antarctica, providing a baseline of several thousands of kilometres.

Note: telescope specifications and requirements are currently being discussed within the industrial partnership. An estimate of the cost of the necessary technology, the power supply, means of hardware transportation, and communication requirements as well as initial estimates of the annual running costs have been provided in May 2009 at the 3rd ARENA Conference by the EIE & Thales Alenia Space representatives.

Top-level requirements
This document presents only the top-level design or performance capabilities needed to meet the science goals of this project. The science objectives require a 25m aperture to operate at submillimetre wavebands. Efficient operation at 200µm implies the net effective surface error to be less than 10-12µm so that telescopes would be able to find and track a source with an accuracy of better than 0."2 arcsec. Therefore, there are four main critical areas that still need to be very carefully analyzed and discussed.

Active Surface
Fabricating, setting and maintaining a 10µm surface on a 25m diameter radio telescope is probably the most difficult challenge for this project. It also implies that active surface control would be necessary. Because the thermal distortions will be very critical at Dome C, it may be necessary to implement a dynamic closed loop control system using sensors and feedback. This is commonly done at optical/infrared wavelengths using edge sensors and optical instruments that measure the wavefront errors in real-time.

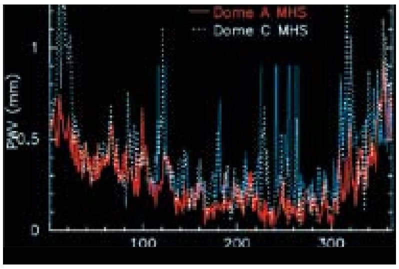


Fig. 5: PWV contents at Dome C (white) and Dome A (red) extracted from the MHS NOAA satellite dataset. The blue plot represents the SUMMIT08 data. Red curve is generally below white curve. Note however that MHS data give lower values of PWV than SUMMIT08.

Optical design
The optical design of the telescope is determined by optical, mechanical and focal plane instruments constraints. It must enable efficient operations in the defined wavelength range and field of view (10-20 arcmin in diameter). As a baseline optical design we have chosen, for now, the CCAT Ritchey-Chrétien optical system, with a Cassegrain focal ratio of f/8, a main reflector focal ratio of f/0.6 and a back focal distance of B = 11.0m.

These parameters enable operations at the Nasmyth focus of the telescope, and allow a receiver cabin of the appropriate size and the construction of a rigid mechanical structure (and elevation bearings positioning) at an acceptable cost, but then require quite a large subreflector (~ 3m). This implies a possibly expensive secondary, and also a complex and expensive mechanism for nutating the subreflector at frequencies of ~1 Hz.

Pointing and tracking
The diffraction-limited beam for observations at 200µm is only ~2 arcsec, and pointing and tracking a 25m telescope with 1/10th beam accuracy is a challenging task. Achieving this goal will require careful attention to all aspects of the mount and drive system. As with most radio telescopes it is anticipated that a pointing model will be developed that allows blind (*i.e.,* absolute) pointing anywhere on the sky to within one or two beam widths to allow for quick source acquisition and refinement of the pointing using bright submillimetre sources.

The telescope must then be able to track the target source to within about 1/10th of the beam for an hour or so before correcting the pointing on a nearby strong source. Because of the requirement to also observe during the day, it is desirable to achieve this pointing and tracking performance without a dedicated special offset (optical/IR) guiding system.

Extension to mid-infrared
The large aperture of the telescope and high atmospheric transparency at Dome C offer unique scientific opportunities for high spatial resolution imaging in the MIR (<~ 40µm). The system wavefront error budget of 12µm rms will not support diffraction-limited imaging short of ~200µm with the full aperture of the telescope. On the individual panel scale, however, the wavefront error is significantly diminished. Alternative options could be: (i) a Fizeau beam combination of many subapertures (panels) spread over the disk would enable inteferometric image reconstruction with the full resolution of a 25m telescope over a narrow field of view (as proposed for CCAT). (ii) Using the first (or first and second) ring(s) of panels of the primary reflector would enable the use of the telescope as a MIR single-dish with the equivalent collecting aperture of a 6.8m (10.8m) telescope. Either option would require the panels (assumed here to be 1.84m, square-like panels) to have IR quality surface and an overall RMS of less than 5µm. Option (ii) would additionally require the first/second rings of panels to be kept aligned to within MIR specifications.

Roadmap and funding
The necessary site conditions prerequisites for the future deployment of large telescope infrastructure have been tested in the years 2007 to 2009, and are planned to continue until 2012. A knowledge of the atmopsheric transmission, frost formation and temperature gradient are fundamental parameters needed before starting to raise funds for a feasibility study. The telescope specifications and requirements are currently beeing discussed within the industrial partnership. Joint efforts between Italian, French and Spanish teams within the ARENA consortium, together with the support of the IPEV and PNRA polar institutes, led to the building and progressive deployment of IRAIT, a 80cm infrared telescope. One of the goals of IRAIT, as a newly-installed IR telescope, operations will be as a path finding experiment for submillimetre astronomy in 2011-2012. It will perform atmospheric and sky-noise measurements with a bolometer array, prepare a catalogue of source calibrators in the far southern sky, and attempt several science observations of the Sun and of star-formation regions.

In parallel, the COCHISE upgrade to operate at submillimetre wavelengths should be studied, as well as the possibility of installing a medium size antenna paving the path to a future large telescope facility. Various complementary reports are available at *irfu.cea.fr/Sap/Antarctica.* ■

4c Optical and infrared interferometry

Working group activities

The goal of the ARENA Working Group 3 (WG3) for interferometry was to define and realize a pre-feasibility study of an Antarctic interferometer dedicated to the characterization of exozodiacal light with the required sensitivity (30 times the solar dust density level) to discriminate sources suitable for future exo-Earth spectroscopic analysis. The scientific study was performed by astronomers from IAGL (Liège) and LESIA (Paris).

The engineering study was carried out at AMOS, based on a concept by Thales Alenia Space derived from the GENIE instrument studied for ESA, and partly at Thales Alenia Space for studies of the beam combining nulling instrument. Particular emphasis was put on the compatibility with Concordia logistical and operational constraints, for which input was provided by IPEV. The group activity has been coordinated through different meetings and AMOS delivered a pre-feasibility report in July 2009. This section includes conceptual proposals for the telescopes, structure, interface with the snow, azimuth mechanism, top railway, and nulling instrument. The preliminary results are very encouraging, so that we recommend moving forward with a proposal for a full industrial feasibility study (1-2 M€) that could be submitted to FP7 and/or to ESA.

Science and context

The detection of biomarkers in the atmosphere of potentially habitable exoplanets requires a spectroscopic analysis, and therefore the direct detection of photons from those objects. An ESA study dedicated to the discovery and infrared characterization of habitable exoplanets has shown the important role played by exozodiacal dust for the feasibility and dimensioning of future exo-Earth characterization missions. Indeed, considering the solar system as an example, the intensity of the infrared flux emitted by zodiacal dust (1 zodi by definition) is 300 times brighter than the Earth. This radiation, and its possible asymmetries, can be a significant noise source for the survey of exo-Earths, and may even jeopardize detection for dust clouds brighter than about 30 zodis. This calls for a survey of exozodiacal dust clouds down to that sensitivity level, around potential targets, in order to mitigate risk on the space mission and not waste time on sources where exo-Earths cannot be detected.

This noise due to exozodiacal dust radiation is significant for visible light coronagraphs as well. Hence, whichever way an exo-Earth characterizing mission is defined, the issue of exozodiacal light is inescapable. A dedicated pathfinder interferometer is therefore required which will have the sensitivity needed to prepare the future space mission. A study carried out by ESA to implement such an instrument (GENIE) at the VLTI has validated the science case but has also shown the limits in performance due to the fast seeing at Paranal, and the feasibility hurdles due to integration into a less than optimized facility. Securing the massive time allocation required for such a survey on the 8m VLT Unit Telescopes (UTs) is also an issue.

Artist view of ALADDIN

The Keck Interferometer Nuller has paved the way towards such an instrument, by enabling the detection of 300-zodi disks in the thermal infrared (N band) at Mauna Kea.

The LBTI might improve these performances in the near- to mid-term future, although its final sensitivity to exozodiacal disks is currently unknown. However, as for the GENIE project, these 10m-class facilities at temperate sites will not be dedicated to an exozodiacal disk survey, so that the associated instruments will only partially fulfil the prerequisite for future Earth-like planet characterization missions. It must also be noted that these instruments will only cover the Northern hemisphere.

Dome C potential

The Antarctic plateau may provide a better option. Extensive simulations have shown that at Dome C, an optimized interferometer (such as the ALADDIN concept) located above the turbulent layer would be more sensitive with a pair of 1m collectors than GENIE with the ESO 8m UTs, and be compliant with the 30 zodis requirement. This is due to a combination of factors that make the Antarctic plateau particularly suitable for infrared nulling interferometry. These are primarily:

• A large r_0 above the turbulent layer (enabling phased 1m apertures in L band without the need for adaptive optics). Based on site testing data, the working group established that 18m is a reasonable height that enables the instrument to be above the ground layer about 40% of the time;

• Long coherence times which result in much more efficient optical path length control loops for ultra-low phase residuals between sub-apertures;

• A consistently dry air which alleviates the need for active phase dispersion control;

• A cold environment for reduced background emission.

An Antarctic infrared nulling interferometer would provide a performances competitive with that of a space interferometer concept such as PEGASE, while a more compact space interferometer like FKSI would provide better sensitivity, at the 1-2 zodi level. However, the estimated cost of a space mission is much higher (700 M$ *vs* 15-20 M€ for ALADDIN) and this added sensitivity might simply be an overkill with respect to the original objective. We see these facts as a formidable opportunity, both for the space programs (since risk can be retired on a major mission for a small fraction of its cost) and Antarctic astronomy in general, which would benefit from the momentum created by such a project. Initial mission scenarios considered by the WG indicate that, after an initial summer for commissioning and performance verification, the input catalogue of ALADDIN could be surveyed in two winter overs. After its primary mission is complete, ALADDIN could either be dismantled or used for more general science, if adequate support for extended operations can be found. Its observational niche is the characterization of faint environments around central point sources, a common feature of many astrophysical objects. It would be, for example, an exceptional tool to characterize circumstellar disks around Young Stellar Objects, circumstellar matter ejected by stars in the late stages of their evolution, dust tori around bright Active Galactic Nuclei, or even the K or L-band spectroscopy of a few close-in giant exoplanets around very nearby stars.

Instrumental requirements

When designing the facility, many challenges have to be faced to deal with the peculiar site conditions.

• The first one concerns the interface between the facility and the ground. Snow consists by essence of low-density materials, and moreover that snow moves due to the general motions of the Antarctic glacier.

Fig. 7: The track and boggies prototype system at AMOS.

The facility could be erected on three feet similar to those supporting the Concordia buildings (see **Fig. 6**). These feet have already been built and people have experience with their installation on site. As far as one knows, their behaviour is acceptable. The area on the snow surface is adapted to the maximum load allowed by the snow which is about 0.2 bars and to the weight of the structure which will be about 120 tons.

Therefore, the three feet could support an annular track allowing for the azimuth motion (see **Fig. 7**). The diameter of the track has to be about 8m with flatness of about 1mm/m. The track is about 4m above the snow level and lies on a cylindrical annulus designed to allow wind to pass through the structure and avoid the accumulation of snow.

• The second challenge consists in keeping the azimuth axis of the device in a vertical or, as a minimum, stable position.

Fig.6: The six feet supporting the Concordia building. Three similar feet will support the interferometer.

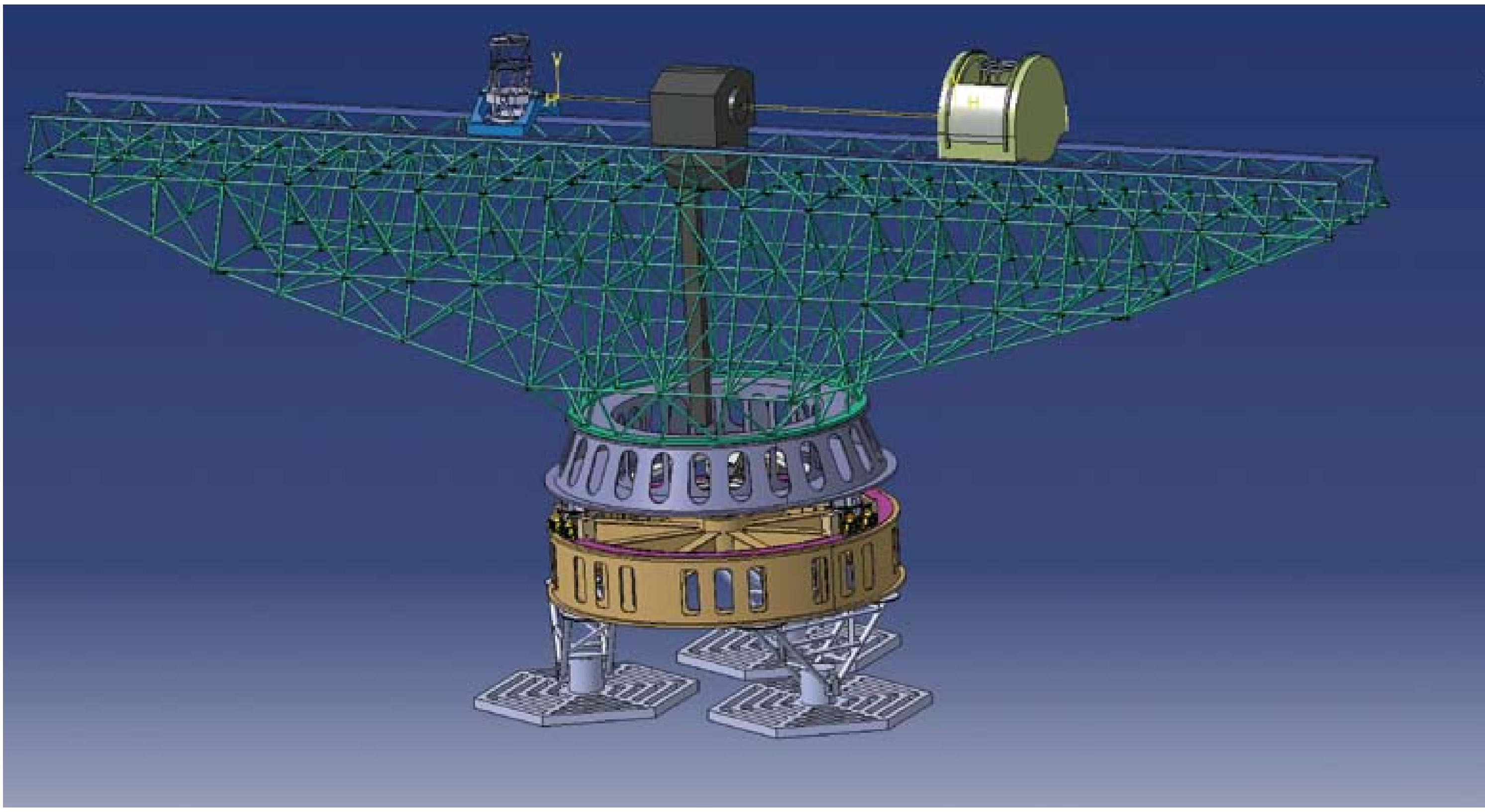


Fig. 9: General view of ALADDIN.

This is obtained by active wheels driven by inclinometers that can compensate in real time the slope or errors of the horizontal plane of the track. This system has been built under an ESO-EC contract as a prototype for the azimuth axis of the ESO-ELT project. It is shown in **Fig. 7** during performance tests in the AMOS workshop. In this design, three boggies rotate on the track. The latter supports, through a large beam structure (illustrated in **Fig. 8**), a railway on which circulate, at 18m above the snow surface, two 1m telescopes. These constitute the collecting devices of the interferometer (illustrated in **Fig. 9**).
Those telescopes can be adapted from the design of the Magdalena Ridge Observatory Interferometer developed by AMOS and having the same kind of technical specifications, nevertheless for 1.4m telescopes. They have to be protected by domes. Both telescopes deliver parallel optical beams compressed to about 2cm diameter to the cryostat situated in a small vacuum chamber between the two telescopes.

ALADDIN's instrument design, shown in **Fig. 10**, is derived from the preliminary definition of the VLTI/GENIE nulling instrument taking into account numerous simplifications provided by the outstanding atmospheric stability at Dome C and the optimised system design. The main simplifications with respect to GENIE are:
• removal of the long-stroke delay line;
• removal of the dispersion corrector;
• removal of the dispersion closed-loop control (H-band fringe sensor, dispersion control actuators);
• removal of the intensity closed-loop control;
• removal of the VLTI interfaces and constraints;
• strong relaxation of the requirements on the fringe tracking control loop (in particular, significantly reduced closed-loop repetition frequency).

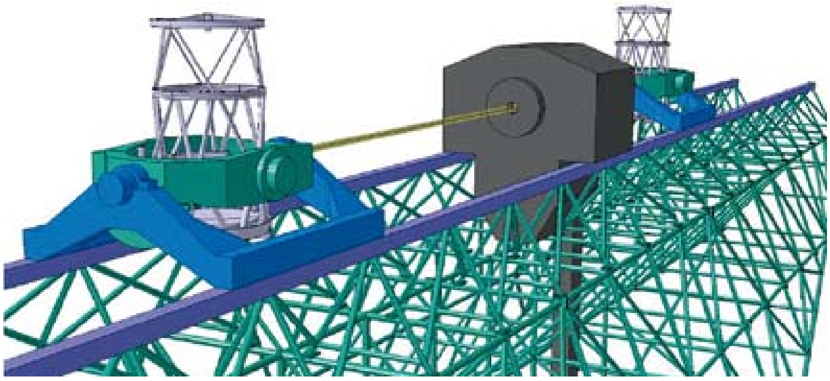


Fig.8: Top railway of the system allowing the telescopes to move.

Note that the design of **Fig. 10** is conceptual: significant improvements are envisaged and should be analysed and incorporated as soon as a dedicated Preliminary Design Study is started. The vacuum chamber does not only provide performance optimisation through optics cooling but also protects the instrument and Antarctic environment from each other. Such an arrangement calls for a fully remote-controlled and autonomous instrument with no human intervention on-site during the operational life, thanks to the extensive experience of the space industry in those matters. As far as development in the industrial phase is concerned, the instrument enjoys substantial heritage from existing nulling breadboards:
• MAI² has demonstrated stable 10^{-5} polychromatic non polarised nulling in Thales Alenia Space labs;
• CNES-led PERSEE, in integration at Paris Observatory, is dedicated to perturbations control of a nuller very similar to ALADDIN.

Later on, the autonomous design will also allow complete verification of the instrument (and system) in a temperate site, before transfer to Dome C. A careful comparison will be made between the expected performance of ALADDIN at Dome C and at the best temperate astronomical sites which will be soon selected for E-ELT, TMT, *etc*. A preliminary comparison with Cerro

Paranal has already suggested that temperate sites cannot compete with Dome C for this type of instrument.

Although a precise cost estimate of the project cannot be provided based on this preliminary study, previous experience and comparison with similar projects suggests a total cost of 15-20 M€ for the project, including installation, commissioning and operation during two winters. The main foreseen impacts (or lack thereof) on the Concordia stations are listed here below:

- transportation fully compatible with current vehicles - total of ~110 tons to be transported;
- assembly of the structure during summer on a compressed snow area, carried out by five people, and fully compatible with current Concordia facilities (*e.g.*, weight and height of the telescopes compatible with the Concordia crane);
- one operating room at Concordia, with an on-site supervising astronomer or technician during winter-over (only part-time);
- average power consumption during winter of 2kW per day, with a peak consumption of 15kW, not taking into account possible frost removal device;
- high-bandwidth connection between ALADDIN and Concordia, low bandwidth connection with the outside world.

Conclusion and roadmap

A nulling interferometer designed to detect and characterize exozodiacal disks, typically brighter than 30 times the solar zodiacal cloud density level around stellar targets potentially harbouring exo-Earths, appears to be feasible (no show stoppers identified at this stage of the industrial study) on the Antarctic plateau. This appears to be the optimal location for such a facility. A typical height of 18m above the ice is both sufficient, and practical, to operate free from the ground-layer turbulence. Key design challenges for the structure and instrument have already been addressed in the framework of other projects.

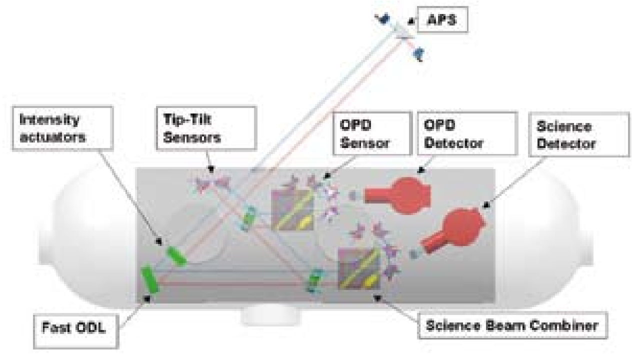
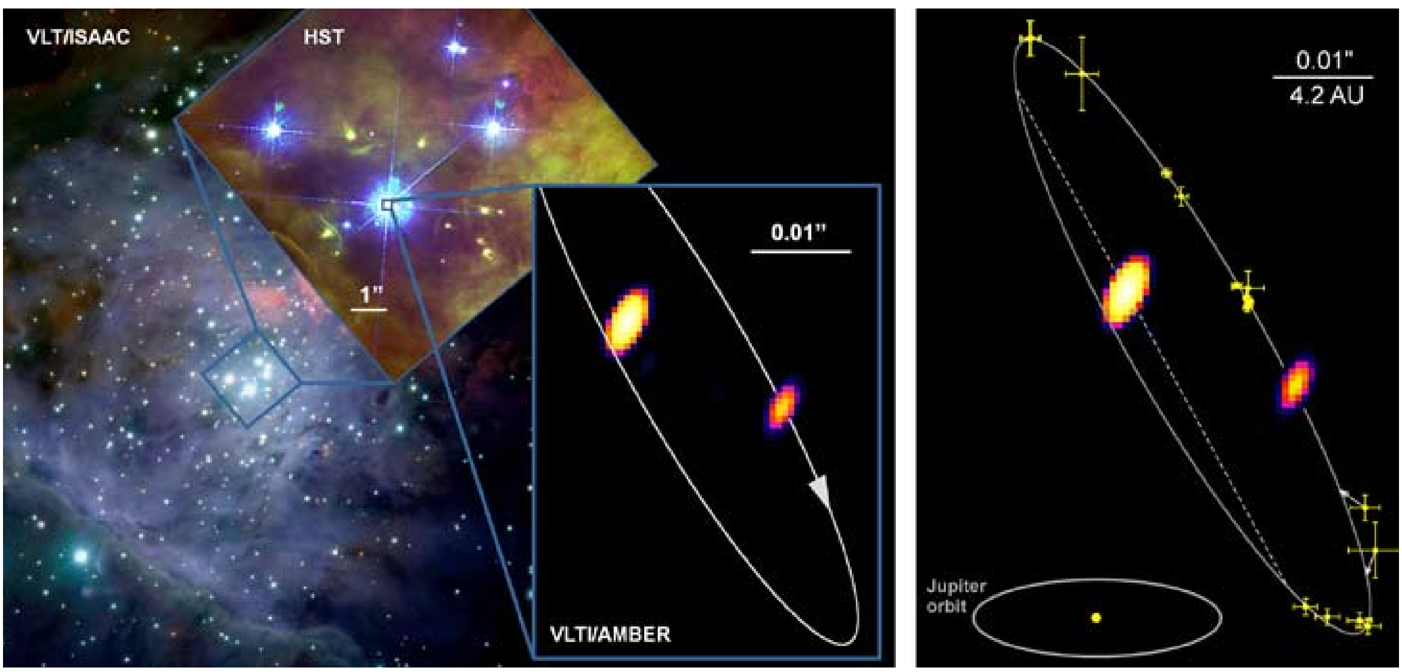


Fig. 10: The ALADDIN nulling instrument design is greatly simplified wrt GENIE and can be accommodated into a cooled vacuum chamber of less than 1m³/1ton.

The science objective is compelling for a medium-size Antarctic project. Such a facility would also be a precursor to a high sensitivity, imaging kilometric array alike KEOPS (with full-sky coverage made possible by the large isoplanetic angle) that represents the consensus of the interferometric community in the post-ELT era. Other possible precursors (ICE, Mykerinos) have been proposed but await both a definition and a pre-feasibility study before further consideration. We therefore highly recommend carrying out simultaneously:

- either a full size Phase A industrial study of ALADDIN as an example of a mid-term Antarctic interferometry project or a joint FP7 industrial study of common key elements to ALADDIN and other projects proposed by the different working groups;
- an observational confirmation of the expected exceptional properties of the atmospheric parameters particularly relevant to the performance of high angular resolution systems (coherence time, isoplanetic angle). ■

An example of the success of near-infrared interferometry: measurement of the orbital revolution of the companion of theta Orionis made with the instrument AMBER at the VLTI. (Kraus et al., 2009, A&A 497, 195).



4d Long time-series photometric observations

Working group activities

The ARENA Working Group 4 (WG4) evaluated the potential of Dome C for astronomical time series observations and reviewed a series of projects to perform such observations at Dome C. A dedicated workshop "Time-series observations from Dome C" was held in Catania, Italy, in September 2008 and further discussions were organised at the three main ARENA conferences.

Science and context

We define time-series as the continuous process of data taking resulting in information about the temporal behaviour of the objects under investigation. Historically, such observations have been performed to investigate variable stars, but more recent developments, mostly driven by the much higher precisions that became available with electronic detectors, have opened two further areas of research using time-series: studies of stellar activity in stars previously considered 'quiescent' and the detection and characterization of extrasolar planets. With a large part of the scientific advance coming from being able to do things that previously could not be done, state-of-the-art time-series projects typically include one or several of the following requirements:

- Long observing coverage in stable conditions, often in combination with high duty cycles
- Very good seeing and/or low scintillation
- Observations in spectral ranges that have been little explored to date.

The first requirement is certainly the most limiting one for observations from normal sites. Long continuous observations are required in many contexts; *e.g.*, in order to obtain reliable transformations of time-series into frequency space, where daily interruptions pose serious restrictions to the frequency coverage and precision that is obtained; or for the detection of rare events, where any interruptions lower their detection probabilities. In some cases, this need for long observations with high duty cycles has been satisfied by observations from networks at temperate sites (*e.g.*, GONG, PLANET, HATnet). Networks present however several disadvantages: complex coordination, calibration issues and an uneven distribution of good sites around the globe. A further step to circumvent these limits came from space-based projects such as MOST, CoRoT, Kepler, SOHO *etc.*, but with the disadvantages of very high cost, long development cycles, and the impossibility of maintenance. Dome C emerges therefore as an alternative that may better meet the requirements of many science cases that are dependent on time-series observations.

Potential of Dome C

Observing coverage and duty cycle

During the Antarctic winter, long observing runs with high duty cycles may be obtained at Dome C. However, a *daily cycle* with significant twilight around noon is present even at mid-winter. So, it depends on the maximum permissible sky-brightness if week-long coverage without daily interruptions can be obtained or not. The *seasonal cycle* requires that all observations have to be performed within

ASTEP set up (2009)

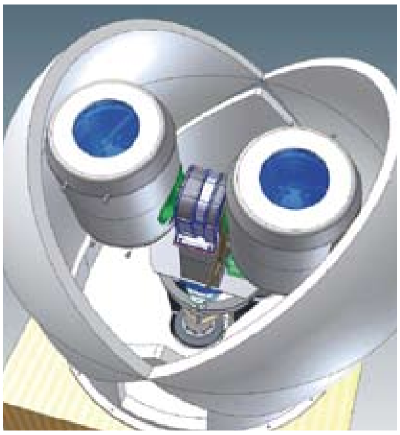
about 7 months per year. The combination of observations from Dome C with those from a network of telescopes at temperate sites may, however, be considered for projects that require year-round or permanent coverage. The weather conditions at Dome C favour also *high duty cycles*, with suitable observing conditions up to 87-98% of the time, values that have never been reached by temperate-site networks.

Accuracy

The major impact from the presence of the Earth's atmosphere comes from scintillation, which generates variations in the number of photons from a stellar object that fall into an instrument's aperture. Dome C has the lowest known scintillation noise from any site on the ground. Scintillation is mainly due to light paths being bent by turbulences in the higher layers in the Earth's atmosphere - hence photometric experiments that require high precision may benefit from a location at Dome C even if mounted *without* a tower *i.e.*, at ground level. Scintillation in infrared and other spectral bands still requires further site testing. Seeing, which is mostly caused by ground-layer turbulences, is in general less important for time-series work, since it affects photometric precision only as a second-order effect. We note that the non-negligible diurnal cycle also has to be taken into account for any estimations of photometric precision over longer observing spans. Variations in sky-transparency, such as faint dark cirrus at high altitudes, would also affect precision photometry. Their effective influence is however unknown at present. Confirmation of the quality of sky transparency should be an urgent action and a principal topic of the currently employed photometric instrumentation.

Spectral range

Dome C may also allow ground-based time-series observing in spectral ranges that are barely exploitable in temperate ground sites. One refers here especially to observations in the near-to-mid IR and in the sub-millimetre wavelength range. Observations of the sky brightness at 11µm made during the summer at Dome C showed that the sky stability is exceptionally good. In the IR range from 1.5 to 14µm the background brightness at the South Pole is up to an order of magnitude lower than at Mauna Kea, one of the best temperate sites. Such low background emission clearly favours time-series observations in bands like K, L, M, N and Q, with the K_{dark} band around 2.4µm showing an especially good combination of low sky emission and good transparency. At Dome C, the corresponding background brightness and its stability are however essentially unknown and should be better characterized before serious investments are made.



Artist view of ICE-T

Science cases

The science cases that were considered, given in more detail below, may be put into two groups: detection and characterization of extrasolar planets, and stellar studies (asteroseismology, stellar activity). Additional science cases may include *e.g.*, Gamma Ray Bursts, Active Galactic Nuclei and Quasars, up to moving objects like Near Earth Objects and Trans Neptunians. We note that solar studies are treated in **Section 4f**.

The small IRAIT telescope

Detection and characterization of extrasolar planets

The detection of extrasolar planets via transits in front of their central star allows the determination of the planetary radius and - if combined with radial velocity measurements - their mass and mean density. Thanks to the possibility of long time-series observations with high photometric precision from Dome C, the detection of smaller planets than achievable with comparable instrumentation at normal sites should be possible. Furthermore, the low IR sky-brightness at Dome C may give a unique opportunity to search for transiting planets around small late-type dwarf stars (types M and K) in the NIR, where these stars are much brighter than in the visible.

Photometric planet detections are also possible from surveys of stellar microlensing or from the detection of variations in the timing of periodic photometric signals. From Dome C, the microlensing method may detect planets down to the mass of Mars in orbits around either G to L-dwarf central stars or around giant planets in these systems. Detections from the timing of photometric signals may be disentangled in the highly periodic p- or g-mode pulsations of subdwarf B stars and white dwarfs, in the eclipses among binary stars and in transits of known planet-star systems. Similar to transit searches, these methods will greatly benefit from long observing spans under good conditions. Using a combination of techniques, it is possible to measure the mass and orbital distance distribution of planets, and the frequency of planetary systems; several of these methods (*e.g.*, searches for transits and microlenses) may be joined into single observing projects.

The characterization of known transiting planets (*e.g.*, detection of atmospheric constituents, secondary transits, reflected light) has delivered spectacular results in recent years from both ground and space-based observatories and the importance of this subject may only be expected to increase. Characterizations may be done with high-precision photometry, optionally in multiple colours, but the highest potential is in spectroscopic observations.

Table 10 Science cases and related projects

	Method*1	FOV*2	Aperture*3	Time Resolution	Time Duration*4	Possible project
Exoplanet transit search (detection)	CCD phot, IR Phot	Wide-Ultra Wide	All	10min	Months-Years	ASTEP400, ICE-T, PILOT
Exoplanet characterization	IR Phot	Small	Mid-Large	1min	Hours	IRAIT, PLT
Exoplanet timing (detection)	CCD phot	Wide	Mid	30sec	Months	ICE-T, ASTEP400
Microlensing (detection)	CCD phot	Ultra Wide	Mid	hour	Months	ICE-T
Microlensing (tracking)	CCD phot	Small	Mid	10min	Days	PLT
Asteroseismology	CCD phot	Wide	All	10sec	Months	ICE-T
	HiRes spec	Small	All	1min	Months	SIAMOIS
Long-period pulsation variables	CCD phot	Wide	All	10min	Months-Years	ASTEP400, ICE-T
	HiRes spec	Small	All	10min	Months	SIAMOIS
Stellar activity (detection)	CCD phot	Wide	Small	10min	Days-Months	ASTEP400, ICE-T
Stellar activity (characterization)	CCD phot	Wide	Mid	10min	Months	ICE-T, IRAIT
	HiRes spec	Small	Large	20min	Months	PLT, SIAMOIS

Notes: ***1. Method** *Phot: photometry; Spec: spectroscopy.* ***2. FOV (Field of View)** *Ultrawide: >> 1deg; Wide: 1deg; Small: arcmin.* ***3. Aperture (Telescope aperture)** *Small: 0.5m; Mid: 0.5-1.5m; Large: >1.5m.* ***4. Time duration** *Typical length of continuous time-series for a given time resolution.*

In general, characterization observations are of shorter duration, between a few hours up to about a day, but require very high precision, and the presence of very stable atmospheric conditions is essential. For Dome C, we expect unique opportunities for planet-characterization of long-periodic planets with transit durations longer than about 5 hours (which are degraded by the diurnal cycle at other sites) using telescopes of 2m or larger. Photometric and spectroscopic characterization observations in the NIR-MIR, may also be performed under uniquely stable conditions, *e.g.*, for the measurement of the direct light of the planet by detecting secondary transits, or for the detection of planetary atmospheric constituents. The following key science cases are therefore pointed out:

Concordia is an ideal site to observe planetary transits.

Key science for extrasolar planet detection and characterization

- detection of long-period and/or small extrasolar planets
- detection of extrasolar planet transits around small (faint) M stars
- photometric and/or spectroscopic characterization of long-period extrasolar systems
- characterization of the stellar activity of the planet host stars.

Stellar studies

Asteroseismology and studies of stellar activity are considered here. Asteroseismology is undisputably the most important technique to unravel stellar interiors. However, the observational requirements are extreme, requiring high cadence, long continuous time coverage, and ultra-high precision. This goal has been reached from the ground for bright stars in the instability strip of the Hertzsprung-Russell diagram but, so far, only in very limited ways for solar-like stars. Contrary to space-borne photometric observations, as conducted by CoRoT and Kepler, ground-based observations of solar-like stars will be done through spectrometric observations. The resulting Doppler data, less affected by the stellar activity noise than photometry, have a much better SNR, even with a small telescope. They yield a more precise mode structure inversion, and thus a high-precision determination of the stellar interior structure. Compared to space, precise Doppler observations of nearby bright targets, in addition to interferometric and high-resolution spectrometric measurements, will allow the detailed investigation of the physics governing the stellar structure and evolution. In order to compete with Dome C, temperate-site ground-based instruments such as proposed by the SONG project require at least 8 sites all around the Earth. Time-series photometry of subdwarf B and white dwarf pulsators is also proposed here, as these targets will only marginally be covered by CoRoT and Kepler.

Stellar activity and its modulation due to stellar rotation is the signature of strong stellar magnetic fields. Cool starspots, just as sunspots, are the most easily detectable tracers of stellar activity. Starspots also enable the precise measurement of stellar rotation rates which are among the key ingredients for the expected internal magnetic topology. This is particularly important in the light of more and more precise exoplanet detections around solar-like and likely spotted host stars. In order to make use of all available photons, most photometric transit-searches are carried out in white light. However, a typical solar-type star has cool photospheric starspots and warm chromospheric plages at the same time, as does our Sun, and spots will contribute to the "red" part of the bandpass and plages more than to the "blue" part. For the case of white-light photometry, these effects are therefore intermingled and the observed amplitude and shape of the light curve are not separable anymore. Consequently, inversions of rotationally modulated stellar white-light data can only determine spot longitudes and follow their variations in size, but cannot determine true spot areas and temperatures. Hence, very precise light curves in at least two bands are needed to separate spot and plage effects as well as to constrain the spot-temperatures and the stellar limb darkening. Dome C represents here a unique opportunity for photometry that is directly astrophysically interpretable.

Key science for stellar studies

Asteroseismic observations

- Doppler observations of solar-like oscillations in cool bright stars and in giants
- Doppler observations of pulsations in δ Scuti, γ Dor, PMS stars
- Interior structure of nearby stars: primary parameters, age determination, composition
- Convection; diagnostic of convective cores; depth of convection and of second helium ionization zone; damping, excitation mechanism
- Non-linear physics, saturation effects, mode coupling; stochastically excited modes
- Comparative study: photometry/ Doppler techniques
- Time-series photometry of subdwarf B and white dwarf pulsators

Stellar activity observations

- Map the short-term evolution of starspots and plages
- Determine spot coverage as a function of stellar rotation and age
- Observe and quantify starspot decay
- Relate photospheric chemical compositions to magnetic activity
- Monitor quantitatively the activity of planet-host stars
- The impact of stellar activity on the evolution of planetary systems

Instrumental projects for time-series observations

Instruments in the development/ construction phase

• *ASTEP400* is a 40cm telescope dedicated to exoplanet transit detections. Its field of view is 1°x1° and it is specified to reach a photometric noise of 3mmag per acquisition, reaching 1mmag during one hour for at least 1,000 stars. For at least the first years, ASTEP400 will require human intervention for winter operation. The delivery of the whole instrument to Dome C is scheduled in 2009. It is currently being set up.

• *ICE-T* is a 0.6m double optical/near-IR wide-field robotic photometric telescope. Its core scientific objective is the detection and investigation of the combined effects of extrasolar planets, stellar magnetic activity and non-radial pulsations on the structure and evolution of stars. It is designed to perform time-series photometry of approximately 300,000 stars in a single circumpolar field of size of 8°x8° during several Antarctic winters. Summer use to perform solar full-disk imaging is also being contemplated, with the ASPIRE instrument. German funds to construct this instrument have been obtained and commencement of observations at Dome C is aimed for by 2013. However, its relocation to Concordia and the funding of its operation is at present still in need of being secured.

• *SIAMOIS* is a ground-based asteroseismology project to pursue Doppler velocity measurements from Dome C that will achieve a scientific programme complementary to CoRoT and Kepler. The core of the instrument, providing the necessary sensitivity and stability, is a Fourier tachometer similar to the helioseismic network GONG, fully automated and without moving parts. SIAMOIS may first observe with one dedicated collector, then with two collectors feeding the Fourier Transform interferometer. To enlarge its potential, one of these collectors should be a 2m-class telescope like PLT. The high duty cycle accessible for the spectrometric observation of bright targets, a crucial point for asteroseismology, is comparable to the best space-borne observations; the photon-noise limited performance, about 1 to 10cm/s, is comparable to 0.1 to 1ppm in photometry. Funding for phase B needs the roadmap for Dome C to be fixed.

The IRAIT telescope at Concordia

Table 11 Status of the projects considered in this roadmap

Project	CDR*1	PDR*2	FDR*3	Financial status	Logistics status	First science year and anticipated duration of operation
sIRAIT	…	…	…	Funded	Removed	2007 (2 yrs)
PAIX	…	…	…	Funded	Installed	2008 (? yrs)
ASTEP South	…	…	…	Funded	Operable	2008 (2 yrs)
IRAIT	…	…	…	Funded	Preparation	2010 (4 yrs)
ASTEP400	**P***4	**P**	**P**	Secured	Installed	2010 (2 yrs)
ICE-T	**P**	**P**	**2009**	Construction funded	On hold	2013 (4 yrs)
SIAMOIS	**P**	**2009**	**2010**	In preparation	Under design	2013 (4 yrs)
PLT (or similar 2m telescope)	**P**	**2012**	**2014**	In preparation	Under design*5	2018 (6 yrs)

Notes: ***1. CDR** *Conceptual Design Review.* ***2. PDR** *Preliminary Design (Phase A) Review.* ***3. FDR** *Final Design (Phase B) Review.* ***4. P** *Passed.* ***5.** *funding for Phase B dependent on resolving issues of site-access and international collaboration.*

Early-phase project studies

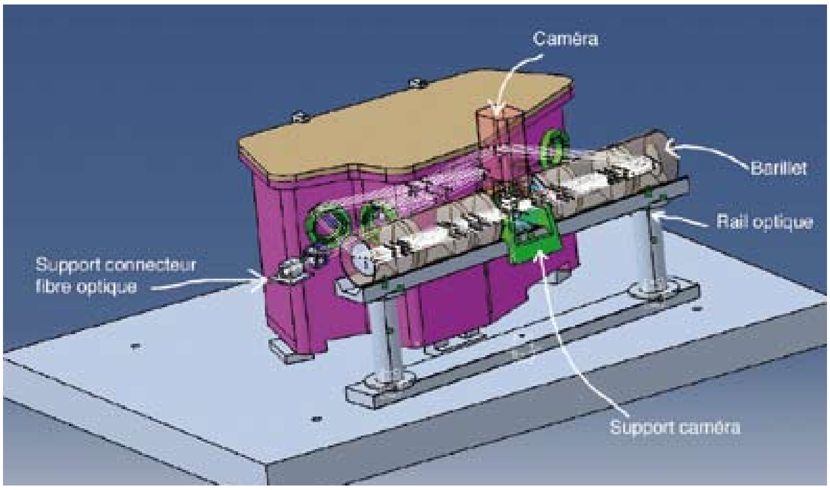
• *The Polar Large Telescope (PLT)* derived from the earlier PILOT, project proposed by Australia, is a pathfinder for an international large optical telescope. A design study resulting in a 2.5m wide-field (1deg^2 FOV) optical/IR telescope on a 30m tower at Dome C has been completed. It is a multi-purpose instrument intended to exploit almost all the unique capabilities of the site. The phase A study of PILOT was finished successfully in 2008 but the following phase B study was not supported by the Australian funding agencies. Discussions are in progress to propose a version of PILOT (PLT) as an international joint venture between Australia and Europe.

Roadmap and funding

Table 11 gives an overview of the projects involving time-series observations at Dome C, and lists their status as of mid 2009. The projects that are currently in the construction or in the planning phase are described in the following paragraphs.

One may note that all main science cases put forward to date can be served by one of the instruments proposed.

Some science cases can already be addressed by instruments in their construction phase for Dome C (ASTEP400 and IRAIT). Future dedicated instruments (ICE-T and SIAMOIS) will then provide the basis for long-term photometric and spectroscopic time-series observations. Beyond these projects, there is support for a PLT instrument since some key science cases need the "large" aperture of a 2m-class instrument, but can be performed with shorter time-series, lasting from hours to weeks. The full development of the potential of Dome C requires also the provision of telescopes that are open to the community.



Design of the SIAMOIS instrument. In order to insure the required performance, the inteferometer is enclosed in an insulated vacuum vessel (in purple).

The major projects for top-level science on time-variable phenomena from Dome C lead to the following roadmap:

2009-2010

• *IRAIT* and *ASTEP400* are considered "accomplished" projects. IRAIT has been delivered to Dome C and waits for on-site implementation in 2009. ASTEP400 has been delivered in 2009 and will commence observations in 2010. These instruments must be now treated with priority as they form fundamental steps towards larger scale projects.

2013-2014

• *ICE-T (International Concordia Explorer Telescope)* has been granted the top priority instrument for time-series photometry at Dome C and is expected to become a reference for stellar activity studies. Its construction is funded, but site-access and operational issues need solutions. Deployment should be around 2013-2014.

• *SIAMOIS (Seismic Interferometer Aiming to Measure Oscillations in the Interior of Stars)* is graded the top priority dedicated instrument for advanced time-series spectroscopy at Dome C and is expected to become the reference in stellar Doppler studies. Its deployment is foreseen for 2013-2014, with two small collectors. In a second phase, feeding SIAMOIS with a 2m-class telescope, its scientific return will be enlarged to include specific dim targets.

Beyond 2014

• *PLT (Polar Large Telescope)* is considered a cornerstone as a future multi-programme instrument. It should give open access to the scientific community to perform time-series observations on shorter time-scales with higher precisions, or on fainter sources. PLT may also be a valuable precursor for a telescope of similar size dedicated to time-series observations in the long-term perspective. ■

Artist's impression of the newly discovered planetary system Gliese 581

4e CMB experiments

Precision CMB measurements: the unique potential of Dome C

Precision Cosmology with the CMB

At the beginning of the 21st century we have entered the era of Precision Cosmology: sensitive measurements of the Cosmic Microwave Background, of large-scale structures through 3D galaxy surveys, and of the expansion of the universe through SN-Ia standard candles, are all consistent with a cosmological model based on an adiabatic inflationary Universe, filled with radiations, baryonic matter, dark matter, dark energy.

However, even if this model is described by well-constrained parameters, inflation, dark matter and dark energy are largely unexplained in standard physics. Precision Cosmic Microwave Background (CMB) observations can produce invaluable information on these topics, and are expected to provide enough data to answer these fundamental questions.

ESA's Planck mission (launched in May 2009) will complete the study of the primordial temperature anisotropies down to angular scales of ~5 arcmins by observing the CMB with an experiment essentially limited only by the ability to remove foregrounds. The next major step in CMB science is an equivalent study of the polarization anisotropies and of the compelling science to which they provide unique access, including primordial gravity waves, the dynamical importance and nature of dark energy, possible relations between dark matter and dark energy, neutrino mass, the reionization process, and potential violation of the equivalence principle. This step has already begun and the future of CMB research is twofold.

- Accurate measurements of CMB polarization promise to demonstrate the existence of an inflationary phase in the very early evolution of the Universe, a fundamental topic in cosmology, but also a unique tool for the physics of ultra-high energies, not accessible with particle accelerators.
- High resolution observations of secondary anisotropies, like the interaction of the CMB with the hot gas in clusters of galaxies, will be used to constrain the cosmological parameters and the formation of structures in the Universe.

The current generation of CMB experiments is carried out from space (BOOMERanG, Archeops, other balloon experiments, WMAP, Planck) but is also ground-based, with experiments located in exceptionally cold and dry sites, like the Atacama Desert, or Antarctica. There is a general agreement in the CMB community worldwide that a new space mission devoted to CMB polarization will be needed after Planck, but this mission has not been selected yet by ESA, nor by NASA, even if both agencies are strongly supporting these studies. A new CMB polarization mission will not fly before 10-15 years from now, and a lot of experimental activity is required to refine the experimental methods in this perspective. This calls strongly for new ground-based as well as for balloon-borne CMB experiments. Ground based experiments are to be preferred for the study of intermediate and small angular scales, due to the size of the telescopes/interferometers, and to the longer integration time required.

Fig 11: The "Bullet Cluster" (1ES0657-556). X-ray plasma emission is in red, while the blue blobs indicates the position of dark matter (identified by means of the gravitational lensing).

The 10m South Pole Telescope, already funded by NSF (tens of millions USD), and the BICEP polarization experiment testify the importance of CMB observations and the recognized necessity to use the best environmental conditions to fully exploit their potential (see **Fig. 12**). In fact, the signals to be measured by precision CMB experiments have an antenna temperature of the order of 1K or less, with a spectral brightness peaking at 220GHz. In the same frequency range atmospheric emission is due to rotational transitions of water vapour, oxygen and ozone. A sample model emission spectrum is compared to CMB fluctuations in **Fig. 13**.

The windows at 95, 150, 250GHz are evident. Atmospheric emission in this frequency range features brightness temperatures of a few K in the best windows. This means that advanced offset removal techniques have to be used for anisotropy measurements, starting with beam switching at constant elevation. In this respect, the real killers for these measurements are atmospheric gradients and instabilities, related to turbulence, wind and so on. The linear polarization of atmospheric emission at these wavelengths is quite weak, and is generated by the Zeeman effect of Oxygen lines in the Earth magnetic field. This also produces a much stronger circular polarization. Here the killer is low-level conversion of intensity and circular polarization into linear polarization inside a real polarimeter. This disturbance, however, is proportional to the stability of the O_2 atmospheric emission.

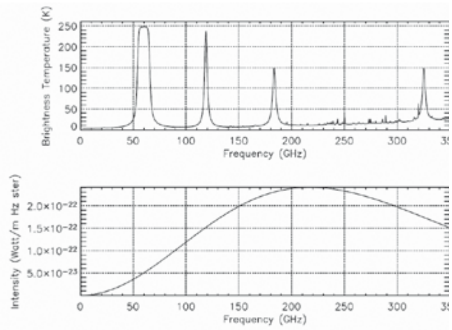


Fig.13: Atmospheric emission (top) and CMB anisotropy (bottom) spectra.

The advantages of Dome C

The Dome C site (3,202m asl) is higher than the South Pole (2,900m asl), and is on top of a wide dome, while South Pole is on a slight slope. This results in a more stable atmosphere, with weaker winds and very low turbulence. Radiosounding and extensive testing at 350μm have shown an average optical depth lower at Dome C (respect to SP) and, moreover, the average wind is a factor 2 lower (see **Fig. 14**).

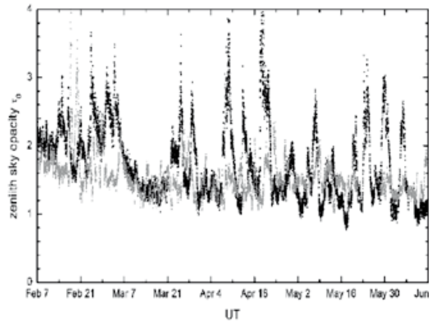


Fig. 14: Optical depth of the atmosphere at 350 microns, measured during the same winter period in Dome C (grey) and SP (black).

Fig. 12: SPT (right) and BICEP (left), two CMB experiments at the Amundsen-Scott South Pole station (from www.usap.gov).

At these frequencies, diamond dust and seeing produced in the lowest 30m of the atmosphere are not as relevant as in the optical range. At the South Pole, scans of the sky at constant elevation are also constant declination scans. It is thus impossible to perform cross-linked scans, as would be required for an efficient map-making procedure. Constant elevation scans carried out from Dome C, instead, change their tilt angle in the sky by ±14° in 24 hours, allowing an efficient drift removal technique. For polarization experiments, this is a very important bonus, allowing measurement of the same polarization direction in the sky with different inclinations of the principal axis of the polarimeter with respect to the ground. In this way an important test for polarized ground spillover can be carried out, which cannot be done at the South Pole.

Both Antarctic sites share the advantage, with respect to low latitude sites like Chajnantor, that it is possible to follow the same sky patch for the full day, thus allowing extremely long integrations with almost 100% efficiency. Due to the day-night and fast elevation change of sources, in low latitude sites the efficiency is lower by a factor 2-3.

This feature is extremely appealing if one wants to focus on the very best sky patch in terms of galactic foregrounds. The so-called BOOMERanG region, observed by the BOOMERanG experiment in 1998 and 2003, features extremely low H and dust columns, and is very conveniently located for observations from Dome C. This region can be observed continuously for the whole winter, and for most of the summer without interference from the Sun.

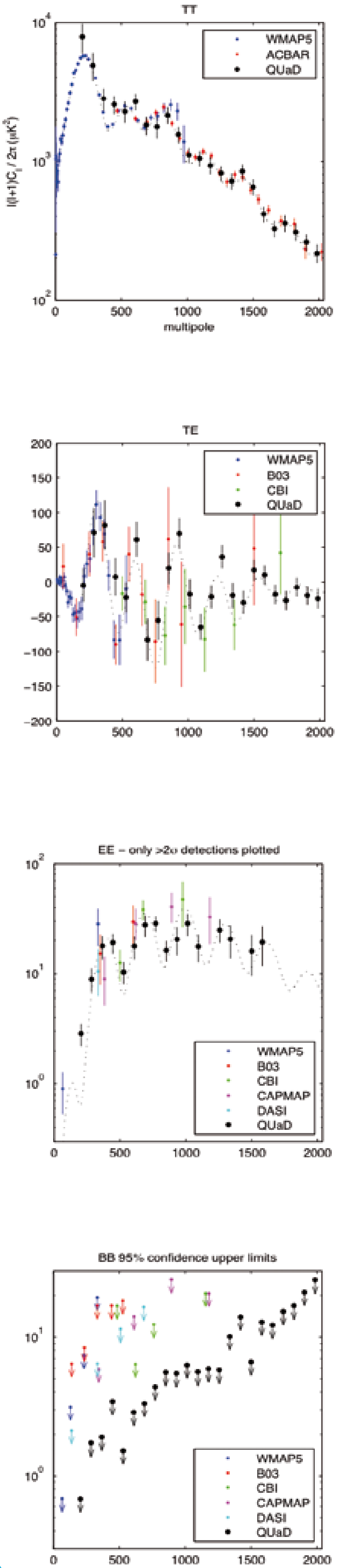


Fig. 15: Current measurements of the power spectra of CMB anisotropy and polarization. From top to bottom are represented the correlations of observables [temperature (T), E-mode polarization (E), B-mode polarization (B)] (same unit in ordinates).

Proposed projects

A bolometric interferometer on Dome C

B-mode CMB polarization is the "holly grail" of cosmology today. Its detection will be very difficult, but fully rewarding. A number of CMB experiments have been carried out from Antarctica, and a few are already acquiring data at the moment. The BICEP experiment is currently measuring CMB polarization at intermediate scales (around 1°) from the South Pole, using the same polarization-sensitive bolometers developed for BOOMERanG-B03 and Planck-HFI. Many other experiments are in preparation, either imagers or coherent interferometers. The expected signal is very weak (100 nK or less), more than ten times weaker than the best current upper limits (see **Fig. 15**). For this reason, significant advances are required in three areas:

- Sensitivity: number of photon noise limited detectors and integration time
- Knowledge of polarized foreground emission (multi-band and tracers)
- Reduction of systematic effects in polarimeters

Therefore, installing a CMB experiment at Dome C makes sense only if the proposed experiment is original, and uses a different methodology with respect to all other experiments. In fact, the expected signal is so small, only multiple consistent detections obtained by very different experimental setups will show that the measured polarization pattern is reliable. The BRAIN collaboration has already carried out site testing campaigns at Dome C to measure atmospheric polarization signals and to test on-site the advanced cryogenic system needed. The collaboration (recently extended to include the MBI team) has proposed a very original approach at Dome C: the QUBIC experiment, combining the extreme sensitivity of bolometric detectors to the optical purity of interferometers. A bolometric interferometer, in a compact configuration, has the following main features:

- Angular resolution is obtained by correlating signals coming from physically distant antennas, rather than focusing onto a detector the radiation coming from a large mirror. Without mirrors to focus radiation, the instrument has an extremely clean beam pattern, defined by corrugated feed-horns, whose response can be modeled very accurately, and whose spurious polarization is negligible. The optical properties of the instrument are then much easier to control thus avoiding "ground pickup", one of the worst instrumental systematics in direct imaging
- The instrument is intrinsically insensitive to most of the atmospheric fluctuations (common mode among different detectors)
- Another big advantage is that the interferometer directly measures the Stokes parameters of the sky, through the measurements of the correlation between x and y components of the electric field. This avoids the need to combine different detectors to measure the polarization (which is subject to large systematic effects due to cross-calibration) or the use of a rotating wave-plate to modulate polarization (which introduces extra systematics)
- Using cryogenic bolometers, the instrument can operate in BLIP conditions, with a NETCMB lower than $100 \mu K\, s^{1/2}$ at 90GHz, *i.e.*, a very high instantaneous sensitivity.
- The signal from all the horns can all be correlated using a quasi-optical combiner: this results in a very complete set of baselines and basically recovers the same sensitivity as an imager.
- Bolometric detectors can be replicated in a large array at relatively low cost, and arrays with hundreds of detectors are already affordable for a medium-size collaborations.

In the baseline configuration, the bolometric interferometer is mounted on a three-axis mount (azimuth, elevation, and rotation about the horns axis). The same kind of mount has been used in Antarctica for the DASI and BICEP experiments. With the additional degree of freedom the detector array can rotate with respect to the target field, so that the u-v plane can be covered efficiently. To benefit from the advantages of interferometers, it is proposed to implement the original and novel concept of Quasi Optical Bolometric Interferometry that solves the problem of complexity and at the same time makes possible use of bolometric detectors to achieve a sensitivity comparable to that of a bolometric imager. The instrument is made as a set of modules, each including an array of 12x12 horns and the same number of detectors. The field of view is defined by the beam of each horn, of the order of 20°. The signal from each horn is modulated by a phase shifter (see **Fig. 16a**). This configuration promises the detection of B-modes with an amplitude r=0.01: *i.e.*, 20 times better than the current upper limits (see **Fig. 16b**). This is close to the level of foreground polarization. Additional modules (up to 8) will be added in order to cover a wide frequency range and allow for separation of the components.

Measurements of polarized foregrounds

The subject of polarized foregrounds has also gained particular visibility (expressed in the several white papers and reports) for the B-mode and will be a targeted priority

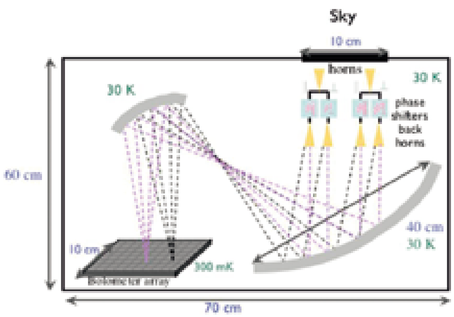


Fig. 16a: The BRAIN-MBI 144 detector module concept. The horn array is visible at the top-right. After modulation by the phase shifters, the beams are combined with an off-axis telescope. The bolometer array is cooled down to 300mK with a $^4He/^3He$ refrigerator.

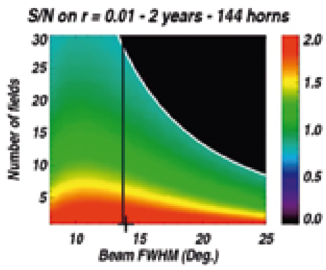


Fig.16b: Signal to noise ratio for the baseline configuration of the bolometric interferometer.

for radio (5-20GHz) near the cosmological CMB window and in the millimeter wavelengths (above the cosmic CMB window). There are a plethora of experiments coming up, and it is quite clear that one expects, for example, proper discovery and mapping of spinning dust emission around 10-20GHz. Although it is not a primary scientific goal, as the B-mode and SZ effect are, it is also important for Dome C to have secondary science programmes operating and complementing these observations already scheduled. It will be a perfect location to produce small absolutely calibrated experiments, producing small samples of sky that may work as calibrators for foreground maps. The community needs much of these to control polarized foregrounds. As an example of the importance of this issue, in 2008 the INSCAF (International Network for Scientific Cosmological Analysis of Foregrounds) has been created, involving several projects in the radio and millimetre foreground surveys.

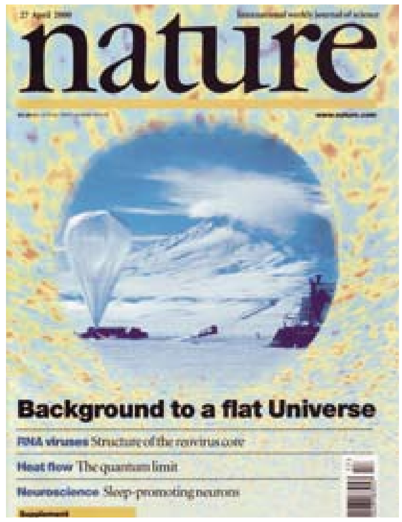
A large dish for millimetre/sub-millimetre astronomy and cosmology

High-resolution observations of secondary anisotropies in the CMB and of early galaxies and dust-obscured AGNs in the millimetre range are of considerable interest. The South Pole Telescope (SPT) is fully devoted to the observation of CMB photons scattered by rich clusters of galaxies. These observations can be used to study the physics of clusters of galaxies and to use distant clusters as probes to measure the cosmological parameters, via the Hubble diagram for clusters, cluster counts and the measurement of $T_{CMB}(z)$.

SPT will carry out outstanding measurements. The main concern in this kind of measurements is that the internal structure of the hot gas in many distant clusters of galaxies will not be resolved by SPT. In fact distant clusters of galaxies have a typical angular diameter of ~1 arcmin, roughly independent of redshift. Only the closest clusters, at a redshift less than about 0.05, have larger angular sizes. SPT is using an optical aperture of 7.5m in diameter, which is large enough just to match the size of the clusters of galaxies: the nominal resolution is $\Delta\theta \approx 1.'5$ at ν=95GHz, $\Delta\theta \approx 0.'9$ at ν=150GHz, $\Delta\theta \approx 0.'6$ at ν=225GHz, but the reconstructed beam size is a bit larger (~1.'2 at ν=150GHz).

In order to resolve the intra-cluster (IC) structures, a larger dish is required. The case for a 30m millimetre/submillimetre dish in Antarctica has been discussed for a long time ago. A telescope of this class, complemented by a large focal plane array, can provide the necessary information from spatially resolved clusters. As a matter of fact we know that the electron distribution of the "atmosphere" of the galaxy clusters is various and complex.

It is a combination of several populations of thermal and non-thermal distributed electrons with different energy spectra and spatial distributions. Each one of the electron populations produces a distinct SZE with peculiar spectral and spatial features. There are three matter components in clusters that provide different sources of electrons: baryons, dark matter, relativistic plasmas. Many galaxy clusters contain, in addition to the thermal IC gas, a population of relativistic electrons that produce a diffuse radio emission via synchrotron radiation in a magnetized ICM. The electrons responsible for the radio halo emission have energies of a few GeV to radiate at frequencies higher than 30MHz in a magnetic field of a few μG. The origin of such relativistic electrons is not certain: they can be produced through a re-acceleration process by IC turbulence, or can be created by the annihilation of dark matter WIMP. The presence of extreme UV / soft X-ray excesses in a few nearby clusters indicates the presence of an additional population of secondary relativistic electrons or a combination of warm and quasi-thermal populations of distinct origin. Further evidence suggests the presence of additional electronic components with peculiar spectral and spatial characteristics.



Front page of Nature (April 27, 2000) advertising the success of the BOOMERanG Telescope in Antarctica

Among them there are: non-thermal heating in the cluster cores, AGN and radiogalaxy feedback, intra-cluster cavities and radio bubbles filled with relativistic non thermal electrons, multiscale magnetic fields. Examples are given in Fig. 11 and Fig. 17. Finally physical arguments suggest that annihilation of Dark Matter candidates can produce secondary electrons with a spatial distribution, which in massive clusters is strictly related to that of the original DM, giving information on the DM mass and physical composition.

There are currently only upper limits to the non-thermal SZE in the literature derived from observations of galaxy clusters which contain powerful radio halo sources or radio galaxies. The problem of detecting the non-thermal SZE in radio-halo clusters is severe because of the associated synchrotron radio emission,

Fig. 17: Cluster MS0735.6+7421 as seen by Chandra (left) and the same cluster with indication of the central back hole and the two cavities, where there is a population of hot gas coming through jets.

Fig. 18a: The BRAIN laboratory and the pathfinder instrument installed at Dome C in 2006.

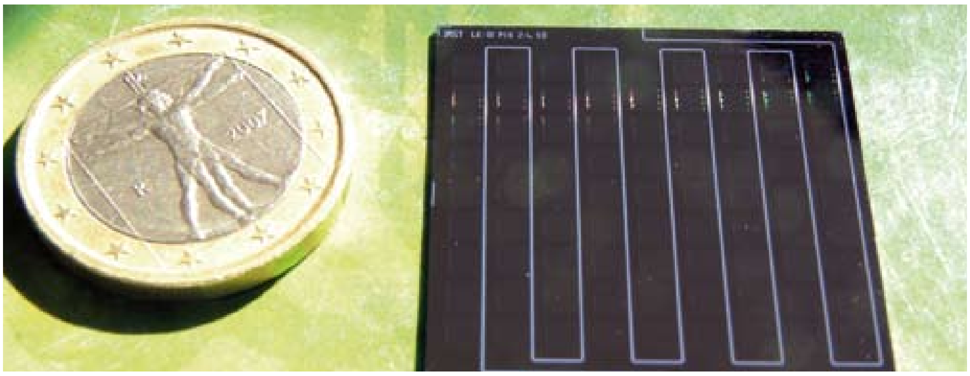


Fig. 18b: Array of Kinetic Inductance Detectors (KID) array (81 pixels) produced by the RIC-INFN collaboration in Italy. The sensors are close-packed superconducting resonators, where 140GHz photons are able to break Cooper pairs and modify the resonance frequency of the resonator. The system can be scaled to a large number of pixels while being readout by two coaxial lines for a carrier frequency around a few GHz. It is ideal for future CMB and mm-wave experiments from Dome C.

which at low frequencies could contaminate the negative part of the spectrum. At higher frequencies, in the positive part of the spectrum, there are in principle more chances to detect the signal of non-thermal SZE. From the Antarctic plateau measurements can be easily done also in the atmospheric windows above the SZE cross-over, in particular in the 250-300GHz frequency band and at 350GHz (see **Fig. 13**). The combination of high frequency with higher angular resolution would allow one both to resolve intra-cluster structures and to recognize the effect of the various electron populations.

Feasibility

A bolometric interferometer at Dome C
This is a medium-size experiment with a realistic cycle of 4-5 years. A first part of the support laboratory has already been installed at Dome C in 2006 (see **Fig. 18a**).

In this laboratory a pulse-tube cryogenerator completed by a ^{3}He refrigerator has been operated successfully at 0.3K for weeks, demonstrating that the logistics of the Concordia base is already able to support experiments of this size. In practice, the logistic requirements can be summarized as follows:

• *Power.* 15 kW continuous for the first installation, growing to 30 kW for the full size experiment.

• *People.* A team of 4 to 6 researchers during the summer installation and upgrade phases, plus a winteroverer full time on the experiment. During the installation occasional access to the electrical, wood and mechanical workshops is required, and also the occasional help of the base staff.

• *Consumables.* For the running of the BRAIN laboratory no dangerous materials are produced. The only fluid necessary on site is a cylinder of gaseous helium to refill the pulse tube when required.

• *Site.* The instrument should be moderately elevated (10 to 15m above the plateau). The snow berm technique has already been used very successfully at Dome C and is perfect for our purposes. At the time being one "control" container is installed at Dome C. A second "control" container should be installed to increase the size of the BRAIN observatory. The laboratory temperature should be kept at a temperature of about 16°C.

• *Communications.* The instrument produces raw data at a rate of one or two GBytes/day, to be stored safely on site. A second storage unit located at the main station can be connected through optical fibers and wireless communications (already used successfully at Dome C). A subset of the data needs to be transmitted to Europe for real time monitoring; a low-speed communication channel from Europe to the experiment is required for command.

• *Cost and timescale.* A total cost around 3 M€ is estimated for all the hardware and labor. This does not include in this cost power and logistic support from the station, nor the use of the station and personnel travels. These costs must be evaluated by the Station agencies. A full cycle of the experiment (from start to publication) is planned: 5 years.

A large dish for millimetre/submillimetre astronomy and cosmology (AST)
This is a very large size project with a long development time (10 years). The working group refers to the submillimetre working group (see **Section 4b**) for a detailed analysis of the feasibility of a telescope of this class at Dome C, but confirms the interest of the CMB community in complementing such a telescope with large format arrays (1,000 detectors per band, 90, 150, 220, 340, 450GHz and or a spectrometer) for Sunyaev-Zel'dovitch science. These arrays are under development in several laboratories in Europe (see **Fig. 18b**). A 30m-class telescope permits the angular resolutions to be achieved as reported in the **Table 12**. ■

Table 12

Frequency	ν (GHz)	90	150	220	270	340	450
Angular resolution	Δθ (arcsec)	23	4	9.4	7.6	6.1	4.6

The BOOMERanG Telescope being readied for launch (2003)

A map of the sky with the superimposed strip of the sky mapped by Planck during the First Light Survey (13/08/09-27/08/09).

4f Solar astrophysics

Working group goals, activities and oganization

WG6, together with WG5, is the most recently formed ARENA working group: it was formed in December 2007, after the Mid Term Review of the project, with the blessing of the EC. The main task was to explore the implications of the suspected remarkable, unusually good, solar seeing conditions of Dome C in summer, and to define a first mid-size facility capable of exploiting those favourable conditions.

The task was particularly challenging given the short time allotted, and the fact that the potential of the Dome C site for solar observations had been studied in relatively less detail than for night-time programmes, the main subjects of the study of all other ARENA working groups.

Following preliminary work on the solar potential of Dome C presented at Tenerife (March 2007) and Potsdam meetings (September 2007), the 10-member group conducted discussions on science, as well as on facility and infrastructure profiling and design.

The discussions on each specific issue were normally held by sub-group meetings, often involving scientists and engineers outside the formal list of WG6 members (*e.g.*, at the Observatory of Meudon for instrumentation, towers and infrastructure, at the University of Nice for coronal science and instrumentation, at Capodimonte Observatory for science issues, management and reporting, *etc.*).

Discussions were also held during larger meetings (at ARENA conferences and meetings in Catania and Frascati, and at large polar meetings, like SCAR at Saint-Petersburg in July 2008), and, of course, electronically.

CNRS and Observatoire de Paris-Meudon provided support, allowing in particular the design and breadboarding of the facility and its infrastructure (tower).

Solar astrophysics in the space and ground context

Current solar facilities for on-disk observations are either very limited in spectral resolution (*e.g.*,: NSST at La Palma) or in spatial resolution (like THEMIS) and with low duty cycle (the Adaptive Optics - AO - system is generally used less than a few % of the time since it cannot "lock" when seeing is "poor"). Coronagraphs currently in use, on the other hand, are usually small, typically working at the limit of the noise and with very limited spectral diagnostics.

Upcoming facilities (with either on-axis or off-axis design) are the 1.5m GREGOR telescope at Tenerife and the 1.6m New Solar Telescope at Big Bear. They will however have limited capabilities in the IR, and will not provide coronal observations. Diffraction-limited observations are foreseen, but with the same duty-cycle problem of AO activation at small values of the Fried parameter, r_o (<500-600hours/year); and sites cannot provide more than a few hours of continuous observations.

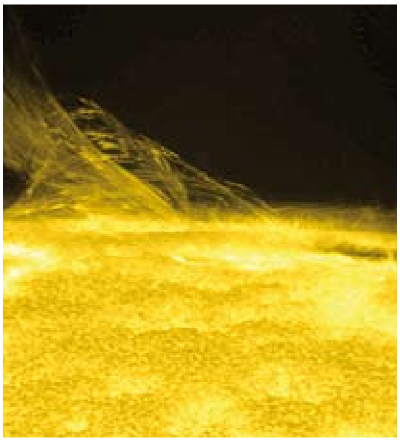
The next-generation large facilities have been designed to provide diffraction-limited resolution and reasonable duty cycles. An example is the planned Advanced Technology Solar Telescope (ATST) that,

however, will only deliver high duty cycles with a state-of-the-art AO system - a subsystem of the facility that is yet to be confirmed.

It is clear, therefore, that, an Antarctic solar facility providing high angular resolution, polarization and direct coronal magnetic field measurements in the near IR, is a definite complement to current, upcoming, and planned solar facilities.

When considering space instruments, an Antarctic facility also finds its place because it could achieve very high angular resolution observations of the chromosphere (following HiNODE, and much before larger missions in 10 or 15 years like SOLAR-C, Japan, or HiRISE, Europe - proposed for ESA Cosmic Vision and intended for the second phase of the programme), and complementary to the only coronagraphic mission to fly in the coming years (expected for 2013-2014): the ASPIICS ESA PROBA-3 mission. The latter, however, is limited to the visible range. Moreover, space missions are preferably targeting the UV or far IR range. And, of course, space instruments are nearly impossible to maintain and improve.

An Antarctic facility, therefore, would be highly complementary, by providing quasi-permanent high resolution in the visible but also in the IR or NIR, allowing observations at the opacity minimum (1.6µm), in lines formed at the temperature minimum (CO lines at 4.5µm) or sensitive to the Chromosphere-Transition Region magnetic field (lines at 12µm); in addition, the prominent coronal forbidden lines of Fe XIII, MgVIII and SiIX at 1,3 and 4µm could also be observed with high signal-to-noise (S/N) ratio, thus allowing direct magnetic field measurements and determination of electron densities from line ratios (*e.g.*, the Fe XIII lines in NIR: 1074.7/1079.8nm and 3.388/1.0747µm).



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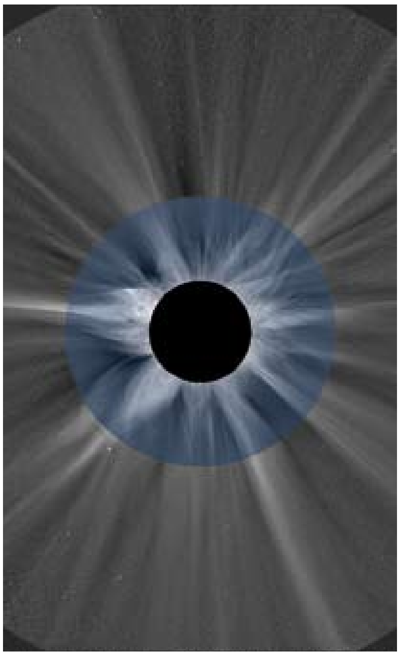


b

Fig. 19:

- a: Fine-scale structure pervades the Sun's chromosphere. Here, flare loop / small prominences seen in the CaII H line, extend from the chromosphere up into the lower corona. The rich structure and waves results from the hot, ionized gas (jets, spicules) interacting with the Sun's magnetic field, noticeably through motions, «wiggles», initiated by turbulence at or near Sun's surface.

- b: This image shows the corona structure up to six solar radii. It is impossible to obtain an image of such quality from either ground based eclipse observations or with SOHO LASCO C2 coronagraph. Ground based observations are influenced by the Earth's atmosphere and the contrast of coronal structures at a distance of six solar radii is so low that it cannot be significantly improved even by sophisticated mathematical methods. On the other hand the SOHO coronagraph, and Lyot coronagraphs in general, has its «blind area» near the Sun up to 1.5 radii since affected by diffraction of the internal occulter («artificial Moon»), and poor resolution. The excellent seeing and sky brightness of Dome C and the large telescope design of the AFSIIC coronagraph gives a unique opportunity to obtain high quality images of the inner and middle corona.

Dome C unique assets for solar observations

ARENA studies have shown that atmospheric optical parameters at Dome C during the austral summer are excellent and typically even better than in winter. Furthermore, the surface turbulent layer, or TGL (Turbulent Ground Layer), is exceptionally thin: it is of the order, on average, of 32m or less, and, in summer, has the interesting peculiarity of almost vanishing for a couple of hours during the afternoon, as shown in **Fig. 21** (seeing data taken from the Concordiastro platform - about 8.5m above the ground - from November 2003 to December 2008).

Moreover, our work in the course of WG6 studies has shown that these positive aspects are not offset by the relatively low solar elevation at polar latitudes (at Dome C, the Sun is never higher than about 40°). Adopting simple but realistic assumptions about the turbulence of the atmosphere above Dome C, we estimated that for observations of the Sun above 15°, the seeing should be degraded by no more than a factor two with respect to observations at the zenith.

The right-hand panel of **Fig. 21** shows the seeing from the Concordiastro platform derived from such a model. It is evident, thanks to the periodic disappearance of the TGL in the afternoon, that it is possible to reach exceptional seeing values towards the sun (~0.″6) for a couple of hours every day, from just a few meters above the ground.

The same condition of free-atmosphere seeing is attained during the entire day by observing above the TGL at elevations of at least 15°. In this case, it would be possible to reach at Dome C the exceptional value of a Fried parameter r_o >12 cm (corresponding to seeing ε < 0.″84 at 500nm), and this *almost permanently* during the 2,000 hours of Sun visibility above 15° (see **Fig. 20**). This is almost a factor 3 more than the best mid-latitudes sites!

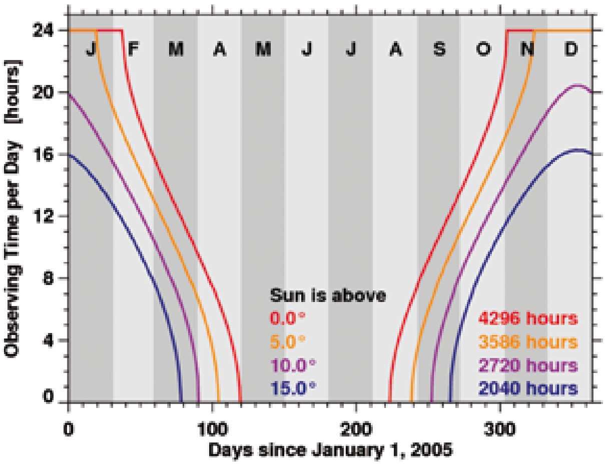


Fig. 20: Duty cycle, in hours, as a function of solar elevation; the red, orange, magenta, and black lines refer to minimum elevation of 0, 5, 10, and 15 degrees, respectively

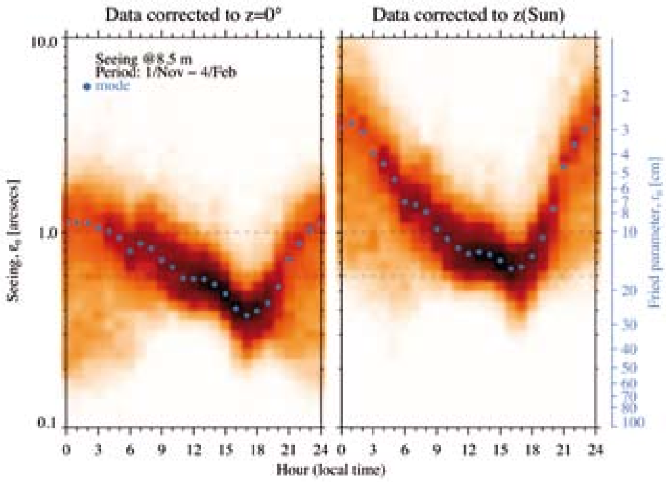


Fig. 21: Two-dimensional histogram of the seeing at Dome C in summer (October through March), as function of the time of the day (from the Concordiastro platform, 8.5m above ground). Histogram created with data from November 2003 to December 2008. (Left) Corrected to zenith; (Right) towards the Sun.

Solar science cases

Taking into account current and future space and ground programmes, and the unique assets of Concordia (see **Table 13**), several science cases can be addressed, broadly divided in two classes as outlined in **Table 14**.

The first set of science cases concerns the physics of the chromosphere-corona interface: at very high angular resolution such studies can effectively be carried out by exploiting the unique potential of an Antarctic facility at Dome C.

The solar chromosphere is the link between the dynamic engine of the outer atmosphere (the convection zone) and the solar corona: it suffices to mention that the energy input to balance radiative losses in the chromosphere exceeds by two orders of magnitude that required to sustain the corona. Moreover, the energy needed to heat the corona will have to pass through the chromosphere, a region where the plasma goes from dominating the magnetic field ($\beta >> 1$ in the photosphere, where β is the ratio of the gas pressure over the magnetic pressure) to a situation where the magnetic field dominates ($\beta << 1$ in the corona). Furthermore, in the intermediate region, we get complicated interactions between different waves modes and much of the waves energy may also be reflected. The heating and dynamics of the solar chromosphere thus have great significance for our understanding of coronal heating.

But, understanding the physics of the chromosphere-corona interface requires the study of magnetic flux elements (flux tubes with magnetic field of the order of kG) on their intrinsic spatial scale, which - outside sunspots - is of the order of 20km or so. Hence the need for high-resolution imagers, spectro-imagers and magnetographs, that can monitor the emergence, dynamics, twist, shearing, mutual interactions and possible coalescence and subduction below the surface of magnetic flux elements, in order to follow their evolution and scrutinize their life cycles and restructuring that could lead to energy dissipation.

Modelling has significantly progressed over the last years and delivered promising "paradigms" for this dissipation. But all those approaches are badly in need of observational constraints, that current or future space-borne and ground-based instrumentation can only partially provide. In that respect, an Antarctic facility, with its excellent potential in terms of high angular resolution, high duty cycles, long temporal coverage, easy access to NIR diagnostics up to the little explored 12μm region, promises to be a major step forward in the investigation of the chromosphere-corona interface.

The second set of key science objectives concerns the exploration via 2D spectroscopy of the inner corona: in particular there is a growing evidence that the innermost 0.5 solar radii of the solar atmosphere is dominated by a physics that is different from that in the extended corona at larger heliocentric distances. The energy that heats the corona and accelerates the solar wind and Coronal Mass Ejections (CMEs) originates in subphotospheric convective motions. The physical processes that transport this energy to the corona and convert it into thermal, kinetic, and magnetic energy are not fully understood. Space missions, and in particular SOHO, have greatly advanced our knowledge about coronal heating, solar wind acceleration, and CMEs, but many key questions remain unanswered. An understanding of physical processes in the corona is important not only for explaining the origins of space weather, but also for establishing a baseline of knowledge in plasma physics that is directly relevant to the Sun, other stars, and astrophysical systems ranging from the interstellar medium to black hole accretion disks.

Understanding this complex system requires the full characterization of the inner corona, its dynamics, plasma parameters and magnetic field. Regarding the latter, direct measurements of the coronal magnetic field remains elusive with present low corona instrumentation ($R<2.5R_{sun}$) in space, and even more so on ground (strongly affected by seeing and atmospheric conditions).

Once more, an Antarctic coronagraph based at Dome C would be a major step forward, should the preliminary indications of the

Table 13 Principal assets of Dome C for solar observations

Asset	Label	Main parameters
Infrared @ high S/N ratio	IR(1)	1-5μm
	IR(2)	12μm
High Angular Resolution	HAR	≈700 hours/year @ < 0.″6
Medium-High Angular Resolution for extended periods of time	M-HAR	≈1800 hours/year @ < 1"

Table 14 Key science cases, methods, means and Dome C relevant advantage

Science Methods	Primary Science Cases	Major Dome C Assets IR(1)	IR(2)	HAR	M-HAR	Instruments
High Angular Resolution	Magneto-Hydrodynamics of Sunspots & Magneto-seismology			x	x	•ASPIRE (2010–...) •AFSIIC (2015–...) •A-FOURMI (2020–...)
	Dynamics of Fine Structures in Chromosphere/Corona Interface	x	x	x	x	
	Local Helioseismology				x	
2D Coronal Spectroscopy	Coronal Magnetic Field	x		x		•Single Ø50-70 cm off-axis AFSIIC telescope for coronagraphy (2012-...) •AFSIIC (2015-...)
	Coronal Dynamics of Fine Structures	x		x		
	Coronal Seismology	x			x	

excellent quality of the sky for coronal observations be confirmed. Such an asset will be enhanced by the excellent seeing to provide high S/N observations that will allow access to the inner corona, very near the limb. In particular, direct magnetic field measurements, for instance via full Stokes polarimetry of the Fe XIII 1,074.7 & 1,078.9nm lines, will benefit from the quality of the site at Dome C.

Proposed facilities and infrastructure

One key advantage of the Dome C site is the thinness of the turbulent ground layer (about 30m). By observing above that layer, it is possible to access directly the free-atmosphere seeing - and with an "open tower" to avoid "tower seeing", alike the Dutch Open Telescope at La Palma.

Since a further interesting parameter influencing the design is the wind profile and wind speed, particularly favourable at Dome C (always lower than 14m/s), we decided to use an open telescope approach.

We therefore choose an open frame tower of 30-32m with appropriate damping and control to stay above the TGL; an open telescope(s) structure to limit telescope and mirror seeing; an Adaptive Optics system to phase the elementary telescope pupils when very high resolution is looked for (<<0."1); and a cophasing system to phase a triplet of telescopes. Open tower, open frame, open telescope.

Debate on using a tower or GLAO (Ground Layer Adaptive Optics) results from the supposed difficulty of raising a 20-30 tons 2-2.5m telescope to the top of a 30m tower. Instead, while GLAO systems have not been tested yet and are offering only a partial correction, approaches do exist for designing reliable towers appropriate for the Dome C needs, as we have shown. In the solar case, and since coronagraphy and magnetometry are foreseen, we also need to avoid the adaptive optics train to minimize reflections when observing the corona: this is possible directly for a significant fraction of the time only at 30m, *i.e.*, on a tower. In order to be able to bring to the community a versatile facility, capable of both very high resolution and coronagraphy, we facilitated access to the primary focal plane by having off-axis telescopes. This makes the design more complex but, once more, coronagraphy in the IR is a major asset of Concordia.

Instrumentation for high angular resolution

Solar interferometry, studied in R&D programs with ESA and CNES (3-telescope imaging breadboard with fine pointing, phase control and image reconstruction on the Sun and Planets), has the advantages of compactness (size), cost and mass, while delivering on operational control and image quality. In the case of a compact interferometer like the one proposed for AFSIIC, the image reconstruction is straightforward since it consists of a simple division by the optical transfer function. The interferometer has been extensively studied (structure and recombination) for use in Antarctica at Concordia (proposed for the European FP7 programmes, infrastructures and space, in 2008). The compact design benefits from the thermal venting by slow "laminar" wind through open tubes (carbon-epoxy). Off-axis mirrors allow NIR coronal access. Plus: there is no dust at Concordia, only ice crystals that will not deposit on the "hot" SiC mirrors (anti-frosting issue). Heating and cooling are of concern at Dome C as in space (deep space radiators at -80°C). SiC, highly conductive, also allows gradient control and focusing.

An interferometer is compact and uses, simply, three telescopes of smaller diameter (easier to manufacture and control) to achieve, with phase monitoring and a delay line to adjust optical path, the same performance as that of a "large" telescope. We propose an innovation in terms of the operational modes by having the possibility, like with HiRISE (ESA Cosmic Vision), of using the Ø500mm telescopes directly (and simultaneously, therefore: multi-wavelengths, multi-heights) between imaging-spectrometer and high resolution spectrographs. We require PERMANENT diffraction limited performance at Dome C, with seeing as "bad" (!) as 0."8 at 0.5µm (8.5m above ground: probably 0."5-0."6 at 30m). This means a maximum r_0 of 12.5cm and an 8x8 elements deformable mirror for a more than perfect correction of the 500mm primary pupil (could work also with a 700mm pupil).

When phased by adaptive optics, individual telescopes can then be cophased 3 by 3 to 0."08 for a triplet (AFSIIC) and 0."025 with the full 3x3, 4.3m A-FOURMI interferometer. One of the 3 telescopes - at minimum - is equipped (rotator on optical train) for coronal observations and could be installed first on the platform as soon as 2012 (ASPIICS support).

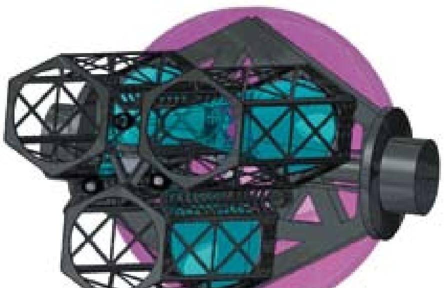
Solar magnetometry

Another very important aspect concerning instrumentation at Dome C is the direct measurement of the magnetic field from the photosphere to the corona. Two techniques allow for detection of both strong and weak coronal fields, and are therefore appropriate for observations at a site like Dome C:

- Zeeman effect and scattering signatures of magnetic fields in forbidden (magnetic dipole) coronal emission lines;
- Hanle depolarization of permitted transitions in coronal atomic ions and in strong lines in prominence plasma.

The Hanle effect is mostly interesting in prominences, in strong lines (Hα, HeI 1,083nm), and allows the vector magnetic field to be determined.

The NIR Fe XIII line at 1,074.7nm presents a factor of 5 advantage over the Fe XIV at line 530.3nm, and there is a definite interest to extend the wavelength range to 4µm to include the Mg VIII and Si IX lines. Ideally, and even though Fabry-Perot experiments are already difficult, it is worth adding the extra complexity of the NIR at 1µm and of the IR extension up to 12µm (since compatible with optical coatings).



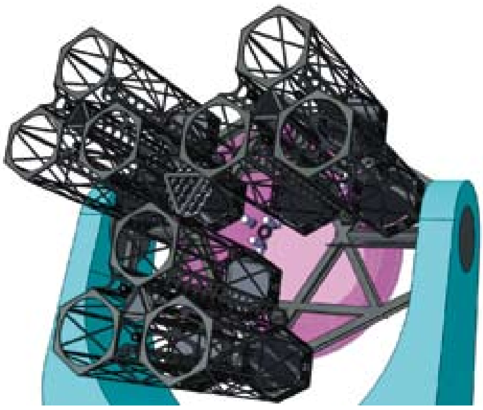


Fig. 22: On-axis triplet design (SiC mirrors and Carbon-Epoxy structure) and stiff telescope support plate of the 3 telescopes (AFSIIC - up) or the 9 telescopes (cophased by triplets, A-FOURMI - down) made of triangles with telescopes at the crossing points.

Instrument package

Three major instruments are considered in the focal plane of AFSIIC. First, a coronagraphic mode where 2D spectroscopy (visible and IR), using a Fabry-Perot, is anticipated as like for ASPIICS and Super ASPIICS. Second, a high-resolution spectro-imaging, 2D spectrograph, providing spatial, high spectral and temporal resolution with either a subtractive double monochromator (SDM) or a triple Fabry-Perot or a combination (SDM as the prefilter of a double or triple FP), will be used. Third, a magneto-optical filter, alike the instrument developed at Capodimonte Observatory, will allow magnetic field measurements and magnetoseismology in the photosphere and chromosphere using two heights in the atmosphere to infer the wave propagation (Sodium and Potassium cells).

These three major instruments are, each, dedicated to a telescope in the AFSIIC instrumental box (shown in pink on **Fig. 22**), placed directly behind the telescopes (and balancing them). They can therefore be used simultaneously to maximise temperature coverage or, alternatively, through relay mirrors in the entrance of the box, the beams from the three telescopes can be combined together in a very high resolution mode to any of the individual instrument: a versatile use to optimise science throughput of the facility.

Operations

AFSIIC combines high resolution, coronagraphy and magnetoseismology with its three off-axis recombined telescopes on a 30m tower. Operation of the Facility benefits from the natural temperature gradient inversion in the afternoon when the temperature gradient momentarily vanishes. At this time, seeing reaches the free atmosphere seeing and stay below 0."5-0."6 for ± 2 hours. Ideal for coronagraphy that can bypass the fine pointing and adaptive optics mirrors train, still having sufficient high resolution to provide direct coronal magnetic field measurement.

Besides the coronagraphic mode in the afternoon, the rest of the time (16-20 hours) is to be devoted to the chromosphere and waves, this time at very high resolution, *i.e.*, <<0."1, using active systems in addition to the high resolution naturally available at 30m above the ground. Other initiatives, complementing the high resolution, waves and coronagraphy ones, are also considered, and in particular synoptic full Sun observations (ICE-T/ASPIRE instrument).

The ultimate facility: the 4m Interferometer (A-FOURMI)

The Antarctica 4m Interferometer is the next step after AFSIIC. From one triplet of telescopes we simply go to three triplets, combined the same way. The same principles are retained: instruments are directly behind the telescopes, without a rotating device (fixed relay: no variable polarization). By going to nine telescopes at 4m spacing, we gain flux and spatial resolution for the ultimate fine structure study of the chromospere-corona interface. A-FOURMI is directly comparable to ATST in high resolution capacities while adding coronagraphy, but (much) lower in cost, although at Dome C, because of the small-telescope approach.

A 30m tower for access to the free atmosphere seeing

Various designs of towers have been proposed (see **Fig. 23**).

Logistic footprint on the Concordia station

Solar observations are done only during summertime, so that power may come mostly from solar panels which generate ~200 watts at Dome C/Concordia. The solar facility presented has an estimated power requirement of 8kW or so, what represents only 40m^2 of solar panels.

In terms of manpower, we estimate to 260-300 hours the raising time of the tower, at sea level. The tower, with its high-stiffness feet with six petals alike the Concordia station, is built directly on ice. With this tower concept, four containers are required for the tubes, junctions and the initial scaffolding to mount the first storey compatible with the 12m crane of IPEV. One more container is required for the mount, one for the telescopes and instruments, and one for electronic, control and consumables, and the solar panels. Mount and telescopes and instruments are shipped assembled in their respective containers. For maintenance and possible alternation of summer and night-time platforms, an 8th one will probably be necessary to built a storage/maintenance hangar.

Conclusions

The ARENA WG6 on solar astrophysics, recognising the unique qualities of the Concordia site: excellent seeing, low sky brightness, low water vapour, continuity and duty cycle of summer observations, recommends a high resolution imaging and spectroscopy facility with coronal capabilities, 1.4 to 4m-class, placed above the turbulent surface layer (30m tower support): it will provide unique science on the chromosphere-corona interface at high resolution, direct magnetic field measurements in the chromosphere and corona, and waves.

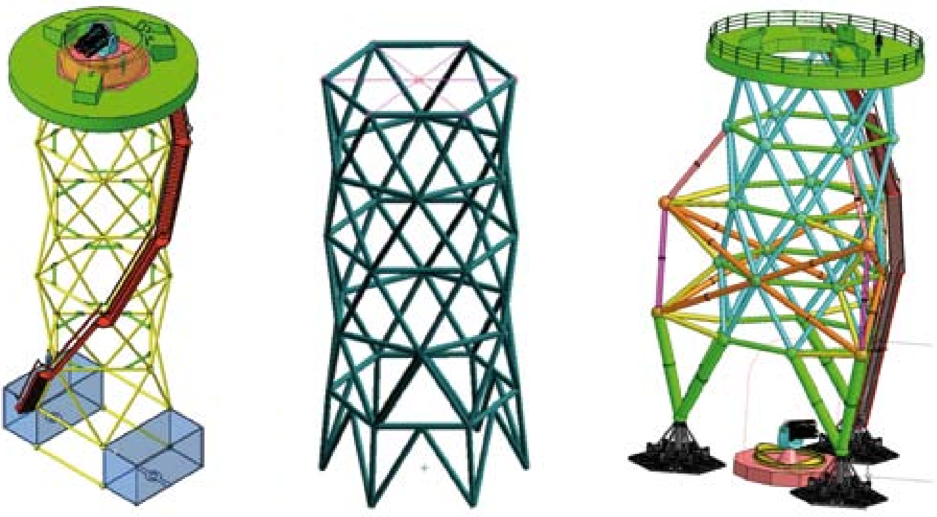
This first medium-size facility proposed, providing very high angular resolution & coronal access, adapted to Antarctica conditions, is AFSIIC *(the Antarctica Facility for Solar Interferometric Imaging and Coronagraphy)* with 3x50cm off-axis telescopes.

It is definitively possible as soon as 2015, with 2D spectro-imaging, spectropolarimetry, magnetoseismology and direct magnetic field measurements in the chromosphere and corona: the "convection-photosphere-chromosphere-corona magnetic link". As a future step, the facility could be upgraded to 4m for ultimate high resolution and photon flux concerns: A-FOURMI. Note that smaller projects that could bring a solar instrument to Dome C on a short time-scale, are highly encouraged by WG6 together with continued activity towards a better qualification of the site's seeing, image quality, sky brightness, IR access, cloud coverage, *etc.*, necessary for the design process of the mid-sized AFSIIC project.

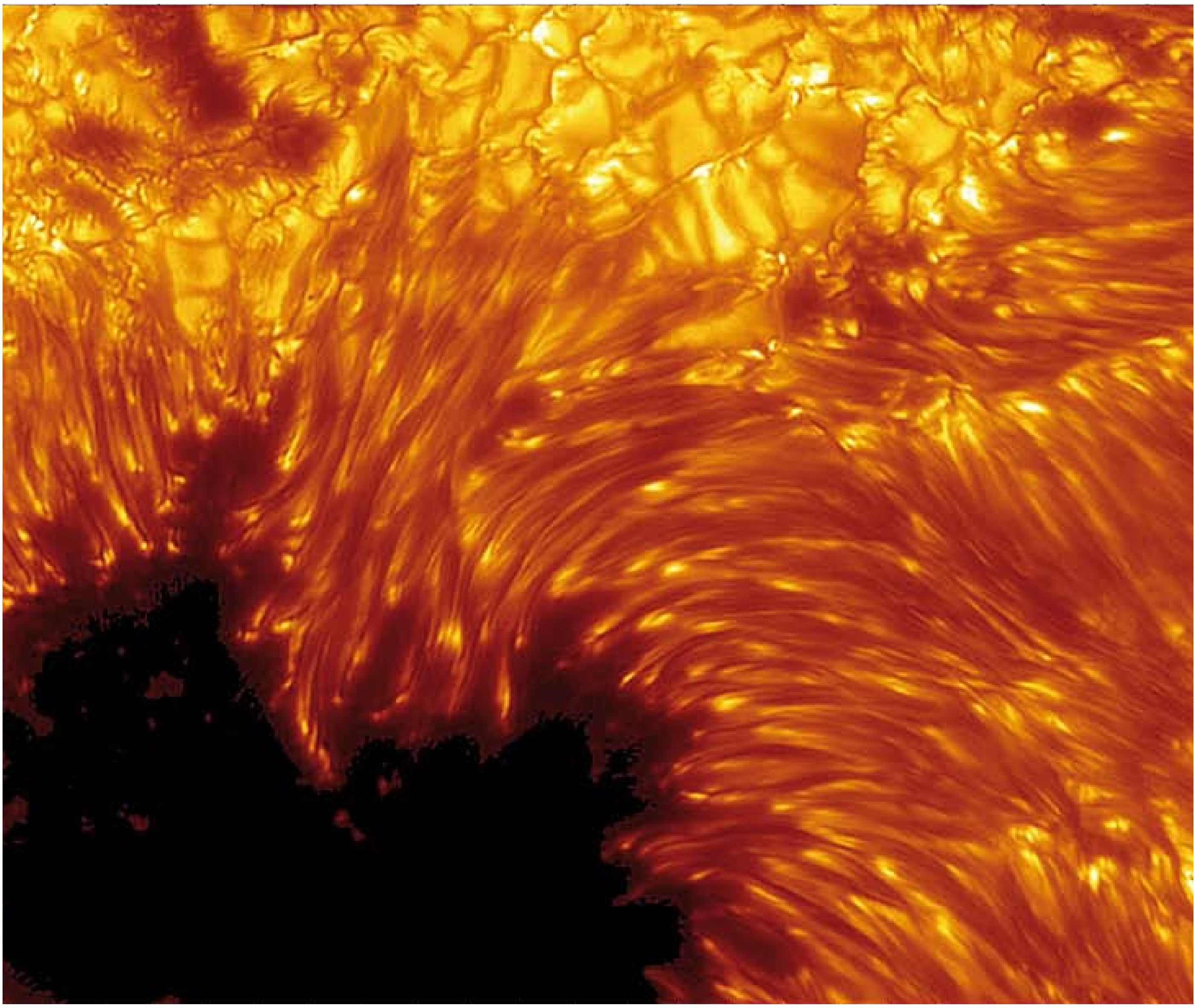
More information, detail and references are available online: *http://solarnet.obs-pm.fr/ARENA*. ■

Fig. 23: 30m tower designs square tower, hexagonal with feet and an optimised compromise between the Amans' tool tower and the hexagonal one, with a double structure for stability (hexagonal heart), ease of assembly with reduced scaffolding and large accommodation for the telescope platform (8m in diameter with 1 m height free). Tubes' section can be adjusted to the maximum anticipated load but a nominal 40 tons tower (not including the feet) with 10 and 20 tons loads was considered for modelling.

Note that the plateau can move up and down thanks to the three winch engines, allowing maintenance of the Solar Facility but, also, to change facility between summer, AFSIIC or A-FOURMI, and winter, e.g., with a 2.5m, 20 tons, PLT telescope.



Sunspot observed with the Swedish Solar Telescope (SST). This image in G-band (430nm) shows the transition from the dark umbra of a sunspot toward the solar granulation. The penumbra in-between shows filaments with central dark lanes.



5 Logistics and polar constraints

5a Astronomy at Dome C and logistics

The future possible establishment of an astronomical observatory in Antarctica is fully dependent on the capability of the logistics. The French and Italian polar institutes have demonstrated their capacity to build, maintain and operate together the Concordia station all year round. ARENA had an activity (NA4) aimed at evaluating the feasibility of implementing the astronomical projects proposed by the working groups. NA4 presents the results of their evaluation, made through close cooperation between scientists and polar operators.

The objectives of the ARENA programme, with respect to the logistics of construction and operation of an astronomical infrastructure at Dome C, are to identify the specificity of the logistics for transporting, building on site and operating the proposed instruments. The subjects addressed by the NA4 action can be summarised in six areas: transportation of equipment, construction of the instrument on site, logistics of consumables, environmental considerations, medical aspects, and telecommunication needs.

The analysis of the instruments proposed by the 6 working groups, performed by the French and Italian polar agencies, IPEV and PNRA, has led to the dismissal of concerns with respect to environmental and medical aspects; no major environmental threat has been identified in the proposed experiments, and no additional medical problem beyond the usual attention for the welfare of a limited crew is involved, in the present formulation of the proposals. However, according to the Annex I of the Madrid Protocol, it is noted that an Initial Environmental Evaluation

Installation of the Concordiastro tower (2003-2004 Summer Campaign)

IRAIT

(IEE) should be conducted for any new infrastructure at Concordia. Such an IEE should provide information on the possible impact of the activity on the environment. If the conclusion of the IEE demonstrates that the impact would be more than minor or transitory, a Comprehensive Environmental Evaluation (CEE) should be initiated and evaluated, at the international level, by the Committee for Environmental Protection (CEP) of the Antarctic Treaty. Such a CEE was necessary, for example, for the ICE-CUBE project at South Pole. This report will mainly consider the areas in which the present resources for Dome C operation are believed to be challenged by the proposed experiments and are therefore limited to the more technical areas of:

- transportation of equipment during instrument installation and transportation of consumables, essentially fuel, during routine operation of the instrument,
- on site construction of the experiment, and
- telecommunication with respect to data transfer in the operational phase.

An analysis of the instruments proposed, which offer an optimal blend among site characteristics and advanced scientific objectives, leads to a preliminary grouping of experiments in three categories, with respect to demand on logistics: small, intermediate and large. These three categories refer in the following analysis only to the expected impact of the instrument demand on the available capabilities; small instruments request the use of capabilities as available presently; intermediate instruments require limited upgrading of present capabilities; large instruments need major upgrading.

The Twin Otter that services Dome C from Mario Zucchelli station.

The same instrument proposed may fall in different categories for different aspects of the logistical impact. One may need limited support for one area of logistics, and larger support in another. A preliminary categorisation is given in the following. The categorisation is based on the declared characteristics; these are sometime insufficiently described because of the early stages of the projects; the final category for each instrument may be modified after more careful design, and concerted transport, construction plans and operational routines are identified by the proposing teams and the Italian and French polar agencies, PNRA and IPEV.

Obviously, the small instruments are easier to accommodate. ASTEP and IRAIT fall naturally into this category. It is to be noted that IRAIT, even being *"small"*, took several years to move to Dome C. It is now entering the operational phase. The main lesson learnt with the IRAIT project is that logistical and technical aspects must be carefully considered in advance to avoid any delay in the phases of transport and construction.

We can categorise the proposals as follows. SIAMOIS and ICE-T are to be considered small, and present no major challenge for installation and operation at Dome C, in any area of logistical support. The solar interferometer is to be categorised as an intermediate instrument with respect to logistical impact. The category of large instruments, among those proposed by the ARENA working groups, comprises the PLT, the ALADDIN and the submillimetre large antenna. ■

5b Plan for the installation of a large instrument

The sequence of operations for the installation of large, heavy equipment at Dome C consists of several phases:

- transportation from the country of origin, to Hobart, Australia, where the French ship Astrolabe is loaded for its trips to Dumont d'Urville, the French winterover base on the coast of Antarctica.
- transportation from Hobart to Dumont d'Urville. The maximum dry load capability of the Astrolabe is around 300 tons, but this is more a function of the volume and the individual weight and volume of each parcels. The ship crane capacity is 32 tons at 8m and the maximum volume of each parcel is 4x4x10m. A typical 300 tons instrument will have to be split into two trips.
- traverse from Dumont d'Urville to Dome C. The traverse load capability is typically 170 tons, and it is to be assumed that only one half of a traverse can be devoted to a single experiment. It will therefore require four traverses to carry a 300 tons instrument to Dome C.

The routes from Italy to Dome C.

These phases are repeated three times per season. The first traverse generally cannot transport equipment that arrives at the beginning of the season, since the ship cannot approach the Dumont d'Urville base early enough in the season, when the ice is still extended.

The equipment that is traversed to Dome C with the first traverse must be stored in Dumont d'Urville at the end of the previous year and winter over there. It is to be assumed that at least two Antarctic summers will be needed to move the equipment from Dumont d'Urville to Dome C.

The French polar ship Astrolabe.

Construction at Dome C will imply devoting a certain number of technicians for the whole summer season to the construction of the experiment. A number of five people is quoted as sufficient, and this is to be compared with the amount of manpower necessary for the construction of the base itself. A large astronomical instrument is equivalent to one of the two towers, and the estimate of five people can be checked against that to evaluate the amount of time required to erect such large instrument; three summers of construction are to be planned. These will most likely be in series with the transportation, and only partial overlap of the two phases can be expected. An expectation of three years from start of transportation to Antarctica, four years from start of the transportation from Europe to the beginning of the operation can be evaluated. It is also important to consider the lifting equipment on site, which is not convenient today for erection of high or heavy installation. Such equipment must be integrated in the projects and added to the total cargo to be sent to Concordia. It is not possible to determine the class of such crane, given the insufficient information available at this early stage of design.

As regards consumables, the transportation requirement during instrument operation will be to move from Dumont d'Urville to Dome C the fuel that is needed to power up the instrument during its operation. The requirements stated in the available documentation range from a few kW, to the maximum 90kW of ALADDIN.

We will assume 20kW as the average requirement, with the expectation that this may increase during final assessment. In the case that this requirement increases towards a maximum of 90kW, the implication may be that a new dedicated power plant should be necessary for the astronomical instrument. The fuel needed is to be evaluated as 0.23kg of fuel per kW of consumption. The anticipated power consumption, typically 20kWh, assuming an operational duty cycle for the instrument of 50%, that is 4,000 hours, we anticipate a typical 80,000kWh, and consequently 20 tons of fuel per year to be transported, for this instrument only. This would take a fraction of the summer traverses during instrument operation corresponding to 4% of the whole season capacity. This may increase to 18% of total capacity if the maximum power is requested.

Data transfer from the instrument to the Dome C main base, and from Dome C to the mainland appear different from one instrument to the other. The small instruments, like SIAMOIS, appear easy to accomplish. ICE-T seems to need local storage of data, due to the amount of data that are generated. The intermediate instrument requirements are not detailed. The large instruments appear feasible, in the case of PLT, and not realistic for ALADDIN, with the current capabilities. The requirements for the submillimetre telescope are not available. The current Concordia telecommunication facility offers a data dial-up connection service capable of transferring up to several megabytes every day at 10€/MByte. The system implemented at Concordia is based on the Inmarsat satellite fleet and does not support a permanent link channel unless MPDS or BGan Inmarsat devices are used. MPDS protocol devices demonstrate limitations on the sustained bandwidth (< 32kbps) and on the data transfer cost as well (just lower than above). On the other hand the BGan Inmarsat service is not fully supported at polar latitudes. Furthermore an analysis of the scientific objectives shows that the construction of a permanent high bandwidth data link at Concordia is mandatory. To this aim the USTP (Info-Telecommunication of PNRA) proposes to carry on technical tests to validate the site with respect to satellite communication feasibility starting with the Dome C 2009-2010 summer campaign. To allow a simple hardware transportation to Concordia and turn on the link soon an antenna of 2.4m was chosen. Should the test be positive the goal is to perform a winterover test, through a non definitive antenna radome. The facility is tailored for a direct internet access with a starting bandwidth of 256kbps. A specific word of caution is to be said with respect to instrument positioning at Dome C. The large instruments are generally requested to be in a place where no exhaust fumes disturb the observations; the request of using the clean areas cannot be accepted. Two positions may be recommended: either on the radius Concordia - the American tower, or on the opposite direction (Concordia – summer camp). It appears likely that astronomical instruments will prefer to be removed from other installations, and the direction towards the American tower will eventually be preferred.

Additional important work is to be carried out before a final statement can be issued with respect to feasibility, especially with respect to the instruments that pose a major challenge, the large ones. After a decision is taken with respect to which instruments will be eventually selected for implementation, and which will be their sequence of installation, detailed final analysis of the actual characteristics of the equipment, and detailed flow charting of the logistical steps for their transportation to Dome C, for their physical installation on site, and for the subsequent operation of the individual instruments, will be required before the duration of the whole operation can be assessed. ■

The «raid» from Dumont d'Urville to Dome C.


CNRS, explorer les pôles, comprendre la planète
ANR
IPEV
AÉROPORTS DE PARIS

6 Public outreach

6a Introduction

The fascination for astronomy and polar research in the public is strong. The recent International Polar Year (2007-2008) and International Year of Astronomy (2009) were major events that stimulated this public interest. ARENA recommends that the momentum created by these actions be maintained through regular popular events presenting the most recent results and achievements of polar astronomy to the public.

Astronomy and Antarctica are two appealing words by themselves. Astronomy in Antarctica is a fascinating blend for which ARENA is attempting to define a roadmap for future challenging instruments and observations.
In order to publicize its activities during the past four years and also in order to prepare the public towards future activities, the ARENA network has developed two tools as starting points:
- the ARENA leaflet,
- the ARENA public outreach website.

ARENA has also taken advantage of two major international events to present its activities, *i.e.*, the International Polar Year (2007-2009) and the International Year of Astronomy (2009), as well as more local events in various locations in Europe. ■

6b ARENA leaflet

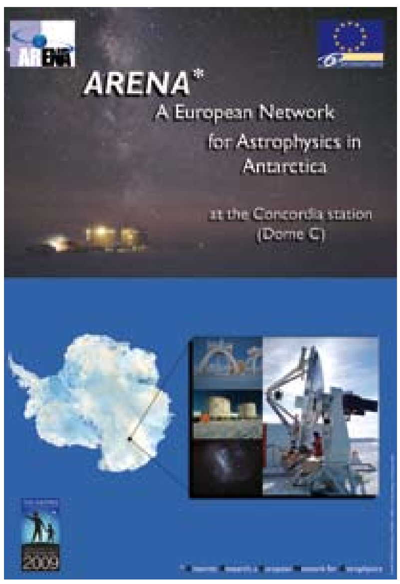
In order to describe the ARENA activities to a large public (teachers, professional and amateur astronomers and also the general public), a 4-page leaflet has been realized. It has been elaborated to answer the following questions:

- Why is Antarctica appealing for astronomers? What is the ARENA network? Who are the ARENA partners and what are the objectives of this network?
- What are the advantages for astronomers to observe from Dome C?
- Where is Dome C and what does it look like?
- What are the fundamental astrophysical questions that an observatory at Dome C can tackle?
- What are the instrumental projects to answer these questions?

3,000 French and English copies have been released. They were sent to the 22 ARENA partners, outreach science centres and journalists.
1,000 leaflets were distributed during the opening ceremony of the International Year of Astronomy at UNESCO in January 2009.

The leaflet is now available in three languages: English, French and Italian.

It can also be downloaded from *http://arena.unice.fr/IMG/pdf/ARENA_leaflet_english.pdf*. ■



ARENA leaflet front page in english

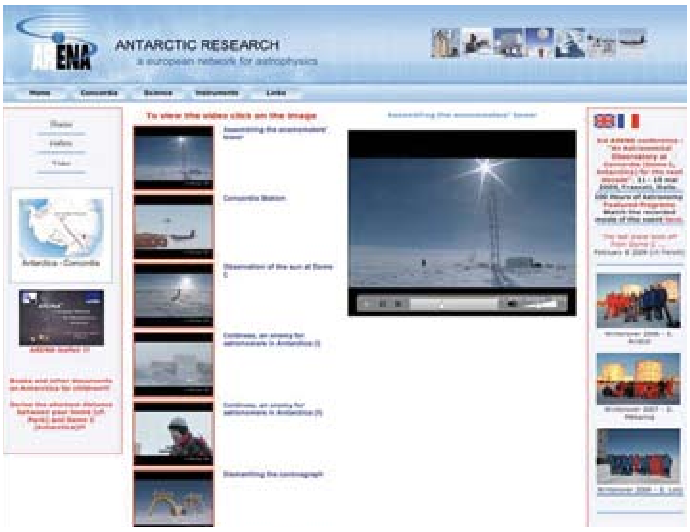
6c ARENA public outreach website

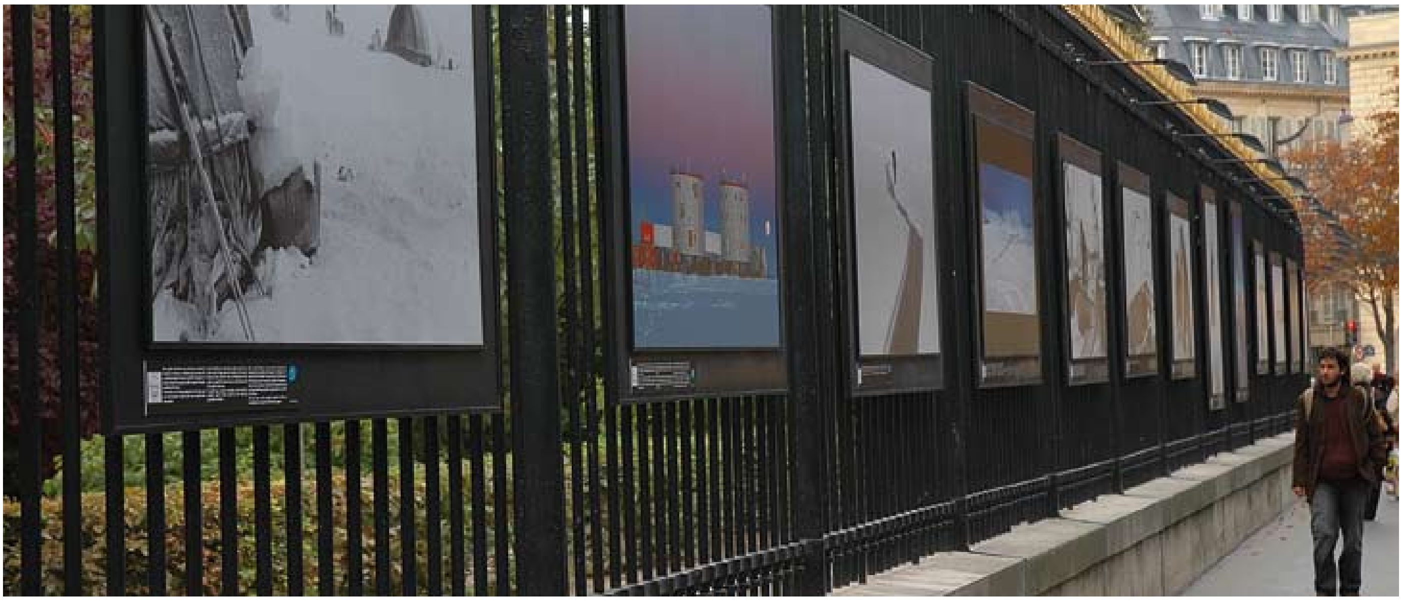
There are numerous websites and blogs about Antarctica, Concordia and about activities linked to Astronomy in Antarctica. Extracting the information of high value, synthesizing it by assembling and selecting the best visual material (images and videos) related to astronomy and Antarctica was one of the priorities of the work done when the network started to develop the ARENA public outreach website (http://www.arena.ulg.ac.be/).

The goal of the latter was and remains to reach and motivate the wide public and especially teachers and students of different level of education systems. The main aim of this website is to present the unique potentialities of Antarctica to set up an astronomical observatory that will perform exceptional observations as well as to describe the scientific programmes and instruments. Its content is in English and French.

Antarctica does host an excellent site for future astronomical ground based observatory in the 21st century, there is indeed an obligation of generating an effective flow of information about the contributions made to the European knowledge and scientific excellence, the value of collaboration on a Europe-wide scale, and the benefits to EU citizens in general. The website will strive at making this possible. ■

http://www.arena.ulg.ac.be/





6d Recommendations for future activities

Examples of exhibitions in the framework of the International Polar Year (Luxembourg Garden near the French Senate -up-, Musée des Arts et Métiers -down- *in Paris)*

The public outreach website ought to continue being updated in the near future. Beyond that, there exists a clear need for coordination in order to maximize the impacts of what has been achieved in the present context of ARENA. This is important in the frame of long term cooperation on Antarctic astronomy at an international level. Several actions can be thought of at this point in time, although they may appear a bit premature as far as the present roadmap is concerned. For instance:

Action 1
Develop a European level platform for communication and coordination amongst education, outreach and communication professionals with online forum to discuss ideas in advance and meet on line to identify interests and priorities. Create an expert database with open source material

Action 2
Establish a network which will actively follow-up the "Vision towards European Astronomy in Antarctica" and a team to coordinate the inputs at the international level.

Action 3
Develop a resource centre about Astronomy in Antarctica in forms of a portal including virtual press, public, scientific rooms. Financial support provided by government education ministries, national or international funding agencies or individual research institutions is highly needed to develop further planning of communications actions with full-time/professional communicators.

What is clear nevertheless is that a considerable outreach effort will have to be included in the next steps towards establishing an important astronomical outpost in Antarctica. Such a project will indeed be comparable to major ground based projects or programs such as VLT/VLTI, ALMA, E-ELT, to large space missions, such as HST, Planck, XMM, INTEGRAL, Mars & Venus Express or to solar system exploration missions. In all these cases, a considerable outreach programme has been set up and this must be taken as example to be followed in the case of European Astronomy in Antarctica. One must start preparing it as of now. ■

7 Funding and manpower requirements

7a Cost and funding

The Concordia station could become during the next decade a major platform for astronomical observations benefiting from unique atmospheric conditions. Europe is in a foremost position to be a world leader in this challenging endeavour. We estimate that the injection of 50 to 100 M€ during the next 10 years for the study and implementation of state-of-the-art astronomical equipments is a prerequisite to give the necessary impetus to a European Astronomical Observatory in Antarctica.

A meaningful roadmap necessarily includes an estimate of the funding and man power resources that must be raised and deployed to carry out its recommendations. Although these projections are still uncertain at this stage, particularly for the largest projects, we outline in this chapter the budget that the working groups are requesting. We estimate that the injection of an overall amount of 50 to 100 M€ during the next ten years is desirable to start a significant European Observatory in Antarctica, including 5 to 6 small instruments and a mesoscale facility.

Funding, implementing and running small projects of a few million euros is feasible at the level of one country or laboratory. They do not need a heavy and sophisticated project management. For instance, ASTEP a project of less than 2 M€ (consolidated) is basically funded by France through INSU and ANR grants and is managed at the level of the Fizeau Laboratory. IRAIT, an instrument of comparable cost, is basically supported by the University of Perugia and the Italian agencies (INAF/PNRA) with some smaller contributions from Spain (Granada, Barcelona) and France (CEA).

More ambitious projects exceeding an overall cost of 10 M€ (mesoscale projects) such as PLT will require the creation of an international consortium able to raise the funding and manpower to carry out the successive phases of the project from the concept study to the routine operations and data analysis. A consortium agreement between partners from different countries with possible contributions of international agencies has to be set up. National and possibly international agencies should include the project in their own plans, simultaneously.

The ARENA working groups were asked to draft a cost estimate of the different phases of their projects over the next decade. These financial projections are only rough estimations and should become more accurate as the industrial studies progress. The only mesoscale project for which a complete phase A study has been fully achieved is PILOT, from which PLT is derived.

Tables 15 to **17** synthesize the status, cost estimates and possible dates of operations of the instruments documented by the ARENA working groups. The cost of projects that have not yet started a phase A study are obviously very rough estimates. **Figures 24** and **25** show projections of the annual costs that would be required by the projects proposed by the working groups. They include consolidated phase A and B studies, and unconsolidated construction costs. The consolidated costs of construction will result from the phase B studies. **Figure 26** shows the relative costs of the different projects proposed by the working groups.

From **Fig. 24**, it is immediately apparent that if all these projects (PLT, ALADDIN, AST) were to be developed in the next decade, the peak of funding would occur by 2014-2018 and the total injection of money into these projects would exceed 100 M€ during the decade, which is likely to be unrealistic.

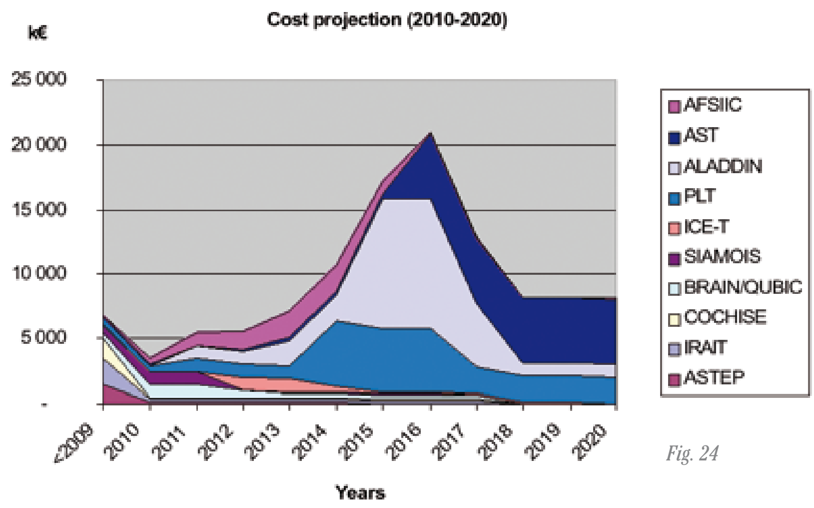


Fig. 24

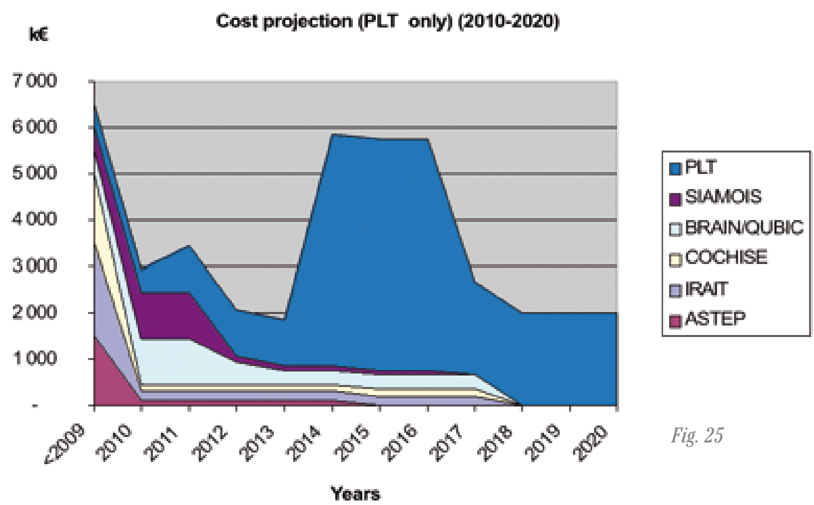


Fig. 25

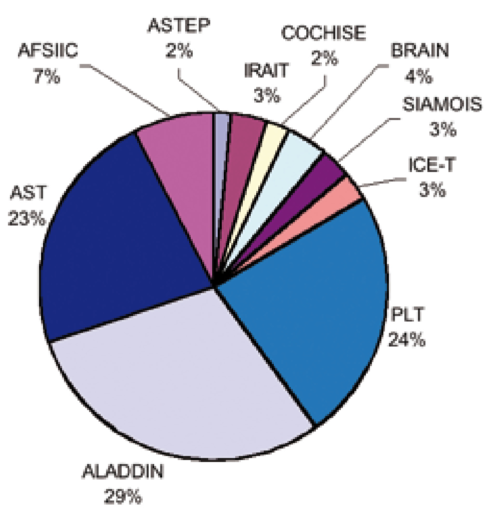


Fig. 26

Besides, the polar agencies could obviously not cope with the simultaneous implementation of three major projects on the site in this decade. Therefore, to be realistic, the only mesoscale project that has a chance to be effectively implemented in the next ten years is PLT: the other ones will have to be shifted to the subsequent decade.

The overall budget needed to run the existing instruments, and to implement SIAMOIS and PLT, would add up to about 50 M€ in the decade (see **Fig. 25**).

The main possible sources of funding are the national agencies, the European Commission through its Research Infrastructures Programme, mainly for design studies and other international organizations. For instance, the PLT team is aiming to submit a proposal for a phase B study. Although it is unlikely that ESO will contribute to the funding of projects in Antarctica in the coming years, we stress the fact that its support would give a strong impetus to European Antarctic Astronomy. ■

Fig. 24: Cost projection for the next decade including all projects considered in the roadmap (overall cost 115 M€). The cost per year of each project corresponds to the height of the respective colour area. The profiles are preliminary estimation based on the information provided by the working groups.

Fig. 25: Cost projection for the next decade including PLT as the only meso scale instrument implemented during the next decade.

Fig.26: Relative cost estimations of the projects proposed by the working groups over the next decade.

Table 15 Instruments currently under implementation at Dome C

Instrument	Present status	Estimated consolidated cost	Main sources of funding	Start full operation (estimated)
ASTEP	In commissioning	~2 M€	ANR, INSU	2010
IRAIT	In commissioning	~2 M€	INAF, PNRA, CSIC, UGR, CEA	2011
COCHISE	In operation	?	PNRA, *Università di Roma*	2008
BRAIN/QUBIC	In construction	3M€ + Logistics	IN2P3, PNRA	2014

Table 16 Instruments in phase B Study

Instrument	Present status	Estimated cost PhaseB/ construction	Phase B status/possible source(s) of funding	Construction, possible source(s) of funding	Start full operation (estimated)
SIAMOIS	Ready for construction/ seeking funds for implementation	100 k€/ ~2 M€	done/Observatoire de Paris	INSU, ANR	2012
ICE-T	Ready for construction	180 k€/2.5 M€	done/AIP	AIP	2016
PLT	Phase A done (PILOT), seeking funds for phase B study	4 M€/20 M€ *Including 1 focal instrument and infrastructure*	to be done/ EC, Australia	Europe, Australia	2018-2020

Table 17 Instruments in phase A or concept study

Instrument	Present status	Estimated Overall cost (2010-2020)	Phase A, possible source(s) of funding	Phase B, possible source(s) of funding	Construction: possible source(s) of funding	Estimated date of operations and running costs
AST	Concept study	> 25 M€	CEA, INAF, Industries, FP7			> 2020
ALADDIN	Concept study	> 20 M€	EC, ESA?	EC, ESA ?	?	> 2020
AFSIIC	Concept study	~ 8 M€ *Including 3 focal instruments and infrastructure*	ANR, FP7 Space (Support of ASPIICS ESA PROBA-3)	ANR, FP7 Space (Support of ASPIICS ESA PROBA-3) FP7 Design Study	France, Italy, Germany, Belgium and Russia	2012-2013 *1 telescope* 2015-2016 *Complete 50 k€/year.*

7b Personnel and training

Personnel represents an important issue in the future development of astronomical facilities in Antarctica. There is no doubt that the polar agencies are able to manage the implementation of any reasonably large project at Dome C, to deploy the appropriate means of conveyance and building resources and to host adequately the necessary personnel during the construction phase.

However, the careful investigation made by the ARENA activity NA4 ends up with the final conclusion that PLT (or PILOT) is the only project fitting within the present logistics capability. The other large projects would necessarily require a significant upgrade of the station capacity and logistics that would result in a significant extra cost.

From the scientific personnel point of view, the situation is more uncertain. Working in Antarctica, particularly in winter, requires special skills and training. Excellent physical and psychological conditions for a life of several months in small group in complete isolation from the world are an obvious prerequisite. The increasing number of instruments and the future installation of larger facilities would require a significant increase in the number of well-trained staff. A clear separation must be made between dark and bright time programmes. Although a winterover at Dome C is an appealing experience, the number of candidates having the required expertise is not unlimited and thus, if larger instruments were to be installed, we would strongly recommend broadening the call to apply for winterover runs.

This call should not be limited to the Italian and French communities, but be open to other countries in the framework of a trans-national access agreement that the EC, for instance, could support through its future 8th FP. Australia, which is expected to be a major partner in astronomical developments at Dome C in the future, should be part of such a trans-national access agreement. The real cost of one person spending a winter at Dome C should also be evaluated accurately to be taken into account in the consolidated costs for future European proposals.

In any case, the number of the winterover staff, which is currently about 15, is unlikely to increase significantly in the next ten years. This number is basically limited by the hosting capacity of the station (rooms, fuel and food provision…).

Therefore, the implementation and operation of any instruments should be consistent with this manpower upper limit. The construction of new service buildings at Concordia is unlikely to be undertaken in the period that this roadmap encompasses.

Since the winterover staff are essentially dedicated to the functioning of the station, the number of "astronomers" staying during winter will be two, or at most three. In addition, only very limited outdoor activity is allowed in winter. For these reasons, a high degree of automation and robotic operation of the telescopes and instruments should be a major priority in their future design. Scientific programming of the facility should avoid any sort of instrument configuration change over or maintenance during winter. As for the period of construction of buildings and heavy structure in summer, this is essentially limited to three to four months a year: consequently, any construction that needs a year in *"normal"* conditions will need three to four years at Dome C.

Taking into account the delays imposed by the shipping of heavy structures and pieces of material to Dome C, and considering the recent delays observed in setting up even small instruments, the construction of a mesoscale facility (PLT class) will not be less than five years. Daytime instruments (such as solar, radio and thermal infrared waves) may have a different status. To take advantage of the much more comfortable operating conditions in summer, we strongly recommend that PLT be also operated in bright time in the appropriate spectral range (beyond 3μm).

The proper management of the construction and planning is *per se* a major task that should be thoroughly considered in any phase B study. Polar Agency expertise and good communication with their operational staff will be extremely important during this phase. ■

8 Synthesis of the roadmap and final recommendations

The following statements have been endorsed by the CMC following the 3rd ARENA Conference held in Frascati in May 2009. They are translated hereafter into ARENA recommendations so that as of January 2010 the necessary studies be initiated and undertaken in order to enable the "European Observatory in Antartica" project.

Statement 1
On the overall interest of Antarctica conditions to the development of European astronomy and astrophysics

Considering the exceptional atmospheric conditions prevailing at Dome C, the ARENA consortium strongly supports the creation of a European/international astronomical facility on the Antarctic Plateau, building upon the successful establishment of Concordia station by France and Italy.

Statement 2
On the medium-and long-term objective of the ARENA roadmap

The ARENA consortium strongly encourages international cooperation in Antarctica, in particular with respect to the establishment of large observing astronomical facilities at Dome C (or possibly elsewhere on the Antarctic plateau if another even better site were to be discovered). The ARENA roadmap will serve as a guideline to the national and international agencies and the European Commission for the developments of these facilities in the coming decade (2010-2020).

Statement 3
On the size of projects

The ARENA consortium strongly supports the need of meso-scale facilities to be developed. Nevertheless it also supports small experiments as site testers and pathfinders.

Statement 4
On the present status of site assessment and recommendations in the future

The ARENA CMC strongly emphasizes the need to widely open access to the site of Concordia to teams that contribute to the assessment of the site, to the resulting databases as well as to provide a free access to these data on as short a time-scale as possible after they have been collected. A dedicated entity should be in charge of maintaining these data bases after the end of ARENA. In addition, the ARENA consortium strongly recommends that ESO be involved in the future site testing at Dome C.

Statement 5
On the most promising science cases

The ARENA consortium commends the science cases proposed by the working groups and described in statement 9, herebelow.

Statement 6
On the instrumental polar constraints. State of the art R&D. International pooling of expertises.

The ARENA CMC recommends that appropriate R&D studies specific to the Antarctic constraints be made in advance of any decision to implement a meso-scale facility. Among them are, frost mitigation, specific ground layer adaptive optics (GLAO), 20-30m tower construction. The CMC strongly recommends that a simple GLAO system be implemented and assessed in the polar environment *e.g.*, using already installed telescopes such as IRAIT. In addition, design studies, design and model building of highly stiff towers able to support different types of instruments (solar or night telescopes) are strongly encouraged. The CMC further recommends to foster a politics of pooling of the polar expertises acquired by the different teams.

Statement 7

On the need to upgrade logistics

The ARENA CMC strongly recommends improvements of the following issues:

• Alternative clean energy production. New larger astronomical facilities will require a significant improvement of electric power production, preferably avoiding atmospheric pollution of the site by aerosols that would degrade the unique sky properties.

• Increase drastically the communication bandwidth. Fast and wide band interaction with "the rest of the world" is essential to carry out a project and to treat interactively huge amounts of data. It constitutes an essential advantage over space missions.

Statement 8

On seeking for funding and relationship with agencies

The ARENA CMC recommends that further funding be sought from the EC and (inter-) national agencies to continue its coordination activities. The necessary efforts should be made to include the Concordia station in the ESFRI roadmap in order that its scientific research equipments be implemented rapidly. A peer reviewing process by the ESF units may help on this issue.

Statement 9

On the projects presented by the working groups and their endorsement by the ARENA CMC

From statements to recommendations: the following paragraphs aim at extracting the quintessence from the 6 working group reports in order to convert the statements above into ARENA recommendations.

WG1 - Wide-field optical IR astronomy

PLT (Polar Large Telescope) is the most mature project in the mesoscale category. The Phase A worked out by the Australians in 2007-2008 for PILOT should serve as a robust basis for further PLT studies. This project is also supported by WG4 for a phase B study (ending by 2013). The PLT facility should be able to enter into a construction phase by 2014 and start being implemented in 2015-2017 at Dome C, with a first light by 2018.

WG2 - Submillimetre-wave astronomy

The ARENA CMC recognizes the exceptional interest in the project, which proposes a large telescope facility highly complementary to the Herschel space observatory and to ALMA, in a site which seems to provide much better conditions in the THz domain than any site in Chile. AST (Antarctic Submillimetre Telescope) is thus recommended for a rapid phase A study.

WG3 - Optical/IR interferometry

ALADDIN is the most advanced project for interferometry at Dome C (concept studies made by an industrial team). It is thus recommended for a more detailed phase A study. A stronger support from the interferometry community should be obtained. Alternative projects of pathfinders toward a European kilometric array interferometer are also to be investigated in parallel. We recommend to measure and monitor relevant atmospheric parameters (turbulence profile, isopistonic angle, coherence time, outer scale).

WG4 - Long time-series photometric observations

The CMC endorses the recommendations made by the WG4, which essentially supports 4 small projects presently in different phases of implementation and the PLT project.

• IRAIT is a milestone of ARENA (being part of its workprogramme). It should be set up rapidly and made operational this next summer season (2009-2010), for first light in winter 2010.

• ASTEP received its first light at Dome C in November 2009. It should rapidly provide scientific data (2010-2011) and thus be strongly supported by the relevant agencies.

• ICE-T is graded the top priority instrument for time-series photometry at Dome C and the CMC recommends that an agreement be made with the French and Italian polar agencies to host this instrument at Concordia.

• SIAMOIS is graded the top priority dedicated instrument for advanced time-series spectroscopy at Dome C.

WG5 - Cosmic Microwave Background

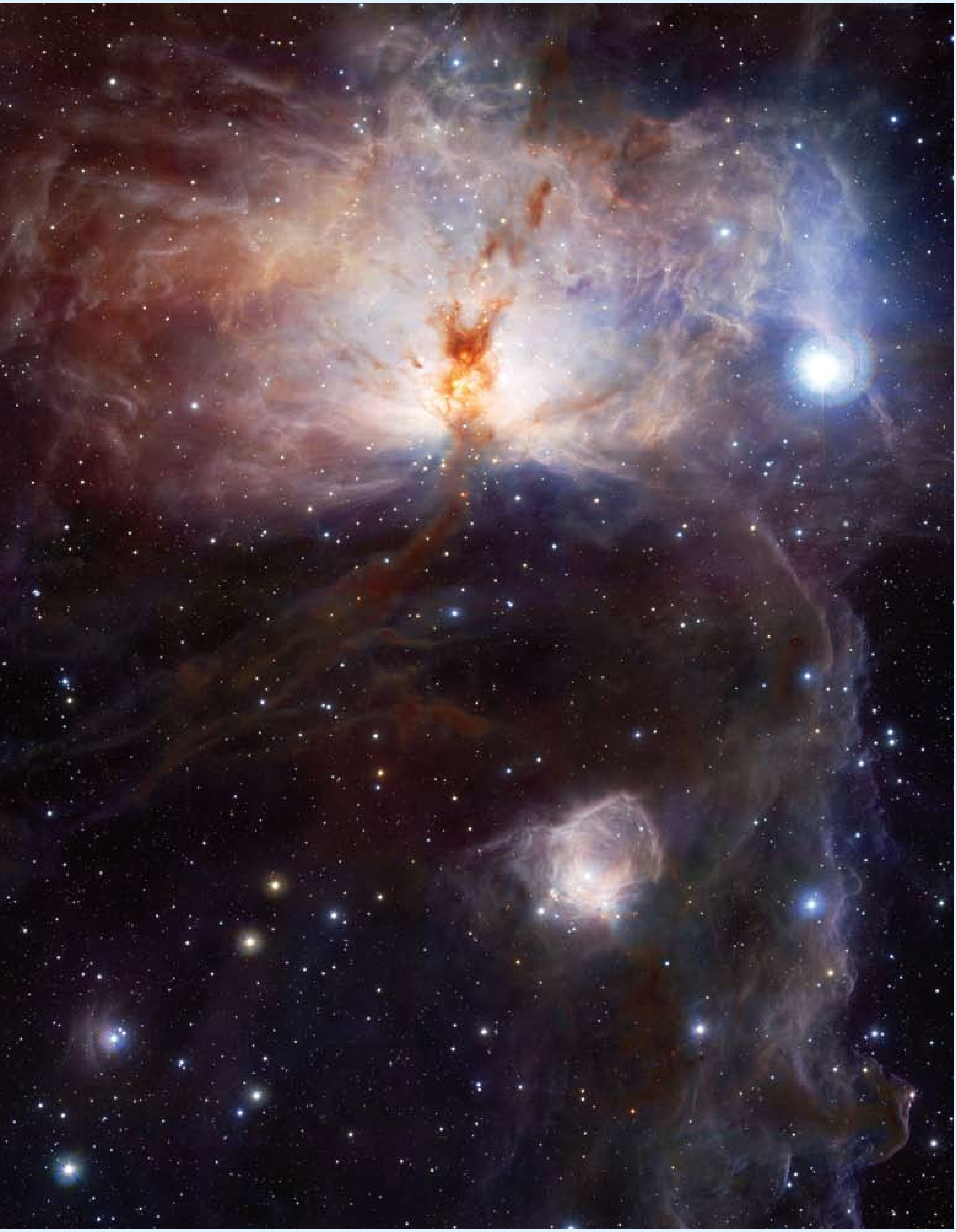
Antarctica offers exceptional conditions for CMB research due to its cold and dry climate. Dome C offers particular advantages, relative to South Pole, for the accurate measurement of the CMB B-mode polarization, one of the major goals of cosmology in the coming years. The ARENA CMC strongly supports efforts to establish CMB experiments at Dome C and in particular the international QUBIC project whose bolometric interferometer will combine the sensitivity of bolometric detectors with the optical acuity of interferometers. The ARENA CMC also supports efforts to further explore synergies between the CMB projects and the 25m AST project.

WG6 - Solar astrophysics

Solar astrophysics could take considerable advantage of the exceptional seeing conditions regularly recorded in summer time at Dome C. The CMC recommends a phase A study for a high resolution imaging and spectroscopy facility with coronal capabilities, first, of 1.4m equivalent diameter (3x0.5m off-axis).

The instrumentation would enable 2D spectro-imaging, spectropolarimetry, magnetoseismology and direct magnetic field measurements in the chromosphere and corona. The proponents must however demonstrate on a temperate site that the required interferometric technique is feasible for such instruments. ■

First publicly released image from VISTA, the world's largest survey telescope, showing the spectacular star-forming region known as the Flame Nebula, or NGC 2024, in the constellation of Orion (the Hunter) and its surroundings.



Annexes

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Ab List of instruments at Dome C

past, in operation, or being set up in 2009

Site testing

Meteorology

AWS
(Since 1980): Automatic Weather Station measuring ground level pressure, temperature, humidity, wind speed and direction.

Meteo balloons
(Summer since 1995, winter since 2005): measuring profile of temperature, pressure, humidity, wind speed and direction.

COBBER
(Winter 2003-2004): low power mid-infrared thermopile detector measured cloud cover statistics.

ICECAM
(Winter 2002-2003): autonomous self-powered visible CCD camera measured cloud cover statistics.

Vaisala
FD12 (Summer 2004): visibility sensor measured precipitation rates.

Gattini
All sky (Winter since 2006): wide-field optical camera to measure cloud cover and auroral distribution.

STABLEDC
(2004-2005): an array of instruments measuring the thermal structure in the boundary layer.

GIVRE
(Winter since 2007): an experiment to measure frost and ice accumulation on exposed surfaces.

Sky emission and opacity

Solar hydrometer
(Summer 1996-1997, 2007): measured precipitable water vapour.

APACHE96
(Summer 1996-1997): 0.6m millimetre-wave telescope measured atmospheric stability and sky noise.

SUMMIT
(Summer 2003-2004, winter 2008-2009): submillimetre tipper measuring opacity and emission at 200 and 350µm.

PAERI
(Summer 2002-2003 and 2003-2004): infrared FTS measured sky emission and opacity from 3-20µm.

Nigel
(Summer 2004-2005): fibre-coupled optical spectrometer measured sky spectral emission.

Gattini
SBC (since winter 2006): narrow field optical camera to measure sky background in the visible.

sIRAIT
(Since 2006): a 0.25m optical telescope for asteroseismology and site qualification.

PAIX
(Since winter 2007): photometer designed for measurement of the optical atmospheric extinction.

COCHISE
(Since winter 2008): a 2.6m diameter millimetre-wave telescope designed for cosmological science but should also measure atmospheric opacity.

TAVERN-SP
(Planned for winter 2010): a small optical telescope designed to measure aerosol densities.

ASTEP
(Since 2008): a 0.42m optical telescope designed for exoplanet detection and photometric site characterisation.

IRAIT
(Planned for winter 2010): a 0.8m near- and mid-infrared telescope to be equipped with the AMICA instrument with science priorities but site qualification capabilities.

Turbulence

DIMM
(Summer since 2000, winter since 2005): Differential Image Motion Monitor measuring integrated seeing close to surface.

GSM
(Since 2006): Generalized Seeing Monitor measuring outer scale, seeing and isoplanatic angle at ground level.

MOSP
(Since 2008): Monitor of Outer Scale Profile.

SSS
(Since 2005): Single Star Scidar: Monitoring of C_n^2 profile.

SODAR
(Summer/winter 2003-2004): commercial acoustic radar measured turbulence within the 30-900m surface layer.

MASS
(Winter 2004): Multi-Aperture Scintillation Sensor measured turbulence profile of atmosphere from 0.5-22km.

Microthermal balloon
(Winter 2005): temperature sensors measuring the atmospheric turbulence profile.

Microthermal mast
(Winter 2005-2006): tower mounted microthermal sensors measuring the turbulence in the 0-30m surface layer.

Sonics
(Since 2006) measuring temperature and wind speed components in the surface layer from ultrasound emission, and derive C_n^2 profile through a model.

Ac List of abbreviations

A

AAA (triple A)
Astronomy and Astrophysics from Antarctica (a SCAR initiative)

AAO
Anglo-Australian Observatory

AASTINO
Automated Astrophysical Site Testing International Observatory

AASTO
Automated Astrophysical Observatory for Antarctica

AAD
Australian Antarctic Division

A-FOURMI
Antarctica 4m Interferometer

AFSIIC
Antarctica Facility for Solar Interferometric Imaging and Coronagraphy

AIP
Astrophysikalisches Institüt Potsdam, Germany

ALADDIN
Antarctic L-band Astrophysics Discovery Demonstrator for Interferometric Nulling

ALMA
Atacama Large Millimetric Array

AMANDA
Antarctic Muon and Neutrino Detector Array

AMICA
Antarctic Mid-Infrared CAmera (for IRAIT)

ANR
Agence Nationale pour la Recherche (French National Research Agency)

APEX
Atacama Pathfinder Experiment

ARENA
Antarctic Research, a European Network for Astrophysics

ASPICS
Association de Satellites Pour l'Imagerie et l'Interférométrie de la Couronne Solaire

AST
Antarctic Submillimetre Telescope

AST/RO
Antarctic Submillimetre Telescopes and Remote Observatory

ASTRONET
ERA-NET for Astronomy and Astrophysics

ATP
Advanced Telescope Project

ATST
Advanced Technology Solar Telescope

AWI
Alfred Wegener Institute (German Polar Agency)

AWS
Automatic Weather Station

B

BAS
British Antarctic Survey

BICEP
Background Imaging of Cosmic Extragalactic Polarization

BLIP
Background Limited Infrared Photometry

BOOMERanG
Balloon Observations of Millimetric Extragalactic Radiations and Geomagnetics

BRAIN
Background RAdiation INterferometer

C

CCAT
Cornell Caltech Atacama Telescope

CEA
Commissariat à l'Energie Atomique

CEE
Comprehensive Environmental Evaluation

CEP
Committee for Environmental Protection

CFHT
Canada-France-Hawaii Telescope

CMB
Cosmic Microwave Background

CMC
Consortium Management Committee (ARENA executive committee)

CMEs
Coronal Mass Ejections

CNRS
Centre National de la Recherche Scientifique

COBRA
Cosmic Background Radiation Anisotropy Experiment

COCHISE
Cosmological Observations at Concordia with High-sensitivity Instruments for Source Extraction

CRAL
Centre de Recherche Astrophysique de Lyon

D

DASI
Degree Angular Scale Interferometer

DENIS
DEep Near Infrared Southern Sky Survey

DIMM
Differential Image Motion Monitor

DLR
Deutsches Zentrum für Luft- und Raumfahrt

E

EC
European Commission

EIE
European Industrial Engineering

E-ELT
European -Extremely Large Telescope

EMILIE
Emission Millimétrique

EPICA
European Project for Ice Coring in Antarctica

ESFRI
European Strategy Forum on Research Infrastructures

ESA
European Space Agency

ESO
European Southern Observatory

ETSRC
European Telescope Strategy Review Committee

F - G - H

FOV
Field Of View

FP6/7
Sixth/Seventh Framework Programme (of the European Commission)

FTS
Fourier Transform Spectrometer

GB
Galactic Bulge

GENIE
Ground-based European Nulling Experiment

GLAO
Ground Layer Adaptive Optics

GONG
Global Oscillation Network Group

GSM
Generalised Seeing Monitor

HATnet
Hungarian-made Automated Telescope network

HST
Hubble Space Telescope

I

IAGL
Institut d'Astrophysique et de Géophysique de Liège

IAU
International Astronomical Union

ICE-T
The International Concordia Explorer Telescope

ICSU
International Council of Scientific Unions

IEE
Initial Environmental Evaluation

IGY
International Geophysical Year (1957-1958)

IAP
Institut d'Astrophysique de Paris

IN2P3
Institut National de Physique Nucléaire et de Physique des Particules (French Research Agency)

INAF
Istituto Nazionale di Astrofisica (Italian Research Agency)

INSU
Institut National des Sciences de l'Univers (French Research Agency)

INFN
Istituto Nazionale di Fisica Nucleare (Italian Research Agency)

IPEV
Institut Paul Emile Victor (French Polar Agency)

IPY
International Polar Year (2008-2009)

IRAIT
International Robotic Antarctic Infrared Telescope

ISO
Infrared Space Observatory

IYA 2009
International Year of Astronomy (2009)

INSCAF
International Network for Scientific Cosmological Analysis of Foregrounds

J - K - L

JACARA
Joint Australian Centre for Astrophysical Research in Antarctica

JWST
James Webb Space Telescope

KEOPS
Kiloparsec Explorer for Optical Planet Search

LAM
Laboratoire d'Astrophysique de Marseille

LBT
Large Binocular Telescope (Interferometer)

LMC
Large Magellanic Cloud

LUAN
Laboratoire Universitaire d'Astrophysique de Nice (now Laboratoire H. Fizeau)

M - N

MCAO
Multi Conjugate Adaptive Optics

MOLIERE
Microwave Observation LIne Estimation and REtrieval

MOSP
Monitor of Outer Scale Profile

MPIA
Max Planck Institut für Astronomie, Heidelberg, Germany

NCRIS
National Collaborative Research Infrastructure Strategy (Australia)

NSF
National Science Foundation (US)

O - P

OASI
Infrared and Sub-mm Antarctic Observatory

OPTICON
Optical Infrared Coordination Network for Astronomy (an EC FP7 initiative)

OGLE
Optical Gravitational Lensing Experiment

PAERI
Polar Atmospheric Emitted Radiance Interferometer

PAIX
Photometer AntarctIc eXtinction

PILOT
Pathfinder for an International Large Optical Telescope

PISNe
Pair Instability Supernovae

PLT
Polar Large Telescope

PNRA
Programma Nazionale di Ricerche in Antartide (Italian National Programme for Research in Antarctica)

PWV
Precipitable Water Vapour

Q - R

QUBIC
Quasi Optical Bolometric Interferometry

RAMS-CON
RAMS-CON Management Consultants

S

SBM
Sky Brightness Monitor

SCAR
Scientific Committee on Antarctic Research

SDM
Subtractive Double Monochromator

SDSS
Sloan Digital Sky Survey

SIAMOIS
Seismic Interferometer Aiming to Measure Oscillations in the Interior of Stars

SMC
Small Magellanic Cloud

SNIa
Supernova of type 1A

SNe
Supernovae

SODAR
SOnic Detection And Ranging

SOFIA
Stratospheric Observatory For Infrared Astronomy

SOHO
SOlar Heliospheric Observatory

SPICA
Space Infrared Telescope for Cosmology and Astrophysics

SPIREX
South Pole Infrared Explorer

SPOT
South Polar Optical Telescope

SSS
Single Star Scidar

STABLEDC
Study of the STABLE boundary layer at Dome C

SUMMIT
Sub-millimeter tipper

SZE
Sunyaev-Zel'dovich Effect

T - U

TGL
Turbulent Ground Layer

TMT
Thirty Meter Telescope

UGR
Universidad de Granada, Spain

UNS
Université de Nice Sophia Antipolis

UNSW
University of New South Wales (Sydney, Australia)

V

VISTA
Visible and Infrared Survey Telescope for Astronomy

VLBI
Very Large Base Interferometry

VLT(I)
Very Large Telescope (Interferometer)

W

WIMP
Weakly Interacting Massive Particles

WISE
Wide-field Infrared Survey Explorer

WMAP
Wilkinson Microwave Anisotropy Probe

2

2MASS
Two-Micron Sky Survey

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