SAN PEDRO MARTIR

ASTRONOMICAL SITE TESTING

SPM Site Testing Group

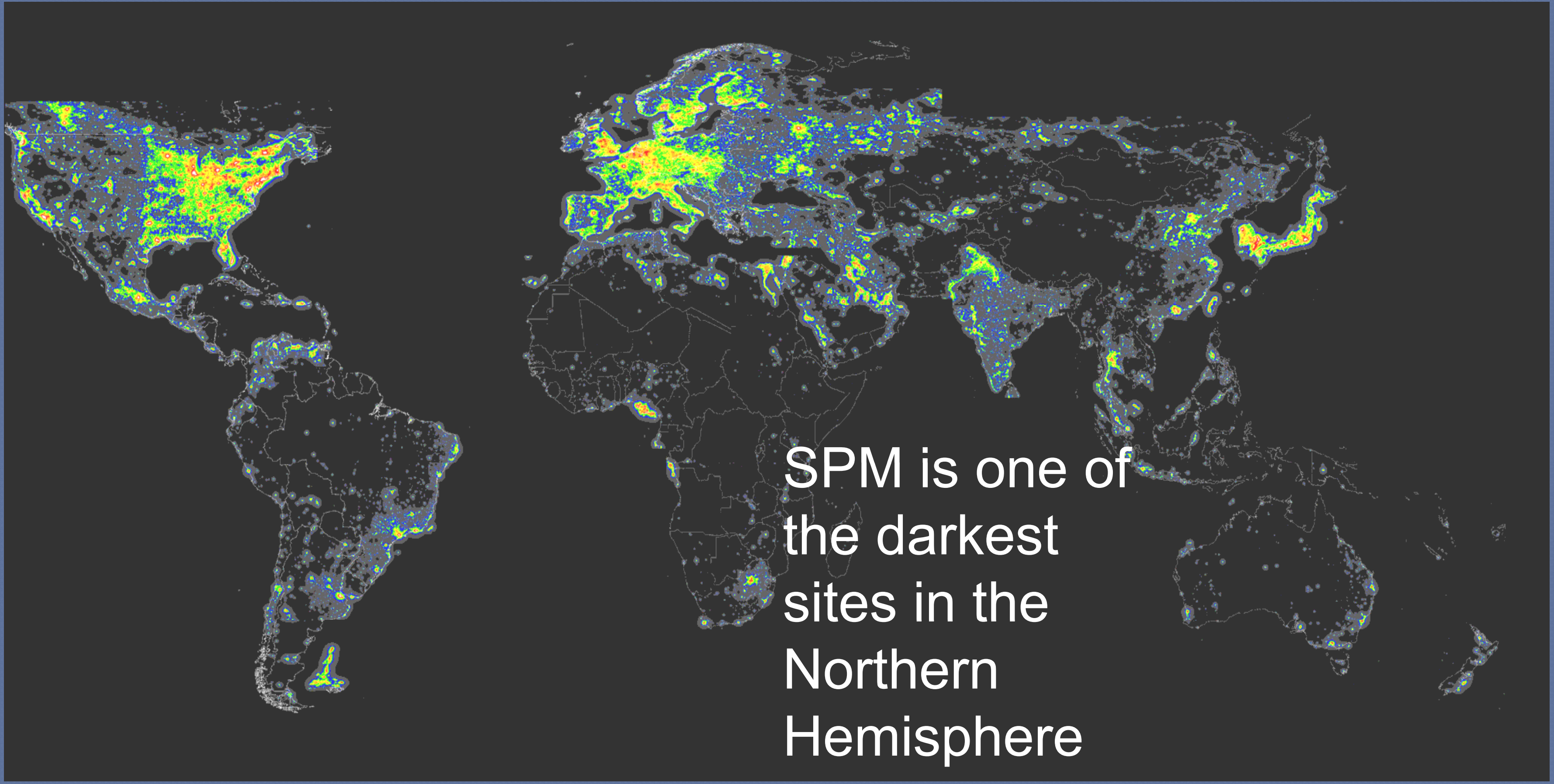
Instituto de Astronomía
Observatorio Astronómico Nacional
UNAM

San Pedro Mártir

- For over 30 years, the Universidad Nacional Autónoma de México (UNAM) has been operating and developing the National Astronomical Observatory at the summit of the Sierra San Pedro Mártir
- SPM sierra located in the northern central part ~50 km inland **of the Baja California Peninsula.**

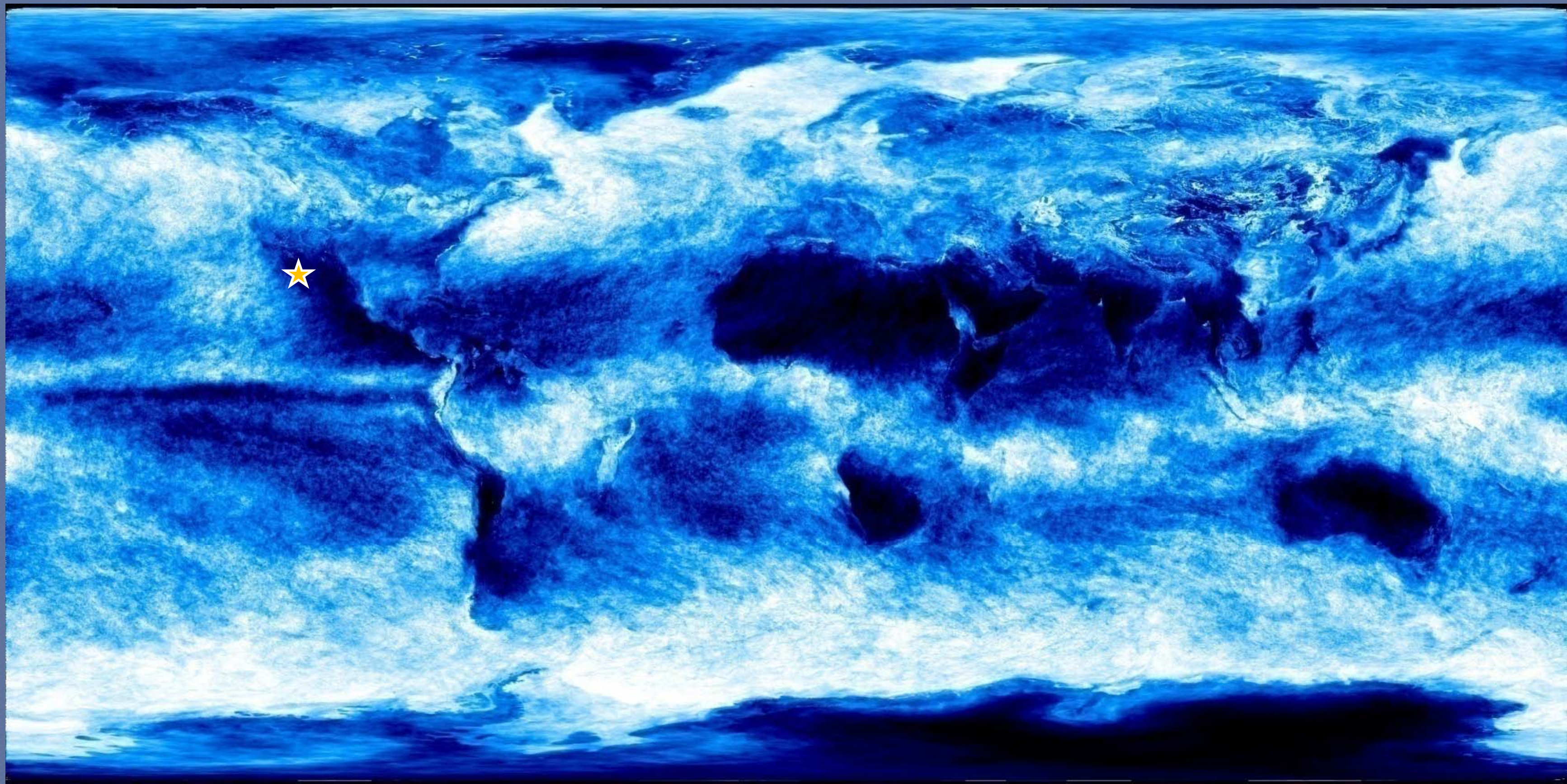
- **Latitude: 31°02'39" N**
- **Longitude: 115°27'49" W**
- **Elevation: 2830 m above sea level**

Sky brightness



SPM is one of the darkest sites in the Northern Hemisphere

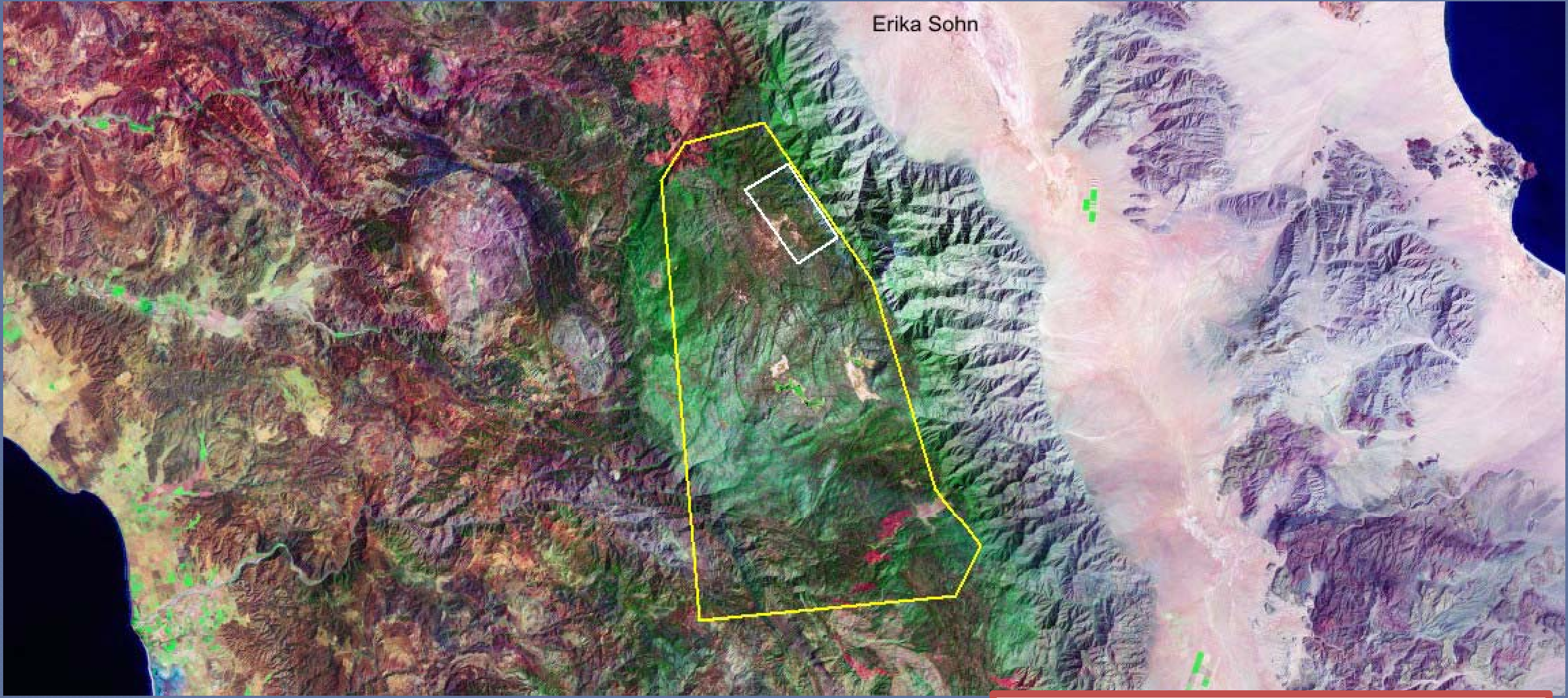
Cloud coverage



February 1- March 1, 2007

Imagery by Reto Stockli, NASA's Earth Observatory, using data provided by the MODIS Atmosphere Science Team, NASA Goddard Space Flight Center

Sierra San Pedro Martir National Park (yellow) and OAN (white) boundaries overlain on Landsat imagery



SPM NATIONAL PARK

Protected 63,000 ha area

E. Sohn 2007

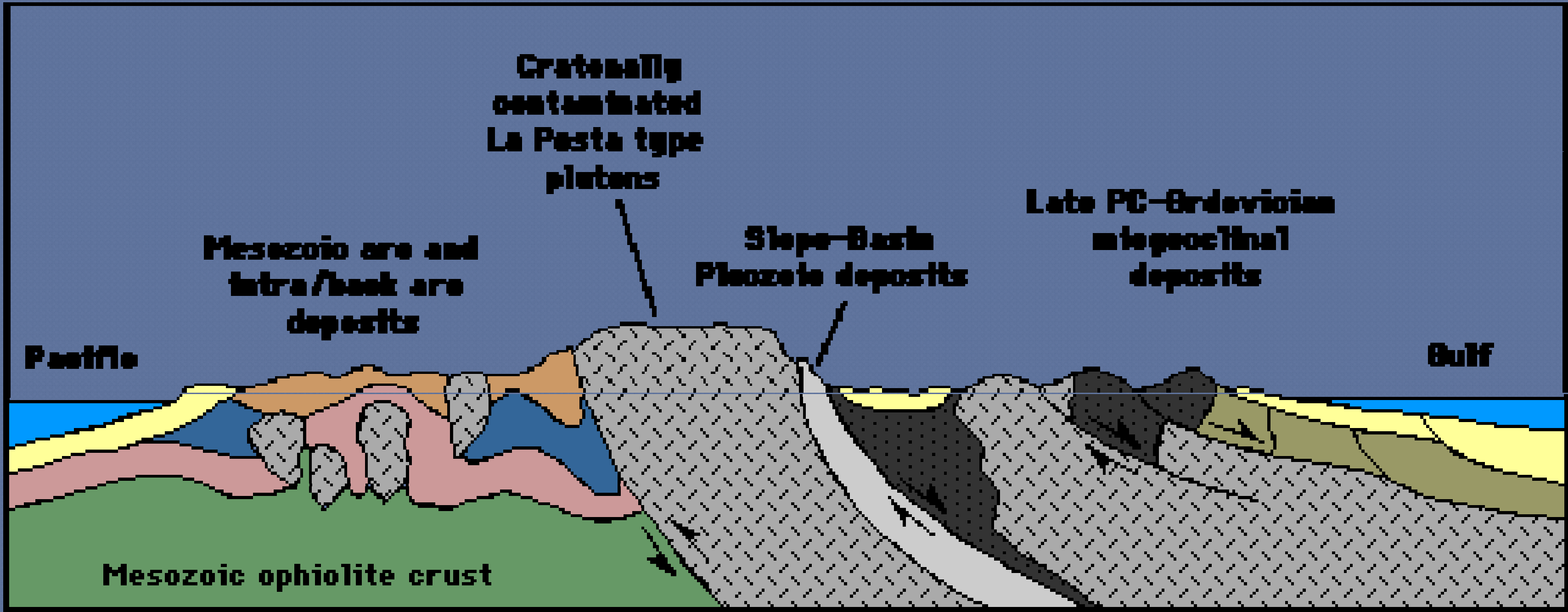
OAN BOUNDARIES:

Name	Easting	Northing
OAN 1	11 R 647162	3428815
OAN 2	11 R 650413	3430931
OAN 3	11 R 646285	3437176
OAN 4	11 R 642672	3435008

Geological setting (details E. Sohn 2007)

OAN atop eastern edge of SPM pluton, Mesozoic granitic body, part of Peninsular Ranges batholith (1600 km 34°N to 20°N)

Cross section of northern Baja California, R.G. Gastil , Special paper GSA, 1993



Geologic map of the northern section of the state of Baja California

Gastil, Phillips, Allison, 1971. Geologic Society of America, Memoir 140, Plates 1A & 1B, 1:250,000

2m site located atop a massive quartz, feldspar & muscovite pegmatitic dike with ca. 10cm crystals

Geotechnical studies (TIM site)

The Comisión Federal de Electricidad (CFE, Mexican Electricity Company) conducted topographic, geological and geotechnical studies

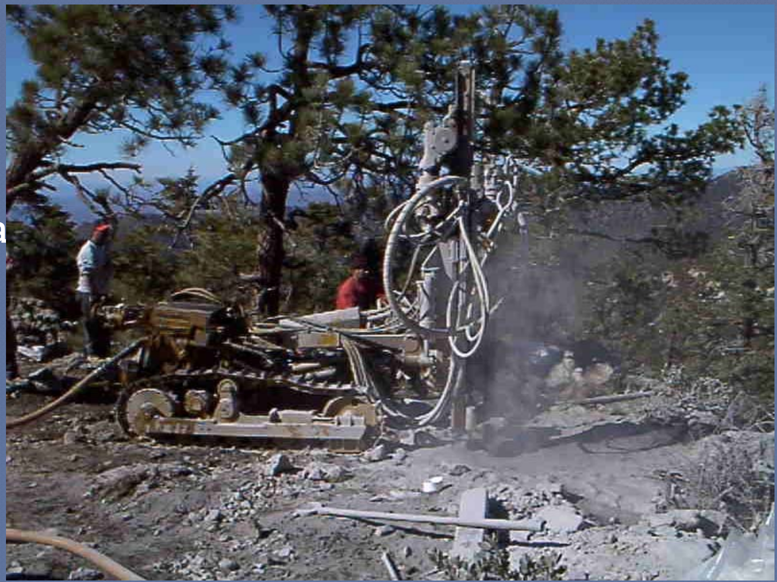
- Excavations of 22 m depth borings showed that only 2 to 3 m are required to reach a layer of fractured rock adequate for telescope foundations

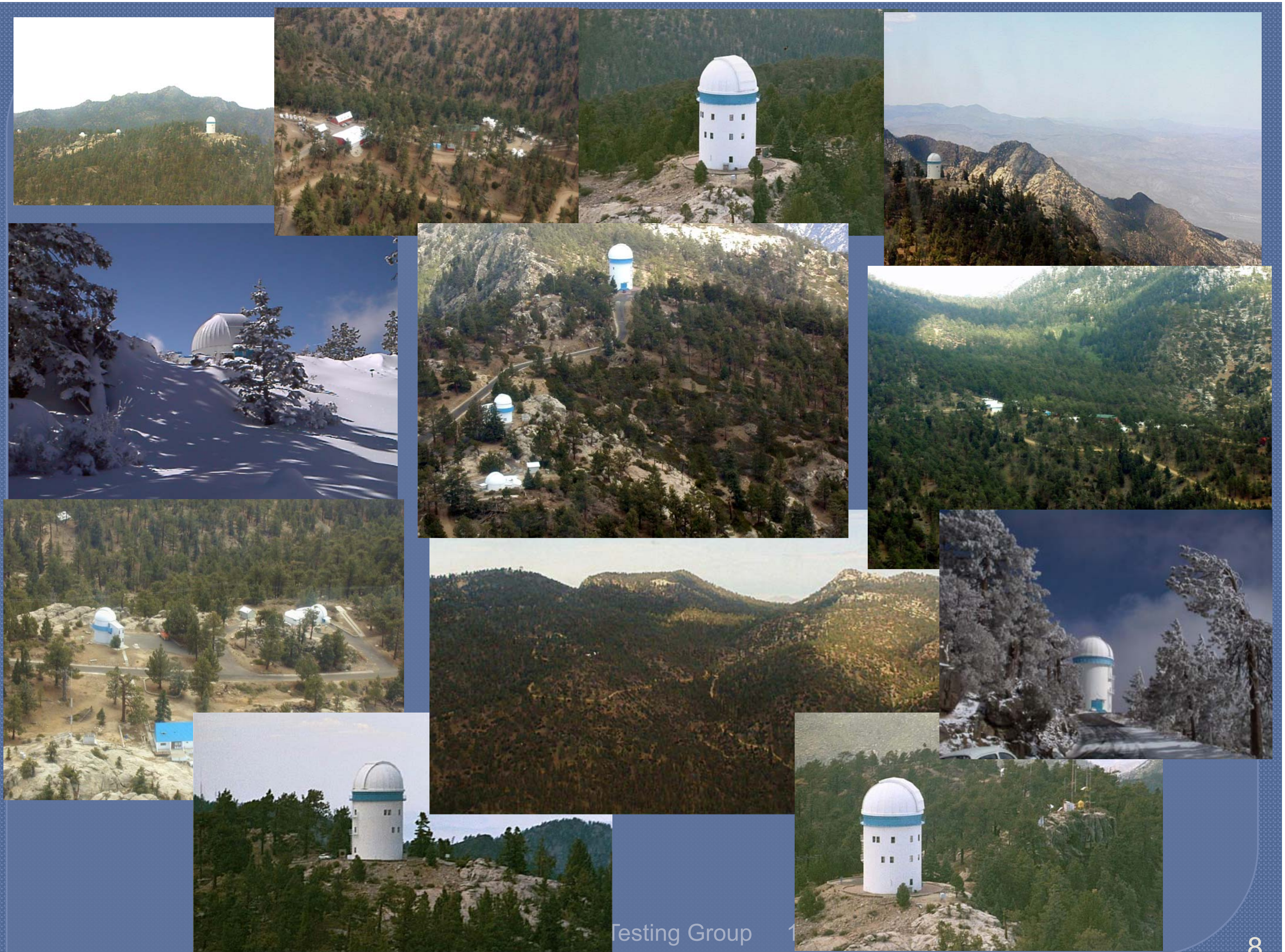
.

- Characteristics of layer:

Rock quality designation :	65-80%
Thickness:	10-12 m
Geological Strength Index:	73
Dynamic modulus of elasticity:	6000-19000 Mpa
Dynamic modulus of rigidity:	2000-7000 Mpa
Static modulus of deformability:	7300 Mpa
Poisson's ratio:	0.34
Deformability modulus (beneath that layer)	~22600 MPa

B. Sánchez et al. 2003





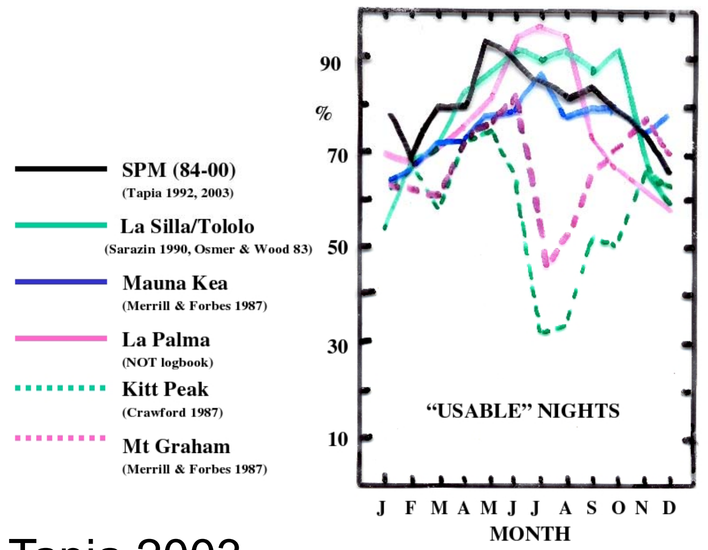
SPM SKY TRANSPARENCY

- Twenty years of weather and observing statistics 1982-2002 (based on telescope logs):

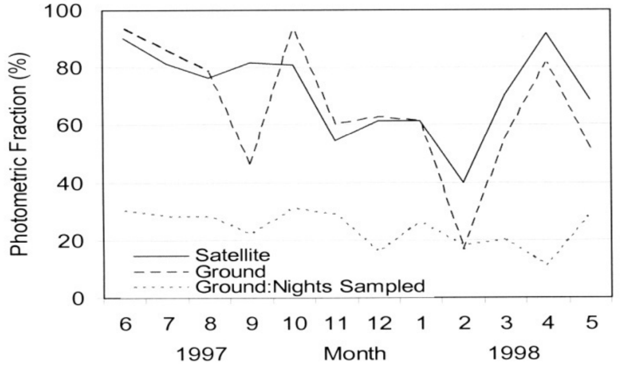
"Photometric" nights:	63.1 %
"Spectroscopic" nights:	80.8 %
"Bad weather" nights:	22.2 %

Tapia 2003

- Note: similar values found by Erasmus & van Staden 2003, CELT study of NW USA & Mexico.
- SPM confirmed to have the largest fraction of clear nights of any site in the Northern Hemisphere



Tapia 2003



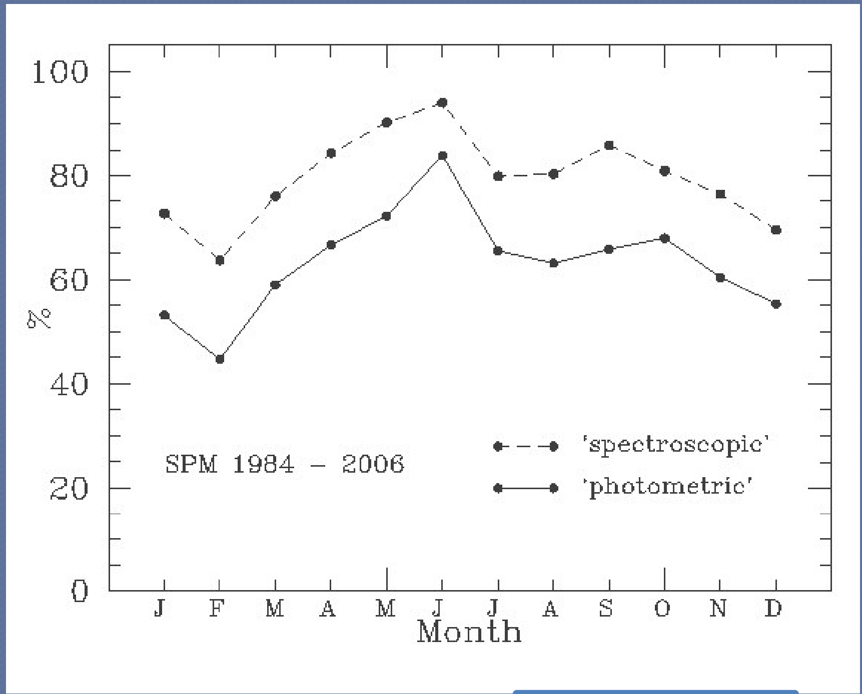
SPM SKY TRANSPARENCY

2006 update

- Twenty four years of weather and observing statistics 1982-2006 (based on telescope logs):

- “Photometric” nights: 64.1%
- “Spectroscopic” nights: 80.2%
- “Bad weather” nights 21.2%
- (“not observed”)

Tapia+ 2007

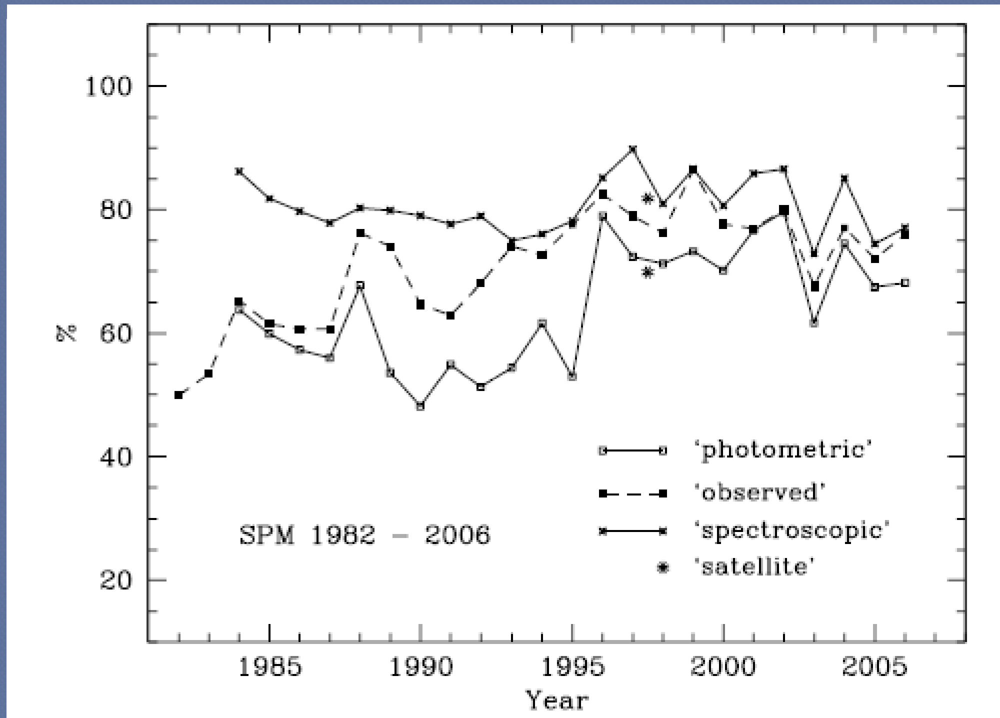


Tapia 2007

SPM SKY TRANSPARENCY

- Yearly fraction of nights of photometric & spectroscopic quality in SPM during Jan 1984 to Dec 2006.
- Also shown actual use of 2.1mT from Jul 1982 – Dec 2006
- Asterisks refer to mean satellite Jun 1997 – May 1998 measurements by Erasmus & van Staden 2002

(see Tapia, Hiriart, Richer, Cruz-Gonzalez 2007)



Tapia+ 2007

SPM SKY TRANSPARENCY

Tapia+ 2007

TABLE 1

SPM 2.1-m TELESCOPE OBSERVING STATISTICS: JULY 1982 TO DECEMBER 2006

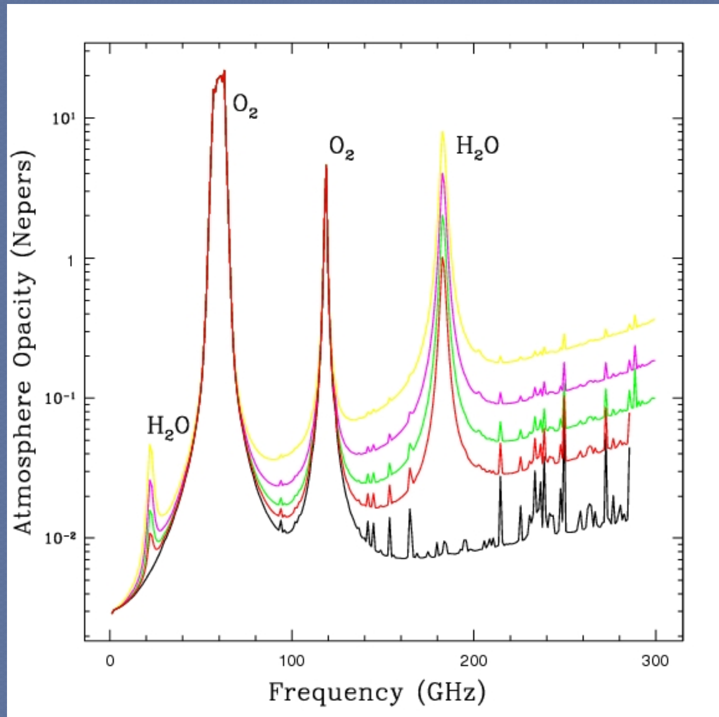
	Number of nights	% Over total number of calendar nights	% over number of scheduled nights
Total calendar	8950	100.0	–
Engineering	676	7.6	–
Scheduled for observation	6847	76.5	100.0
Observed	4875	54.5	71.2
Lost due to weather	1465	–	21.4
Lost due to telescope/dome/guider failure	146	–	2.1
Lost due to instrument failure	219	–	3.2
Lost due to other circumstances	92	–	1.3
Not scheduled	1430	16.0	–

Precipitable water vapor (PWV)

- Zenith atmosphere opacity, in Neper units, on the 0 to 300 GHz window for the atmosphere above SPM.
- PWV of 1.0, 2.0, 4.0, and 5.0 mm as modeling using ATM code.
- Dry atmosphere opacity.
- Note the resonant lines for molecular oxygen and water as well as some trace molecules.
- Relation between the zenith atmospheric opacity at 210 GHz and the PWV from calculations of the ATM code:

  PWV (mm) = 20.48 * TAU (NP) - 0.327

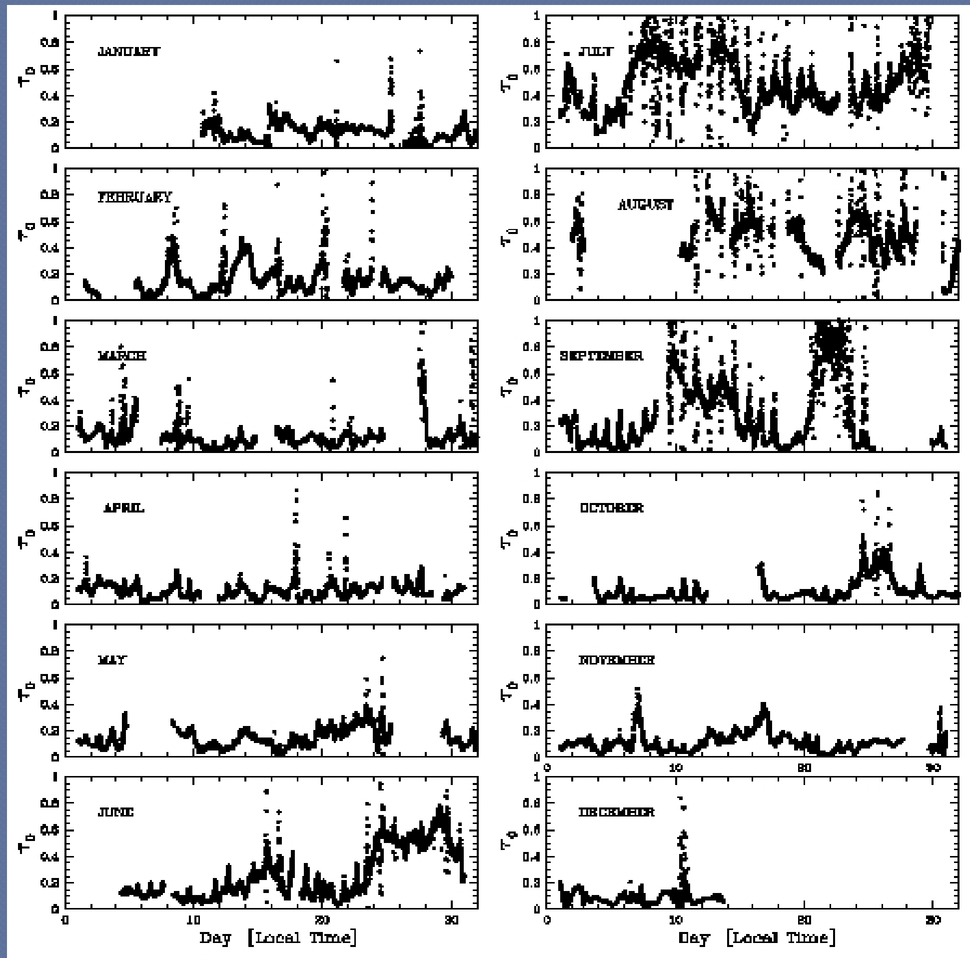
- Also found relation between $TAU_{210\ GHz}$ & TAU_{MIR} using the CID MIR camera.



Hiriart & Salas 2007

Precipitable water vapor (PWV)

- Eight years (1995-2002) of radiometric measurements of the zenith atmospheric opacity at 1.4 mm (210 GHz
- Plotted 1999 values, note the American monsoon affects Jul-Sep.
- Satellite Erasmus & van Staeden 2002: 2.4 mm



Hiriart 2003a,b

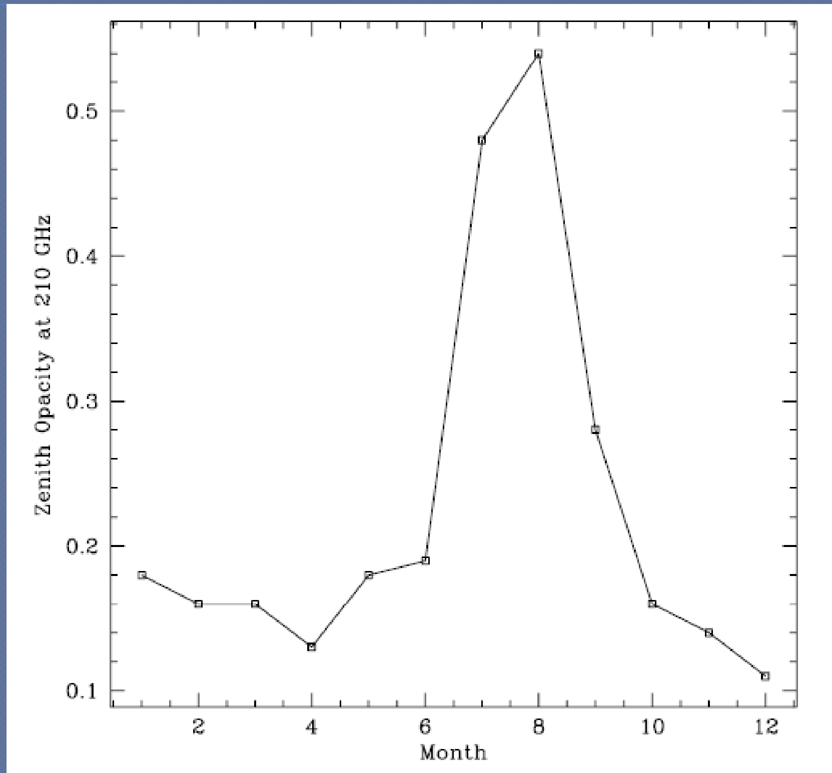
Tapia+ 2007

Precipitable water vapor (PWV)

- Radiometric measurements (1995-2002) of the zenith atmospheric opacity at 1.4 mm (210 GHz):
- Median: 0.143 np ~ 2.55 mm
  Daytime: 0.18 np
  Nightime: 0.17 np

- => 15-20% of nights with PWV< 1 mm
- SPM is good for IR observing

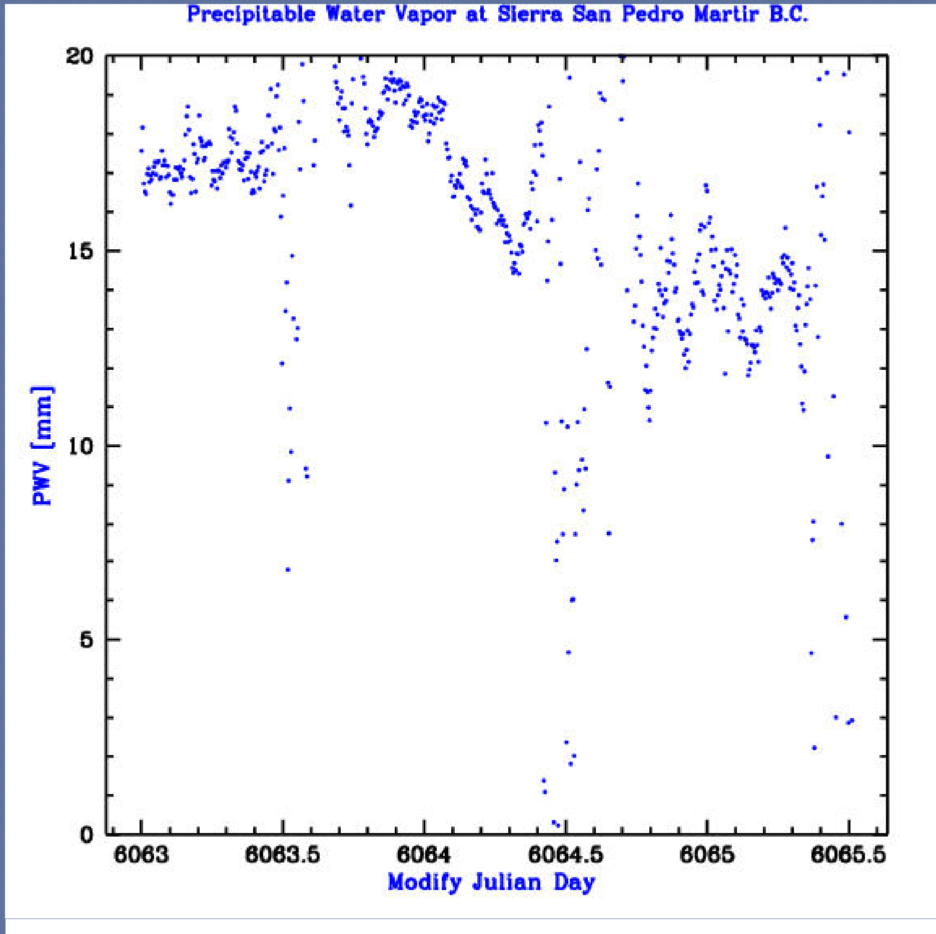
Hiriart 2003a,b
Tapia+ 2007



SPM weighted monthly opacity

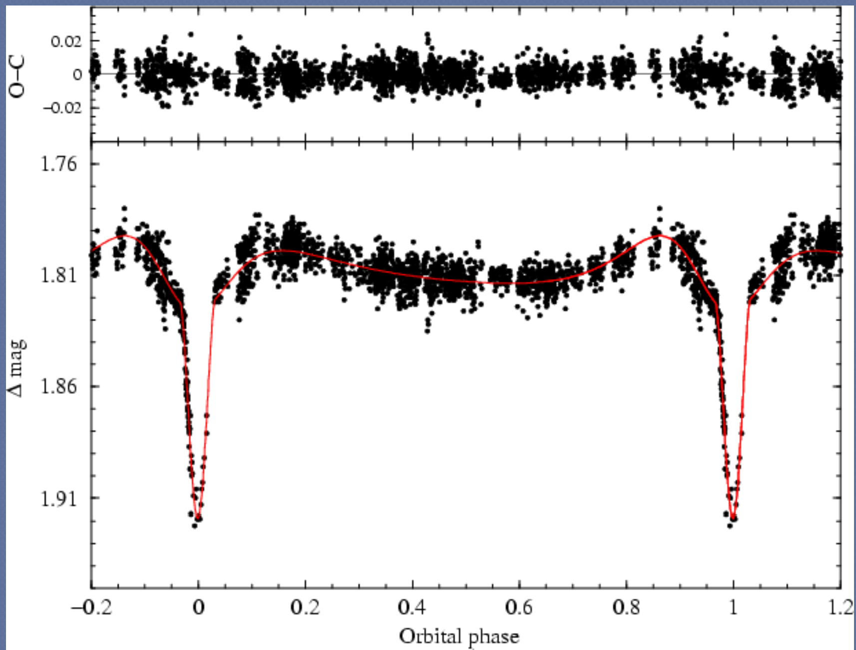
Web IAUNAM -> OAN

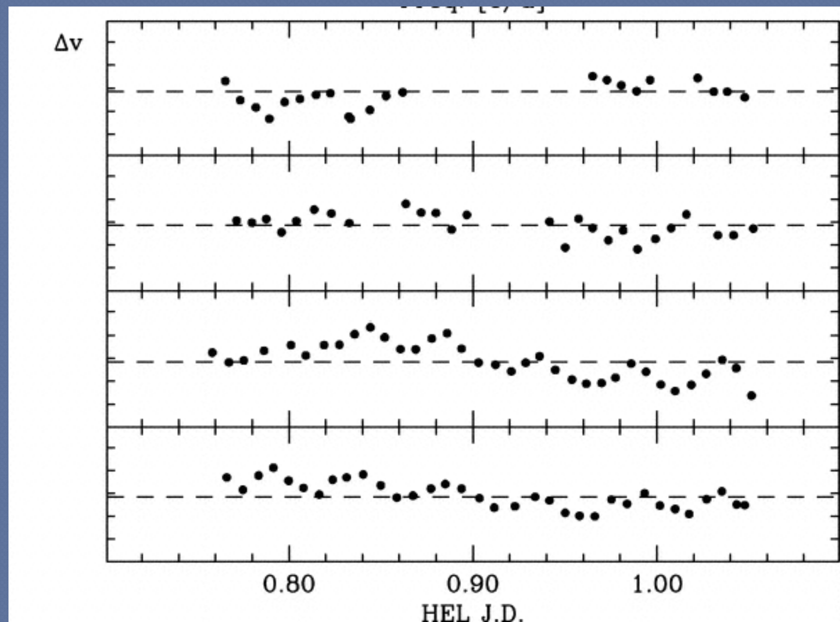
- **Condiciones actuales / Current conditions**
- Radiómetro: Opacidad en el cenit del cielo en SPM a 210 MHz
- Radiómetro: Zenith opacity at 210 MHz in SPM



Photometric stability

Examples of differential light curves
(Poretti et al. 2004, 2005)





y ≈ 7; r.m.s. = 0.004

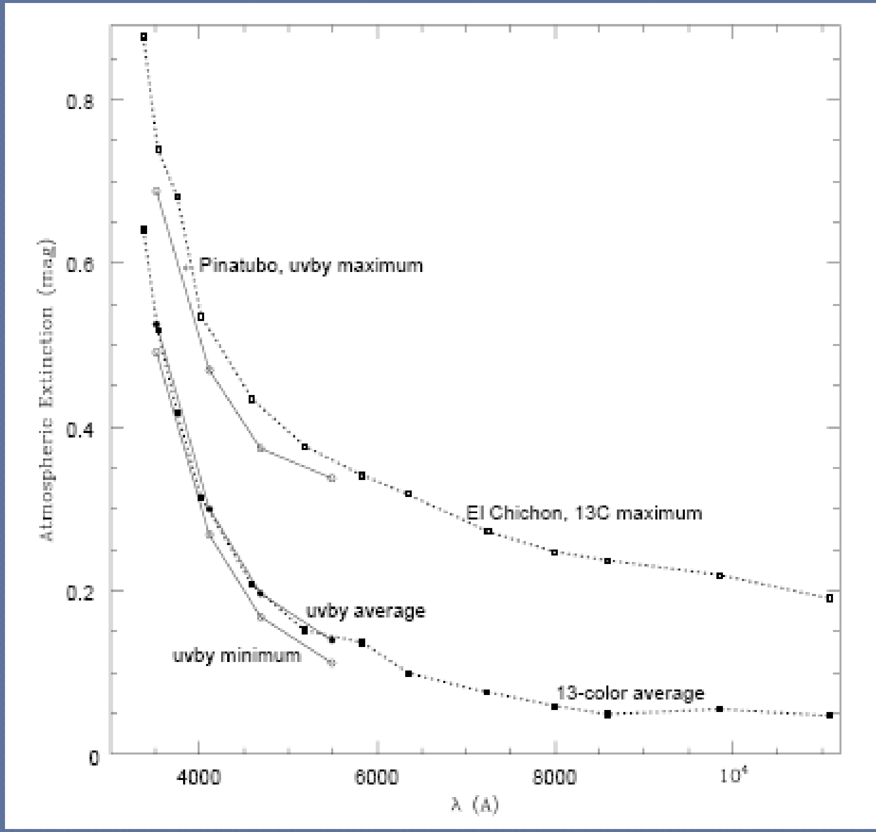
V ≈ 9; r.m.s. = 0.002

SKY TRANSPARENCY

- Mean extinction curve (1973-1999) and extinction coefficients:

  Visible: $k_y = 0.14$
  Red: $K_R = 0.05$

- 2/3 of photometric nights $k_y \leq 0.14$
- Best photometry in October & November.
- SPM is an excellent photometric site, comparable to La Silla, Cerro Tololo, Kitt Peak, Mc Donald & Mauna Kea



Parrao & Schuster 2003

SKY TRANSPARENCY: IR

IR extinction coefficients:
Carrasco et al. 1991, PASP 103, 987

Our determination of the mean extinction coefficients in the air-mass range [1,3] for the San Pedro Mártir Observatory yields the following values.

$$\langle E_J \rangle = 0^{\mathrm{m}}.0918 \pm 0.0048/\text{air mass}$$

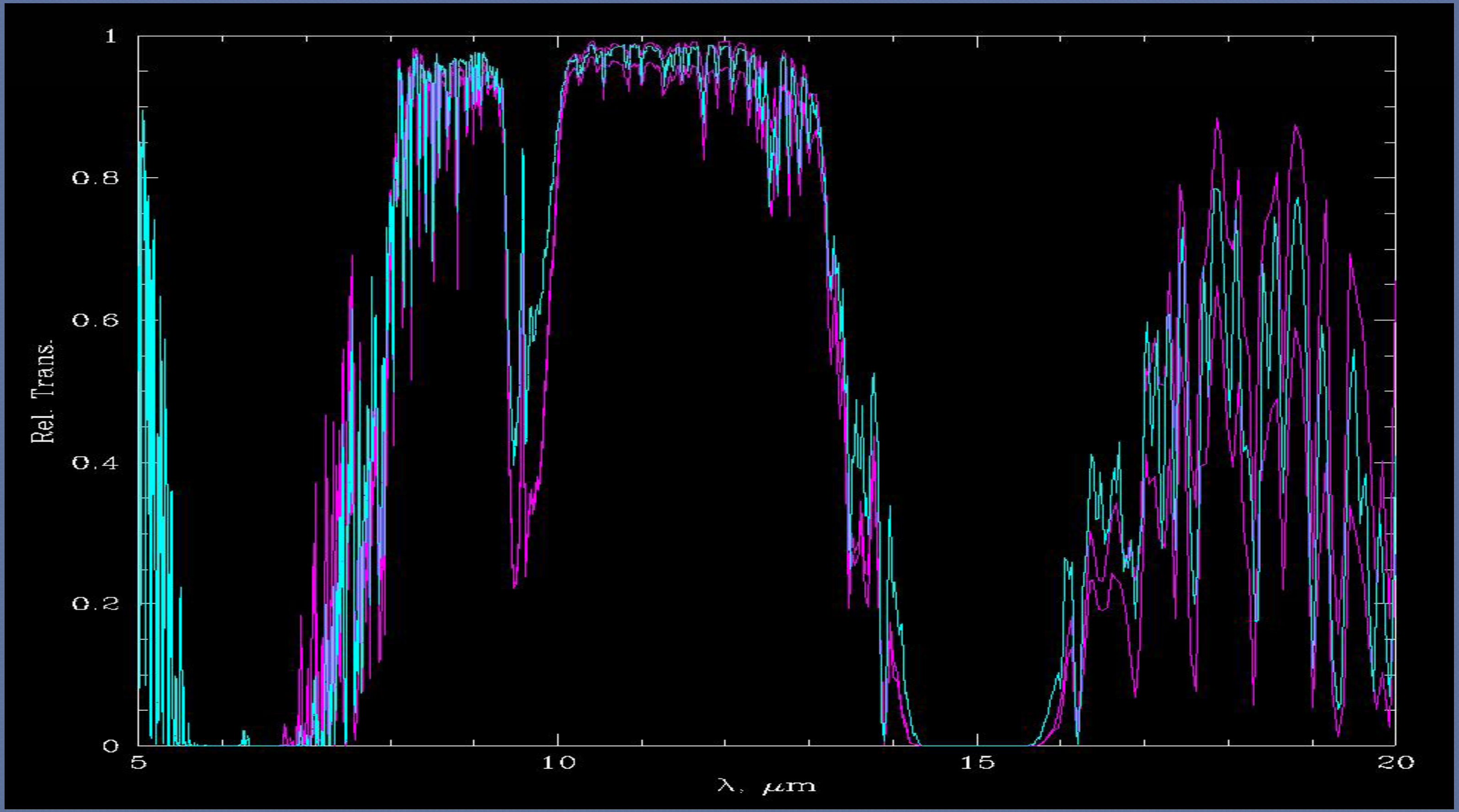
$$\langle E_H \rangle = 0^{\mathrm{m}}.0315 \pm 0.0045/\text{air mass}$$

$$\langle E_K \rangle = 0^{\mathrm{m}}.0449 \pm 0.0045/\text{air mass}$$

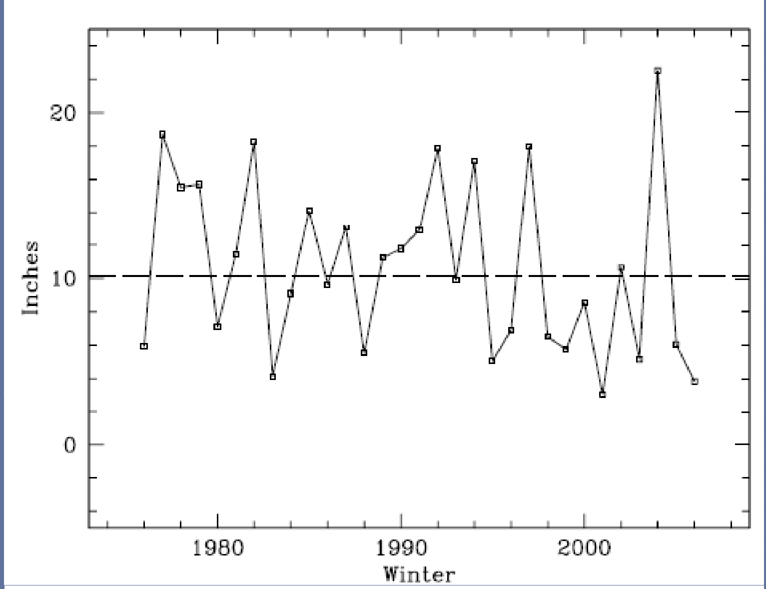
These values are in good agreement with those expected for a dry site (Manduca & Bell 1979).

SKY TRANSPARENCY: IR

MODTRAN model atmosphere: Mauna Kea & SPM

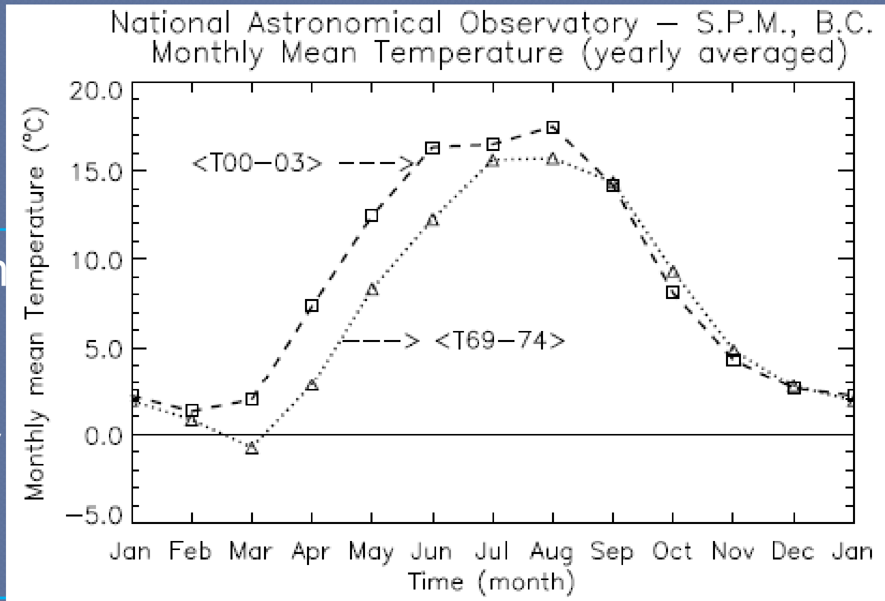


Weather



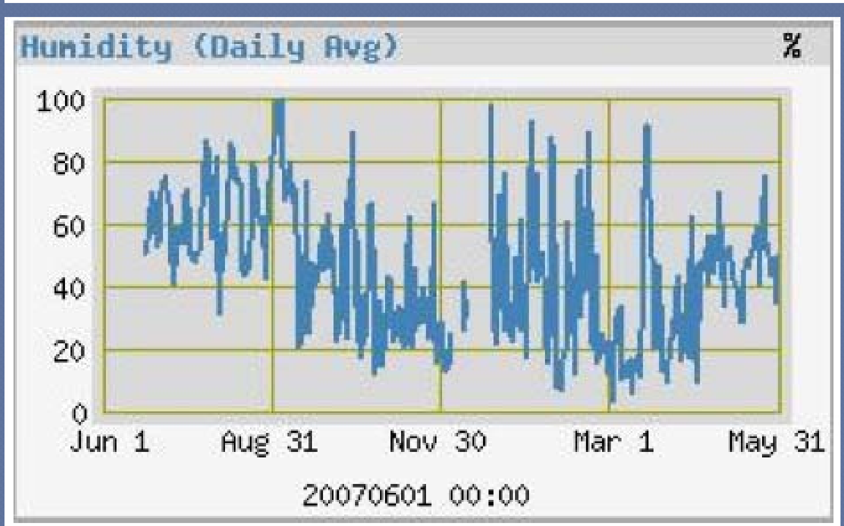
Total annual (Jun-Jul) precipitation in San Diego from 1976-2007.
• Dashed line is 150 yr mean.
• 9/11 last years well below mean.
Tapia+ 2007

Dome 2.1mT 1998-2006 winter minimum 14 C & summer maximum 25 C (Tapia+ 2007)
Mean temperatures at SPM Observatory 1969-1974, 7.3 C, 2000-2003, 8.6 C.
Alvarez+ 2007



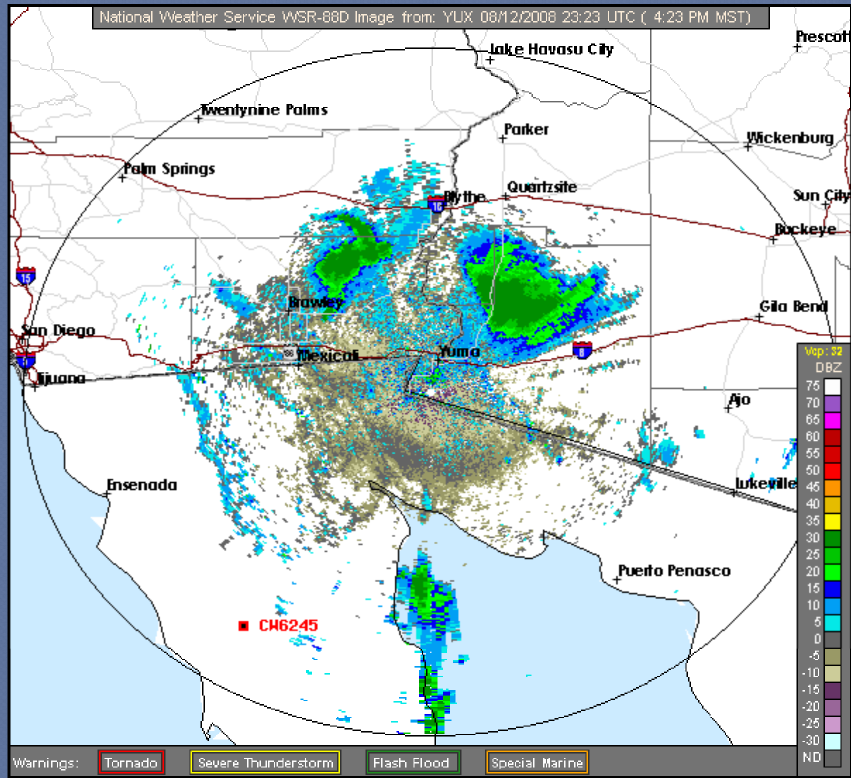
Web IAUNAM -> OAN

- **Condiciones actuales / Current conditions**
- [Meteorological Station Telescope 1.5m]
- Temperature & humidity plots for June 2006-May 2007



Web IAUNAM -> OAN

- **Condiciones actuales / Current conditions**
- Estación Meteorológica Telescopio 1.5m
- Meteorological Station 1.5m Telescope
- Aug/12/08

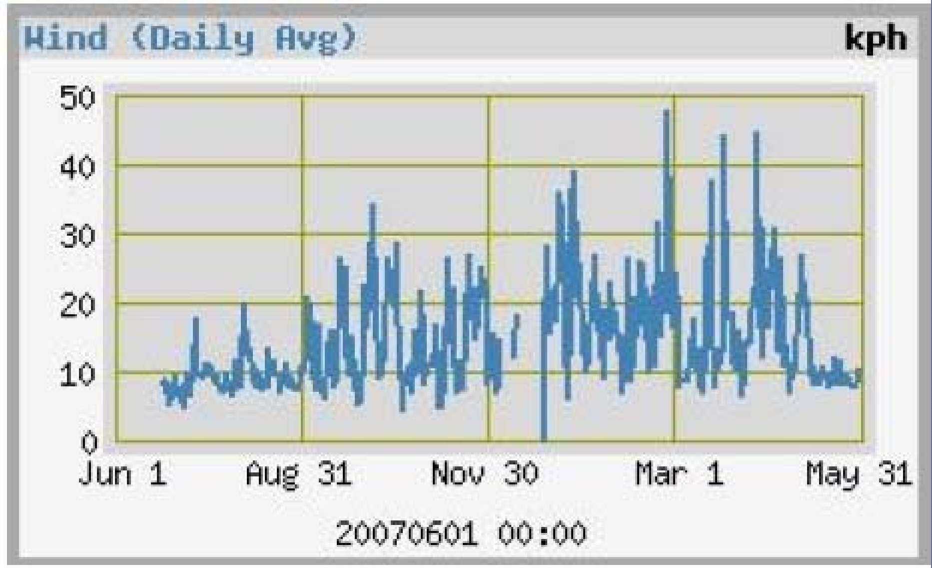


Wind velocity

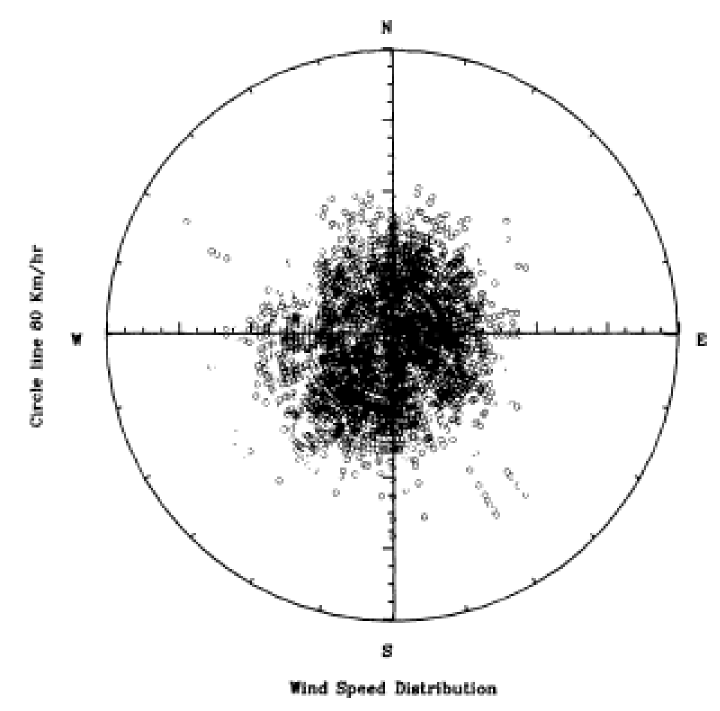
- Satelite wind velocity monthly variation over a period of 16 years, 1980-1995.
- Two different data sets, the GGUAS and NCEP.
- Wind at 200 mbar (12 km height): annual average: ~27 m/s

E. Carrasco & Sarazin (2003)

Weather



Daily average wind speed
recorded 06/06-05/07
Tapia+ 2007



•Night-time **wind spatial distribution.** Echevarria+ 1998
•**Wind speeds** < 11 m/s, median 5.3 m/s
•Strongest from SSW, rarely from E and WNW (Michel+ 2003)

Broad-band Sky Brightness

- Obs: M. Richer+
- Optical Johnson-Cousins filters
- Blank field images within 30° zenith
- Period 26/08/04-22/02/06
- Full moon values approx.

U+2.8mag,B+2.9mag,V+2.1mag,R+1.4mag,I+1.0mag

Tapia+ 2007, RMxAA, 31,47

TABLE 4

SKY BRIGHTNESS IN SAN PEDRO MÁRTIR

Filter	dark sky (mag$\square''^{-1}$)	N[a]	exp. time (s)
U	21.7	3	1800
B	22.4	3	1200
V	21.5	3	900
R	20.7	4	600
I	19.2	4	600

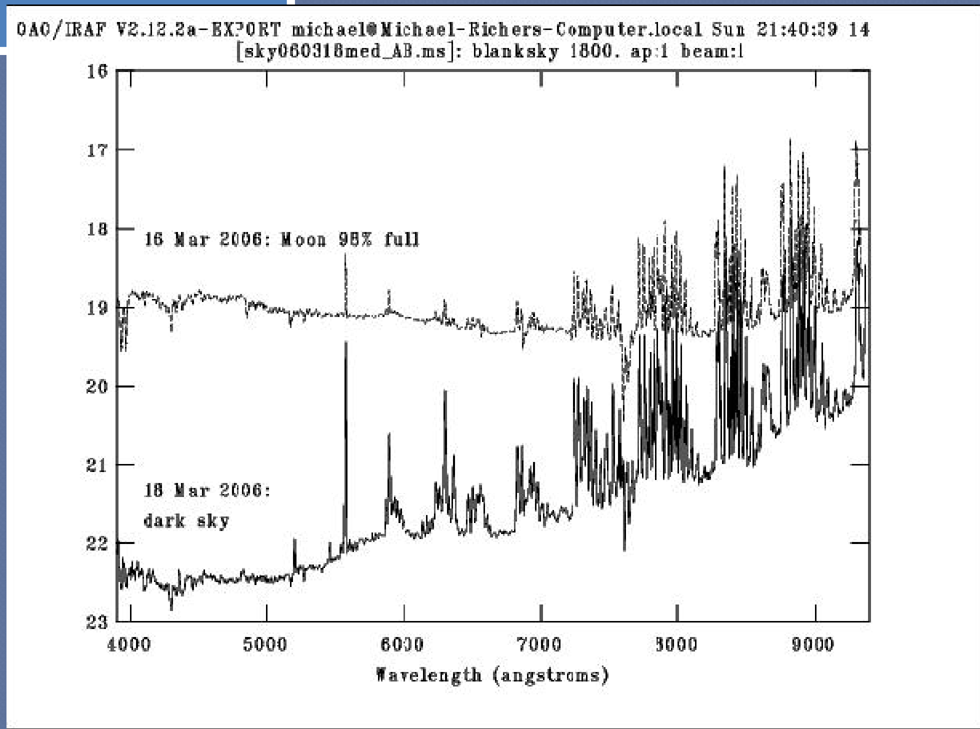
Broad-band Sky Brightness

- Obs: M. Richer

•B&Ch spectra (R=9A) of SPM sky brightness on AB mag scale

•Blank sky 4000-9300 A 16&18Mar2006

Tapia+ 2007, RMxAA, 31,47



Broad-band Sky Brightness: IR

Obs: M. Richer
Near-IR JHK' filters
Mar&Apr 2005 May 2006
Tapia+ 2007, RMxAA, 31,47

TABLE 4

SKY BRIGHTNESS IN SAN PEDRO MÁRTIR

Filter	Mar-Apr 2005 brightness (mag □″$^{-1}$)	Mar-Apr 2005 N[a]	May 2006 brightness (mag □″$^{-1}$)	May 2006 N[a]
J	16.0–16.9	2		
H	14.1	1		
K′	14.4–15.1	8	13.6–14.0	3

[a]Number of measurements.

ATMOSPHERIC TURBULENCE

- Medium-term seeing monitoring at SPM for over a decade.
- Three totally independent seeing measurement campaigns:

(1) "Carnegie" monitor (Echevarría et al. 1998) 1992-1993.
(2) "Steward" STT (Echevarría et al. 1998) 1992 – 1994.
(3) DIMM (Michel et al. 2003) 2000 – 2002.

	(1)	(2)	(3)
Median values	0.63"	0.61"	0.60'
1st quartile	0.48"	0.50"	0.47"

Diferential Image Motion Monitor (DIMM)

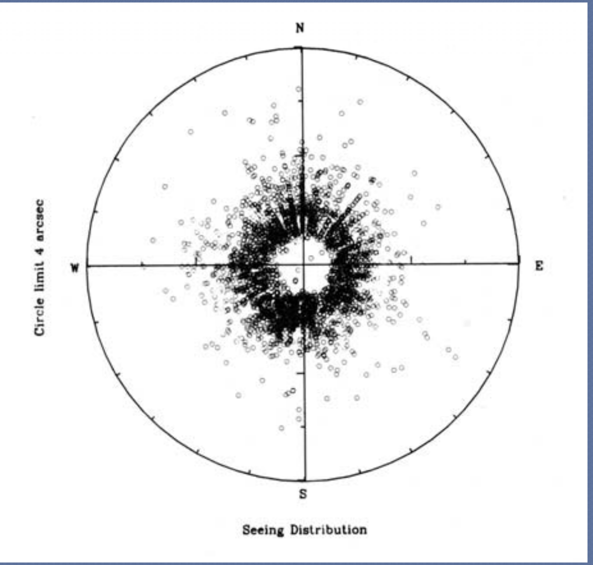
(1,3) at h=8.3m

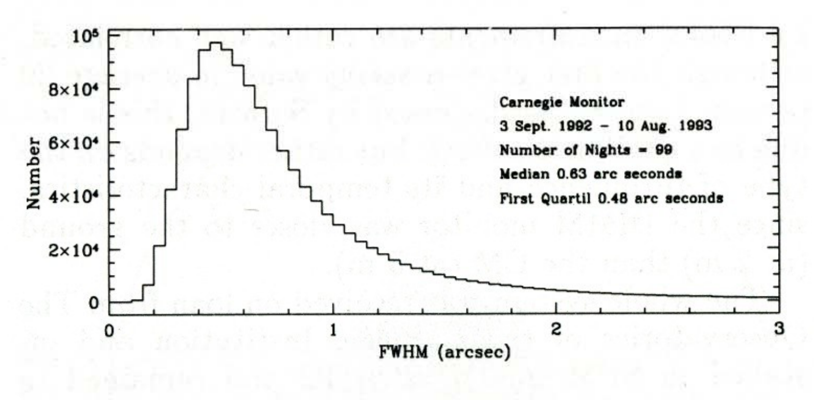
(2)

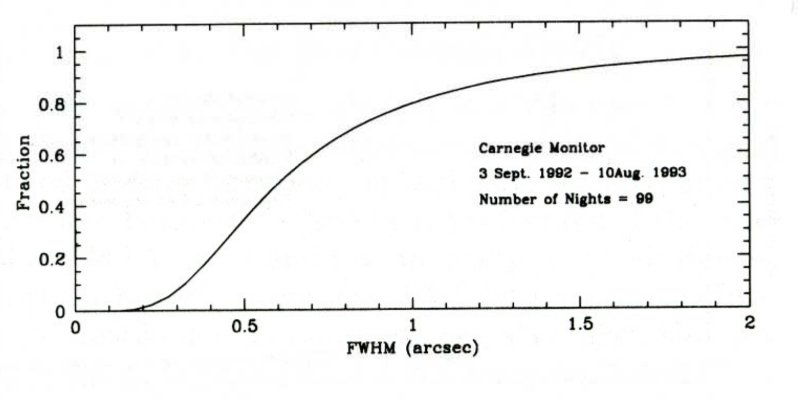
Seeing size distribution

Echevarría et al. (1998)

Size independent of (moderate) wind direction







ATMOSPHERIC TURBULENCE

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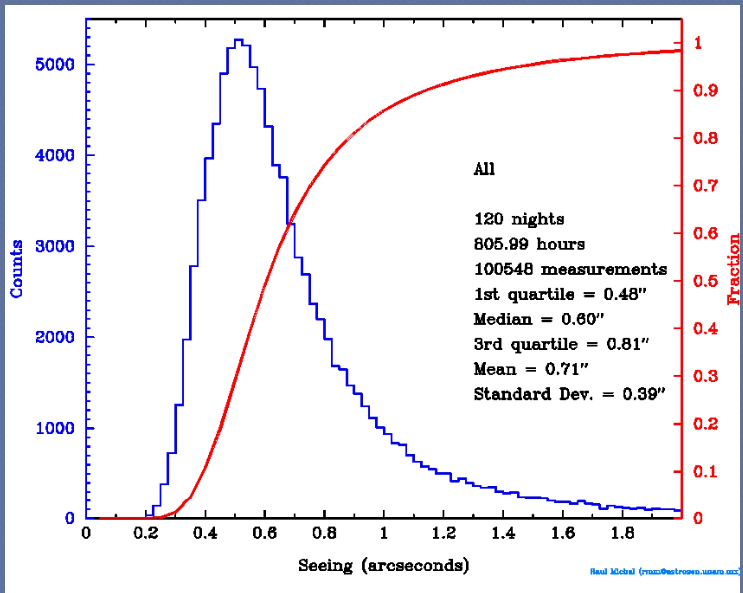
Measurements during 123 nights Aug. 2000 - Jun. 2003

- Instrument: DIMM
  Altitude range: >8m
- Median value: 0.59''
  First quartile: 0.48''
  Excelent night: 8 hrs with 0.37''

Michel et al. (2003)

Diferential Image Motion Monitor (DIMM)

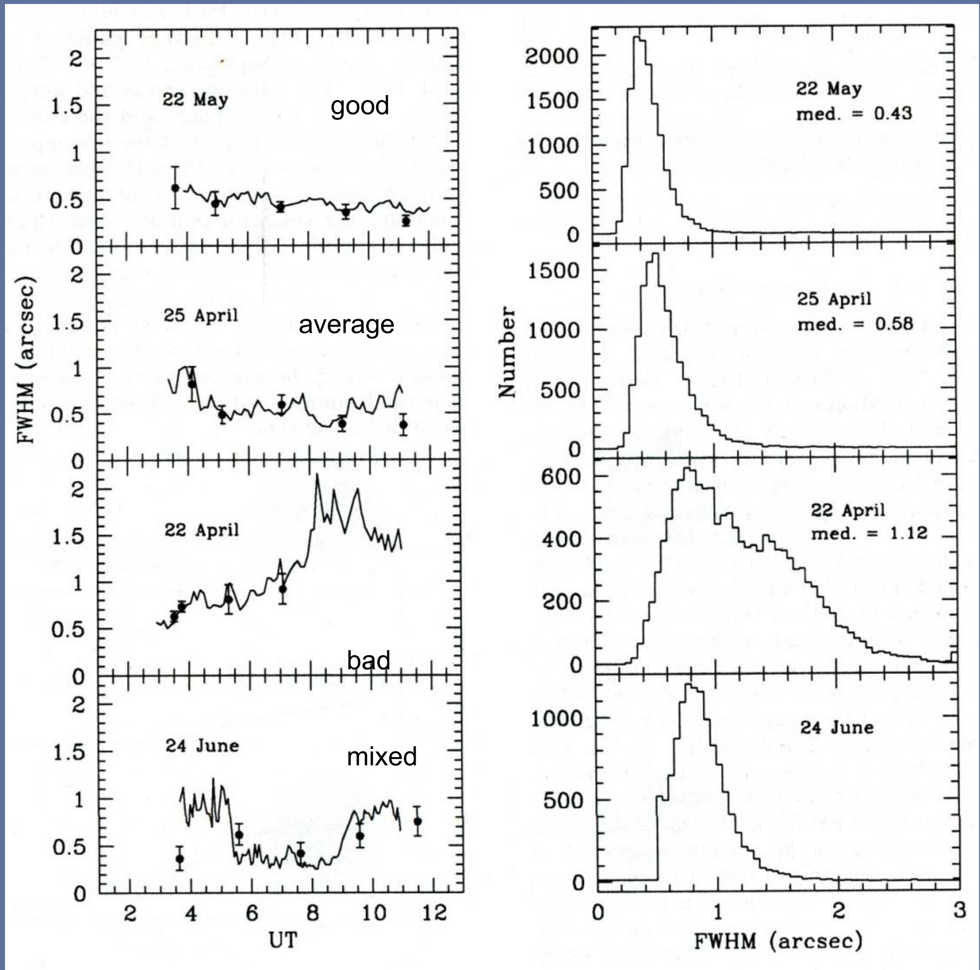


Slightly better in summer

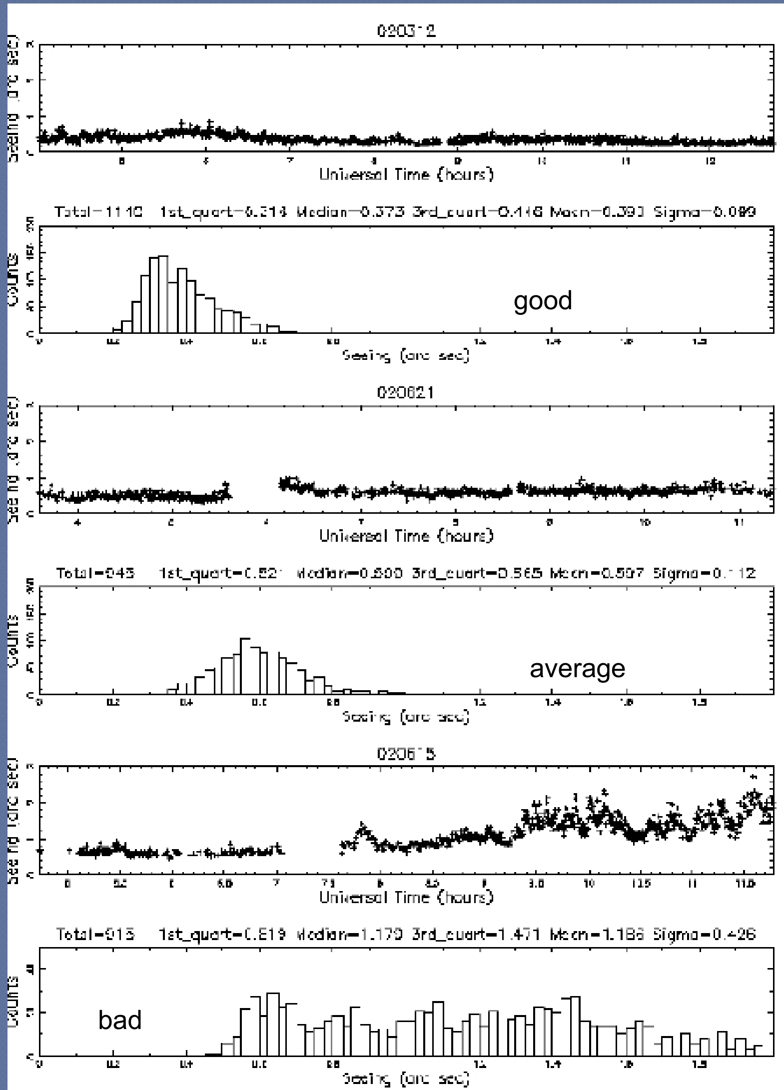
Slightly worse in winter

ATMOSPHERIC TURBULENCE (SEEING)

Carnegie monitor (line) vs. STT (points)



Echevarría et al. (1998)



Michel et al. (2003)

DIMM measurements at different sites

Site Name	Site Alt. (m)	DIMM Elev. (m)	Exp. time (ms)	1st Quart {	Median (arcsec)	3rd Quart	Mean }	No Nights	Start	End	Reference
San Pedro Mártir, México	2800	8.3	06	0.47	0.59	0.76	0.67	97	08/00	10/02	This Work
Cerro Chico, Chile	5150	2.5	10	0.49	0.61	0.75		38	07/98	10/00	Giovanelli et al. (2001)
Maidanak, Uzbekistan	2580	6.0		0.55	0.69	0.90	0.76	725	08/96	11/00	Ilyasov (2002)
La Palma, Spain	2400			~ 0.52	0.69	~ 0.90		233	10/94	08/98	Wilson et al. (1999)
Sierra Negra, México	4600			0.61	0.78	1.04	0.90	83	02/00	05/02	Carrasco E. (2002)
Paranal, Chile	2636	6.0	20	0.64	0.82	1.08	0.91	~ 1700	03/98	11/02	ESO (2002)
Gaomeigu, China		4.0	20				0.70	234	05/95	12/96	Qian et al. (2001)
Mount Fowlkes, USA	2002				0.86			35	05/01	07/01	University of Texas (2001)
Mauna Kea, USA	4123				0.88		0.92	13	05/02	06/02	Chun et al. (2002)
La Silla, Chile	2335	6.0	20	0.70	0.89	1.15	0.97	~ 1400	03/99	11/02	ESO (2002)
Cananea, México	2480			0.78	0.91	1.08			02/99	10/99	INAOE (2002)
Karoo Plateau, South Africa	1760	1.0		0.74	0.92	1.16			04/94	02/98	Erasmus (2000)
Cerro Tololo, Chile	2200	6.0		0.79	0.96	1.17		58	05/02	07/02	Tokovinin et al. (2002)
Kunming, China	1940	4.0	20				0.95	256	05/95	12/96	Qian et al. (2001)
Devasthal, India	2540	2.0	10		1.07		1.20	37	10/98	12/98	Stalin et al. (2001)
Siding Springs, Australia	1130	2.0	10				1.20	64	06/93	12/93	Wood et al. (1995)
Apache Point, USA[a]	2788			1.19	1.47	1.84	1.58	250	02/99	03/01	Rest (2002)
South Pole	3200	12.0	30	~ 1.20	1.7	~ 2.20		28	05/95	09/95	Loewenstein et al. (1998)

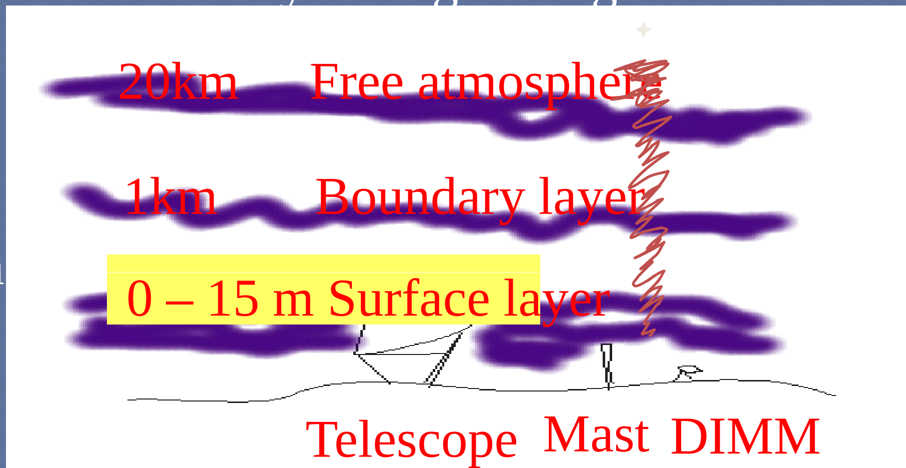
SPM2000 intensive testing campaign

Instrumentation and Purpose

- Seeing Monitor DIMM (Differential Image Motion Monitor)
  - Dedicated telescope installed beside instrumented mast
  - Measures seeing and scintillation continuously during the night
  - Integrated seeing
- Instrumented Mast
  - Pairs of microthermal sensors

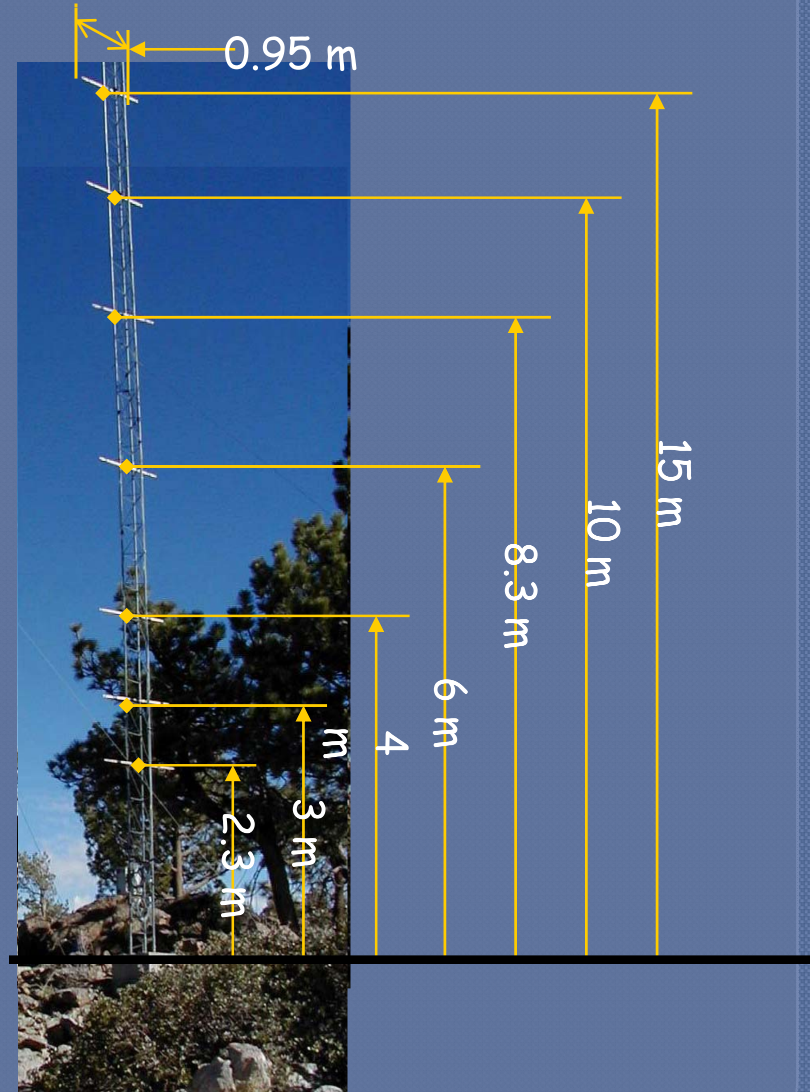
  at heights: 2.3, 3, 4, 6, 8.3, 10, 15 m
  - Measures $C_n^2(h,t)$ and

  Temperature (h,t)
  - Surface layer (up to 15 m) seeing contribution to the total seeing
- Details in Sanchez+ 2003, 2007



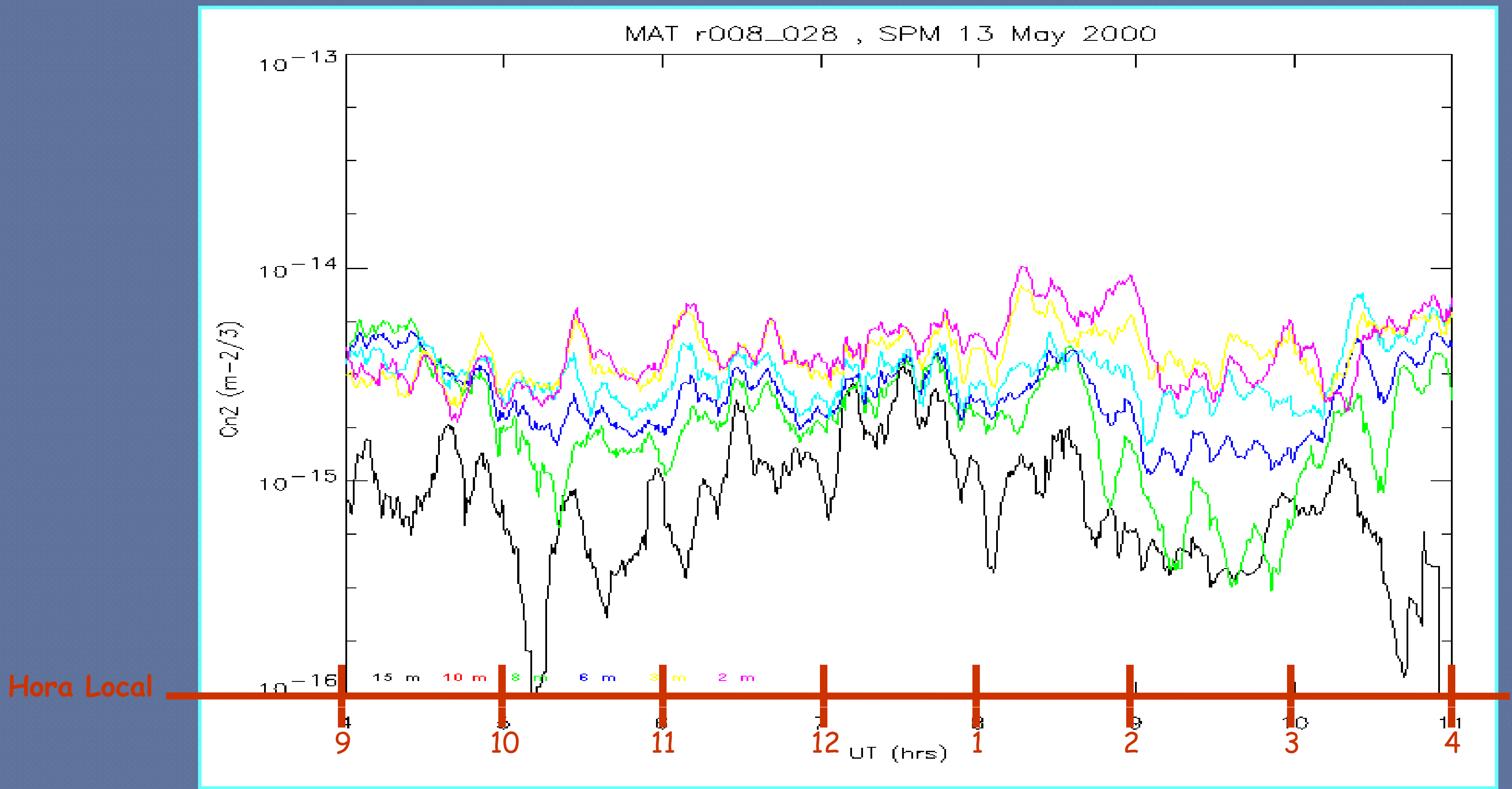
Instrumented Mast with microthermal sensors at different heights

DIMM   2.1m Telescope



$C_N^2(h,t)$ altitude and temporal variation

$C_N^2(h_1,t) > C_N^2(h_2,t) > C_N^2(h_3,t)$ for $h_1 < h_2 < h_3$



ATMOSPHERIC TURBULENCE

- Surface layer seeing:
  Instrument: Microthermal sensors
  Altitude range: 2.3-15 m
  L. J. Sánchez et al. 2003, 2007

- Mean value: 0.16”
  Surface layer contribution to total C_N^2 of 5%, which corresponds to mean degradation of 3% of total seeing

Microthermal sensors → Temperature structure constant

Refractive index structure constant

$$r_{o_{\substack{Surface\\Layer}}}(t) = \left[16.7\lambda^{-2}\sum_i C_n^2(h_i,t)\Delta h_i\right]^{-3/5}$$

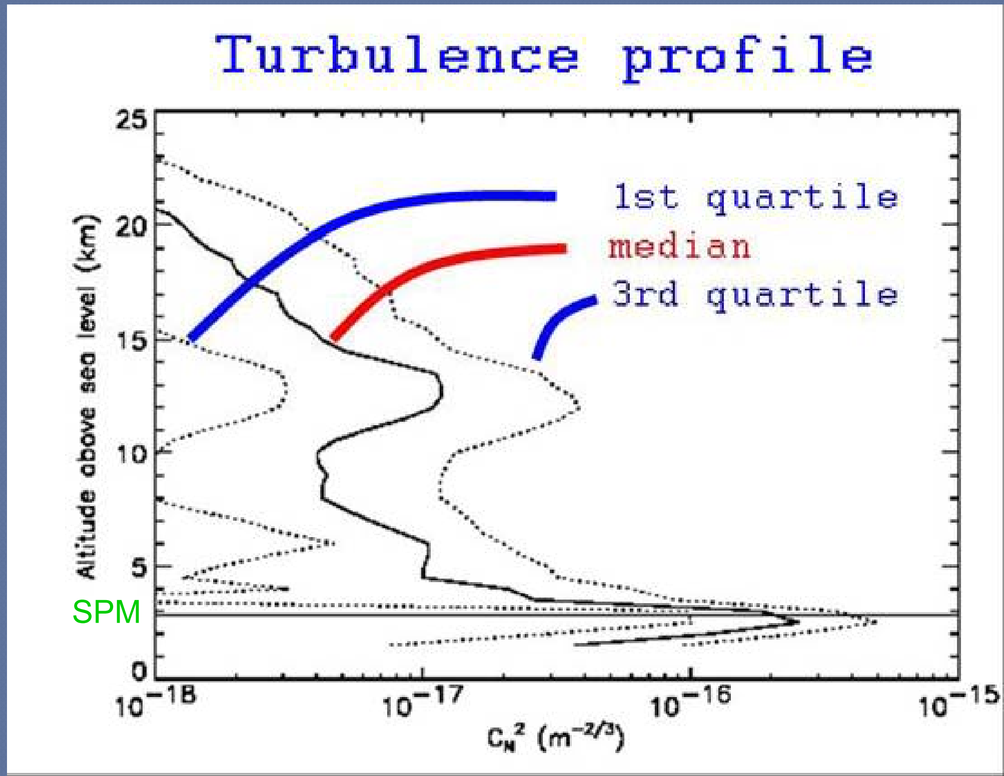
$$surface\ layer\ seeing_{fwhm}(t) \propto \frac{\lambda}{r_{o_{SL}}(t)} \propto \left[\int_{2.3m}^{15m} C_n^2(h,t)\right]^{3/5}$$

ATMOSPHERIC TURBULENCE

- **Turbulence and wind profiles.**
  Instrument: **Generalized Scidar**
  Avila et al. (2003
- 1997 & 2000 campaigns

Median seeing	Height
0.44"(**)	2-4 km(*)
0.17"	4-9 km
0.24"	9-16 km
0.08"	16-21 km
0.02"	21-25 km

(*) Above sea level
(**) Excluding dome seeing



ATMOSPHERIC TURBULENCE

- **Wind profiles**
  Instrument: Generalized Scidar
- Turbulent-layer median speed
  The median of the wavefront coherence--time is 6.5 ms, in the visible.
- The $C_n^2(h,t)$ and **V** profiles are extremely important for the choice of the site for an OIR telescope with adaptive optics.

Median wind speed	Height
2.3 m/s 11.3 m/s 24.4 m/s 9.2 m/s	2-5 km(*) 5-10 km 10-17 km 17-25 km

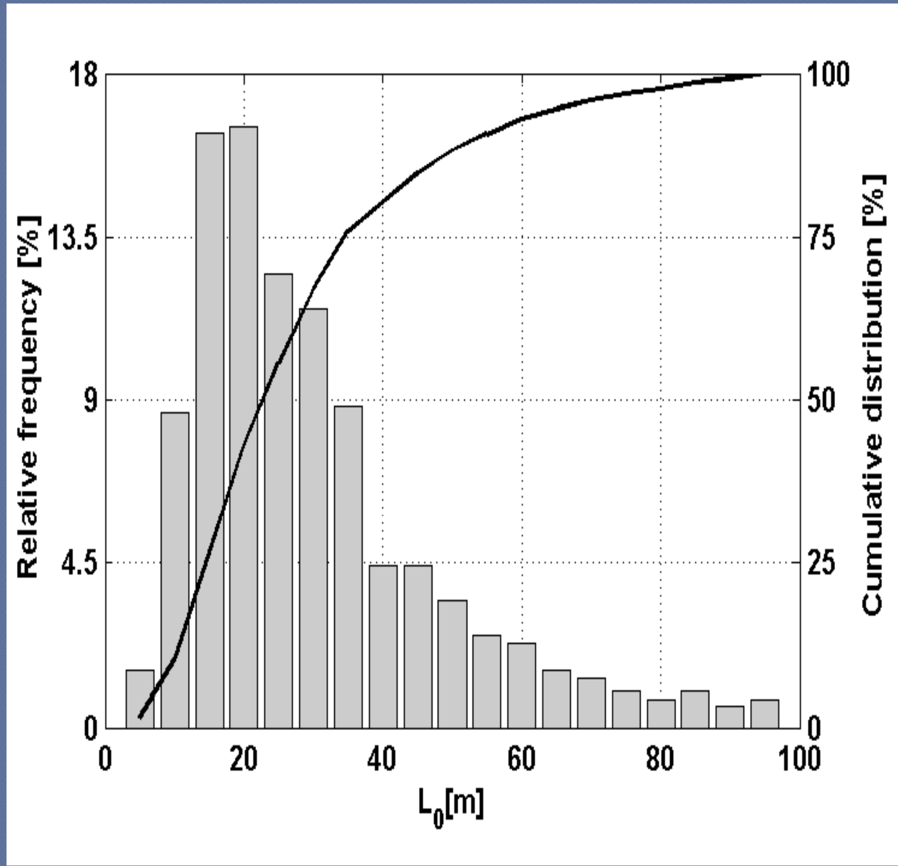
Avila et al. 2003, 2007

(*) Above sea level
(**) Excluding dome seeing

ATMOSPHERIC TURBULENCE

- **Wavefront outer scale**
  Instrument: Generalized Seeing Monitor
  Altitude range: >1.5 m
- L_0 has a strong impact on the performance of high angular resolution instrumentation.
- Median value: 27 m

Conan et al. (2003)

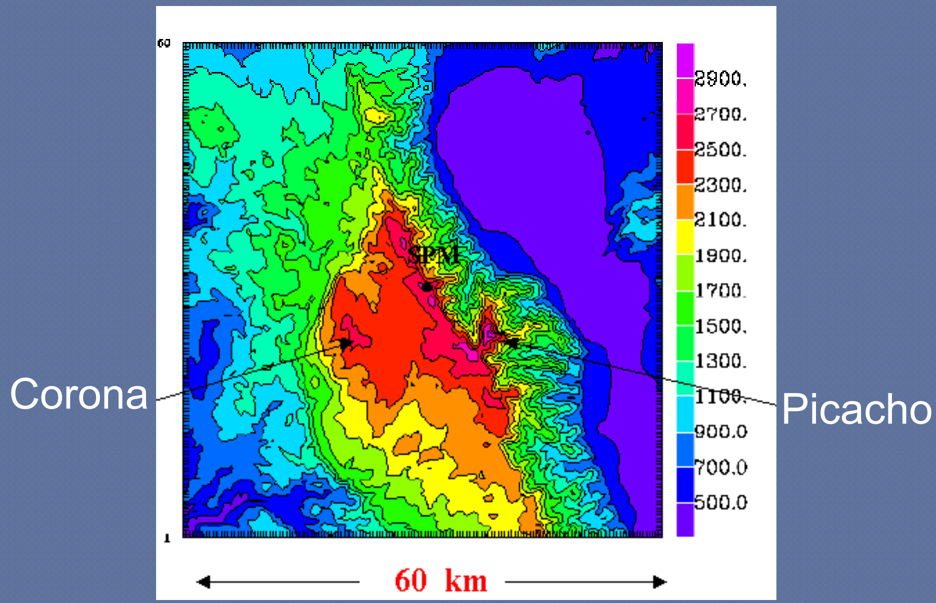


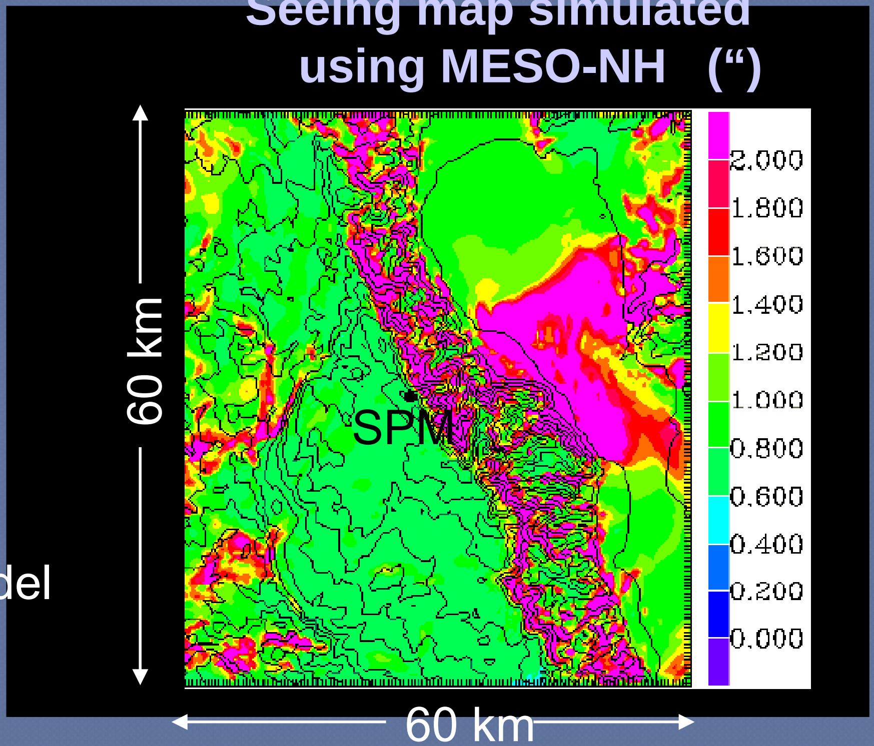
ATMOSPHERIC TURBULENCE

Results obtained so far favor San Pedro Martir among the best suited sites for the next generation OIR telescopes.

Numerical simulations

SPM orographical map





Innovative technique using atmospheric model (Meso-Nh) and site orography to simulate climatological V,T, p and optical turbulence. Masciadri 2001, 2002, 2003

Recent campaigns

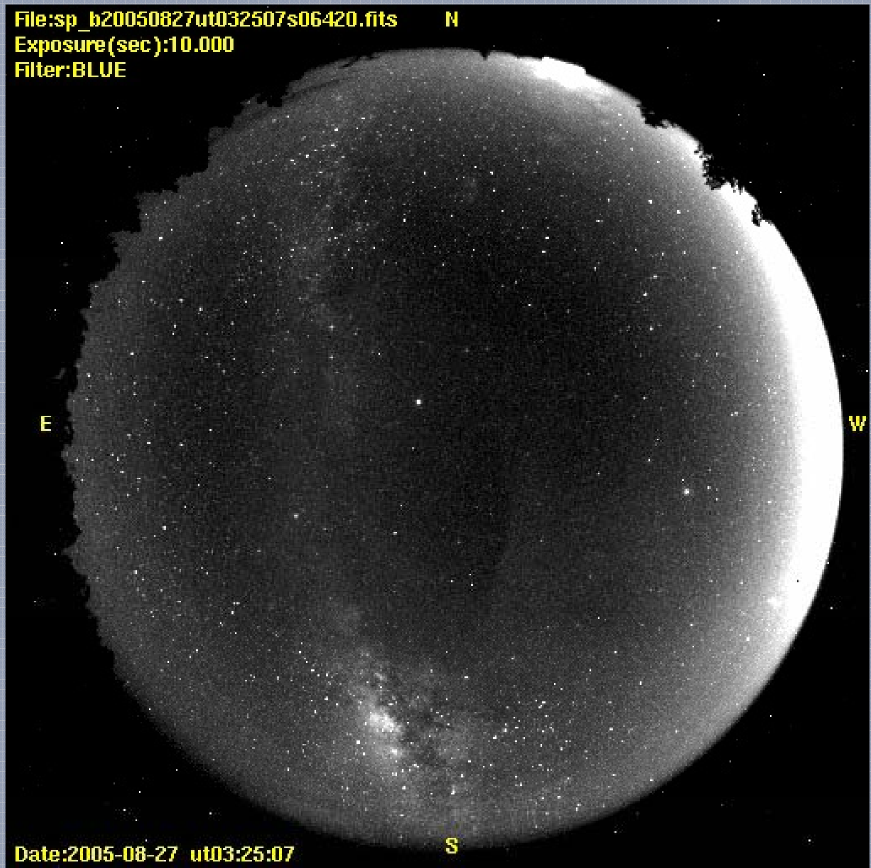
Telescope projects:

- Advance Technology Solar Telescope (2002)
- Large Synoptic Survey Telescope (2005)
- Thirty Meter Telescope (2004)

Advanced Technology Solar Telescope Survey

- Diurnal Seeing measurement
- Aerosol and dust monitors
- Weather stations
- http://atst.nso.edu/ project & site information
- Halekala, Hawaii was selected

LSST site survey



Started operations with an all-sky camera (MASCA) in July 2005. All sky images taken with 5 filters: G, R, Y, Z and Na for:

- **cloud patterns (cirrus)**
- **OH "waves"**
- **2-d multicolor sky brightness**
- **light pollution**

Also ~30 meter antenna with 4 sonic anemometers.

See http://www.lsst.org

- Cerro Pachón (2,682m) in northern Chile, was selected as the LSST site in May/17/2006

TMT Site Evaluation

Details in Schöck+ 2007, RMxAA, 31, 10

TMT Site Evaluation

Details in Schöck+ 2007, RMxAA, 31, 10

Characterization of Candidate Sites

The **technical side** of the site decision is based predominantly on multi-year on-site testing of the candidate sites. Site characteristics studied are :

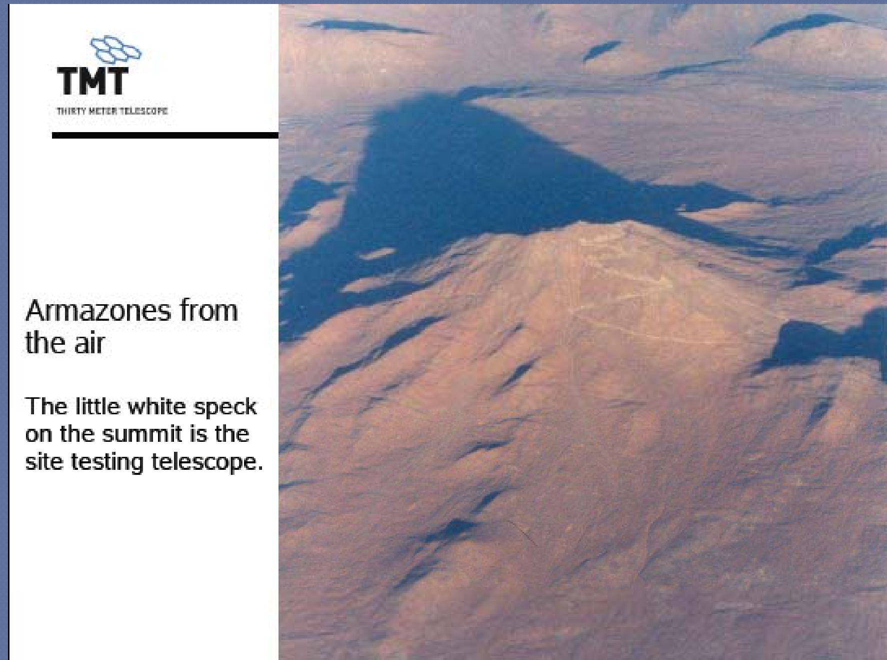
Parameter	Instrument
Cloudiness	All-sky camera, satellite, DIMM/MASS photometry
Meteorological parameters	Weather station, sonics, SODAR (wind), 30m tower
Seeing	DIMM, MASS, SODAR
Turbulence profiles	MASS, SODAR
Isoplanatic angle	MASS
Dust	Dust sensors
Light pollution	All-sky camera
Precipitable water vapor	Infrared radiometer

Details in Schöck+ 2007, RMxAA, 31, 10

TMT site survey at SPM

Operational Oct 2004-Aug 2008

Short list of TMT sites



Wind modelling

Model: 3D hydrodynamic code for a steady, incompressible and isothermal fluid.
Input: fixed topography and variable wind speed and direction.
Why: explores topographically induced turbulence, pinpointing promising (and unpromising) sites.

Vogiatzis & Hiriart (RMxAA 40, 81, 2004) modelled 5 sites with 8 wind regimes. We found:

Best site: La Corona
Slightly better than the Observatory: Venado Blanco
Slightly worst than the Observatory: Altar (Alamillos de arriba) and Botella Azul.

We need higher resolution, specific sites, more wind directions and thermal effects

Site TIM-O1 +31º 02.720’ -115º 28.086’ 2800 m

Alternative Sites

Portable system:
- 6 meter tall foldable tower
- Data centre & living quarters
- Power plant
- DIMM (SPM and/or NOAO)
- Sonic anemometer
- Weather station (temperature, wind, humidity, irradiation, etc.)

5 sites tested => no significant differences

Conclusions

- We have described site testing studies of San Pedro Martir Observatory carried out over the last three decades. These cover many of the characteristics that have to be assessed for a large telescope. Including fractional cloud cover, precipitable water vapor, long-term weather patterns, prevailing winds and wind flow across local topographic features, seeing (upper and ground layer turbulence profiles), geologic activity, geotechnical characteristics and light pollution.

- We conclude that the summit of the Sierra San Pedro Martir in the Baja California peninsula of Mexico, is one of the best candidate sites for the next generation of telescopes.

- San Pedro Martir's characteristics place it among the best three astronomical sites in the Northern Hemisphere.

- For details see RMxAA, Vol. 19, Eds. Cruz-Gonzalez, Avila & Tapia (2003) & RMxAA, Vol. 31, Eds. Cruz-Gonzalez, Echevarria & Hiriart (2007)

Site testing at SPM

Our plan is to continue site testing studies: e.g. MASS-DIMM from CTIO & generalized SCIDAR for systematic long-term atmospheric turbulence studies.