Antarctic Planet Interferometer

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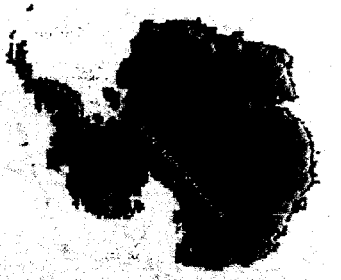
Mission Statement

The purpose of API is to characterize extrasolar Jovian planets, their environments and formation mechanisms, and detect ~ Earth mass extrasolar planets using interferometric methods from the best accessible site on earth. The unique properties of the atmosphere at Dome C should enable high contrast, high precision interferometric observations in the1.5 to 28 micron region of the spectrum which are substantially better than would be possible from any other accessible place on Earth.

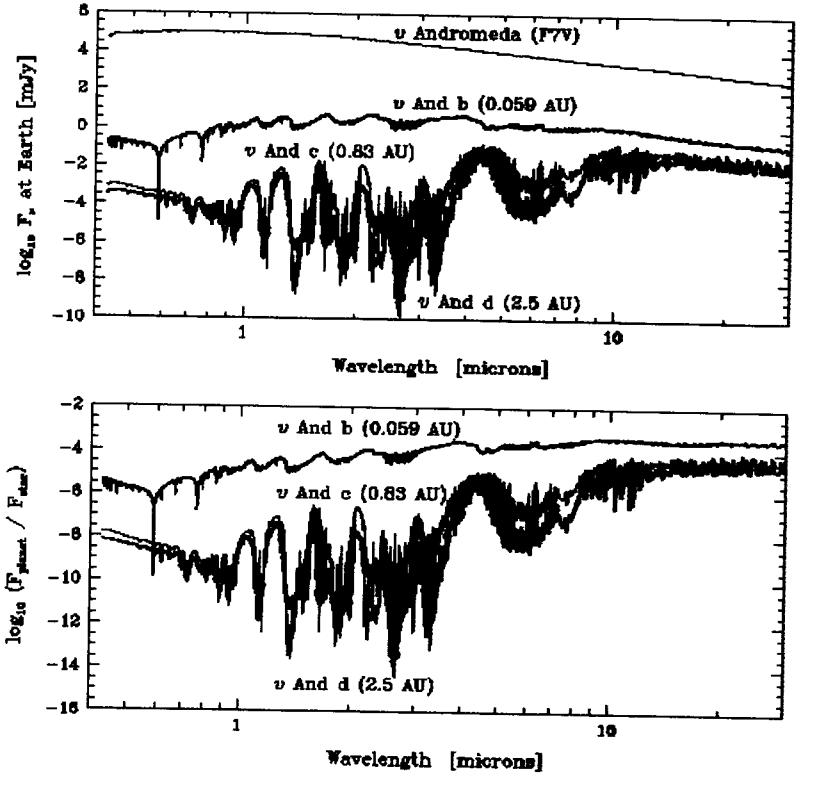
Primary Science Goals



- Detection of Earth mass class planets in habitable zone.
- Jovian class planet characterization.
  - SED measurements 1.5 to 28 microns.
  - Observationally test models for planetary atmospheres.
- Extrasolar planet environments.
  - Dust content of disks.
  - Dust distribution, gaps.
- Study planet formation in protoplanetary disks.
  - Disk chemistry and dynamics.
  - Observe unique signatures of planet formation.

Extrasolar Jovian SED

- Models imply a premium on very high contrast measurements.
- Present models do not have all molecular lines which may relax contrast requirements at particular wavelengths.
- Very high contrast ratio observations (~1e5) required for planets in ~ 1 AU orbits.



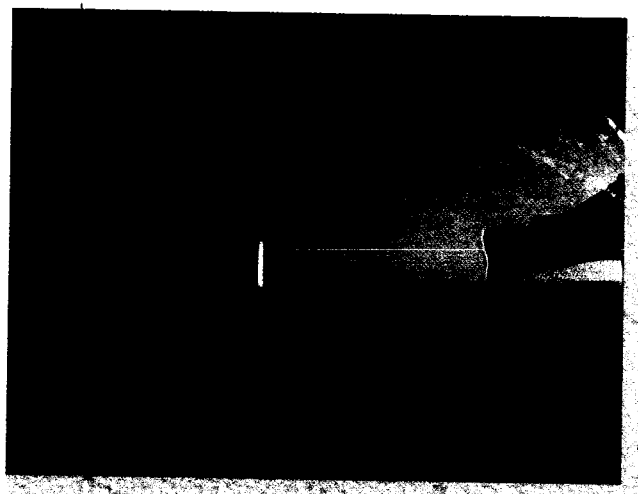
Model by A. Burrows

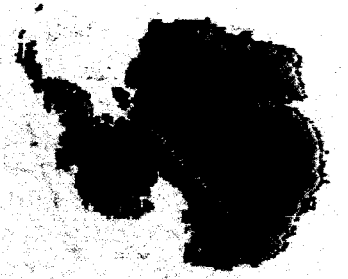
Secondary Science Goals

- YSO and proto-planetary disk formation
- Star formation and the ISM
- Active Galactic Nuclei.
- High angular resolution measurements from 1.5 to 200 microns provide follow on/complementary science for
  - Hubble
  - SIRTF
  - SOFIA
  - Herschel
  - NGST

Instrument Overview

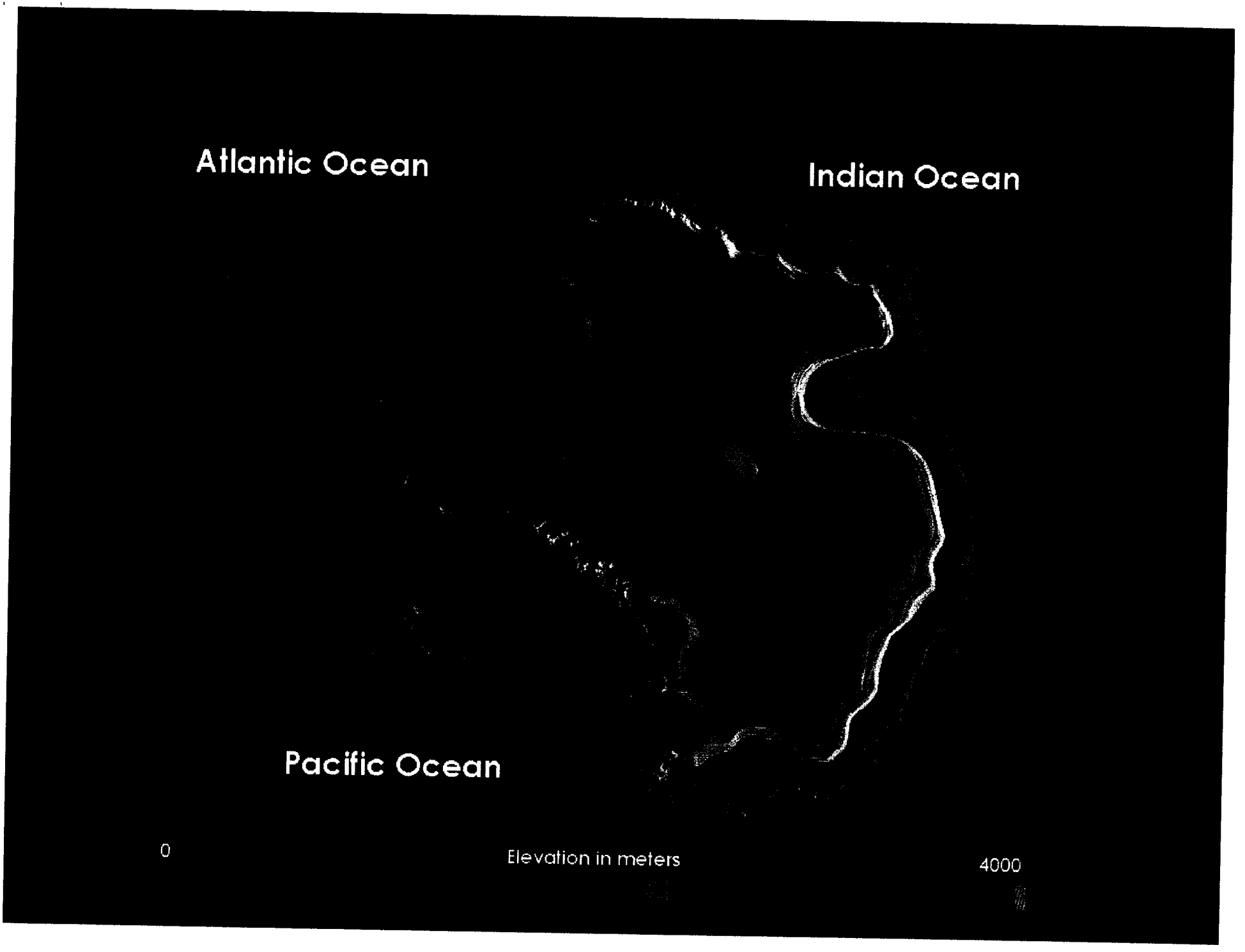
- 2 or more telescopes, 1.8 meter diameter or larger.
- Telescope separation adjustable from few to 250+ meters.
- 1.5 to 200 micron operation (with polarization in selected bands).
- 1.5 to 28 micron "optical" beam train.
- "Dual star" capability.
- V^2, narrow angle astrometry, differential phase, nulling, synthesis imaging, and FTS observing modes.
- Low emissivity, low loss beam train.
- Far-IR/submm beam transport above ground.
- Nominal location – Antarctic Dome C.





Antarctic Dome C

The most space-like environment accessible on Earth.


Atlantic Ocean
Indian Ocean
Pacific Ocean
0
Elevation in meters
4000

Antarctic Plateau Katabatic Wind

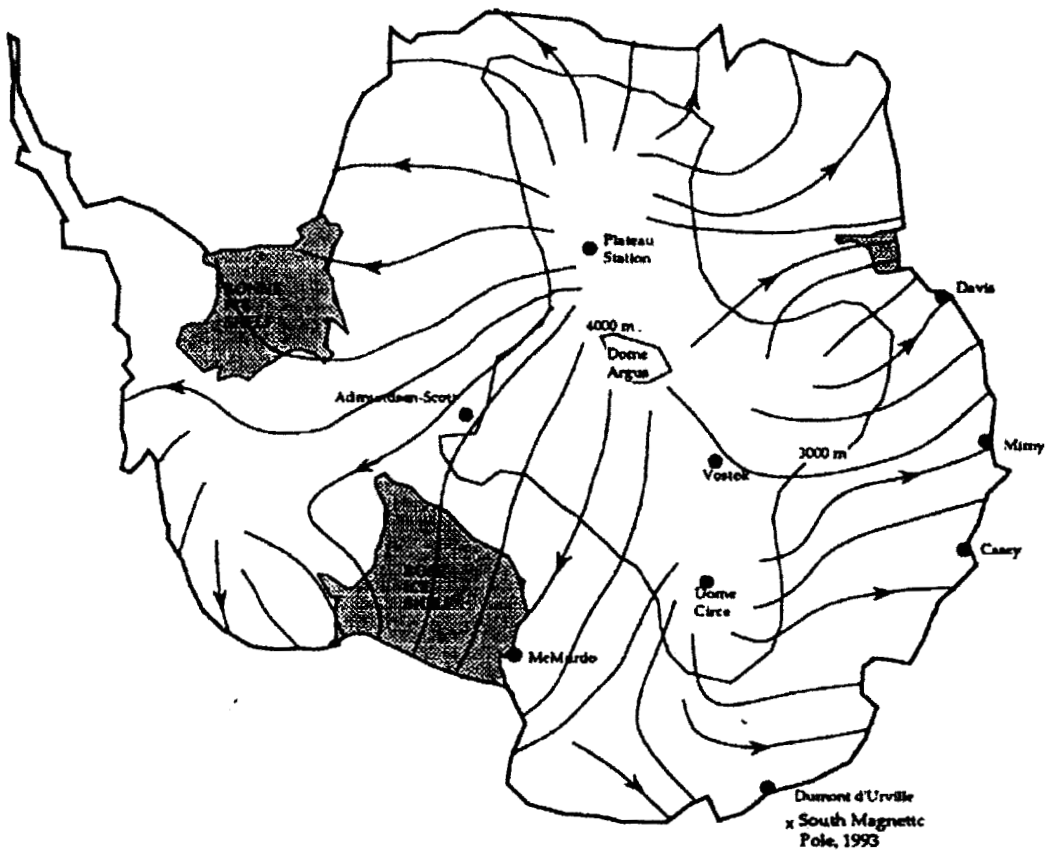
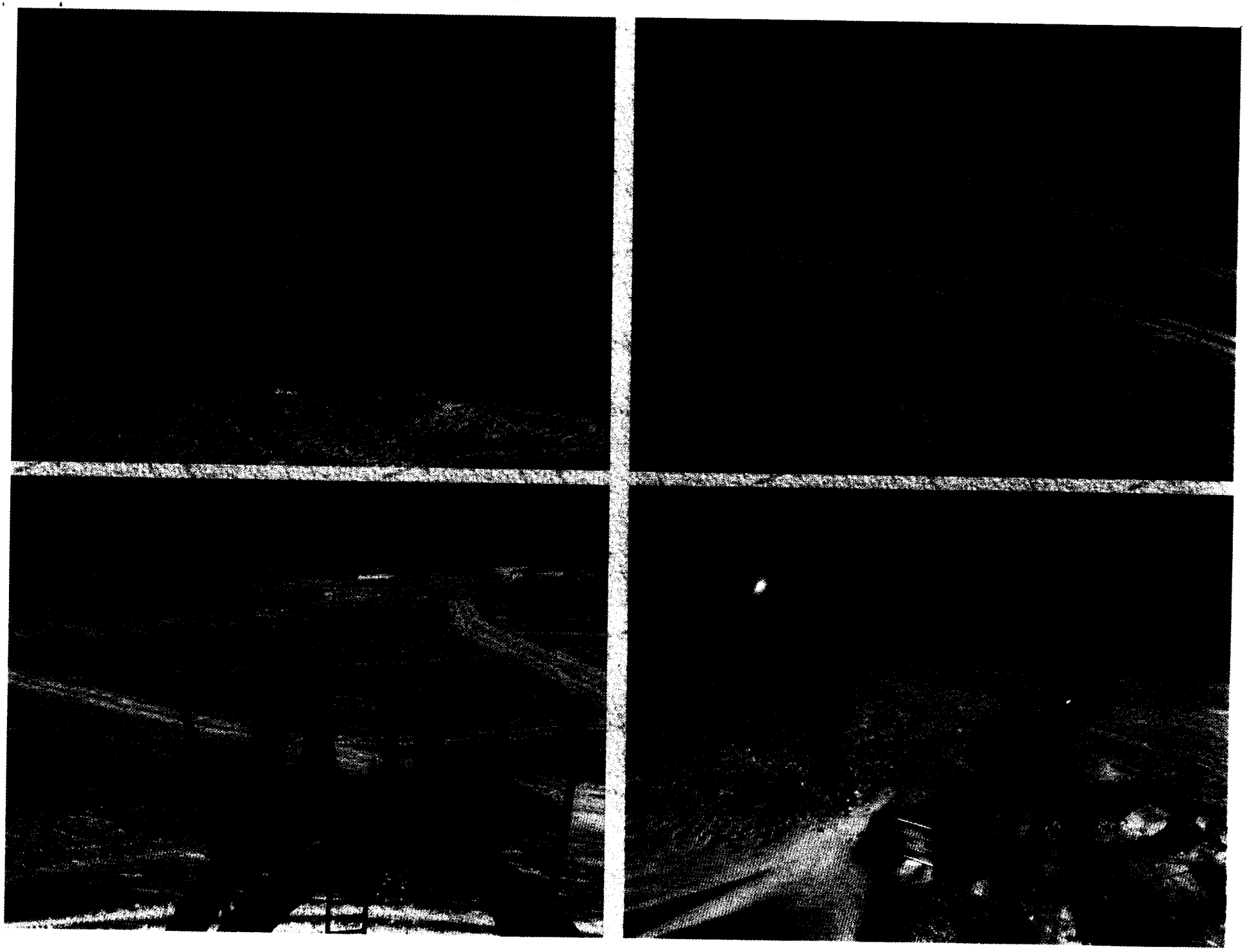
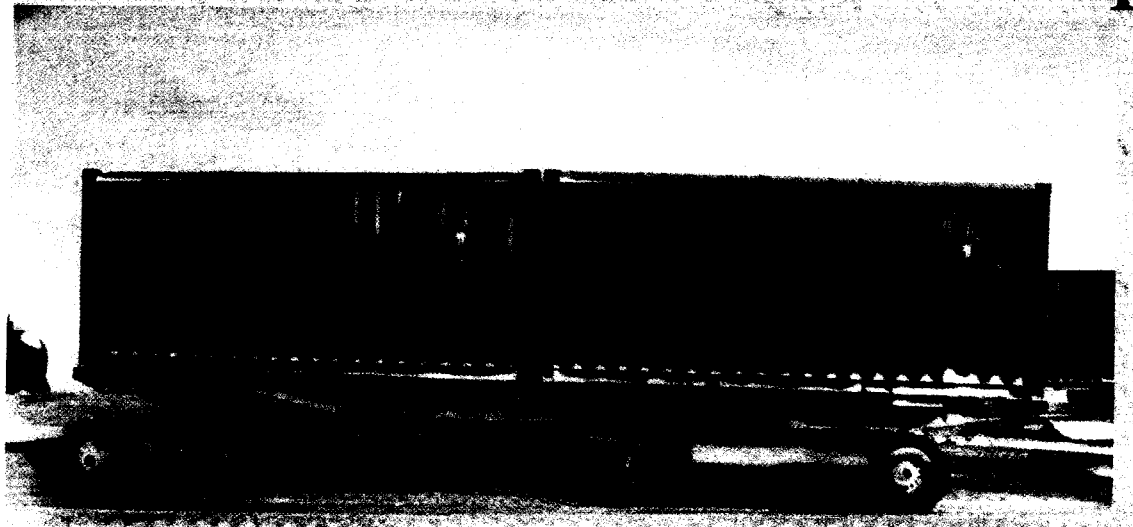


Fig. 8. Contour map of surface wind speeds over Antarctica, from Dopita 1993, based on results of Schwerdtfeger 1984
Marks et al., A&A Sup., 134, 1999



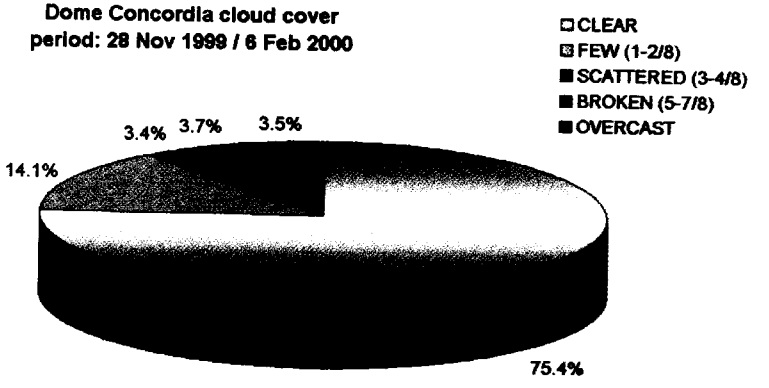
Concordia Base Transport



6 March 2003

Concordia Astronomy Highlights

- Likely best interferometric atmosphere in terms of the combination of τ_0 , r_0 , and θ_0 accessible on Earth.
- ~220 K instrument increases thermal infrared sensitivity.
- Low water vapor content; excellent IR transmission.
  - ~200 microns PWV
- Low thermal infrared sky brightness.
  - 20 to 100 x lower than Mauna Kea
- Low wind speed.
  - 2.8 m/s average



source: Dome Concordia Automated Weather Station
courtesy ENEA Peogetto Antartide

Sensitivity Increase from Reduced Sky and Instrument Background

- Sensitivity increase relative to Mauna Kea including instrument, sky, and read noise.
- Lower Sky background important; sky background limited in K band and in L at 200 K (H band read noise limited).

	H	K	L	M	N
300/220	4	25	11	6	2
300/200	4	31	21	10	3

Ratio of background NEP at Mauna Kea to Dome C including telescope and sky background components.

Area ratio for a 10 m and a 1.8 m telescope is 30.

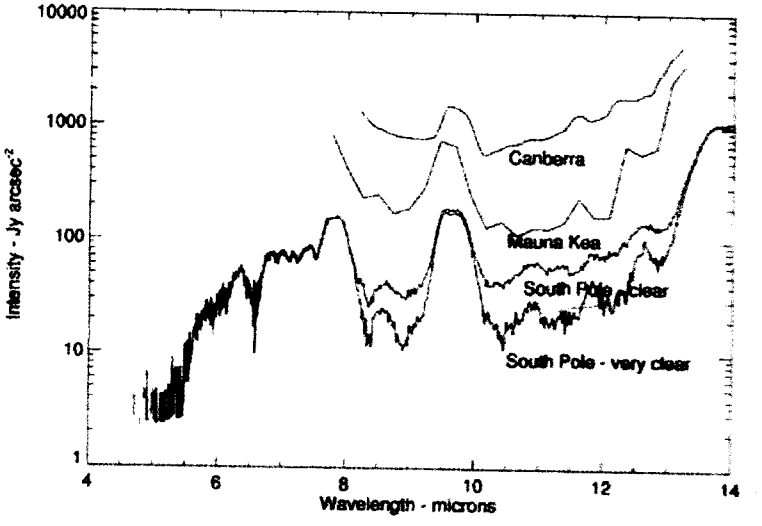
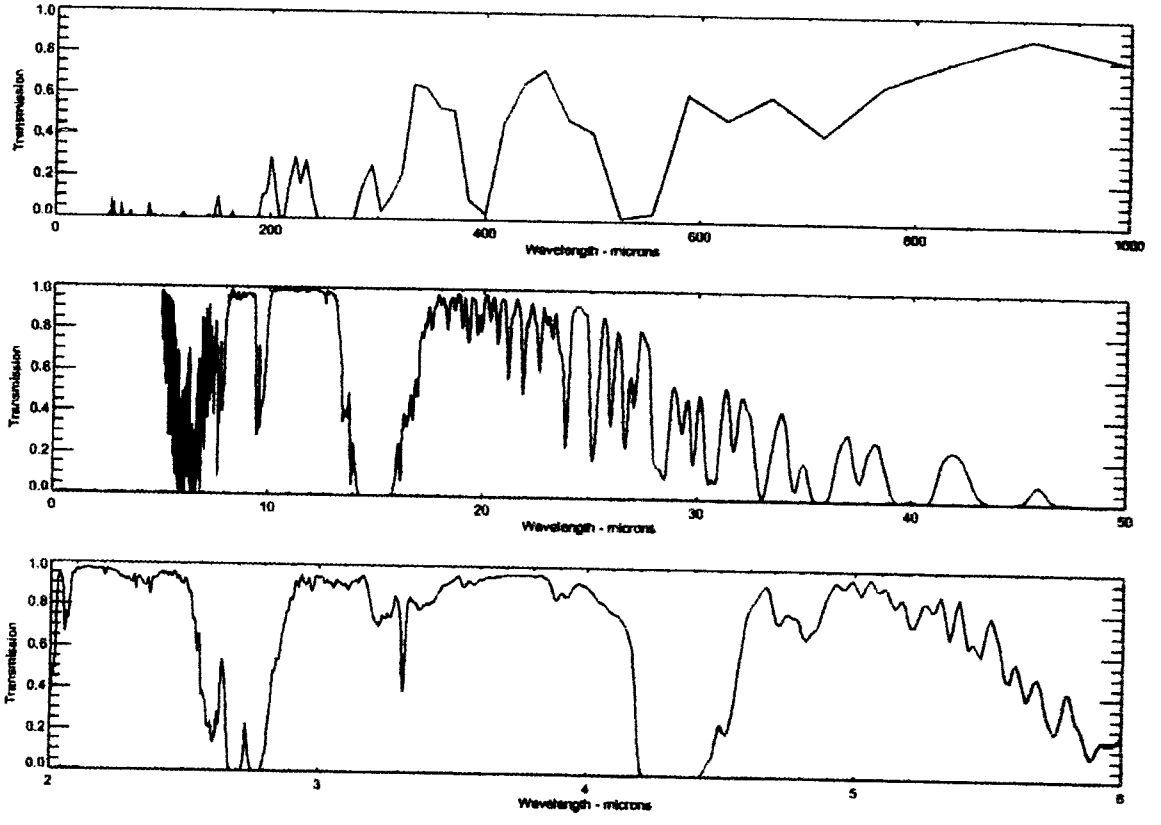


FIG. 13.—Comparison of emission spectra taken in clear conditions at Canberra and Mauna Kea (Smith & Harper 1998) with data from the South Pole (this work).

Chamberlain, ApJ 535, 2000

Increased Wavelength Coverage

- Excellent atmospheric transmission in thermal infrared.
- M band improved over mid latitude site.
- Observing bands in the 18 to 28 micron range.
- Based on good South Pole data; Dome C likely better.

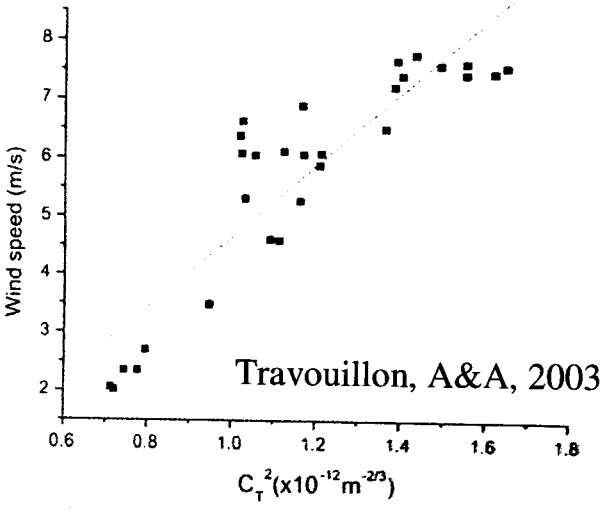


Chamberlain, ApJ, 535, 2000

South Pole C_N^2 scaled to Dome C

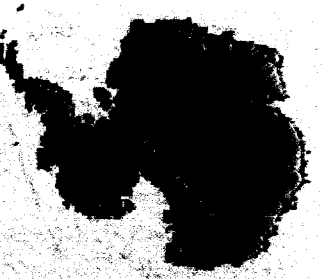
corresponds to best 25% weather

- SP "type 1" atm (70 m layer, 6.0 m/s wind)
  - r_0 (2.2 μm) = 67 cm
  - τ_0 = 0.1 sec
  - θ_0 = 3'
  - σ_δ = 2.5 μ" (1 hr integration, 250 m baseline)
- Dome C (scale SP type 1 to 30 m layer, 2.5 m/s wind)
  - r_0 (2.2 μm) = 151 cm
  - τ_0 = 0.6 sec
  - θ_0 = 30'
  - σ_δ = 0.56 μ"
    - (1 hr integration, 250 m baseline)



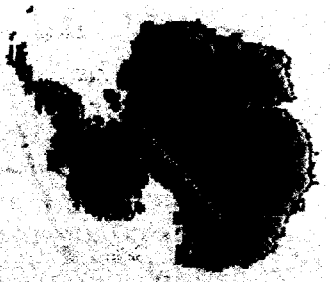
Travouillon, A&A, 2003

Dome C Location Interferometer Sensitivity Improvements



- Astrometry
  - Depends ~ int($h^2 C_N^2$) so low elevation seeing helps
  - Longer baselines possible (than Mauna Kea)
  - Large isoplanatic angle
- Differential Phase
  - Water vapor limited sensitivity ~ σ_{PWV}/SNR ~ 25/SNR
  - photon limited with phase referencing ~ 20 μrad
    (K_{magn} = 5, 10 min int, 1.8 m telescope, 10% throughput)
- Null depth
  - Optimized experiment design (spacing, cross-combiner)
  - Lower thermal background and long integrations
  - Water vapor limited sensitivity scales as differential phase
- Background limited sensitivity improvement ~ sqrt(τ_0)
  - ~ $T_{NEP} \times$ sqrt(τ_0) ~ 4.7 K_{magn} , 2.5 N_{magn}

A Comparison of Sites



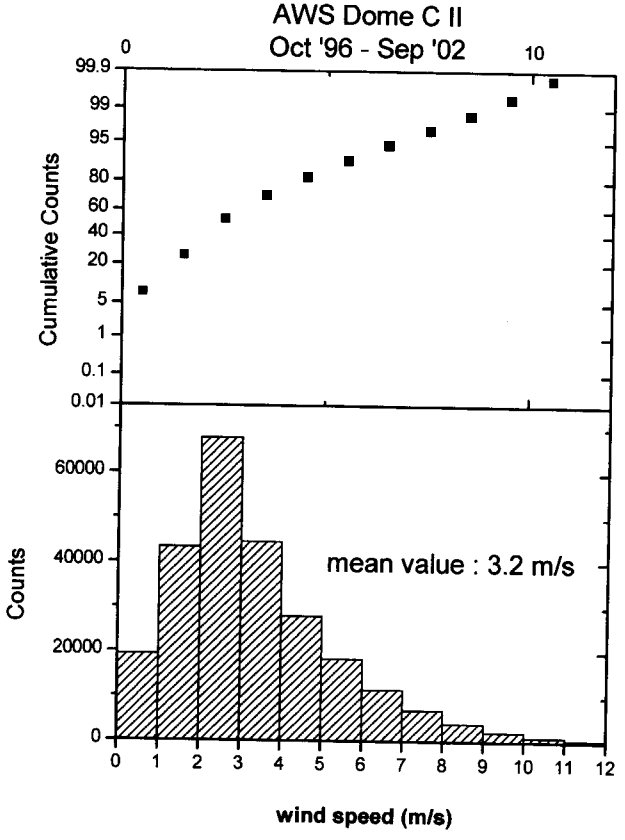
	V_{wind} Grnd/max (m/s)	PWV (μm)	Temp. (K)	R_0 (cm)	Θ_0 (arcmin)	τ_0 (s)	Sensitivity Increase (K_{magn})	σ_δ (μ")	σ_{DP} (mrad)	Null Depth
Mauna Kea	5/12	800	290	150	0.3	0.1	-	30/19*	1	1e3 to 1e4 (N)*
Cero Parannel	5/30	~1400	300	154	0.3	0.05	-	30/15*	~1	~1e5 (N)
South Pole	6/15	400	220	67	3	0.1	+3.7	2.5	0.04	1e5 (M)
Dome C	2.5/8	200	200	150	30	0.6	+4.7	0.6	0.02	1e5 (M)

This table mixes a comparison of sites and instruments in some cases.

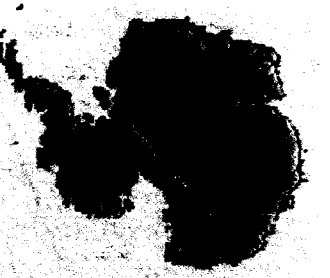
Astrometric accuracy at MK and CP noted with* are shot noise limited.

Dome C Location
Implications for Interferometry

- Excellent thermal infrared sensitivity.
- No adaptive optics necessary.
- Reduced phase fluctuations.
- High-precision observations in M band.
- Increased FOV for phase reference.
- Slower fringe tracking.
- Enables 18-28 micron observations.
- Long continuous integration times.
- Excellent u-v coverage.
- **Reduced systematic errors.**
- **Expanded wavelength coverage.**
- **Increased sensitivity in all "precision modes".**



The Importance of the Free Air Turbulence

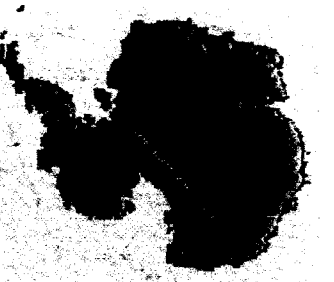


- Ordering of scientific priorities.
  - Which is the most important observing mode?
  - If potential for astrometric accuracy < 1 μ" then astrometry might be the top priority.
- Profound effect on instrument design.
  - ~ 1 μ" class astrometry may require siderostats.
  - Telescope pivot error tolerances become ~ 1 μm for ~ 1 μ" astrometry.
- Dome C still likely best accessible site on Earth.

Antarctic Plateau "Free Air" Turbulence

- The seeing contribution from above the boundary layer is not clear.
  - Data may contain "wake turbulence" and are interpreted as an upper limit.
  - The Richardson number values for the free air over the South Pole are often used to argue fee air seeing component is nearly zero.
- The effect of small amplitude, high altitude free air turbulence can be important to interferometers.
  - may contribute only a few % to r_0 becomes the major contributor to astrometric error and limitation to isoplanatic angle.

The Possible Effect of Free Air Turbulence



- Estimated effect by adding 200 m thick layer with $C_N^2 = 2e\text{-}16\ m^{-2/3}$ at 8 km above South Pole.
- Plausibly consistent with measured South Pole date.

	units	Surface layer	Surface + 8km	8km free air
seeing	"	0.98	1.01	0.19
r_0	cm	62	60	328
τ_0	sec	0.05	0.06	0.21
h_{eff}	m	170	1525	8200
θ_0	'	4	0.4	0.4
σ_δ	μ"/rt(hr)	6.5	71	71

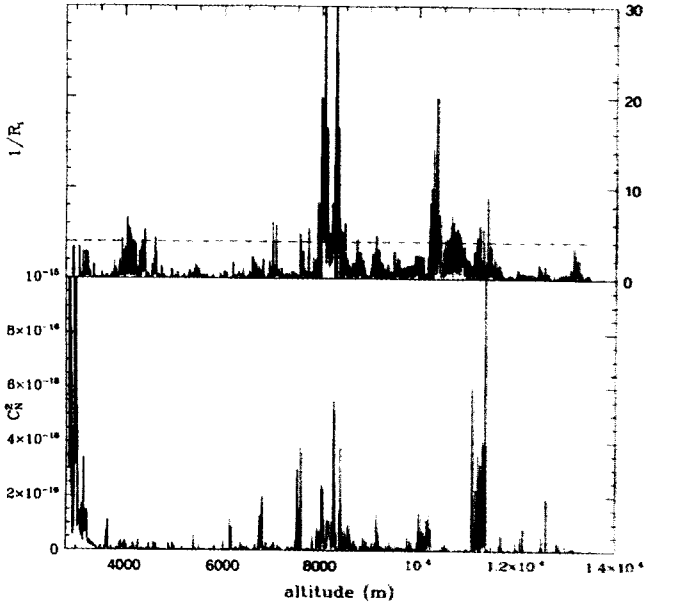


Fig. 6. A comparison of C_N^2 and R_i profiles for 02/07/95. $1/R_i$ is plotted to show more clearly the regions of instability: any peaks above the dashed line satisfy $R_i < 1/4$. The integrated seeing values calculated for this flight were: $\varepsilon_{tot} = 0.83''$. $\varepsilon_{FA} = 0.41''$

Marks et al, A&A Sup., 134, 1999

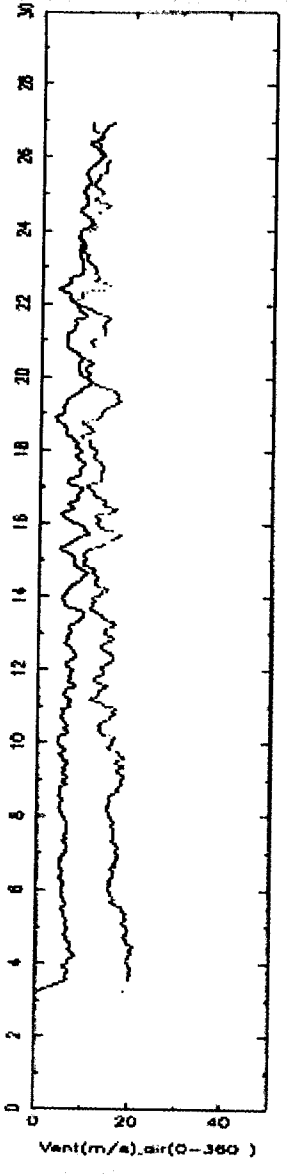
API

present and near future

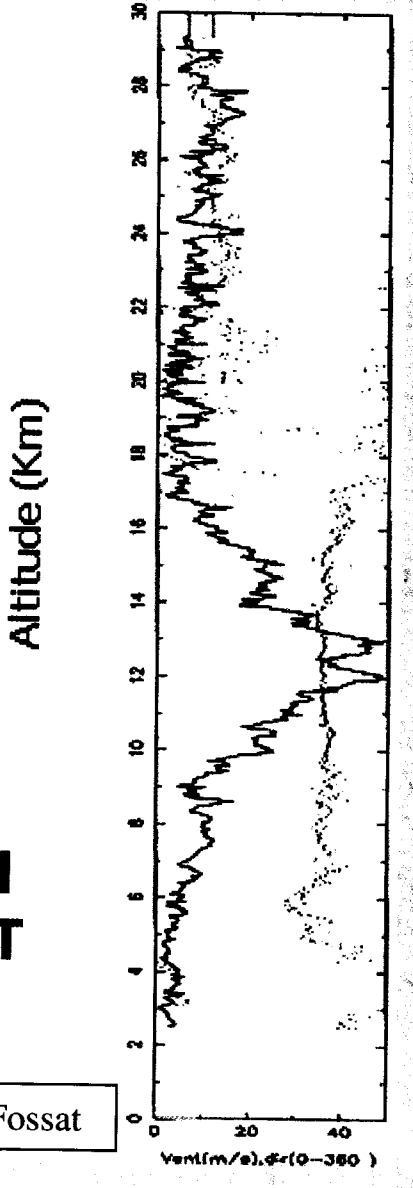
Current Status

- UofA/SAO interested in making the some of the 1.8 meter MMT mirrors available to the API project.
- DIMM/SODAR testing of Dome C ongoing.
- Identifying institutional contributions to API testbed.
- API testbed proposal planned.
- Interferometer design concepts being evaluated.
- Developing ROM cost estimates for API components.
- Building international collaboration.
- Establishing collaboration science priorities.
- Specific proposal strategies being developed.

Dome C Wind Speed



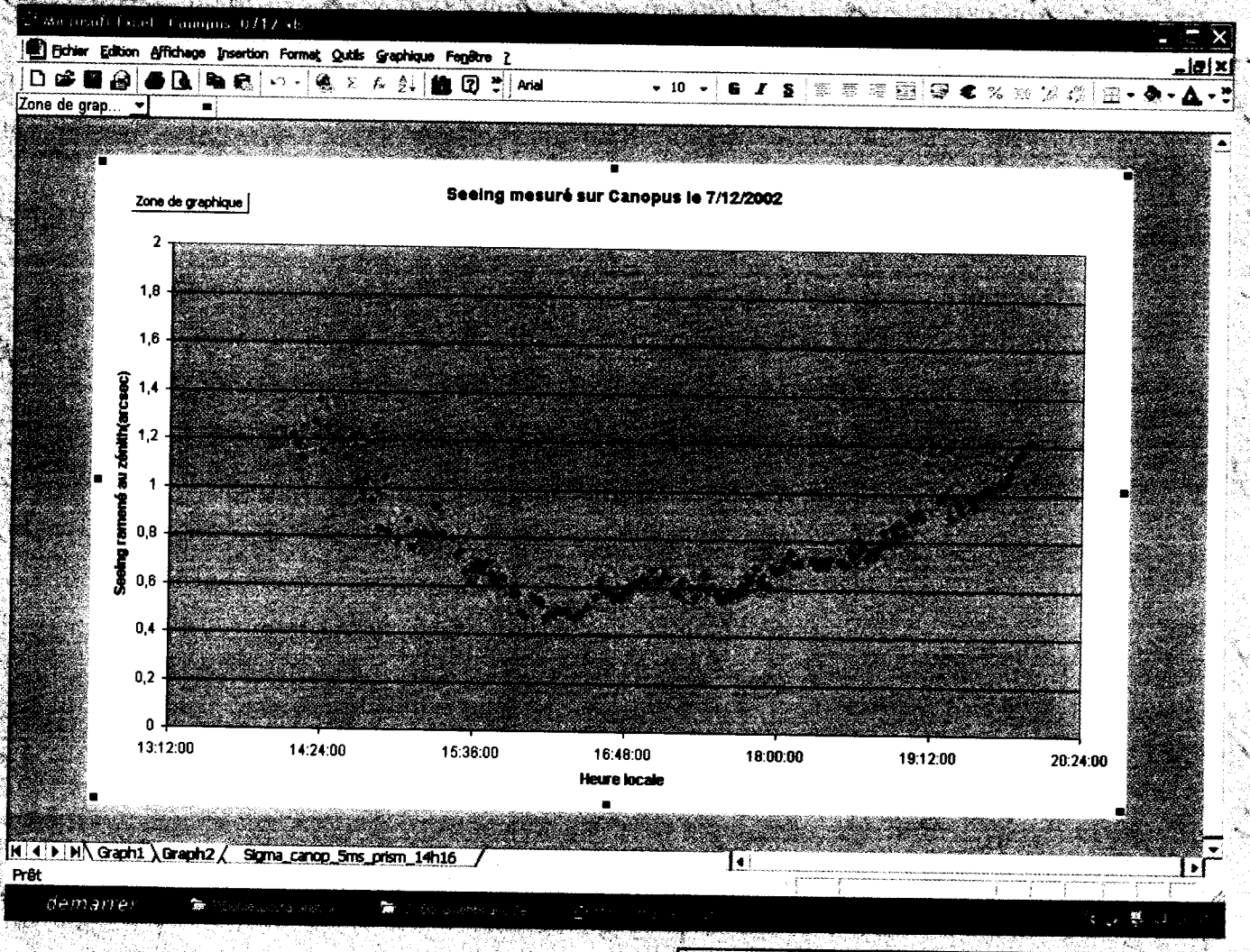
Dôme C
Concordia



Paranal
ESO-VLT

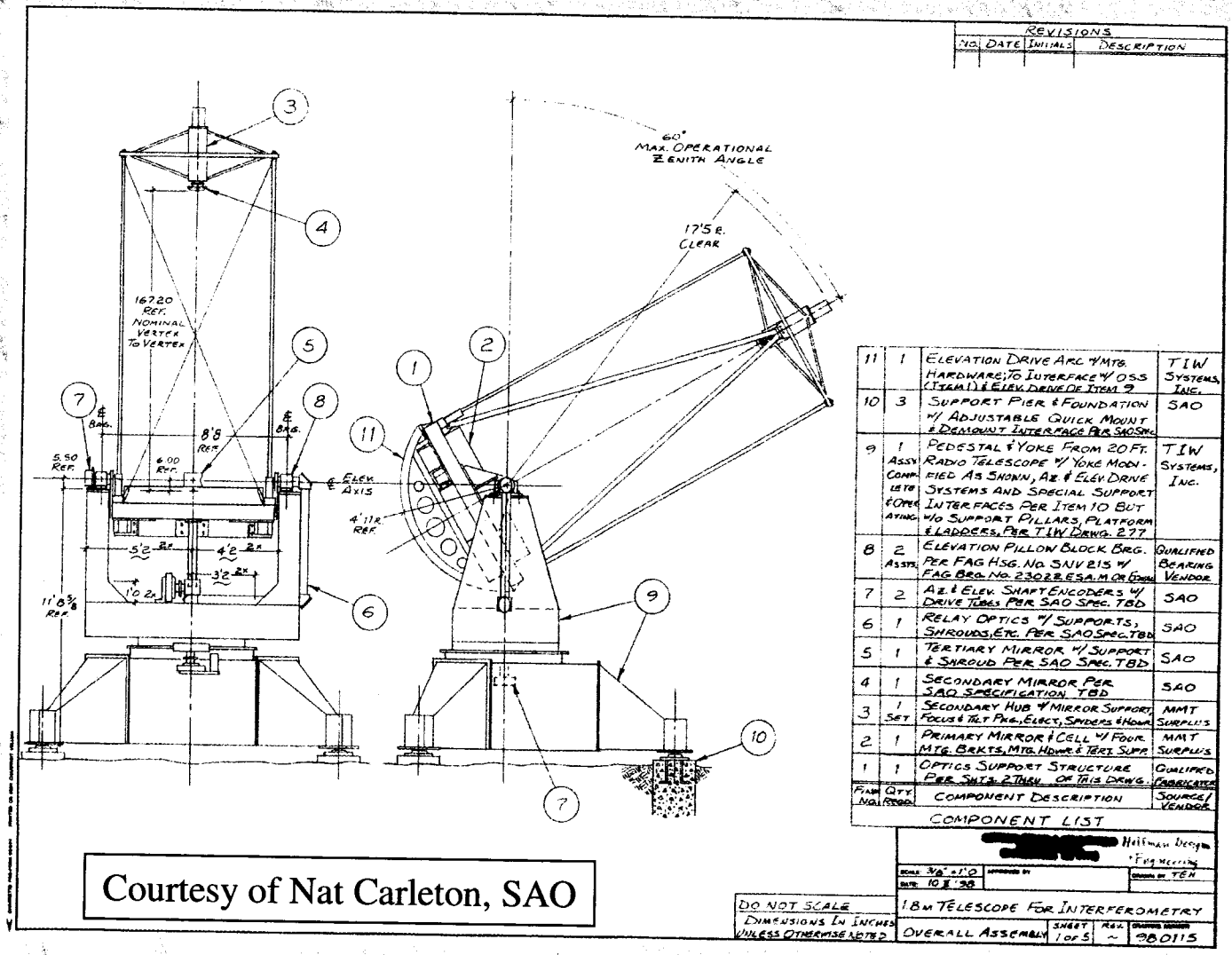
Courtesy of E. Fossat

Typical Summer Seeing



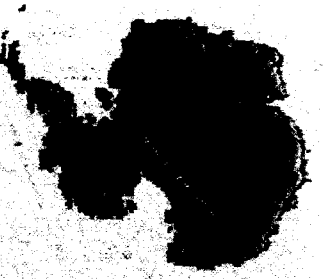
Courtesy of E. Fossat

Transportable Telescope Concept



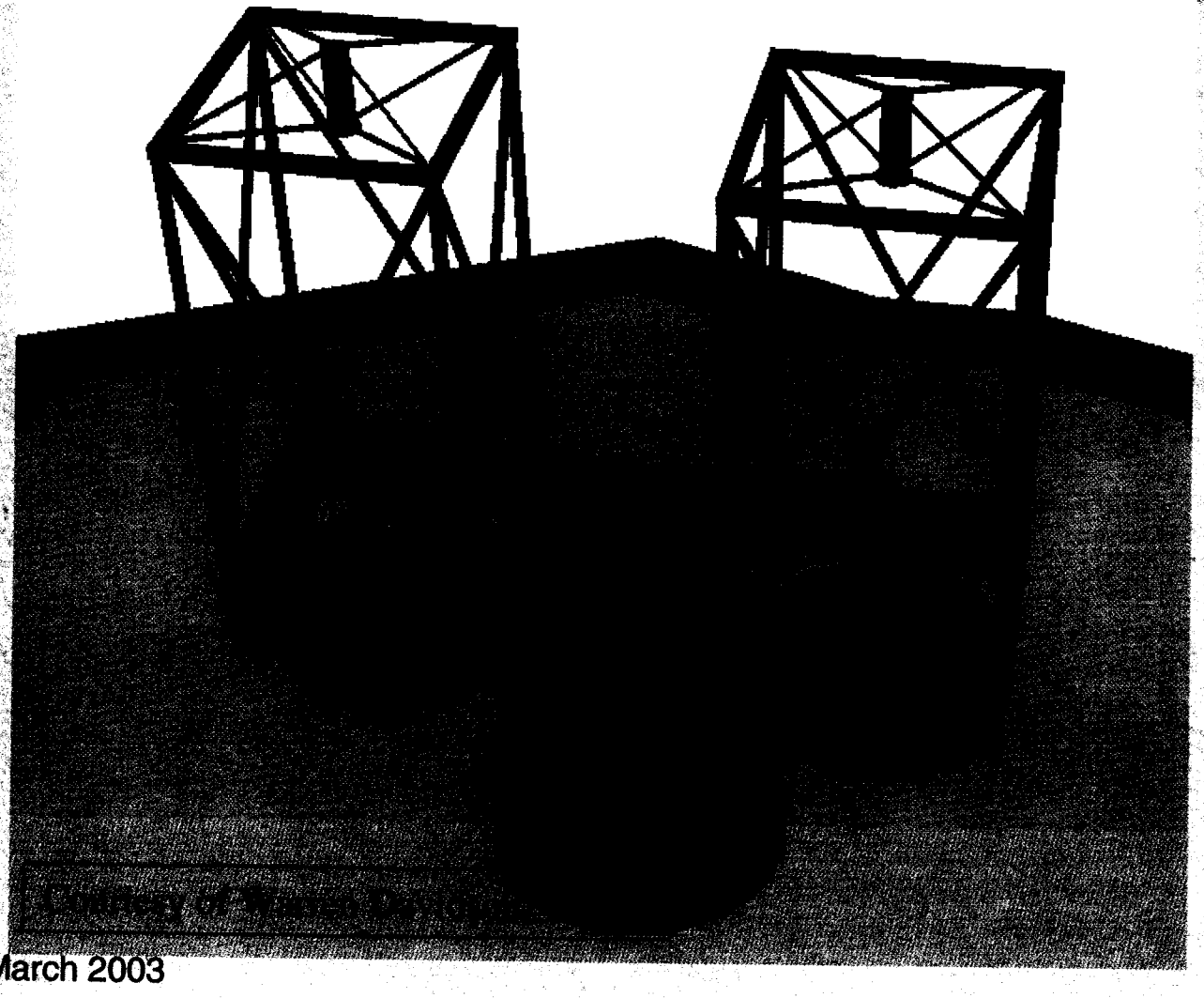
Courtesy of Nat Carleton, SAO

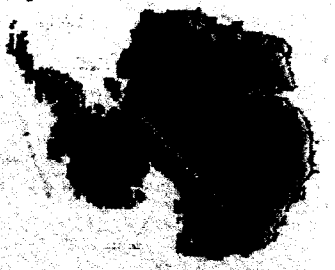
Important Questions



- Which European institutional partners interested?
- Which science priorities?
  - Perhaps this depends on free air turbulence.
- What type of testbed interferometer?
  - A "PTI" scale science capable instrument or a smaller at atmospheric test instrument.
- What consideration should be given to South Pole location?
  - Perhaps easier to get US support; better logistics.
  - Should the testbed be deployed at SP first?
- What is the right scale for the API instrument?

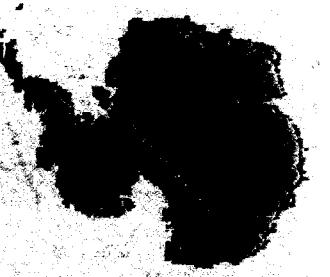
Nulling Telescope Concept





Approach

- Site testing at Dome C.
- API testbed interferometer; operate over winter.
- Build up interferometer unit cell in Northern hemisphere; demonstrate remote operation.
- Modify interferometer unit cell if necessary based on testbed and single telescope experience.
- Deploy IF unit cells at Dome C.
- Retain operational engineering model in Northern hemisphere.



API Testbed Motivation

- Direct test of interferometric atmospheric parameters.
  - Measure the statistics of free air turbulence contribution.
  - Operational demonstration of interferometer in Antarctic conditions.
- Early science results.
  - Could be astrophysics or atmospheric physics depending on scale.
  - Are extensive astrophysical science results required?
- Operational lessons incorporated in API design.
  - Lowers risk of API instrument.
- Build support for a "full scale" API project.
  - What ever the testbed does, *it is essential it work well.*

API Testbed Timeline/Scope

- Explore institutional support (hardware and software contributions).
- Possible June '03 testbed proposal to NSF/OPP.
  - 2 to 3 M over 3 years.
- Build on KI/PTI software and hardware development.
  - Minimize risk, reduce nonrecurring engineering costs.
- Option I – similar to the Mark II interferometer.
  - Optical wavelengths, small baseline.
  - Main goal is characterization of atmospheric properties.
- Option II - similar to a fully "containerized" PTI.
  - 40 cm siderostat at Dome C has comparable sensitivity than Keck outrigger telescope on Mauna Kea.
  - Design for pair of 2 meter telescopes to replace sids for minimal API instrument.

A Possible "Big Picture"

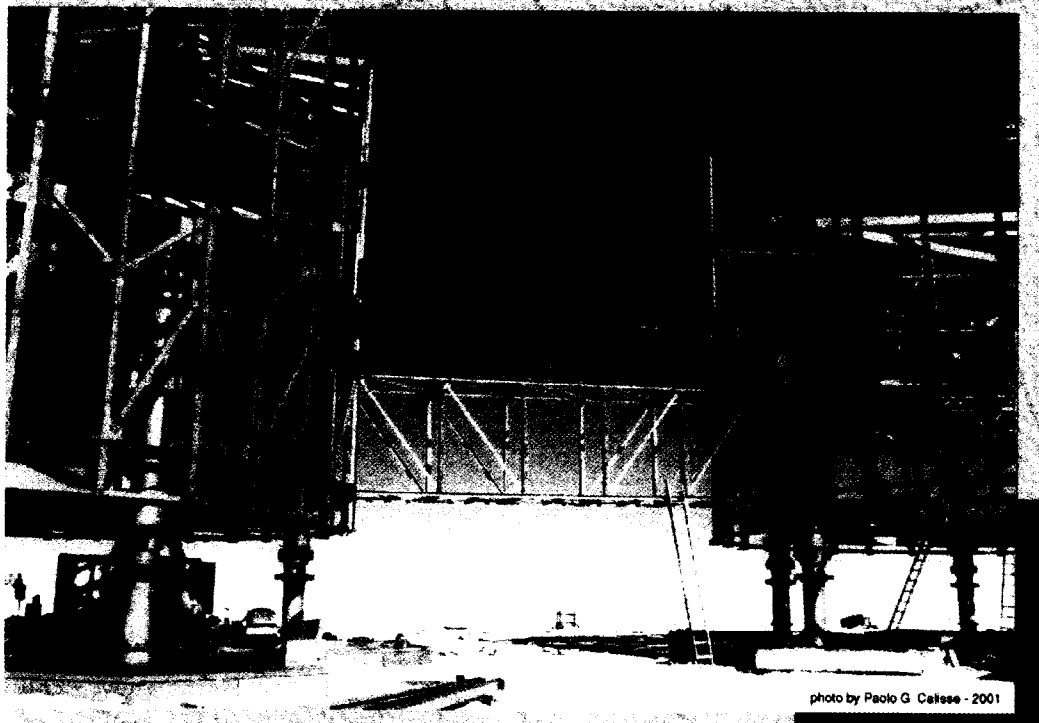
- Exceptional Extrasolar Planetary science.
  - Enabled by the site and optimized instrument design.
- International collaboration.
  - Brings together a broad array of technical expertise.
  - Builds toward a joint TPF/DARWIN mission.
  - Essential for the nominal location.
- Strong institutional team (current partners).
  - Interferometer experience (JPL, SAO, UofA).
  - Antarctic astrometry experience (SAO, UNSW, UofA).
  - Telescope building experience (UofA, SAO).
- Substantial institutional contributions to project.
- NSF potential interest through Office of Polar Programs.
- NASA/ESA potential interest.
  - API as a possible testbed for TPF/DARWIN tech. Development.
  - Complimentary science to TPF/DARWIN mission/s.

Dome C Pictures

Dome C Site Testing

6 March 2003

Dome C Base



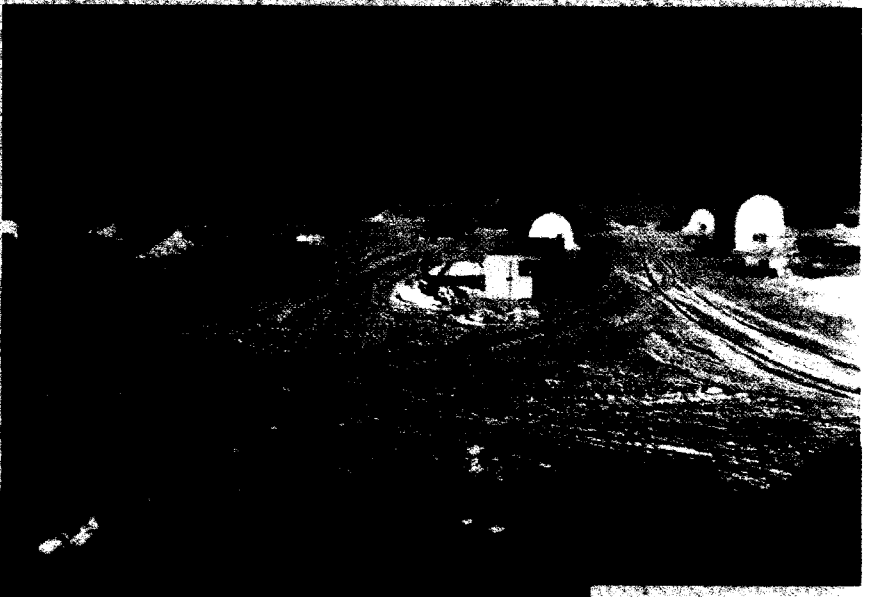
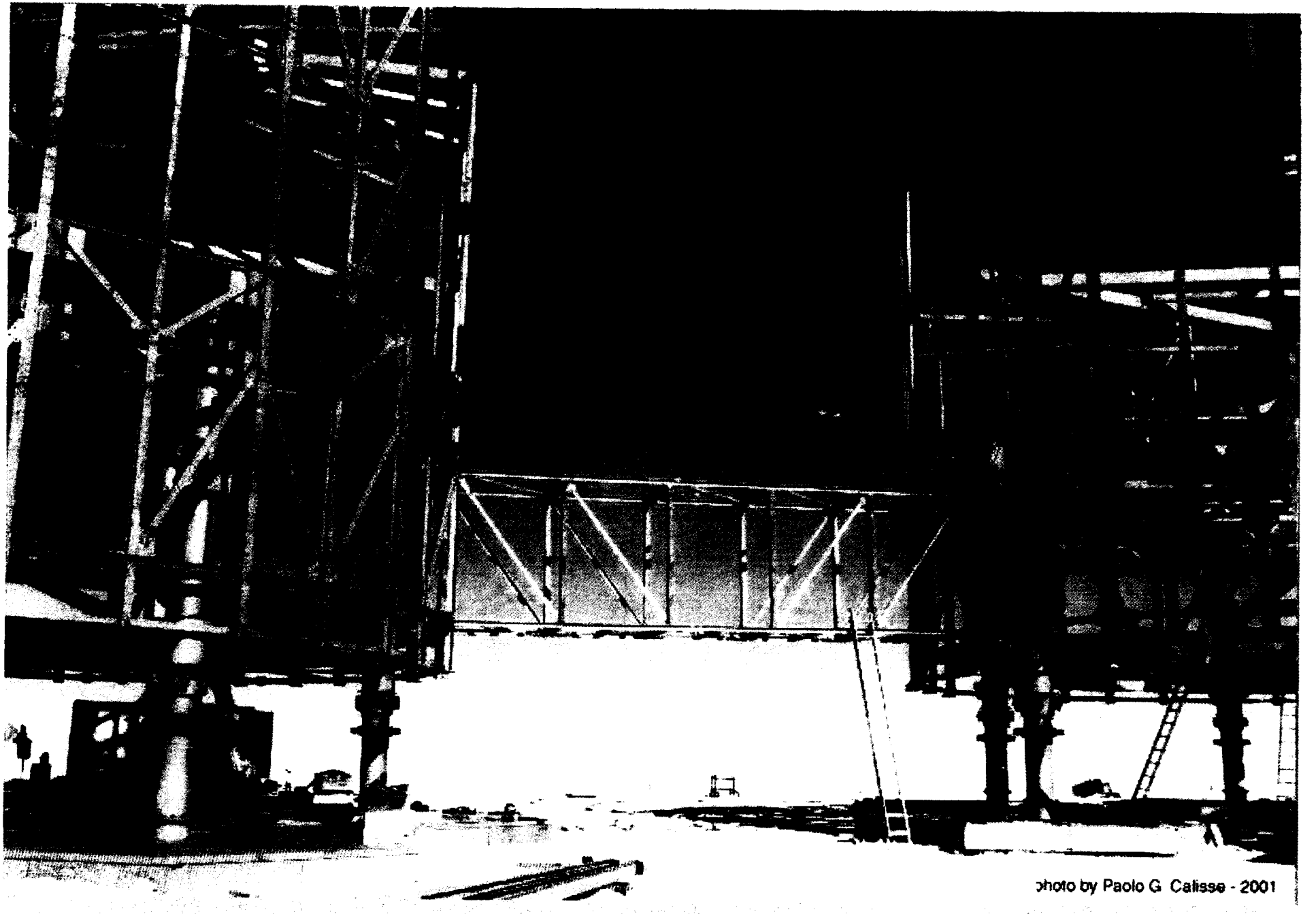


photo by Paolo G. Calisse - 2001

photo by Paolo G. Calisse - 2001

Dome C Transport

6 March 2003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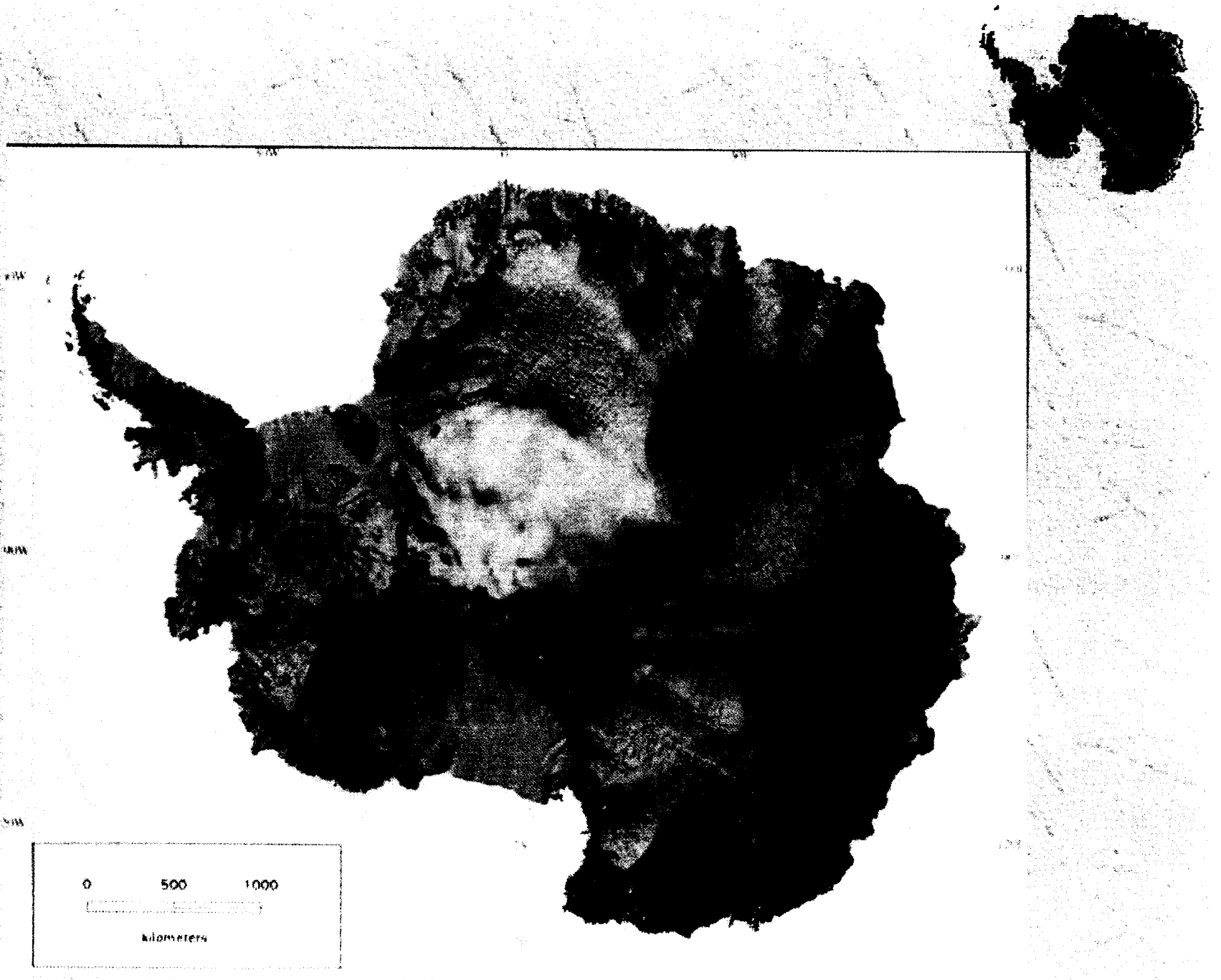
0
500
1000
kilometers