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The Antarctic Planet Interferometer and the Potential for Interferometric Observations of Extrasolar Planets from Dome C Antarctica

M.R. Swain[1], V. Coude du Foresto[2], and F. Vakili[3],

[1] Jet Propulsion Laboratory, 4800 Oak Grove Drive, MS 171-113, Pasadena, CA 91109, United States e-mail: mark.swain@jpl.nasa.gov

[2] Observatory de Paris au Meudon, France

[3] University of Nice, France

Abstract. We present a concept for studying exoplanets using an infrared interferometer with a focused instrument design at the best accessible site on Earth.

Key words. Interferometry – Extrasolar Planets

1. Introduction

We present a concept for the Antarctic Planet Interferometer (API) and discuss the improvements in interferometric detection and characterization of extrasolar planets by exploiting the unique potential of the best accessible site on Earth for thermal infrared interferometry. The best sites on the Antarctic plateau are excellent for infrared interferometry because the atmosphere at these locations is characterized by slow, low-altitude turbulence, low water vapor content, and low temperature. The three high-precision interferometric techniques under development for extrasolar planet detection and characterization (astrometry, differential phase and, nulling) all benefit substantially from these unique properties of the Antarctic plateau atmosphere. At the best sites on the Antarctic plateau, such as the Concordia base at Dome C, an interferometer with two meter diameter class apertures has the potential to deliver space-like performance.

There are four key properties of the Antarctic atmosphere that are beneficial to infrared interferometry.

1. **Cold:** Instrument temperatures of 200 K substantially reduce the thermal infrared instrument background in the 3–5 μm band. This improves the interferometer sensitivity.
2. **Dry:** The Antarctic plateau is the driest place on Earth. Difficulties arising from the wet atmosphere dispersion are minimized, and the infrared sky transparency is improved.

3. **Stable:** Fluctuations in the thermal background and differential dispersion are minimized. This is especially beneficial to the nulling the differential phase modes.
4. **Low/Slow Turbulence:** The atmospheric turbulence is primarily confined to a relatively thin, slow moving boundary layer. This benefits the phase referencing and astrometry interferometry modes. It also increases the atmospheric coherence time.

In addition, at the best sites on the plateau, such as the Concordia station, the seeing is very good. This is because the turbulent layer at Concordia is thiner, slower, and likely involves weaker turbulence than other developed sites on the Antarctic plateau.

2. Thermal Infrared

The improvement in the thermal background limited sensitivity associated with reducing the instrument temperature from 290 to 200 K is a factor of ~30, ~20, ~10, and ~3 in the K, L, M, and N bands, respectively (see Table 1). This improvement comes from (1) the reduction in black body radiation from the telescope due to reduced temperature and (2) a decrease in the sky emission. When compared to a site like Mauna Kea, the reduction in sky emission at Antarctic plateau locations is a factor of 10 to 30 between the K and N bands (Chamberlain *et al.* (2000) and Phillips *et al.* (1999)). The result of reduced thermal and sky noise is to give 2 meter class telescope sensitivity, which is comparable to an 8 meter class telescope at more typical locations. Further, the slow turbulence increases the interferometric coherence time, which increases the interferometer fringe tracking sensitivity. At Concordia, the combination of low temperature, decreased sky emission, and a longer coherence time increases the atmospherically limited phase-coherent sensitivity by about 4.7 and 2.5 magnitudes in the K and N bands, respectively, relative to a site like Mauna Kea.

3. Interferometry

In good weather, the atmospheric turbulence above the Antarctic plateau is confined to a thin boundary layer a few tens to hundreds of meters above the ice. This creates a large isoplanatic angle (estimated to be ~30 arcmin at Dome C), which greatly increases (by a factor of 3000) the number of phase calibrators. Confining the turbulence to a thin boundary layer also dramatically increases the differential astrometric accuracy (Lloyd *et al.* (2002)), which is proportional to the integral of $h^2 C_N^2$.

Differential phase and nulling are both adversely effected by the presence of water vapor. As both techniques must make a water vapor correction, the water vapor limited sensitivity is proportional to (t_{PWV} * SNR)/PWV where PWV = precipitable water vapor and t_{PWV} = timescale for water vapor fluctuations. In good weather, the PWV at Mauna Kea is about 1000 μm vs about 300 μm at the South Pole (Wilner (1999); Stark *et al.* (2001)). Recent measurements by Storey indicate similar PWV levels at Dome C. Assuming the timescale for water vapor fluctuations scales as the interferometer coherence time, the water-vapor-limited sensitivity improves over a site like Mauna Kea by a factor of about 25 (assuming comparable SNR). Because of the mechanics of the Antarctic atmosphere, this likely overestimates the water vapor fluctuations (Lay and Halverson (2000)), and the actual improvement would likely be better.

4. Atmospheric Estimates

For sensitivity estimates, we have assumed an instrument at 200 K with an emissivity of 0.5 and $A \times \Omega = \lambda^2$, an optical efficiency of 0.1, and 1.8 m diameter telescopes. To estimate the interferometric properties of the Dome C atmosphere, we have taken the C_N^2 profile (Type 1; Travouillon *et al.* (2003)) derived from the best 18% South Pole atmosphere data from SODAR measurements. This C_N^2 profile was scaled, based on wind speed, to a thinner layer, and the strength of the C_N^2 terms was scaled based on the wind speed dependent relation between C_T^2 and C_N^2 found at the South Pole (Travouillon *et al.* (2003)). The assumption is that the thermal turbulence above the 110 m thick layer is zero, which is implied by estimates based on balloon-borne microthermal data using the Richardson equation (Lloyd *et al.* (2002)). The synthetic Dome C C_N^2 profile was then integrated to derive r_0 and the astrometric accuracy. A baseline of 250 m and an averaging time of 1 hr was assumed for the astrometric accuracy estimate. The one micro-arcsecond astrometric sensitivity level is an interesting threshold; it is the size of the astrometric signature produced by Earth if our solar system were viewed from 3 pc. The quantities listed in Table 2 are calculated for zenith using

$$r_0 = [0.423(2\pi/\lambda)^2 \int dhC_N^2(h)]^{-3/5}, \quad (1)$$

$$\tau_0 = r_0/v, \quad (2)$$

$$h_{eff} = \left(\frac{\int dhC_N^2(h)h^{5/3}}{\int dhC_N^2(h)}\right)^{3/5}, \quad (3)$$

$$\theta_0 = 0.314\frac{r_0}{H_{eff}}, \quad (4)$$

$$\sigma_I^2 = 19.12\lambda^{-7/6} \int dhC_N^2 h^{5/6}, \quad (5)$$

and

$$\sigma_\Delta^2 = 5.25t^{-1}B^{-4/3}\theta^2 \int dhC_N^2 h^2 V^{-1}(h) \quad (6)$$

where v is wind speed (m/s), B is baseline (m), t is integration time (s), C_N^2 is the turbulent strength ($m^{-2/3}$), θ is the angular separation for the differential measurement (arcmin), and h is height (m). Here we have used the definition of σ_Δ^2 given by Shao and Colavita (1992). We have used the atmospheric model for Mauna Kea and given by Hardy (1998), and a representative profile of Cerro Paranal given in Lawson (2000).

The estimates for interferometry sensitivity at Dome C make assumptions regarding the atmosphere that clearly need to be tested. For comparison, we have included estimates for atmospheric parameters at the South Pole based on data from Marks *et al.* (1999) with $C_N^2 = 0$ for altitudes greater than 1000 m. J. Storey has deployed a SODAR this season that should be able to estimate the C_N^2 profile in the same way it was measured at South Pole.

5. The API Instrument

We envision an infrared interferometer composed of several ~ two m diameter telescopes with a primary science objective of characterizing extrasolar planets. The instrument would be deployed at Dome C and operated as an international collaboration. The API would be optimized to exploit the unique properties of the site and to enable the high contrast (~1e5) measurements necessary to characterize the atmospheres of giant planets in the habitable zone.

In addition to extrasolar planet science, the API instrument would be capable of other ambitious science programs such as:

- Distance scale - measurement of binary star orbits in LMC.
- Mass transfer in compact binary systems.
- YSO and proto-planetary disk formation.
- Active Galactic Nuclei.
- Star formation and the interstellar medium.
- High angular resolution measurements from 1.5 to 28 μm to provide follow on/complementary science for Hubble, SIRTF, SOFIA, Herschel, and NGST.

The scientific objectives of the API project need to be determined through a discussion between the prospective partners. As this concept is still in the early stages, we hope that new institutional partners will join in establishing these science objectives. In addition, more detailed measurements of integrated atmospheric quantities and characterization of the upper level atmosphere is needed to understand fully the remarkable potential of the site. For example, the strength of high altitude turbulence could impact some details of the instrument design.

An important aspect of the API concept is that it requires no new interferometry specific technology. The VLTI, Keck Interferometer, and LBTI projects have either developed, or are in the process of developing, the necessary technology for the high precision observing modes contemplated for API. This has substantial cost saving implications as typically about half the cost of a ground-based interferometer is software. Given the performance gains enabled by the site, which gives 2 m class telescope sensitivity comparable to 8 m class telescopes, and the fact that the control architecture and software is already developed, a very modest investment has the potential to result in the world's premier infrared interferometer.

6. Conclusions

There are additional advantages of an Antarctic plateau location. The long night results in good instrument thermal stability. Most of the sources observed would be circumpolar, allowing extremely long, continuous observations not possible from other locations. These sources would also be excellent targets for interferometric synthesis imaging as they permit full rotation of the interferometer sampling function. Further, because of potentially similar science goals to projects such as DARWIN and TPF and a near-space environment (due to the extreme temperatures and remote location), the API, located at the Concordia base, could serve as a natural technology development testbed for these missions.

Because Dome C is one of the locations where the katabatic winds originate, the atmosphere at this location is quite remarkable. The combination of low temperature, low wind speed, low elevation turbulence, and low precipitable water vapor make the Concordia base at Antarctic Dome C the best accessible site on Earth for infrared interferometry.

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Sky and Instrument Thermal Infrared Background
Comparing Mauna Kea and Antarctic Dome C

contribution	K		L		M		N	
location	MK	DC	MK	DC	MK	DC	MK	DC
N_{sky} (photons/sec)	255	8.5	2.0e5	6.7e3	1.5e7	7.5e5	4.2e8	4.2e7
N_{ITB} (photons/sec)	6006	0.4	4.4e6	7.2e3	3.5e8	3.7e6	5.5e10	7.2e9
N_{total} (photons/sec)	6261	8.9	4.6e6	1.4e4	3.7e8	4.5e6	5.5e10	7.2e9
NEP_{total} (photons/sec$^{1/2}$	79	3	2.1e3	1.2e2	1.9e4	2.1e3	2.4e5	8.5e4
Dome C advantage	26.6		18.2		9.1		2.7	

Table 1. Estimates for the infrared sky and instrument background in the primary thermal infrared bands. These estimates assume an instrument transmission of 10%, an instrument emissivity of 50%, an instrument temperature of 290 K for Mauna Kea (MK), and an instrument temperature of 200 K for Dome C (DC). The estimates are for a single mode of a diffraction limited optical system with $A\Omega = \lambda^2$. N_{sky} is the number of photons/second from the sky, N_{ITP} is the number of photons/sec from the instrument thermal background (ITB), and $N_{total} = N_{sky} + N_{ITB}$. The noise equivalent power (NEP) is the shot noise from the sky and instrument thermal background. The sensitivity advantage of Dome C is estimated by taking the ratio of the NEP at the two locations; this is a lower limit to the sensitivity advantage of Dome C because it does not account for the reduced sky background fluctuations which make longer integrations with SNR$\sim 1/t_{int}$ possible than at other sites. For purposes of this calculation, the infrared bands have been taken as 2.0–2.4 μm (K), 3.3–3.6 μm (L), 4.4–5.2 μm (M), and 10.0–12.0 μm (N).

Interferometric Atmospheric Parameters

parameter	unit	Dome C	South Pole	Mauna Kea	Cerro Paranal
visual seeing	arcseconds	0.36	0.91	0.66	0.40
effective wind speed	m/s	4.4	12.4	13.3	30.0
σ_I^2 2.2 μm	(variance)	0.016	0.051	0.20	0.113
r_0 2.2 μm	cm	169	67	93	154
τ_0 2.2 μm	sec	0.38	0.05	0.07	0.05
θ_0 2.2 μm	arcmin	30.7	4.8	0.1	0.2
h_{eff} 2.2 μm	m	59	150	7303	6906
σ_Δ 2.2 μm	μarcsec (hour)$^{-1/2}$	1.7	5.5	199	155

Table 2. Estimated atmospheric parameters derived from integrating C_N^2 and wind speed profiles. Published data were used for South Pole, Mauna Kea, and Cerro Paranal. A synthetic profile was created for Dome C using the South Pole SODAR data; the synthetic profile (which assumes $C_N^2 = 0$ above 110 m) provides results consistent with limited summer DIMM and winter SODAR measurements. The astrometric accuracy is estimated over a 20 arcsec angle. For comparison, South Pole atmospheric quantities are also estimated using balloon data (where we have assumed $C_N^2 = 0$ above 1000 m).