Thirty Meter Telescope

TMT on La Palma or Maunakea. Construction status. Assessment of alternate sites.

Prepared by TMT DEOPS Team

For TMT ISDT members

Version date: May 26, 2017

TMT.OPS.PRE.17.009.REL01

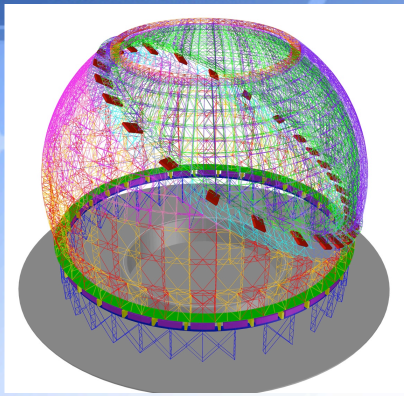
Overview of Talk

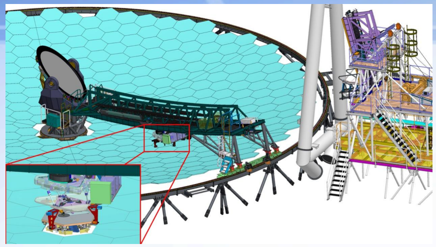
- Observatory Construction Phase Update
  - Technical development
  - The need to identify a site and begin construction
- Assessment of Alternate Sites and the Decision Process
  - Solicitation of proposals
  - Ability of potential sites to support TMT science
    - Site characteristics and system performance
      - The major effort of DEOPS group with AO group
    - Key results
    - Available observing modes and ability to support science
  - ORM supports TMT science, construction and operations

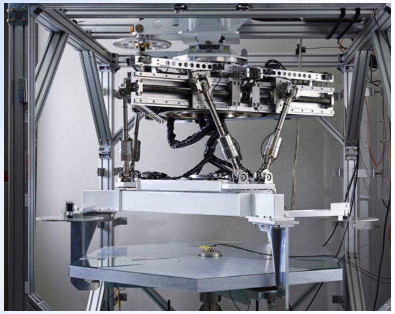
Technical development

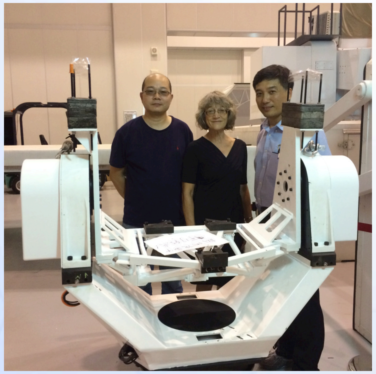
All critical systems in construction or final design phases

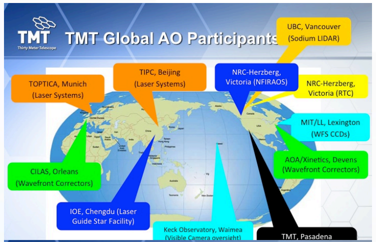
Development proceeding in all areas

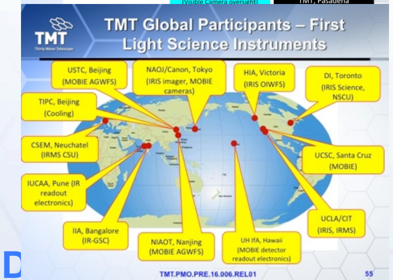


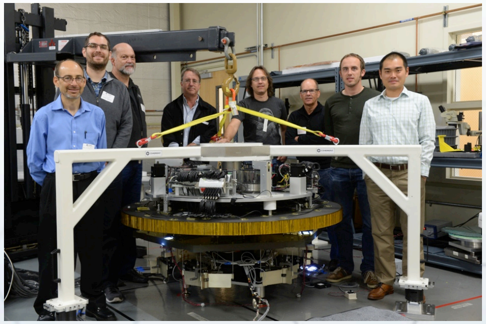












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The need to begin on-site construction

- On-site construction is dominating the critical path items in the project schedule
- Project funding is dependent on following a certain pacing
- Uncertainty about permitting timescales and site access for Maunakea
- Necessary to evaluate alternate options for a site for TMT
  - The site **must** support the science goals for TMT
  - The site **must** support timely construction and operations

Assessment of Alternate Sites and the Decision Process

- Solicitation of proposals
  - On-site construction must begin by April 2018
    - Board decision planned October 2017
  - Following vacation of Hawaii CDUP (Dec. 2015) a call for proposals to host TMT was circulated (Feb. 2016)
    - Proposals included site characteristics, logistical and programmatic information
    - Potential sites after solicitations received:
      - India (Hanle)
      - China (Ali)
      - Mexico (San Pedro Martir)
      - Canary Islands (Observatorio del Roque de los Muchachos)
      - Chile (Mackenna and Honar)
- Initial examination and first down select
  - Due to remoteness both Himalayan sites had very significant logistical concerns and whilst generally very good sites, they were less able to support the specific TMT Science Cases than the others

Assessment of Alternate Sites and the Decision Process

- Further investigations of site characteristics
  - **Large effort by the TMT DEOPS group to develop a confident understanding of the characteristics of potential sites**
- Main tasks were information gathering and analysis
  - Short timescale driven by deadline for decision (Oct. 2016)
  - No time for additional site testing – Use pre-existing sources of information
  - Cross checks of all results from independent data sets
  - Investigating concerns and developing data products to allow performance modeling and scientific productivity to be evaluated
  - Also solicited a detailed climate change study
- Parallel examination of cost, schedule, technical and logistical issues by project management, project teams and sub-group of TMT board – **Very significant effort**

Sources of Information

Site	Seeing/ turbulence	Wind	PWV	Clear fraction	Night time temperature	Sky brightness	Transparency	Ground level dust	Relative humidity	Mirror degradation
ORM	Raw data IAC, ESO, NOAA, WHT/ CANARY. Internal TMT analysis	IAC	Guimar station radiosonde soundings. IAC GPS. Internal TMT analysis	CMT logs, Garcia-Gill et al., 2010	IAC, NOT	Steidel Obs. (M. Pedani, 2004, NewAr)	Raw data CMT. Internal TMT analysis Plus LT, Stetson Obs, Steidel Obs.	Raw data TNG. Internal TMT analysis	Raw data NOT. Internal TMT analysis	GTC, LT, Gemini development , CTA testing
SPM	TMT Site testing for Cerro Pelado, SPM	TMT Site testing for Cerro Pelado, SPM	TMT Site testing for Cerro Pelado, SPM	TMT Site testing for Cerro Pelado, SPM	TMT Site testing for Cerro Pelado, SPM	-	Schuster W., Parrao L. & Guichard J., 2002	TMT Site testing for Cerro Pelado, SPM	TMT Site testing for Cerro Pelado, SPM	CTA testing
Honar	TMT Site testing for Tolonchar	Chajnantor Plateau, Perez & Otárola, 2004	Extrapolated from Chajnantor Plateau (Giovanelli et al., 2001)	Erasmus studies and Giovanelli et al., 2001	Extrapolated from CBI Telescope	-	-	TMT Site testing for Tolonchar	TMT Site testing for Tolonchar	-
Mackenna	TMT Site testing for Armazones	TMT Site testing for Armazones	TMT Site testing for Armazones and Lakicevic et al., 2016, Kerber et al., 2014, Otarola et al., 2015	TMT Site testing for Armazones and Paranal ASCAM	Extrapolated from TMT Site testing for Armazones	Paranal site measurements	Patat, F., 2004	TMT Site testing for Armazones	TMT Site testing for Armazones	CTA testing for Armazones

Assessment of Alternate Sites and the Decision Process

- Site characteristics
  - Comparative results

		ORM	LCO	SPM	Armazones Mackenna	MK 13N	Honar
Parameter	Uncertainty	2250	2500	2790	3114	4050	5400
Usable time fraction	0.03	0.72	0.75	0.80	0.86	0.72	0.79
Median seeing (60 m)	0.05	0.55	0.50	0.57	0.50	0.50	0.51
AO Strehl merit function	0.03	0.93	0.92	0.81	0.92	1.00	0.87
Isoplanatic angle	0.2	2.33	2.05	1.99	2.05	2.55	1.78
Atm. coherence time	0.5	6.0	5.0	5.1	5.0	7.3	5.21
NIR sensitivity (Cohen metric)	0.03	0.74	0.70	0.84	0.80	0.93	1.10
PWV < 2mm	0.03	0.20	0.23	0.26	0.50	0.54	0.76
Mean night temperature	1.0	7.6	13.0	5.4	7.5	2.3	-7.3

Assessment of Alternate Sites and the Decision Process

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- Site characteristics
  - Comparative results

From IMACS user guide
§ Median value for Armazones, TMT site testing
$ 0.132 exc. Mt. Pinatubo eruption

Site characteristics (median values, unless stated)	MKO (USA)	ORM (Spain)	LCO (Chile)
Altitude of site (m)	4050	2250	2500
Fraction of yearly usable time (%)	72	72	75
Seeing at 60m above ground (arcsecond)	0.50	0.55	0.50
Isoplanatic angle (arcsecond)	2.55	2.33	2.05
Atmospheric coherence time (ms)	7.3	6.0	5.0
Precipitable Water Vapor (% of time < 2mm)	54	≥20	23
Adaptive Optics Strehl merit function	1.0	0.93	0.92
Mean nighttime temperature (°C)	2.3	7.6	13.0
Extinction (V mag/airmass)	0.111	0.137$	0.14#
Ground dust concentration (μg/m³)	0.815	1.006	2.289§

Prepared by TMT DEOPS

Assessment of Alternate Sites and the Decision Process

- Site characteristics
  - Key results and examples
    - Ground level dust
    - Mirror Degradation
    - Usable time
    - Extinction
    - PWV
    - Optical Turbulence and Laser Guide Star Operation
- Public documents and information
  - http://www.tmt.org/observatory/site-information/alternate-site-studies

Atmospheric Turbulence and Laser Guide Stars

ORM Turbulence Data

- Site testing has been going on for decades at ORM
  - Lots of different data sets available
  - No long-time MASS/DIMM data set for direct comparison with other TMT sites
- Because we need the 60-m seeing, we need to work with turbulence profiles
  - DIMM data are only used for (successful) consistency checks
- Best available data set: SCIDAR data covering >5 years, almost 200,000 data points
  - Scidar profiles are actually more accurate than MASS profiles for AO performance analyses (because of the higher vertical resolution), but we need to compare to MASS data from other sites → reduce SCIDAR data to MASS resolution
  - Comparison with other site testing data sets and AO performance from observatories are all consistent
- Using same extrapolation to 60m seeing as for Maunakea 13N
  - This is done on a point-by-point basis, assembling statistics afterward
    - But using statistics gives almost identical results (yes, we verified all of that)
    - All distributions very close to log-normal once sufficient data are available

- N.B: Accuracy of (high quality) turbulence measurements is order 10%

Isoplanatic Angle and Coherence Time

- Isoplanatic angle: SCIDAR provides reliable estimate
  - GL does not matter at all
  - We use MASS-resolution profiles from SCIDARs for comparison with other sites
- There is no question that the coherence time is large at ORM
  - This has been shown over and over again
    - 200 mbar wind speed (see backup slide)
    - Weak high-elevation turbulence
    - Consistent with existing measurements

Site	V_{200} ($\mathrm{m\,s^{-1}}$) Mean	Std. dev.
ORM	22.13	11.67
La Silla	33.35	12.94
Mauna Kea	24.33	12.30
Paranal	30.05	13.01
San Pedro	26.55	15.39

Table 9: Results of V_{200} from NCEP/NCAR reanalysis data (1980–2002) at different astronomical sites (García-Lorenzo et al., 2005).

- No time series of τ_0 measurements simultaneous with SCIDAR profiles available
  - Using estimate of average τ_0 for all profiles for AO performance simulations
  - Some uncertainty on exact value, but:
    - Expected to be longer than at the Chilean sites and slightly shorter than at Maunakea
    - Sensitivity and “inverse” analyses show that this has a small effect on NFIRAOS performance
    - 6 ms is a conservative estimate compared to other sites

Laser Guide Star Operation

- Modeling of LGS performance included extinction and scattering effects
  - Rayleigh Scattering, O_3 Chappius Band, Cirrus cloud ice particles, extinction and scattering due to dust (aerosols)
- Cirrus at higher altitude causes more back scattering than dust at lower altitudes for the same level of extinction
- Extinction at ORM (regardless of course) has same statistics as extinction at MK 13N
- Conclusion is that dust at ORM will not significantly affect LGS operation

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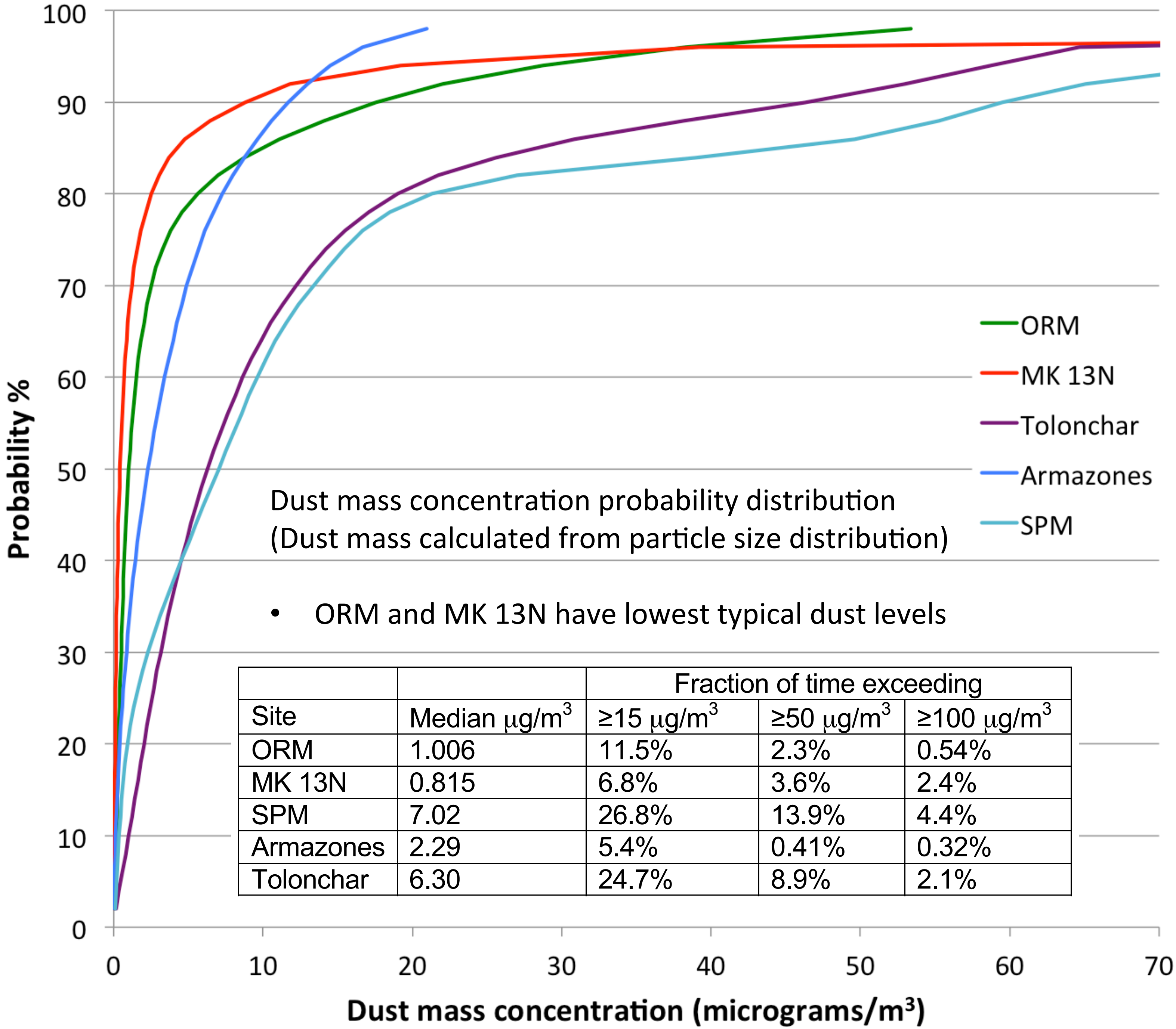
Dust.
Usable Time.
Extinction.

Sources of ground level dust measurements

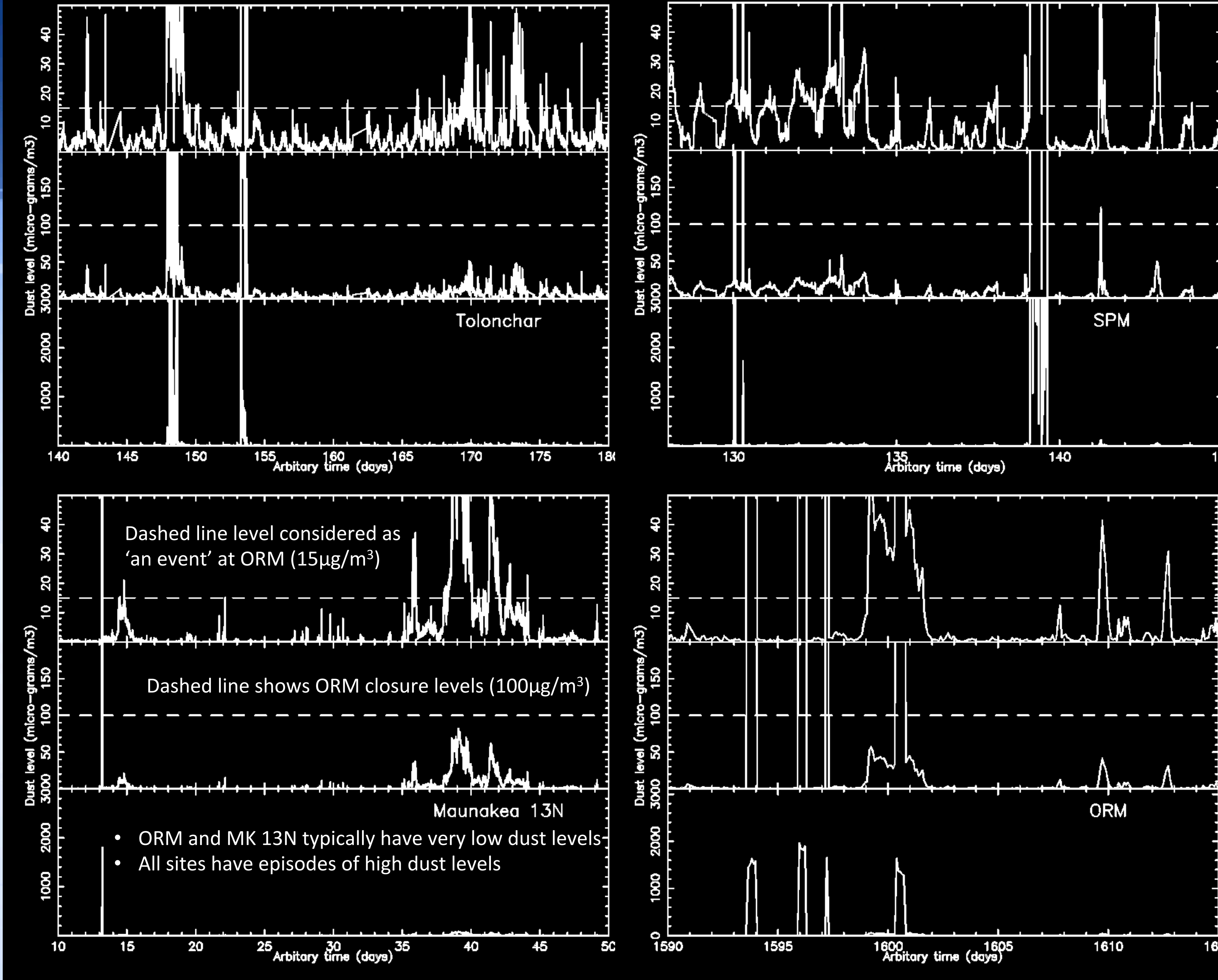
- MK 13N, Tolonchar, SPM, Armazones
  - ~2.5 years at each site
  - Measurements every 5 to 7 minutes
  - Commercial dust sensor at 7m
- ORM
  - 9 years 5 months of measurements
  - Measurements every 2 hours
  - External inlet at 11m on TNG enclosure
  - Commercial dust sensor (different model but same specs as above)



Dust mass concentration probability distribution
(Dust mass calculated from particle size distribution)

- ORM and MK 13N have lowest typical dust levels

		Fraction of time exceeding		
Site	Median μg/m^3	≥15 μg/m^3	≥50 μg/m^3	≥100 μg/m^3
ORM	1.006	11.5%	2.3%	0.54%
MK 13N	0.815	6.8%	3.6%	2.4%
SPM	7.02	26.8%	13.9%	4.4%
Armazones	2.29	5.4%	0.41%	0.32%
Tolonchar	6.30	24.7%	8.9%	2.1%


Dust level (micro-grams/m3)
Tolonchar
SPM
Maunakea 13N
ORM
Arbitary time (days)
Dashed line level considered as
'an event' at ORM (15µg/m3)
Dashed line shows ORM closure levels (100µg/m3)
• ORM and MK 13N typically have very low dust levels
• All sites have episodes of high dust levels

Mirror degradation

- Gemini testing at Pachon
  - Bare Al lost 0.03%/day, protected silver 0.06%/day without any cleaning
  - Both restored to 100% after wet cleaning – no surface degradation
- CTA testing (overcoated Al at SPM, Armazones, Teide)
  - %/day – 0.015 (SPM), ~0.02 (Armazones), ~0.01 (Teide)
- Liverpool telescope (bare Al) experience at ORM
  - 0.1%/day in between CO_2 cleaning, 0.04% on average with CO_2 cleaning on 6 week timescale – same rate as other sites
- GTC (bare Al) experience at ORM
  - CO_2 cleaning procedures ensure no additional mirror degradation due to dust
- "The impact on operations of ground level dust at ORM is much less of a concern than anecdotal reports would lead one to believe." - TMT Internal report (W. Skidmore, et al.)

Usable Time

- Usable time at ORM is estimated from observatory weather loss statistics

ORM	ATC	WHT	NOT	LT	TNG
Mean	**20.7%**	**26.33%**	**26.11%**	**29.94%**	**30.24%**
Std. Dev.	19.8%	5.73%	16.44%	18.74%	20.70%
Max.	69% (11/1999)	36% (2001)	53.4% (02/2008)	74.35% (01/2006)	90.8% (02/2005)
Min.	0% (various)	15% (2000)	0.9% (08/2007)	1.79% (06/2006)	1.5% (07/2003)
Sampling period	04/1999-11/2003	1990-2007	10/2006-11/2008	01/2006-10/2008	01/2000-12/2005
Sampling duration	56 months	18 years	26 months	34 months	72 months
RH limit	observer dependent	90%	90%	80%	85%
Wind speed limit	observer dependent	80 km/h	72 km/h	60 km/h	54 km/h

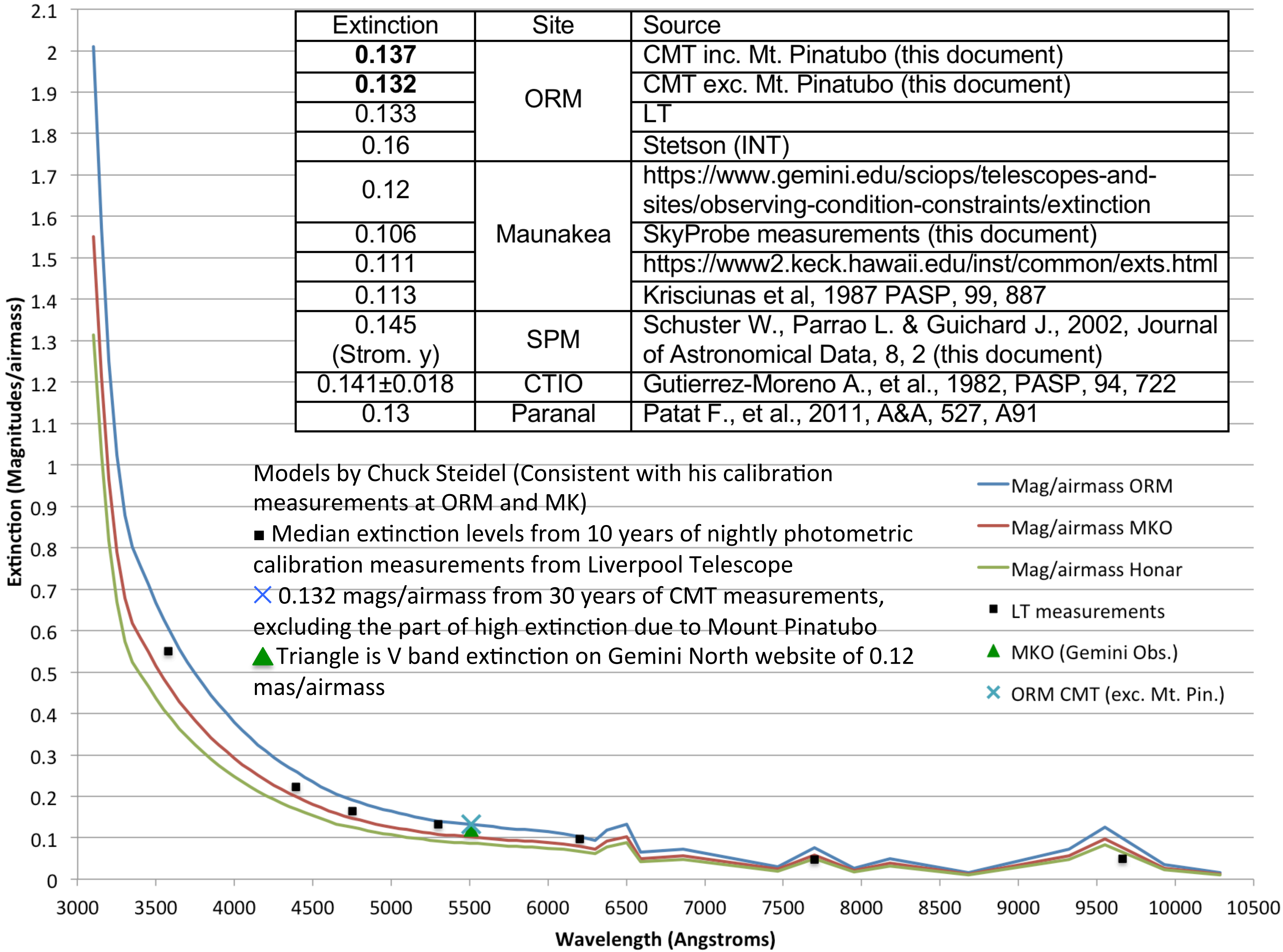
Table 13: Compilation of weather downtime at ORM (García-Gil et al., 2010).

- Shutdown conditions are different from observatory to observatory (incl. TMT)
- Usable time for TMT at ORM will likely be similar to the large telescopes there, i.e., in the 70-74% range (using 72% in SMF)
- Corroborated by "manual" analysis of 5yr 1month of CMT (ATC) observing logs which agree to <2% with value in table above (19.1% vs. 20.7%)

Usable Time

	Clear Fraction	Additional time lost due to weather	Usable Time Best Estimate
ORM			72%
SPM	82%	2%	80%
Armazones	89%	3%	86%
MK 13N	76%	4%	72%
Tolonchar	82%	3%	79%

- "Clear fraction" from the Erasmus satellite studies
- Satellite data cover longer periods than on-site measurements at the sites
- Satellite measurements extensively validated using on-site all-sky camera (ASCA) and MASS transparency, weather station)
- Additional time lost comes from simultaneous ASCA and weather station measurements
- **Use of satellite data means that we have equivalent data for all sites**
- **Relative precision for comparing sites in 2008 report is 5% or better**



Extinction	Site	Source
0.137	ORM	CMT inc. Mt. Pinatubo (this document)
0.132		CMT exc. Mt. Pinatubo (this document)
0.133		LT
0.16		Stetson (INT)
0.12	Maunakea	https://www.gemini.edu/sciops/telescopes-and-sites/observing-condition-constraints/extinction
0.106		SkyProbe measurements (this document)
0.111		https://www2.keck.hawaii.edu/inst/common/exts.html
0.113		Krisciunas et al, 1987 PASP, 99, 887
0.145 (Strom. y)	SPM	Schuster W., Parrao L. & Guichard J., 2002, Journal of Astronomical Data, 8, 2 (this document)
0.141±0.018	CTIO	Gutierrez-Moreno A., et al., 1982, PASP, 94, 722
0.13	Paranal	Patat F., et al., 2011, A&A, 527, A91

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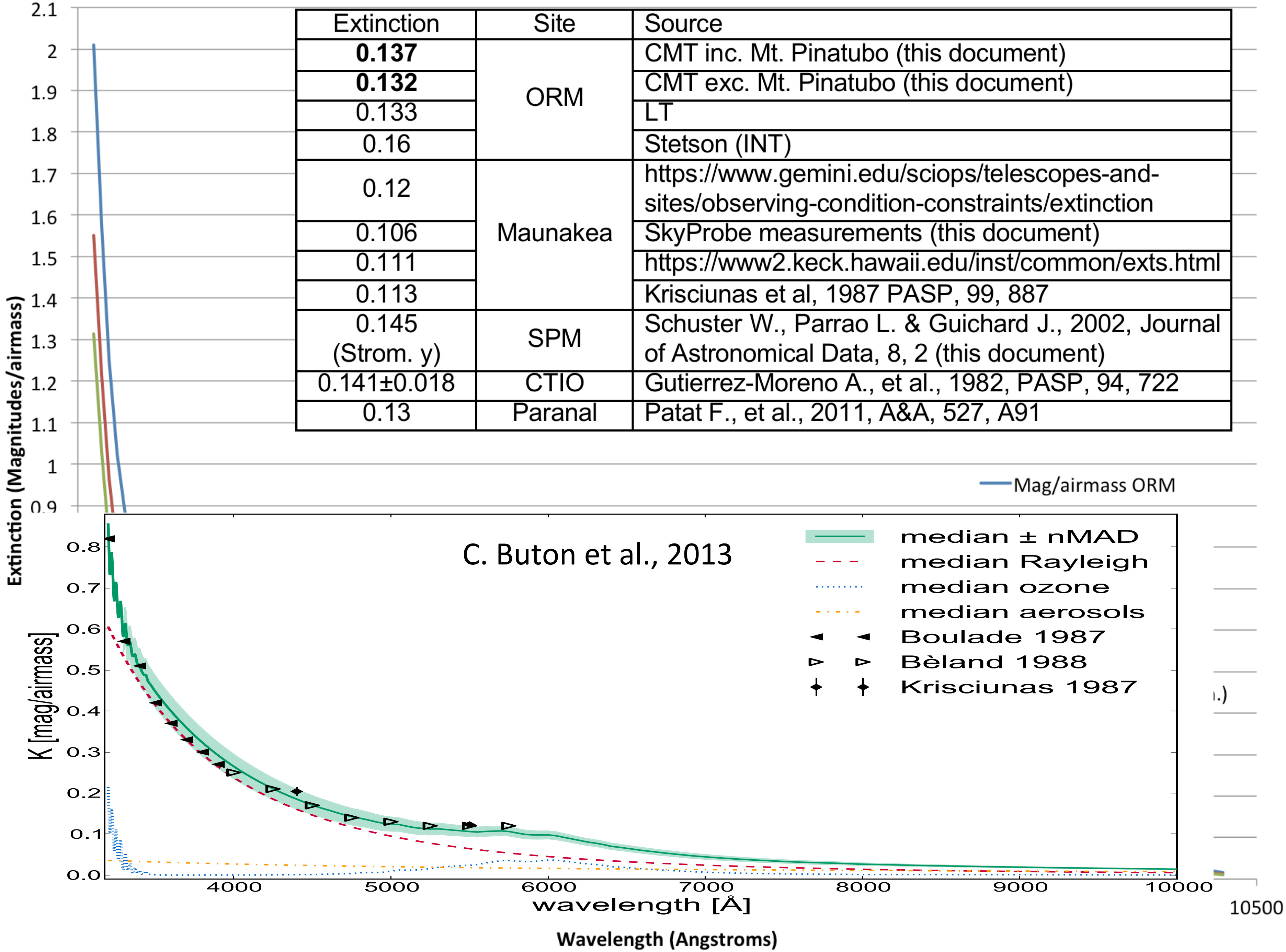


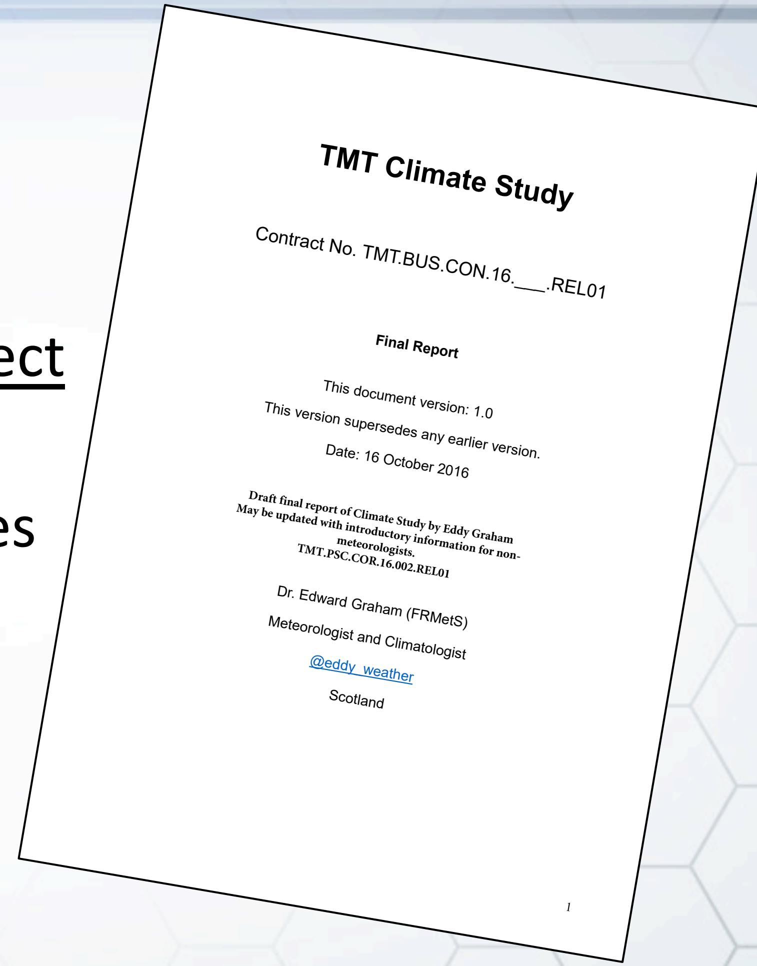
Precipitable Water Vapor

Site	ORM	SPM	Paranal (Mackenna)	Maunakea	Honar
Altitude	2250 m	2830 m	2640 m	4050 m	5400 m
<2mm	20%	26%	44% (50%)	54%	76%
5%	1.02 mm	1.06 mm	0.81 mm	0.59 mm	0.16 mm
10%	1.42 mm	1.29 mm	0.99 mm	0.78 mm	0.23 mm
20%	2.00 mm	1.74 mm	1.32 mm	1.03 mm	0.34 mm
25%	2.20 mm	1.96 mm	1.46 mm	1.15 mm	0.40 mm
50%	4.24 mm	3.12 mm	2.26 mm	1.91 mm	0.80 mm
75%	7.03 mm	6.12 mm	4.04 mm	3.54 mm	1.74 mm
95%	12.2 mm	15.15 mm	9.58 mm	8.15 mm	5.12 mm

ORM PWV derived from Radio Sonde measurements. Published GPS measurements believed to be under-estimate.
<2mm value for Mackenna estimated as evidence suggests PWV scale height is >1.8km at ground level but doesn't provide quantitative value.

Climate Change

- Dr. Eddy Graham
  - Hadley Cells are moving and expanding
  - No evidence that changes will affect the potential TMT sites
  - Some other existing/potential sites may be affected
    - Equatorial regions becoming poorer high/lower latitudes improving


TMT Climate Study

Contract No. TMT.BUS.CON.16.___.REL01

Final Report

This document version: 1.0
This version supersedes any earlier version.
Date: 16 October 2016

Draft final report of Climate Study by Eddy Graham
May be updated with introductory information for non-meteorologists.
TMT.PSC.COR.16.002.REL01

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Available observing modes and ability to support science

TMT potential sites *Altitude (m)*			MKO *(4050)*	ORM *(2250)*	SPM *(2790)*	Chile #1 *(5400)*	Chile #2 *(3110)*
% of usable time for science			72	72	80	79	86
Science cases	Visible spectroscopy/ imaging	WFOS					
	UV/Visible HR spectroscopy	WFOS					
	Near-IR AO	IRIS/NFIRAOS, PFI					
	L/M/N band observations	MICHI					
	(not TMT core-science) Q-band	MICHI					
Main characteristics		**Pros**	(Benchmark)	**AO perf.**	**% clear time**	**UV/Mid-IR**	**% clear time**
		Cons		**Mid-IR**	**Mid-IR**	**Weather**	**N/A**
Site Merit Function		*Visible*	***1.0***	***0.9***	***0.9***	***1.1***	***1.2***
		Near-IR	***1.0***	***0.8***	***0.8***	***1.1***	***1.0***
		Mid-IR	***1.0***	***0.2***	***0.3***	***2.6***	***0.8***
		[40%Vis., 50% Near-IR, 10% Mid-IR] Total	**1.0**	**0.8**	**0.8**	**1.2**	**1.0**

TMT Assessment against science cases

Thirty Meter Telescope

All alternate sites are able to support TMT key science

Color coding (sensitivity wrt MKO): Better | Identical | Acceptable | Compromised | Important loss

Target problems (loss of targets, or challenging observing conditions due to site latitude)

New science cases from 2015 DSC

Differential impact of alternative sites wrt MKO

Science Program			Observing SL/NGSAO/ MCAO/ MOAO/MIRAO/ExAO	Spectral Parameters: Wavelength (µm)	Spectral Parameters: Spectral (λ/Δλ)	Spatial Parameters: Image Resolution (mas)	Spatial Parameters: Strehl (S) / Contrast (C) ratio	Multiplexing: Sample Size	Multiplexing: # of observations	Comments	Comments	U.S.A. MKO (4050m)	MEXICO SP.Martir vs MKO (2800m)	SPAIN R.Muchachos vs MKO (2250m)	CHILE Honar vs MKO (5350m)	CHILE V. Mackenna vs MKO (3100m)
Ratio of clear nights (wrt MKO)												100%	108%	99%	105%	117%
Fundamental Physics and Cosmology DSC 3	Nature of Dark Matter DSC 3.1	Dwarf galaxy	SL	0.51-0.535	>20,000			10000		WFOS	All sites+/- equal at these					
		Dwarf galaxy	MCAO	2 - 2.4	6	10 [20]	> 0.3 [20]	10000 [20]	100-1000 [20]	Ideally WIRC, IRIS	All sites+/- equal at					
		Baryonic	SL	0.35 - 0.62 [2]	1000[2]	800 [2]		280000 [2]	1000 [2]	WFOS	Low altitude sites loose					
		Baryonic	SL		5000 [2]			12800[2]	80[2]	WFOS	sensitivity towards short					
		Galactic	MCAO	2 - 2.4	> 3000 [23]	< 15 [23]		100	120	Ideally IRIS but WIRC	Galactic Center science					
	Dark energy DSC 3.2	Lyman-alpha	SL	0.35 - 0.62	1000 - 5000	800 [2]		12800 -	80 - 1000 [2]	WFOS, same	Low altitude sites loose					
		Supernovae	MCAO	1.5 - 1.7 [21]	4000 [21]			250 [21]	250 [21]	250 SNIa at 1 < z <	All sites+/- equal at these					
	Physics of extreme objects DSC 3.3	Gamma-ray bursts	SL	0.30 - 0.90	7500 [17]	700 [17]		600	600	WFOS	Low altitude sites loose					
			MCAO	0.97 - 1.8 [16]	30000-50000					NIRES	All sites+/- equal at these					
		Supernovae	SL/MCAO [18]	0.3 - 2.5 [18]	1000-5000			200 - 500 [18]	40 - 250 [18]	WFOS/IRIS	Low altitude sites loose					
		Tidal flares	SL	0.30 - 0.90	7500 [17]	700 [17]		2000	2000	WFOS	Low altitude sites loose					
	Variation of fundamental		SL	0.49-0.59 [3]	50000 [3]	700 [3]		50 [3]	50 [3]	HROS	All sites+/- equal at					
	NEW DSC	Dark Matter	MIRAO	MIR	>300			~4	?	MICHI IFU or Imager	All low altitude sites have					
Early Universe DSC 4	First Galaxies DSC 4.3	Primordial	MCAO/MOAO	1.6 - 6.0	3000 [8]	25 [10]		25 - 250	25 [10]	IRMS/IRMOS/IRIS	Thermal-IR sensitivity					
		Characterizin	MCAO/MOAO	1.1 - 1.6	3000 [8]					IRIS/IRMOS	All sites+/- equal at these					
		Topology of	MOAO	0.8 - 2.5 [10]	~3000	25 [10]		150 - 1500 [10]	150 [10]	IRMOS, R=10Mpc	All sites+/- equal at these					
	Intergalactic medium		MCAO	0.9 - 1.3	30000					NIRES	All sites+/- equal at these					
Galaxy Formation and Intergalactic medium	Multiplexed spectroscopy of		SL	0.31 - 1.0	5000 [17]	800 [17]		100 [17]	8 [17]	WFOS	Low altitude sites loose					
	Multiplexed spectroscopy of		MCAO/MOAO	1.0 - 2.5	3270	200		100's	10's	IRMS/IRMOS	All sites+/- equal at these					
	Spatial dissection of forming		MCAO/MOAO	1.0 - 2.5	4800	8	S = 0.5 [7]	1400 [10]	< 140 [10]	IRIS/IRMOS	All sites+/- equal at these					
	IGM: Core samples during		SL	0.31 - 0.60	5000	800 [17]		15000	100	WFOS w/ HROS follow	Low altitude sites loose					
	Epoch of galaxy formation in		SL	0.32 - 0.65	500	800 [17]		120000	1000	WFOS w/ IRMOS	Low altitude sites loose					
Extragalactic SuperMassive Black Holes	SMBHs in nearby galactic		MCAO/NGSA	0.8 - 2.5 [8]	4000-8000	10 [7]	S = 0.5 [7]	340 [7]	340 [7]	IRIS, sample size is	M31 / M33 are not visible					
	SMBHs beyond local		MCAO/NGSA	0.8 - 2.5 [7]	3000 [8]	8 - 10 [7]	S = 0.5 [7]	90 [22]	180 [22]	IRIS	from Southern					
	SMBHs at very high redshift		MOAO/MCAO	0.8 - 2.5 [11]	4800 [11]	50 [11]	S = 0.5 [11]	1200 [11]	35 [11]	IRMOS/IRIS	All sites+/- equal at these					
Exploration of nearby galaxies DSC 7	Probing oldest stars in the		SL	0.33 - 0.9 [3]	40000	700 [3]		100	100	HROS	Note: (1) UV and near-IR					
	Looking deeper: isotope		SL	0.45 - 0.68	90000	700 [3]				HROS	sensitivity impacted for					
	Chemical evolution in the		SL	0.33 - 0.9 [3]	50000	500 [3]				HROS	low altitude sites. (2)					
	Local Group galaxies and		MCAO	1.4 - 2.4 [16]	40000 [16]					NIRES - molecular	Southern sites mean					
	Stellar astrophysics	Diffusion	SL	0.55 - 0.69						HROS - abundances	loosing M31 and other					
		Mass loss	SL	0.4 - 0.7						WFOS - brightest	N.H. galaxies but getting					
	Reconstructing star		MCAO	1.0 - 2.5	4000	10 - 30 [20]	S = 0.6 [7]	2500 / obs [20]	50 / galaxy	IRIS/WIRC	access to Magellanic					
Formation of stars and planets DSC 8	Physics of star	Initial mass	MCAO	1.0 - 5.0 [8]	4000	15	S = 0.5 [7]			IRIS IFU w/	M31 / M33 are not visible					
		Structure and	MIRAO	4 - 5 [15]	100000	80		100 [15]	100 [15]	MIRES/NIRES	from Southern					
	Protoplanetary disks DSC 8.3	Gas	MIRAO	4 - 25 [15]	30000 -			300 [15]	300 [15]	MIRES/NIRES	All low altitude sites have					
		Gaps	MIRAO	4 - 13 [15]	100000			400	400	MIRES/NIRES	All low altitude sites have					
		Pre-biotic	MIRAO	18 - 25 [15]	100000 [15]			100 [15]	100 [15]	MIRES	All low altitude sites have					
Exoplanets DSC 9	Doppler detection of	Planets	SL	0.48 - 0.62	50000 [3]	700 [3]		100's	100's	HROS	Southern sites mean					
		Terrestrial	MCAO	0.97 - 1.7 [16]	50000 -		S = 0.3 - 0.6 [16]	400	400	NIRES	loosing Kepler targets but					
	Direct detection and characterizati	Self-luminous	ExAO	1.63 [14]	5 [14]	30 [14]	S = 0.9 [14]	100's [14]	100's [14]	PFI	All sites+/- equal at these					
		Reflected	ExAO	1.63 [14]	5 [14]	50 [14]	S = 0.9 [14]	1900 [14]	1900 [14]	PFI	All sites+/- equal at these					
		**NEW	ExAO	5-10 mic						High-contrast /	All low altitude sites have					
	(Exo-) Planetary atmospheres	Jovians	ExAO	1.1 - 1.8 [14]	50 - 100 [14]	50 [14]	S = 0.9 [14]			PFI/IRIS	All sites+/- equal at these					
		Jovians	SL	0.5 - 0.9	50000	700 [3]				HROS	Southern sites mean					
		Oxygen on	SL	0.76 - 0.77	40000	700 [3]		< 2500	< 2500	HROS	loosing Kepler targets but					
		**NEW	ExAO	5-10 mic						High-contrast /	All low altitude sites have					
Our Solar System DSC 10	Outer Solar System	Kuiper Belt	MCAO/NGSA	1 - 2.5	1000	7 [19]	S = 0.3 [19]	1092 [19]	1092 [19]	IRIS/WIRC	All sites+/- equal at these					
		Composition	MCAO/MIRAO	3 -5 [16]	100000 [16]	27 [16]		100 [16]	100 [16]	NIRES	Thermal-IR sensitivity					
	Surface physics of Jovian		MCAO/NGSA	0.8 - 2.5 [19]	2000	7	S = 0.7 [19]	25 [19]	25 [19]	Program includes	All sites+/- equal at these					
	Atmospheric physics of		MIRAO	10	100000 [15]	80				MIRES	All sites+/- equal at					

Assessment of Alternate Sites and the Decision Process

- Site evaluation was a multi-dimension process:
  - Astronomical properties of the sites – Ability to support TMT science
  - Legal status for TIO to operate in the host country
  - Processes and timescales for obtaining necessary permits, schedule to start construction
  - Cost to construct and operate
  - An evaluation of the risks to schedule and cost.
- Oct. 31st 2016, TIO Board selected ORM as the alternate site for TMT. Considering:
  - The scientific importance for TMT to be uniquely located in the Northern Hemisphere, securing full sky coverage in combination with the ELT projects located in the Southern Hemisphere.
  - The very good quality of the ORM site, which can support TMT core science programs
    - In particular the turbulence properties and capabilities for AO performance
  - The programmatic advantages with the ORM site including:
    - Shorter timeline to initiate construction
    - Shorter timeline to 'first-light'
    - Lower costs of construction and operations
    - Lower project risks based on existence of support infrastructure
- ORM is the best site among all alternate sites considered, to secure a competitive path to first-light within the TMT budget envelope
- Lower-altitude sites like ORM suffer from lower sensitivity at longer mid-IR wavelengths, hence lower efficiency
  - Operations schedule (technical and scientific) will be flexible to optimize best conditions for demanding science programs
  - Revisiting the priorities for TMT next generation instruments

Adjusted operations

- ORM operations model similar to MKO
  - Maintenance crew traveling daily to summit
  - Science operations done remotely from science HQ (Tenerife) and TIO science nodes
- To optimize science efficiency, flexible scheduling of science and engineering activities is needed at any site
  - Extra emphasis is needed at ORM to utilize the best conditions for the science programs that need them
    - SCMS to include PWV monitoring (collaboration with IAC)
    - Requires additional software development (wrt current plan) to optimize real-time prioritization of program scheduling/execution
- Instrument priorities to be revisited

Any questions?