Antarctica as a launch-pad for space astronomy missions

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ABSTRACT

In the coming decades, astronomical breakthroughs will increasingly come from observations from the best ground-based locations and from space observatories. At infrared and sub-millimetre wavelengths in particular, Antarctica offers site conditions that are found nowhere else on earth. There are two implications of this. First, for tackling some of the most crucial problems in astrophysics, a large telescope in Antarctica can outperform any other ground-based facility. Second, with infrared backgrounds between one and two orders of magnitude below those at other sites, superior sub-mm transmission and extraordinarily low atmospheric turbulence above the boundary layer, Antarctica offers designers of space missions a unique test-bed for their ideas and instrumentation.

Keywords: Space, Antarctica, interferometry

1. INTRODUCTION

The Antarctic plateau is the coldest and driest place on earth. The highest points are at elevations above 4,000 metres. The atmosphere above the plateau is extraordinarily stable, as there is no jet stream, very little wind, and—at the South Pole—no diurnal variation. There is nowhere else on earth that approximates a space environment better than does Antarctica.

In the infrared, for example, the sky brightness is typically 10 to 100 times darker than at the best "temperate" observatories. The sub-mm transmission is superior to that measured anywhere else on earth. However, perhaps the most important feature of Antarctica is the extraordinary stability of the upper atmosphere, which dramatically reduces scintillation and offers large gains in photometric accuracy, field of view and astrometric precision.

2. WHAT IS KNOWN ABOUT SITE CONDITIONS

For many people, mention of Antarctica conjures up images of icebergs, blizzards and leopard seals. However, none of these things is present on the high Antarctic Plateau, where astronomical site-testing work has concentrated. Dome C, for example, has an extremely cold but otherwise very benign climate, enjoying lower average wind speeds than most—if not all—US cities. At South Pole, the wind speed averages around 6 m/s, and is remarkably constant for days at a time in both speed and direction.

Aurorae, while spectacular, do not affect infrared or sub-mm observations.

Temperatures, of course, are extremely low. At South Pole the temperature can drop below -75^{O}C, while sites higher on the plateau can experience temperatures down to -90^{O}C. This is significantly below "dry-ice" temperature, the freezing point of carbon dioxide being -78^{O}C.

2.1 Infrared sky brightness

Across the infrared spectrum, modern infrared array detectors are capable of background-limited performance (BLIP). The sensitivity of cameras and spectrometers at infrared wavelengths is therefore generally determined by the background flux, most of which comes from the atmosphere and the telescope mirrors themselves. On the Antarctic plateau the very low ambient temperatures result in low mirror temperatures, greatly reducing their emission—especially in the near-infrared where one is on the "Wien" side of the Planck function. Additionally, the sky is extremely cold and dry, and both these factors result in a lower sky background flux.

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Measurements of the near-infrared sky brightness by Ashley et al[1] and Nguyen et al[2] showed reductions in sky background flux of up to a factor of 100 relative to established, temperate-zone observatories such as Mauna Kea. A more comprehensive data set was analyzed by Phillips et al[3]. These data not only confirmed the earlier results, but also showed that the reductions in sky-brightness were substantial out to at least 5.5 microns. Recently, a fourth set of data has been acquired with a fully automated instrument[4].

The region around three microns is one of the two darkest places in the interstellar spectrum (the other is around 300 microns). At 2.4 microns, we find that on occasions the sky brightness can come within a factor of a few of the zodiacal light, as measured by rocket experiments.

In the mid-infrared, Smith & Harper[5] showed reductions of over one order of magnitude in the sky brightness; a result that has since been confirmed by the more detailed measurements of Chamberlain et al[6].

Finally, the expected gains in sensitivity that result from the reduced background have been demonstrated to be achievable in real astronomical observations, for example by the deep images obtained with the SPIREX telescope[7,8].

2.2 Submillimetre transparency and sky stability

Over a decade ago, Townes & Melnick[9] analysed water vapour measurements from Vostok and predicted that far-infrared/sub-mm conditions on the Antarctic Plateau would be extraordinarily good. The first measurements at the South Pole by Chamberlin, Lane & Stark[10] confirmed that there was extremely good transmission at 492 GHz. These results have been extended to 860 GHz by Chamberlin[11]. More recently, Lay & Halverson[12] have observed exceptionally low fluctuations in the microwave sky brightness. Preliminary measurements at Dome C by Calisse et al[13] suggest that it may be an even better site than South Pole, as might be expected from its higher and more inland location.

2.3 Microthermal turbulence

Marks and his colleagues[14,15,16] were able to show, from a combination of tower and balloon-borne microthermal measurements, that the atmospheric turbulence above the Antarctic plateau is confined to a very thin boundary layer that extends to just a couple of hundred metres above the ice. More recent acoustic radar (SODAR) measurements[17] have detailed the extent and distribution of this boundary layer turbulence at the South Pole throughout the entire year.

2.4 Continuous observing

From the South Pole, every astronomical source outside the solar system moves around the sky at constant elevation and is, of course, continuously visible. This confers immense advantages to the study of time-varying phenomena, ranging from helioseismology to exo-planet searches.

For Cosmic Microwave Background studies the constant elevation of any patch of sky allows integration over days or even months without need for correction of elevation-dependent ground-pickup or atmospheric emission. This unique property of the Poles has been used to great advantage by the Viper[18] and DASI[19] experiments.

At sites away from the South Pole, such as Dome C, sources suffer only a small diurnal elevation change and many remain circumpolar. The sun, moon and planets are variously observable at particular times of the year, although always at relatively low elevation.

The flip-side of this is that not all the sky is visible, and indeed the area of sky that can be seen is significantly smaller than at temperate locations. Partly compensating for this is that by sheer good fortune many of the most significant astronomical objects are well south of the equator—important examples include the Galactic Centre and the Magellanic Clouds. In addition, for most cosmological studies any one piece of the sky is as good as any other—at least if one subscribes to the notion of an isotropic and homogeneous Universe.

3. THE SYNERGY BETWEEN ANTARCTICA AND SPACE.

Antarctic observatories can play an important role alongside space missions. This role is made up of the following main contributions: astronomical measurements before, during, and after the mission, and technology demonstrators.

3.1 Preliminary measurements

The unique observing conditions in Antarctica make it particularly well suited to carrying out preliminary surveys that can identify potential targets and weed out unsuitable sources. Of particular importance here is the enormous field of view that an Antarctic survey telescope can achieve. This results directly from the absence of high altitude turbulence, leading to an isoplanatic angle that can be orders of magnitude larger than at temperate sites. Recent work by Lawrence[20] highlights the impressive speed advantage that a survey telescope in Antarctica could enjoy over competitors at temperate locations.

3.2 Complementary measurements

In some cases it may be possible to perform some aspects of a proposed space mission from the ground, with little or no loss of capability. This enables the spacecraft to be designed to perform only those measurements that must be done from space. The result can be substantial cost savings, or a re-direction of effort into more mission-critical areas. For example, even a 2-metre telescope at the South Pole can achieve sensitivities within a factor of a few of SIRTF at wavelengths shorter than 5 microns.

3.3 Follow-up measurements

Any successful mission creates more questions than it answers. Earth-based telescopes can follow up these questions immediately, while the next relevant space mission may be years away. This is a powerful argument for having capable Antarctic observatories in place and operating well before the launch of a space craft.

3.4 Technology demonstrators

Between now and the next-generation far-infrared/sub-mm space missions lies the need to develop and validate new technologies. As discussed above, there are many qualities of the high plateau Antarctic sites that render them uniquely suitable for this task. This is particularly so for interferometer experiments, where Antarctica can provide an attractive combination of a cold, stable environment, unlimited flat real estate, and a uniquely transparent and stable atmosphere.

Digging a trench through snow is a lot easier than digging it through rock. Snow is a superb thermal insulator so, a few metres below the surface, the temperature remains remarkably constant year round. In such a trench could be placed interferometer delay lines and other critical optical components, obviating the need for elaborate temperature control systems[21]. This, combined with the absence of a high altitude jet stream, makes Antarctica a particularly attractive location for the interferometer test-beds that will be needed for SIM, TPF and Darwin.

4. LOGISTICAL CONSIDERATIONS

At first sight it may seem that the difficulties of building an observatory in Antarctica represent a major obstacle. However, this is not the case. It is no harder than, but rather different to, building an observatory at a temperate site. The temperature range encountered throughout the year is about 60^{O}C, comparable to the range experienced in some inland US cities. The observatory must simply be designed for a mean temperature of around -50^{O}C, rather than $+5^{O}$C, and this is a straightforward matter of appropriate materials choice and following good engineering practice.

While the difficulties of building a telescope in Antarctica may seem obvious, there are also considerable logistical advantages. For example, the South Pole is currently the only observatory site in the world that is within a few hundred metres of a heavy-lift airport. (Concordia Station, now under construction at Dome C, will be the second.) Wind speeds on the Plateau are very low, and peak speeds for which structures need to be designed are also correspondingly low. Because the temperature never rises above zero, there is no liquid water and hence no re-freezing problems.

In addition, it never rains and there is no dust. A dome, if required at all, need only be of light-weight construction. The air is the cleanest on earth, which, together with the extremely low temperatures, implies a very long life for the mirror coatings. The high plateau is geologically stable, with negligible seismic activity. Security is not an issue, nor is public liability insurance. These considerations, together with the fact that the unique atmospheric turbulence profile renders multi-conjugate adaptive optics unnecessary, have also led to the suggestion the next generation of extremely large telescopes could actually be built more cheaply in Antarctica that at any other location on earth.

Indeed, it may be that it is *only* technologically feasible to build 50 – 100 metre telescopes if they are built on the Antarctic Plateau.

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REFERENCES

1. M.C.B. Ashley, M.G. Burton, J.W.V. Storey, J.P. Lloyd, J.W. Briggs and D.A. Harper, "South Pole observations of the near-infrared sky brightness", *PASP,* **108**, pp. 721 – 723, 1996

2. H.T. Nguyen, B.J. Rauscher, S.A. Severson, M. Hereld, D,A. Harper, R.F. Loewenstein, F. Mrozek, and R.J. Pernic, "The South Pole near-infrared sky brightness", *PASP,* **108**, pp. 718 – 720, 1996

3. M.A. Phillips, M.G. Burton, M.C.B. Ashley, J.W.V. Storey, J.P.Lloyd, D.A. Harper and J. Bally, "The near-infrared sky emission at the South Pole in winter", *Astrophys J.,* **527,** pp. 1009 – 1022, 1999

4. J.S. Lawrence, M.C.B. Ashley, M.G. Burton, P.G. Calisse, J.R. Everett, R.J. Pernic, A. Phillips & J.W.V. Storey, "Operation of the Near Infrared Sky Monitor at the South Pole", *PASA,* submitted

5. C.H. Smith and D.A. Harper, "Mid-infrared sky brightness testing at the South Pole", *PASP,* **110,** pp. 747 – 753, 1998

6. M.A. Chamberlain, M.C.B. Ashley, M.G. Burton, A. Phillips, J.W.V. Storey and D.A. Harper, "Mid-Infrared Observing Conditions at the South Pole", *Astrophys. J.,* **535,** pp. 501 – 511, 2000

7. K.J. Brooks, M.G. Burton, J.M. Rathborne, M.C.B. Ashley and J.W.V. Storey, "Unlocking the Keyhole – H_2 and PAH emission from molecular clumps in the Keyhole Nebula", *M.N.R.A.S.,* **319**, pp. 95 – 102, 2000

8. J.M. Rathborne, M.G. Burton, K.J. Brooks, M. Cohen, M.C.B. Ashley, and J.W.V. Storey, "Photodissociation regions and star formation in the Carina nebula", *M.N.R.A.S.,* **331**, pp. 85 – 97, 2002

9. C.H. Townes & G. Melnick, "Atmospheric transmission in the far-infrared at the South Pole and astronomical applications", *PASP,* **102,** pp. 357 – 367, 1990

10. R.A. Chamberlin, A.P. Lane and A.A. Stark, A.A., "The 492 GHz atmospheric opacity at the Geographic South Pole", *Astrophys. J.,* **476**, pp. 428 – 433, 1997

11. R.A. Chamberlin, "South Pole submillimeter sky opacity and correlations with radiosonde observations", *JGR,* **106 20,** pp. 101 – 108, 2001

12. O.P. Lay and N.W. Halverson, "The impact of atmospheric fluctuations on degree-scale imaging of the cosmic microwave background", *Astrophys. J.,* **543,** pp. 787 – 798, 2000

13. P.G. Calisse, private communication.

14. R.D. Marks, J. Vernin, M. Azouit, J.W. Briggs, M.G. Burton, M.C.B. Ashley, and J.F. Manigault, "Antarctic site testing – microthermal measurements of surface-layer seeing at the South Pole", *A&A Suppl,* **118,** pp. 385 – 390, 1996

15. R.D. Marks, J. Vernin, M. Azouit, J.F. Manigault and C. Clevelin, "Measurement of optical seeing on the high antarctic plateau", *A&A Suppl,* **134**, pp. 161 – 172, 1999

16. R.D. Marks, "Astronomical seeing from the summits of the Antarctic plateau", *A&A,* **385,** pp. 328 – 336, 2002

17. T. Travouillon, M.C.B. Ashley, M.G. Burton, J.W.V. Storey and R.F. Loewenstein, "Atmospheric turbulence at the South Pole and its implications for astronomy", *A&A,* submitted

18. K. Coble et al., "Anisotropy in the Cosmic Microwave Background at Degree Angular Scales: Python V Results", *Astrophys. J. Lett.,* **519,** pp. L5 – L8, 1999

19. N.W. Halverson et al, "Degree Angular Scale Interferometer First Results: A Measurement of the Cosmic Microwave Background Angular Power Spectrum", *Astrophys. J,* **568,** pp. 38 – 45, 2002

20. J.S. Lawrence, "Adaptive optics performance of Antarctic telescopes", *J. Opt. Soc. Am. A*, submitted

21. J.P. Lloyd, B.R. Oppenheimer and J.R. Graham, "The Potential of Differential Astrometric Interferometry from the High Antarctic Plateau", *PASA,* **18,** pp. 318 – 322, 2002