The Image Quality at Gemini South Observatory.

Javier Fuentes Lettura

E-mail: javier.fuentes@noirlab.edu

Outline

- Motivation and context of the project
- Background and definitions
- Data and methodology
- Results:

-- Delivered Image Quality (DIQ)

-- Wave Front Sensors

-- DIQ vs. DIMM, MASS and DIMM

-- Turbulence Parameters

-- Environmental parameters vs. DIQ

- Conclusions
- Future prospects

Motivation

- Why is important to measure the Image Quality?

- The Image Quality (IQ) is an **important metric** for queue observing and scheduling.
- This study attempts to provide an update about the Image Quality (IQ) and site seeing at the Gemini South (GS) Observatory.
- Understand the behaviour between weather and DIQ in order to evaluate the different conditions in benefit to the improvement of operations.
- Use of archival data will allow us to develop a long term assessment between the telescope environmental variants, IQ and atmospheric seeing at the Cerro Pachón site using the observatory's resources as Quality Assessment Pipeline (QAP), Instrument Wave Front Sensors, Seeing Monitor, GEA.

Context

Project time

GEMINI OBSERVATORY
Exploring the Universe, Sharing its Wonders

Long-term study about the Environmental and Image Quality using the QAP metrics at Gemini

Sponsored by: Ariel Lopez

1 Scope

The scope of this study is to create a long-term assessment of behavior of environmental variants and seeing at the Pachón site using the QAP metrics information derived from science imaging data at Gemini South (GS).

1.1 Background

The Quality Assessment Pipeline (QAP) metrics offers fundamental information to search for a wide range of observing variants as it includes Image Quality (IQ) band, Cloud Cover (CC) band, and a Background (BG) band estimation. The metrics also contain metadata information as data label, airmass, and other information related to the instrument and telescope. This tool presents a unique advantage which we need to take advantage of its huge potential. The Data Processing Software Group will release DRAGONS, this product contains data processed by science imaging obtained from several instruments in Gemini North and South since they started to be used, this fact adds an extra plus to explore historical data in both sites.

The QAP metrics reports the delivered IQ right after an acquisition image is taken while observing at nighttime. A key advantage of having such a powerful tool for the Gemini observers is that the pipeline provides the current measurement of the image quality critical for running an efficient observing queue. All the content of the metrics can be easily extracted from the QA metrics database, which provides the metrics information to carry out this project.

1.2 Objective

The objective of this project is going to primarily provide a long-term seeing study of the site using the QAP metrics derived from GMOS science imaging data. Secondly, we will explore the behavior of the environmental conditions, and, with the use of the Principal Component Analysis, identify correlations between seeing and meteorological parameters recorded by the Gemini Weather Sensors. These possible correlations are:

1. Seeing with the azimuth position and wind direction.
2. Seeing with the azimuth position and wind speed.
3. Sky brightness with the azimuth position.
4. Seeing with the temperature and wind direction.
5. ~~Seeing with the cloud cover.~~
6. ~~Sky brightness with the azimuth position and cloud cover.~~
7. Temperature difference and hours from night start with seeing.
8. Seeing with the azimuth position and wavelength versus wind direction.
9. Seeing with the azimuth position and position Angle of the Cassegrain Rotator.

The above relationships to be explored correspond to the first stage of the project, the second part could study the influence of local factors inside dome which might be affecting the image quality obtained from the current instrumentation at GS, namely: M1 temperature and dome seeing respectively.

3 Timeline

The time taken to develop this project is mainly based on best-effort work allocated during Javier's Project Time (PT). An initial estimate to complete the first stage of this study is approximately 6 months.

Description of the activities developed during 2019:

Dates	Activity	Status
Aug. 19-25	Project initialization.	Done.
Sep. 2-8	Kickoff meeting.	Done.
Sep. 16-22	Testing phase with small dataset.	Done.
Oct. 14-20	Downloading QA metrics data. All data downloaded from the FITS server on October 27th.	Done.
Oct. 21-25	Set off all the criteria to filter out the data, also I coded some pieces of them using Python.	Done.
Oct. 26- Nov3	Working in the modeled PSF of GMOS with German, pinhole data taken and data handling with JSON files.	Done.
Dec. 9-13	Coding a script to process the QAP, WFS, DIMM-MASS data. Also, I worked together with Fredrik to analyze his preliminary results on IQ bins using MASS-DIMM seeing.	Done.

GEMINI OBSERVATORY
Exploring the Universe, Sharing its Wonders

NRC·CNRC

Agencia Nacional de Investigación y Desarrollo

Gobierno de Chile

MINISTRY OF SCIENCE, TECHNOLOGY, INNOVATION AND COMMUNICATION

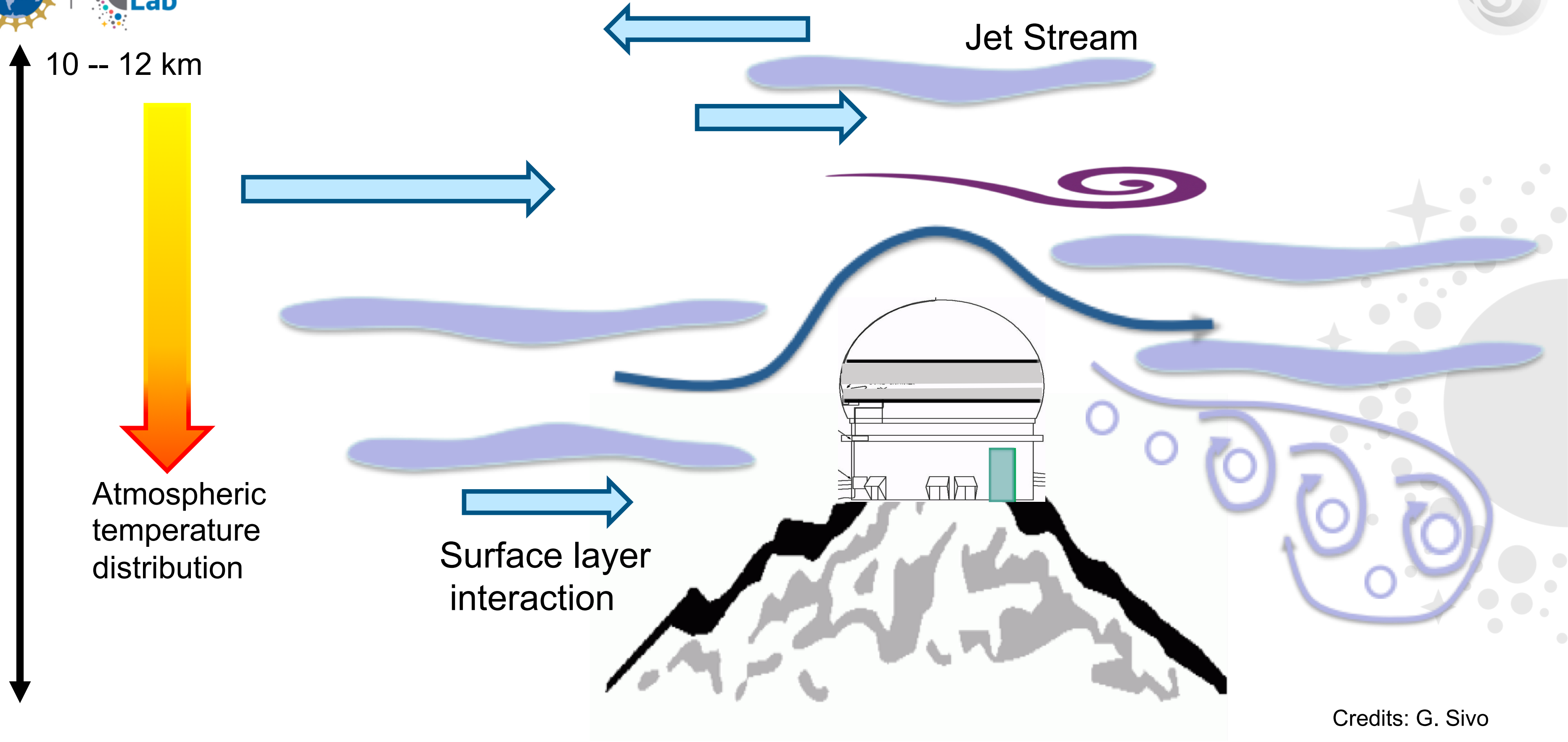
PÁTRIA AMADA BRASIL
BRAZILIAN GOVERNMENT

Background and definitions

- There is a frequent confusion between the Delivered Image Quality and Astronomical "Seeing" for large telescopes.

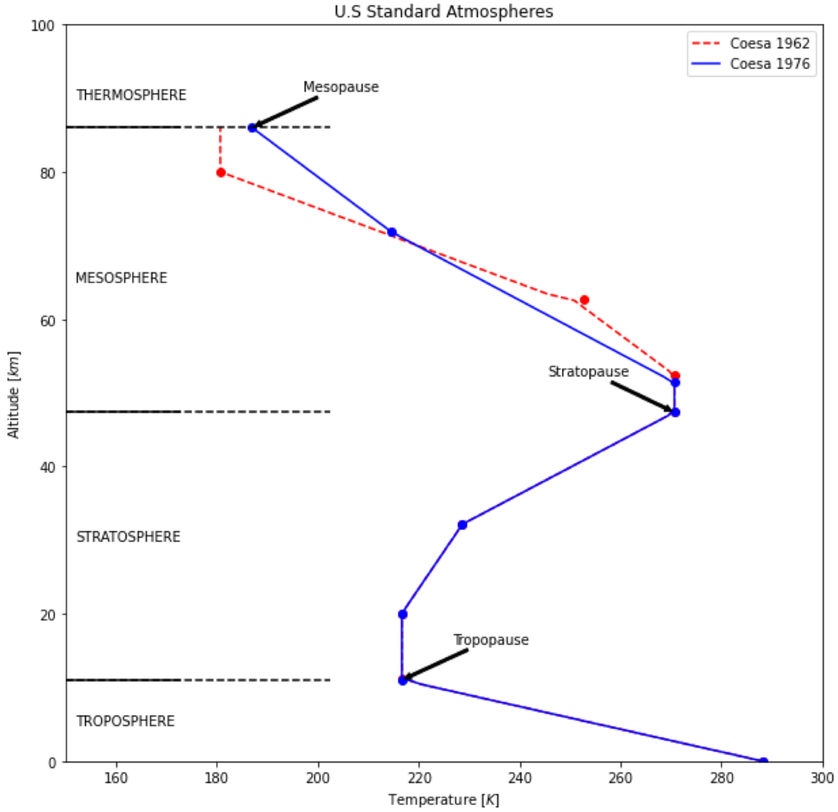
-- Delivered Image Quality (DIQ): The FWHM measured in science images obtained in the focal plane of an instrument mounted on a telescope observing through the atmosphere.

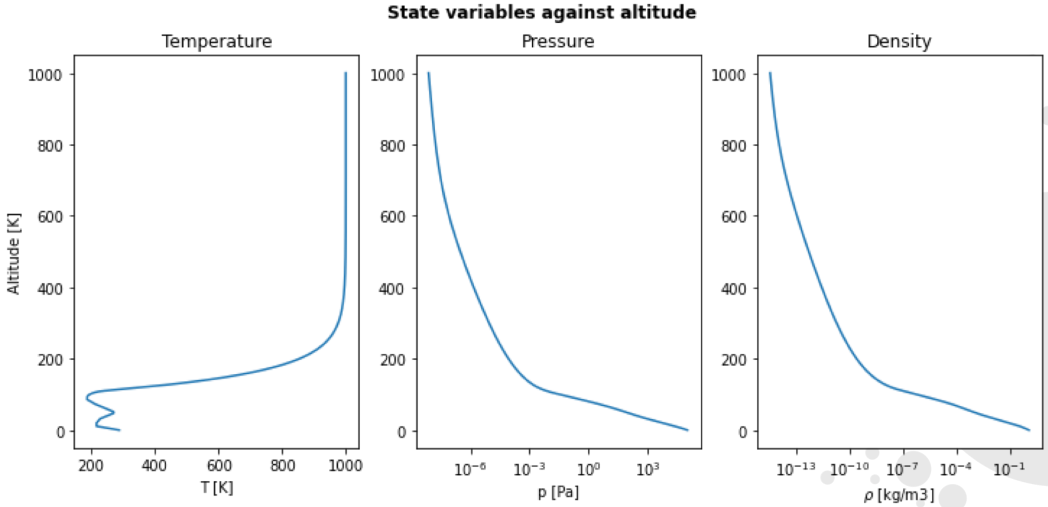
-- Seeing: It is an inherent property of the atmospheric turbulence which is independent of the telescope that is observing through the atmosphere but not on the location (site) where it is measured.



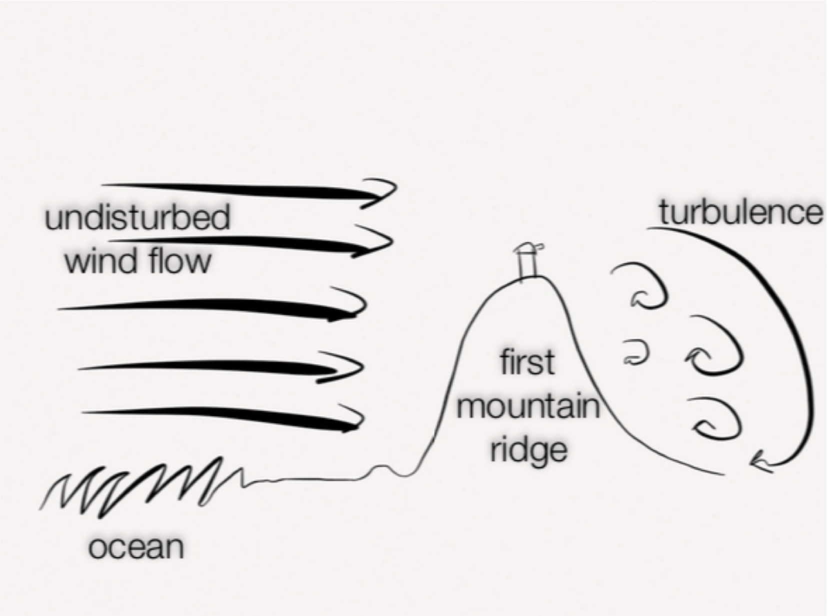
Credits: G. Sivo

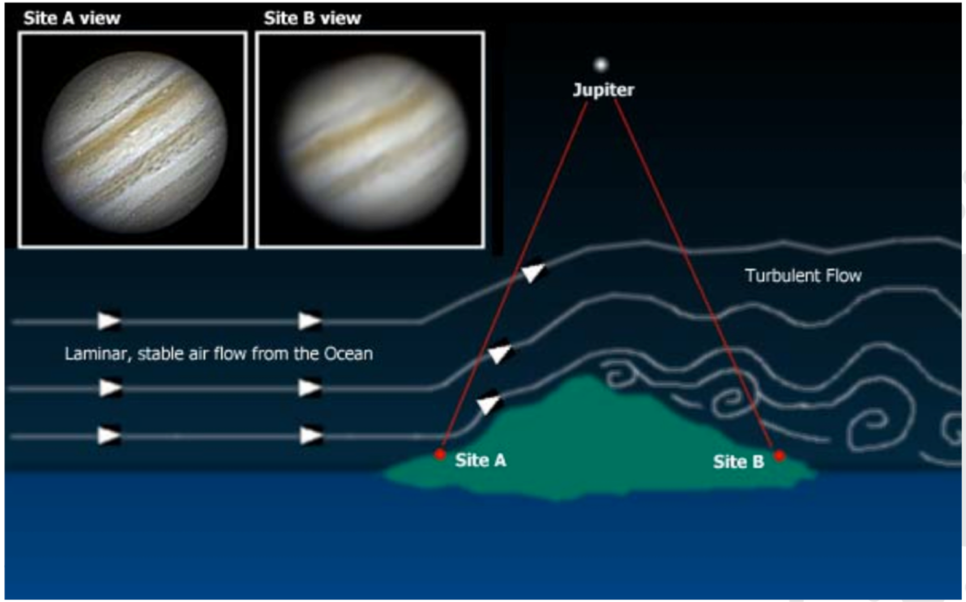
Atmospheric temperature profile





Seeing: how it depends on physical sites?





At most sites, there seems to be three regimes:

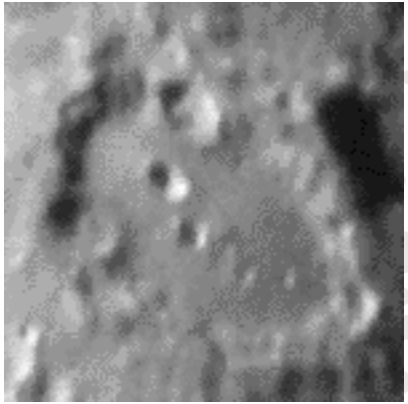
- Surface layers: wind-surface interactions
- Planetary boundary layer: influenced by diurnal heating
- Free atmosphere: at 10 km high wind shears (tropopause)

The world's finest locations for a stable atmosphere are:

- mountain top observatories
- located above frequently occurring temperature inversion layers

Effects of the turbulence:

Double star Zeta Aquarii



The Moon’s surface showing the effects of Earth's atmosphere

Definition of "seeing" = r_0

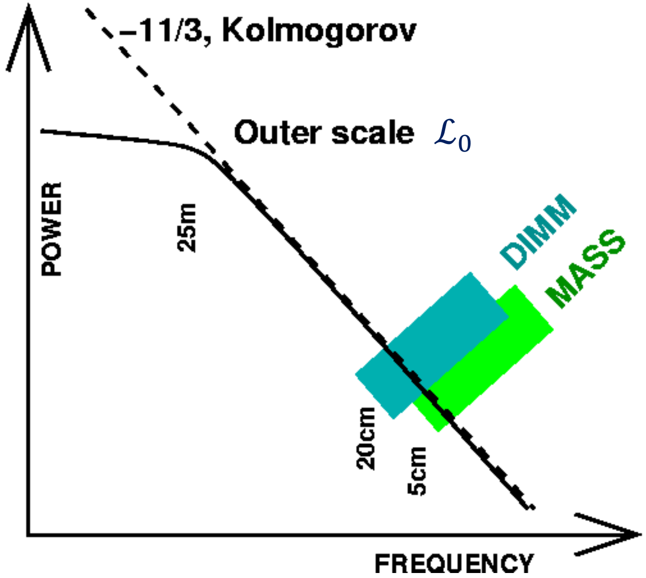
Phase spectrum: $W_\varphi(f) = 0.0229\, r_0^{-5/3}\, f^{-11/3}$

$r_0 = [1.67\, \lambda^{-2}\, (\cos z)^{-1} \int C_n^2(z')dz']^{-3/5}$ Fried parameter (1965)

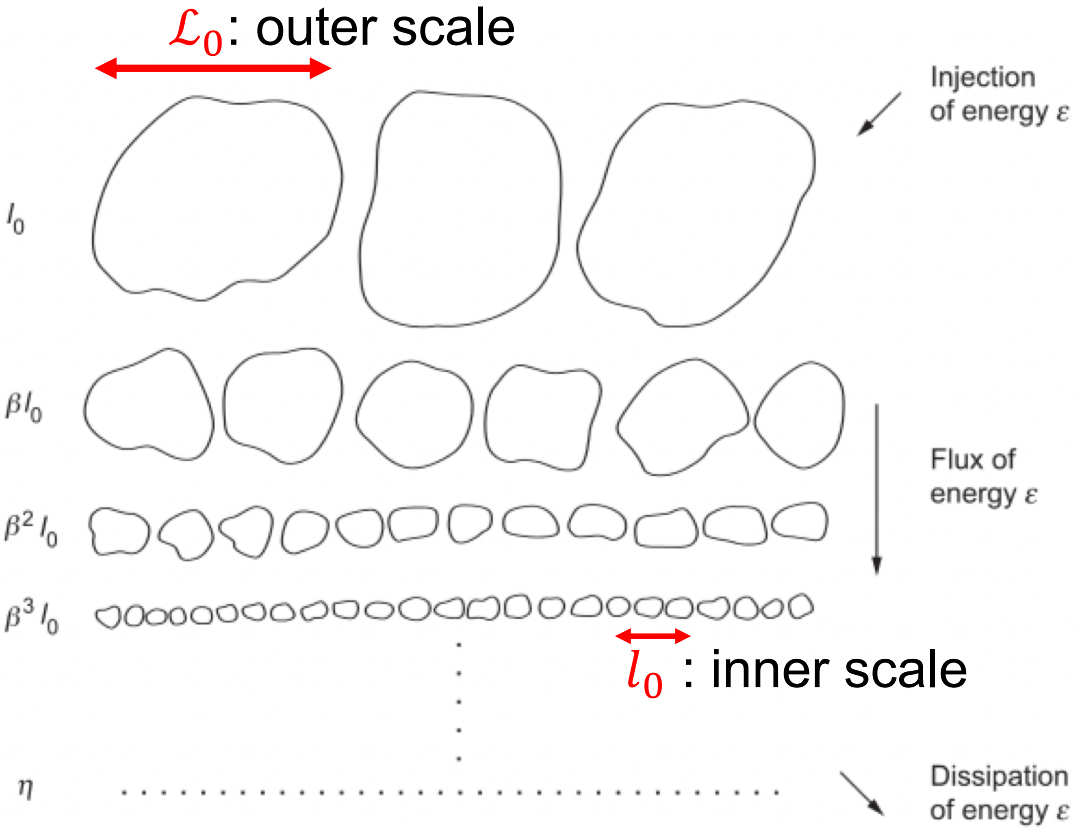
- The Fried parameter is well-describe by integrating C_n^2 along the line-of-sight through the atmosphere, where z is the zenith angle and z is the distance along the line of sight.

Seeing: $\varepsilon = 0.98\, \lambda / r_0$ (this is not FWHM!)

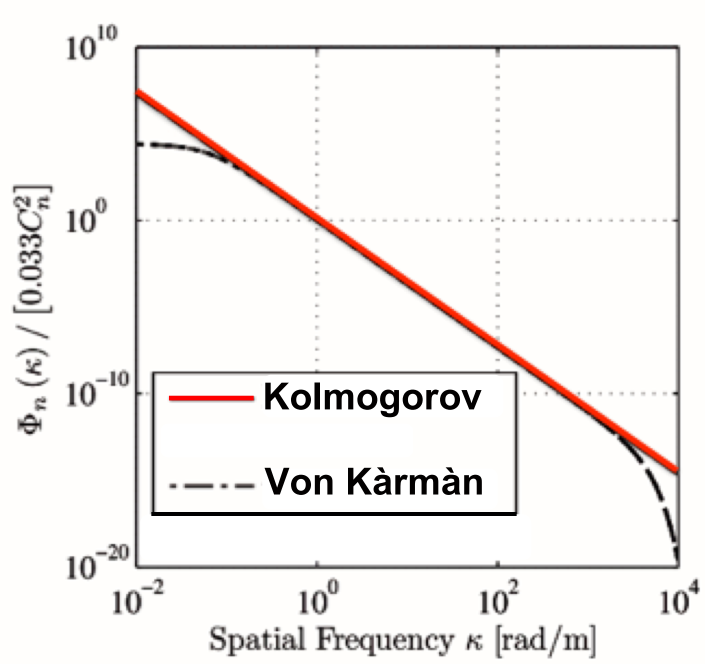
DIMM and MASS measure the wave-front distortions of few cm and infer r_0 on the absolute scale

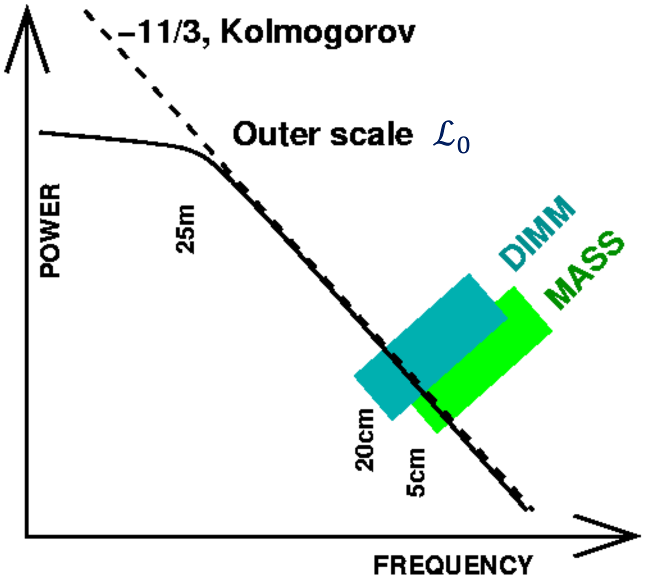


What is the Outer scale?



Turbulence models:

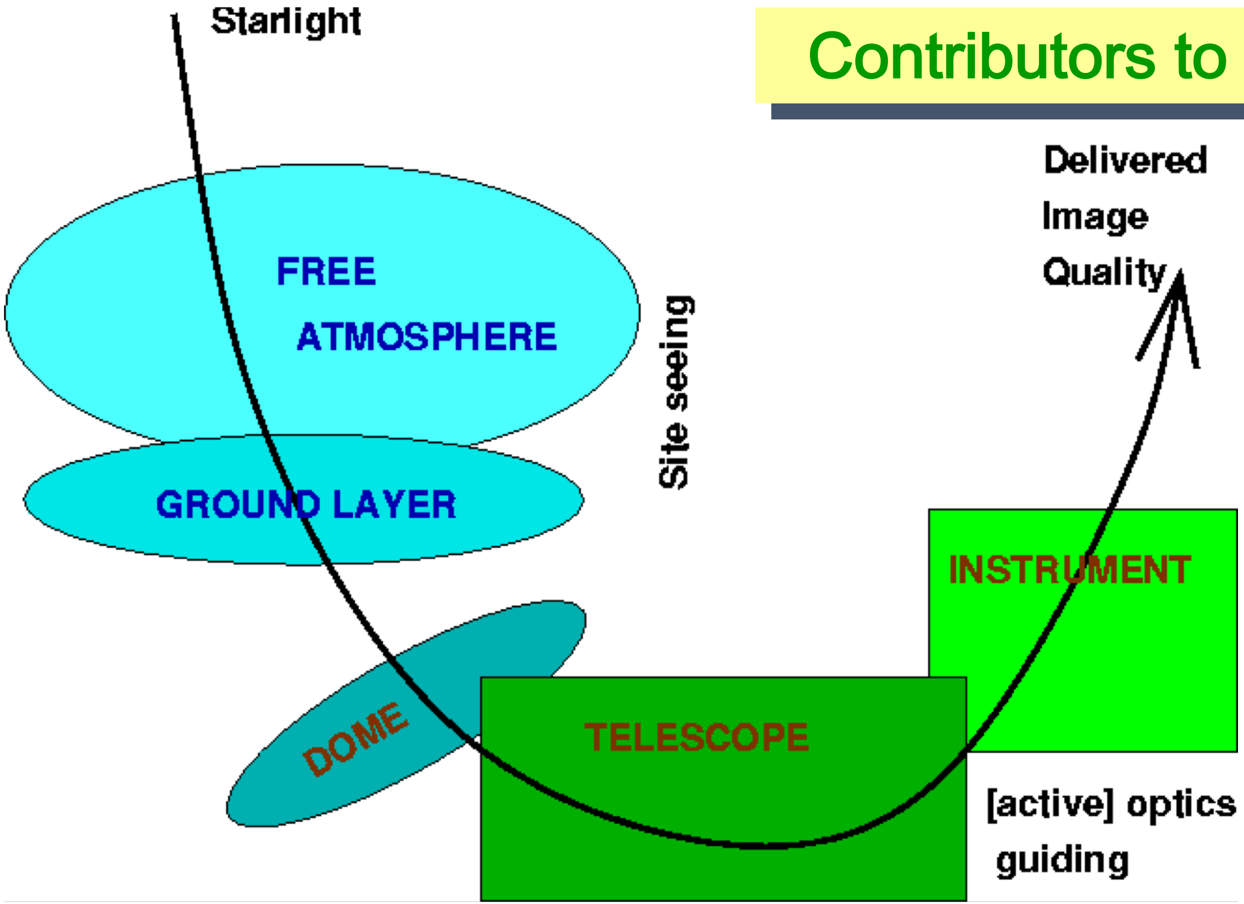




FWHM of the von Kàrmàn PSF: $\varepsilon_{vK} \approx \varepsilon_0 \sqrt{1 - 2.183 \left(\frac{r_0}{\mathcal{L}_0}\right)^{0.356}}$

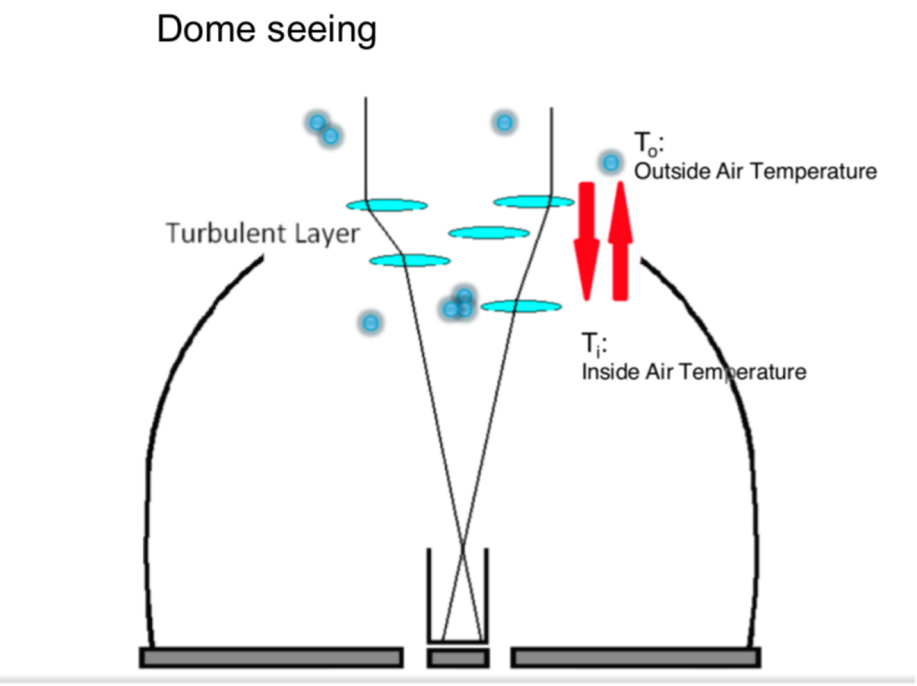
$\mathcal{L}_0/r_0 > 20$ Tokovinin (2002)

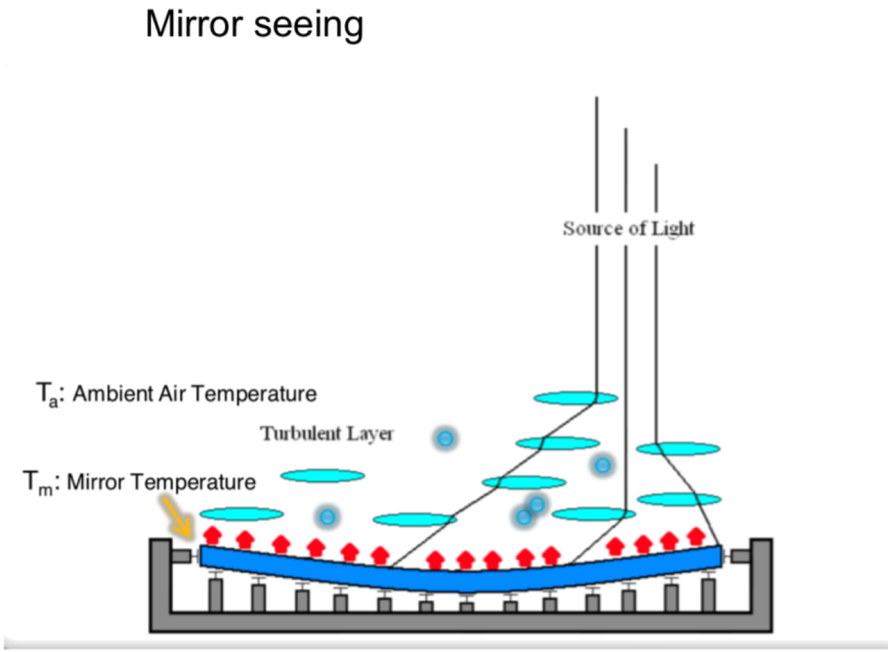
Contributors to DIQ



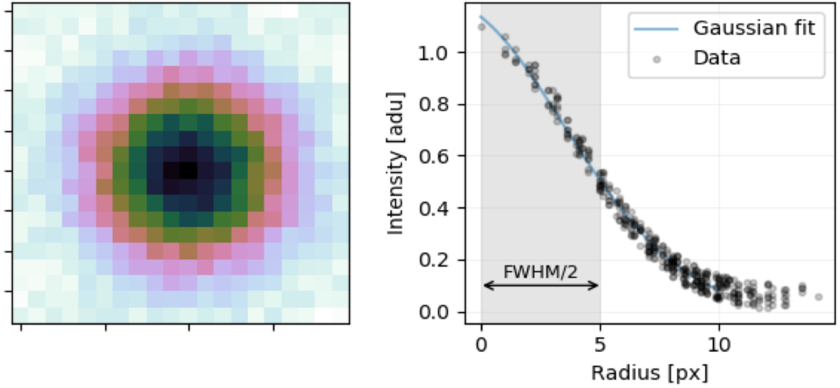
Credits: A. Tokovinin

Heat sources within the dome





How do we measure the DIQ and Seeing?



The DIQ is usually obtained directly from the radial profile of long-exposure stellar images. This is usually done with IRAF's `imexam`

The seeing is measured by the Differential Image Motion Monitor (DIMM) and Multi-Aperture Scintillation Sensor (MASS).

r_0 or seeing
- model-dependent (Kolmogorov)
- non-stationary in space and time

Data

Observatory Resources:

- GEA GEMINI SOUTH Engineering Archive

1. Telescope Wavefront Sensor: GMOS On-Instrument OIWFS and P2, and information from telescope elevation, and azimuth.

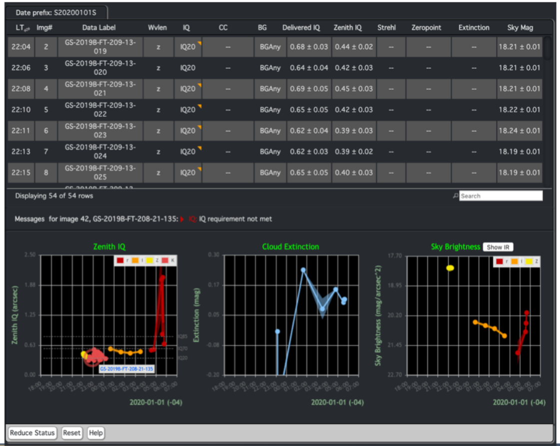
2. Environmental data: We retrieved outside temperature, wind direction and speed from the weather station on top of a mast at 50 m height adjacent to GS enclosure. The truss and primary mirror temperatures taken from inside dome sensors.

- QAP: The QAP is a service that automatically runs on imaging mode for every Gemini instrument at night.

http://cpopipe01:8777/qap/nighttime_metrics.html

- Seeing Monitor

DIMM and MASS.



Methodology

- **Filtering criteria and matching science data and weather readings.**

- **DIQ data set:** We used a data set of DIQ records derived by the QAP tool over GMOS imaging between 2004 and 2022 using the following criteria:

  Exp. time ≥ 30 sec, DIQ ≤ 2 arcsec and Non-sidereal target

- **Gemini WFS data set:** We computed the median seeing during the elapse of the observations from 2014 to 2022.

- **DIMM-MASS data set:** The data set have been filtered using Strehl ratios ≥ 0.4 and $\chi^2 < 30$. We matched the average seeing recorded during the entire science observation sequence.

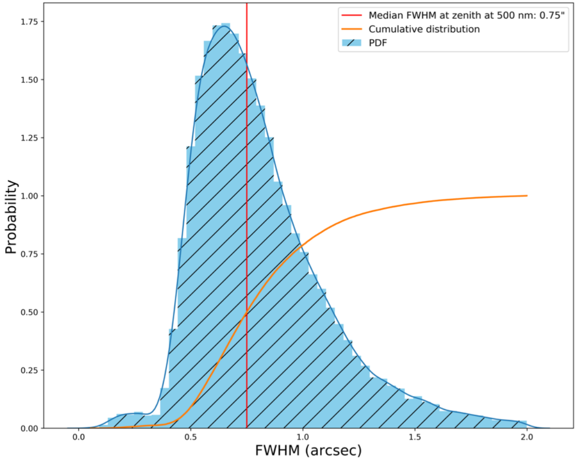
- **Weather data set:** We matched each DIQ record with its closest –in – time outside temperature and wind readings. For same treatment was done with the average M1 and dome temperatures.

For comparative purposes, we adopt a standard wavelength of 500 nm at zenith.

$$IQ(zenith)_{500nm} = IQ(delivered)/(X)^{0.6}\,(500.0/\lambda)^{-0.2}$$

Where X is airmass and λ the effective wavelength of the observations in units of nanometers.

Delivered image quality



The median Delivered Image Quality (DIQ) at the focal plane of long-exposure GMOS-S imaging airmass corrected at 500-nm is 0.75 arcsec.

❑ Statistical facts at Gemini South:

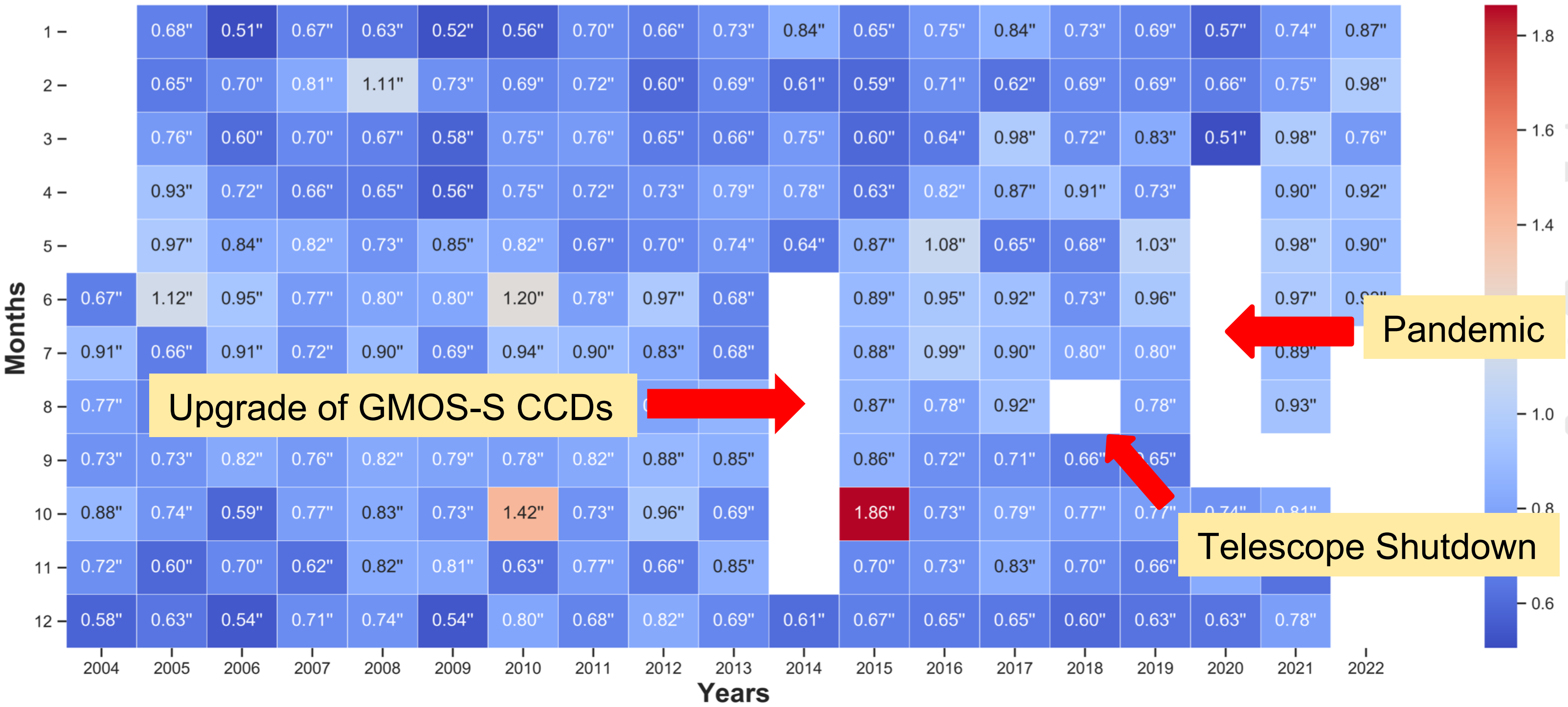
- Number of observations: 48,374 images
- Number of nights: 3,129
- Mean FWHM, std. deviation: 0.81 ± 0.29 arcsec
- Median FWM at zenith at 500nm: 0.75 arcsec
- Most observed year: 2021 (4,905 images)
- Most observed month: January (5,399 images)

	1^{nd} place	2^{nd} place	3^{nd} place
Best Year	2006 (0.61″)	2009 (0.65″)	2014 (0.68″)
Best Month	January (0.64″)	December (0.68″)	February (0.69″)
Worst Year	2021 (0.85″)	2017 (0.82″)	2008 (0.77″)
Worst Month	June (0.88″)	July (0.84″)	August (0.83″)

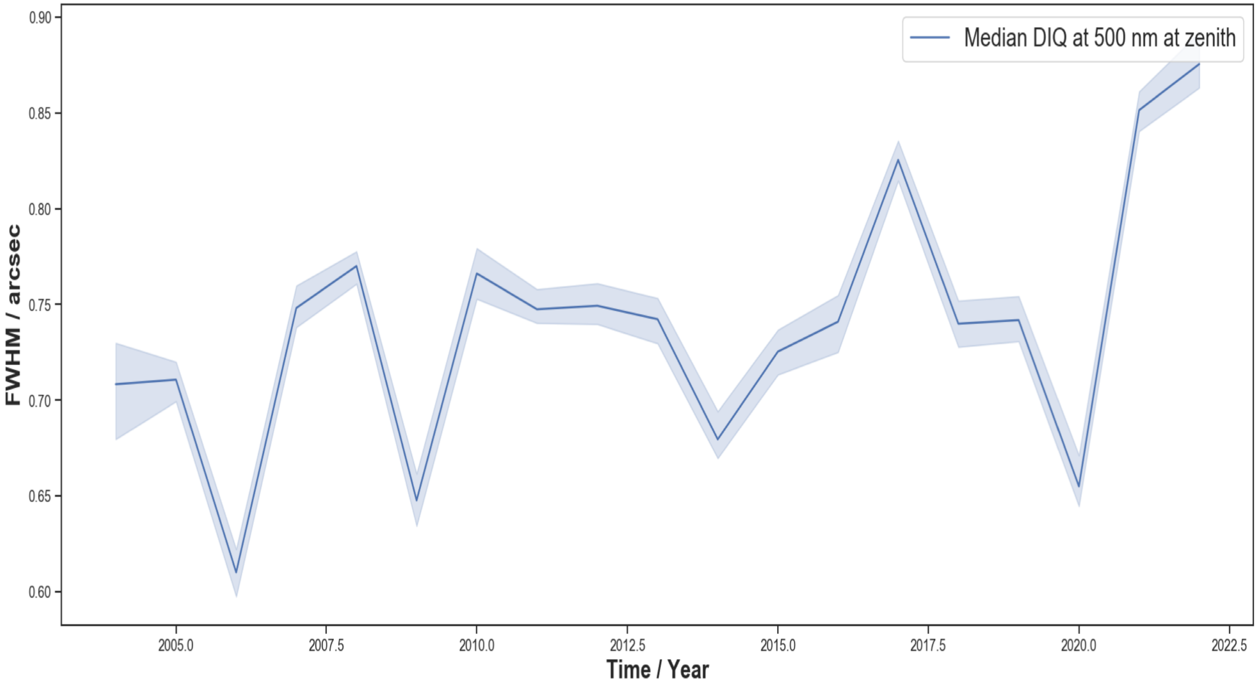
Table 1. Ranking of the best and worst quantitative measures computed by month and year from the median FWHM at 500 nm at zenith (2004-2022).

What about the DIQ at Pachón Site per month? (Continued)

Monthly recorded median DIQ FWHM from 2004 to 2022



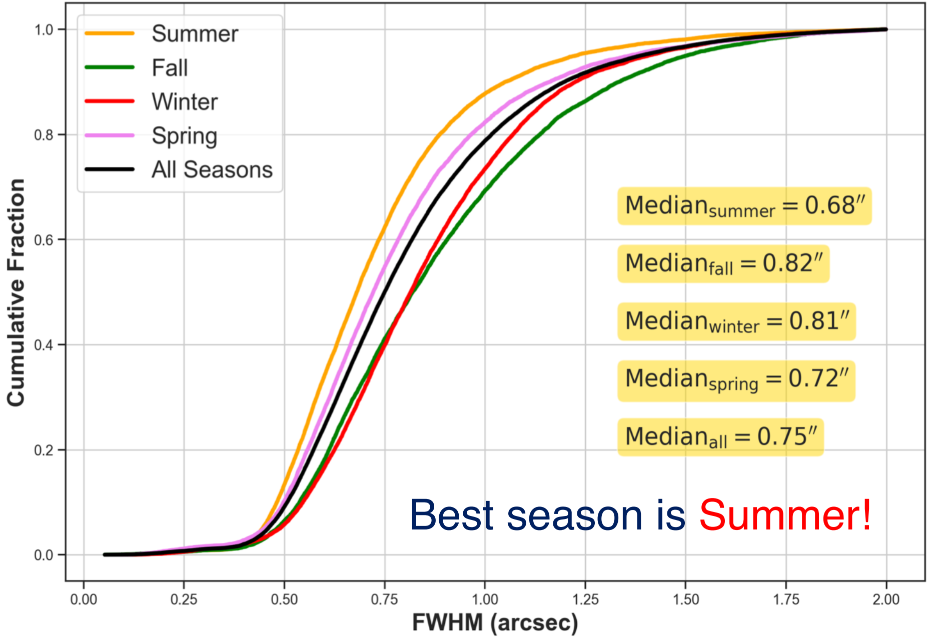
Temporal evolution:



The variations along time show that the DIQ is trending up after resuming the nighttime operations due to the pandemic.

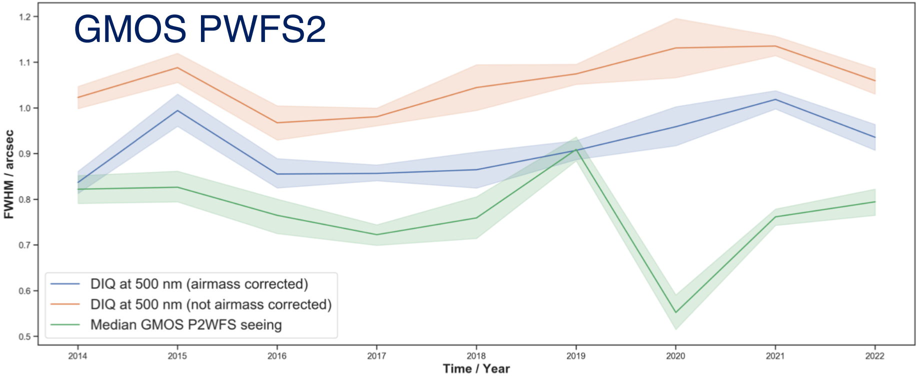
The median DIQ as measured over GMOS imaging data (corrected at 500 nm at zenith).

Seasonal variability:



Cumulative distribution of DIQ FWHM at 500 nm at zenith by season (2004-2022).

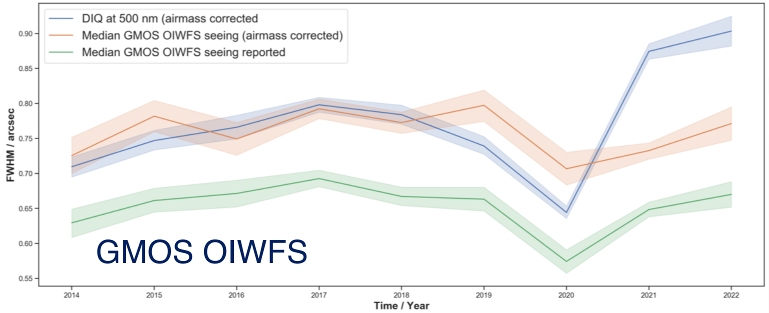
DIQ vs. Wave Front Sensors

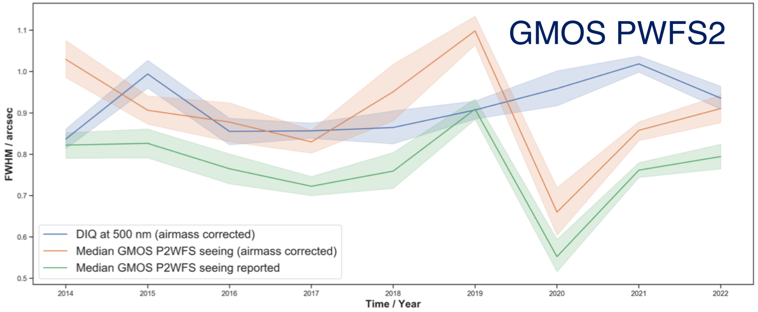


-- The Gemini WFSs estimate the seeing at standard wavelength of 500 nm.

The GMOS P2 Wave Front Sensor does not follows the variations of the DIQ measured over GMOS imaging data.

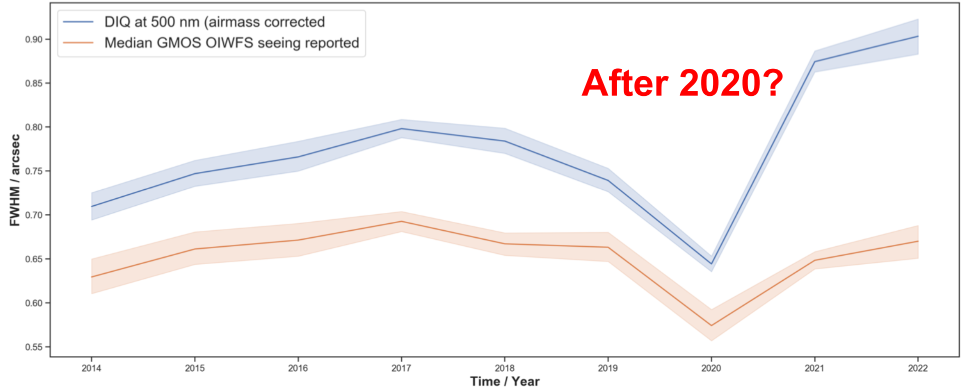
-- The seeing reported by the WFSs is airmass corrected.

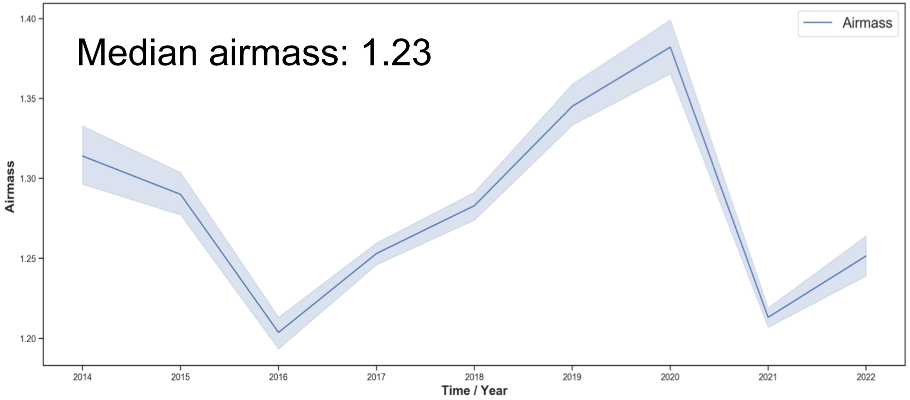




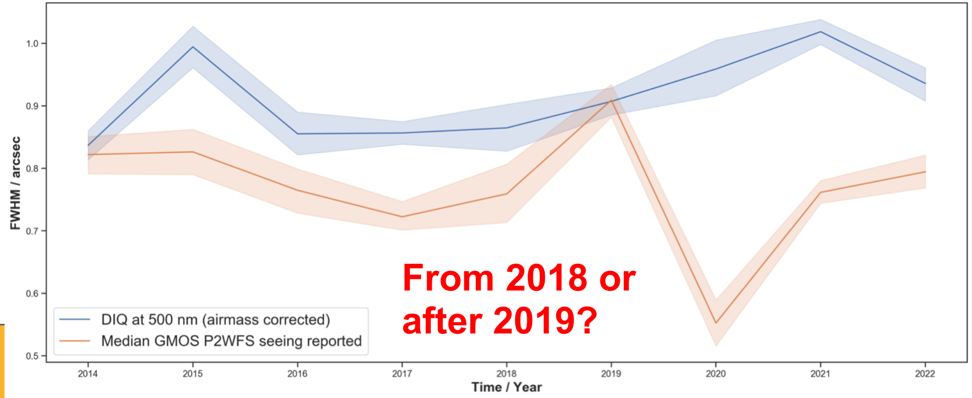
DIQ vs. Wave Front Sensors

GMOS OIWFS





GMOS PWFS2



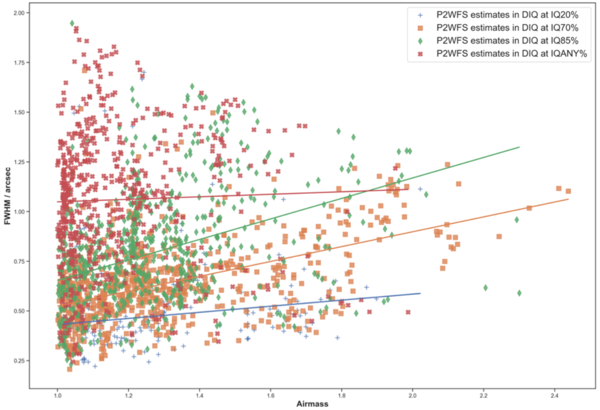
Median airmass by year:

2014	1.22
2015	1.25
2016	1.15
2017	1.22
2018	1.23
2019	1.28
2020	1.37
2021	1.15
2022	1.18

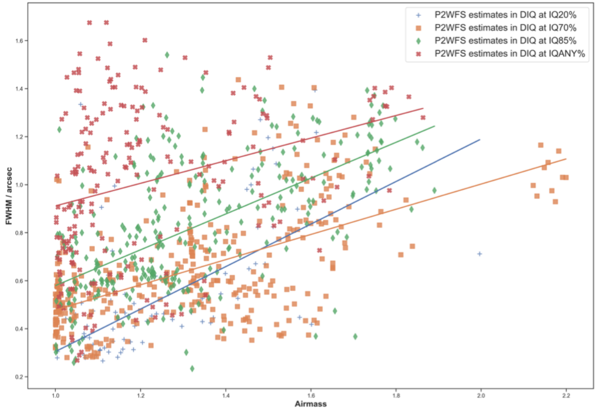
DIQ vs. Wave Front Sensors (continued)

Case 1: GMOS PWFS2

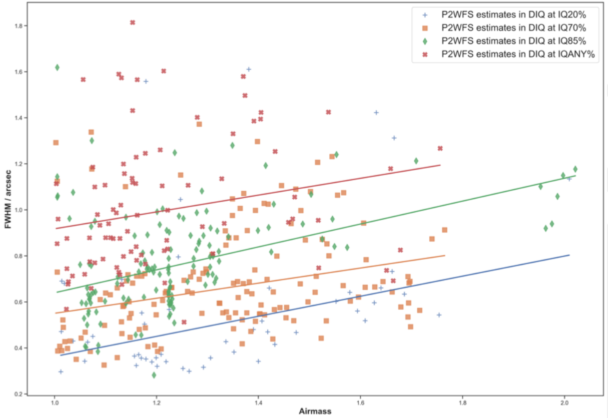
$IQ(X)=IQ(zenith)*X^{0.6}$



Guiding rate – 200Hz



Guiding rate – 100Hz



Guiding rate – 50Hz

GMOS P2 estimates better seeing than the DIQ measured in IQAny at airmass (X>1.2).

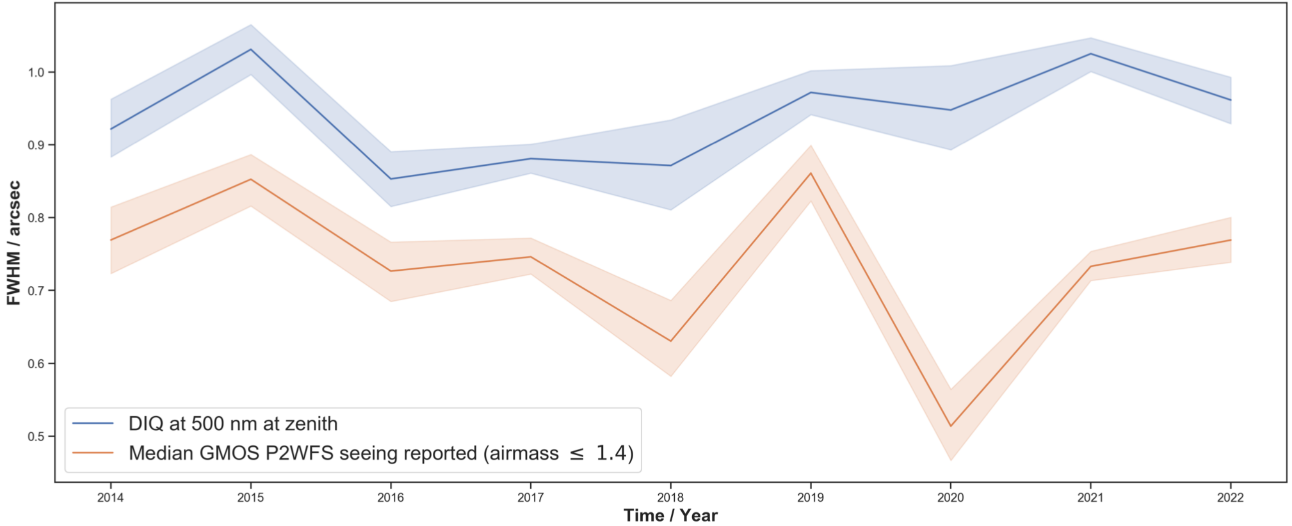
GMOS P2 estimates a better seeing than the DIQ measured in IQ70 at airmass (X>1.35).

GMOS P2 estimates are in agreement with the DIQ measured for all IQ bins

Wavelength	IQ20%-ile	IQ70%-ile	IQ85%-ile	IQANY%-ile
g (0.475 μm)	0.60"	0.85"	1.10"	1.90"

DIQ vs. Wave Front Sensors

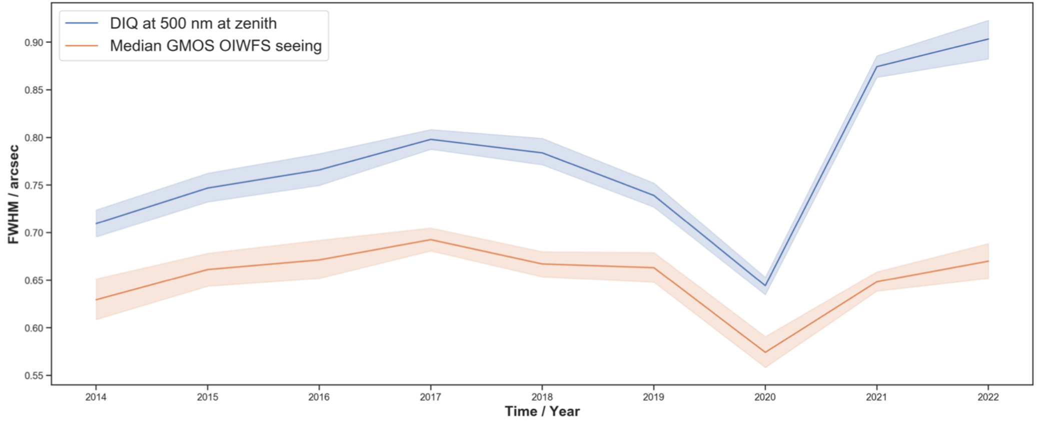
GMOS P2WFS



The GMOS P2 Wave Front Sensor follows the variations of the DIQ measured on GMOS imaging data while airmass is lower than 1.4 until 2019.

DIQ vs. Wave Front Sensors

GMOS OIWFS



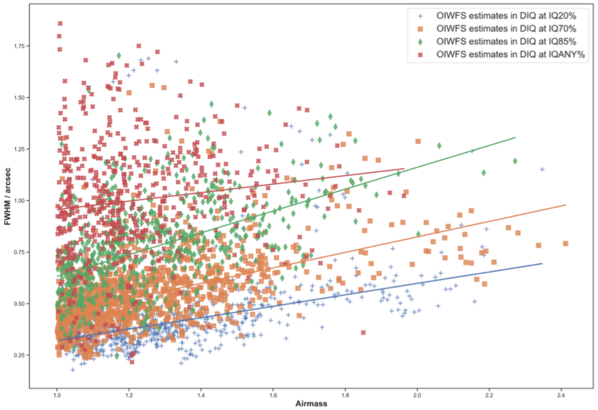
The GMOS OI Wave Front Sensor follows the variations of the DIQ measured on GMOS imaging data, but the OIWFS report a lower seeing.

$$\mathbf{DIQ}_{\lambda 500\mathrm{nm}} = 0.65 \times (\mathrm{OIWFS}[arcsec]) + 0.36$$ (valid relation for all airmass)

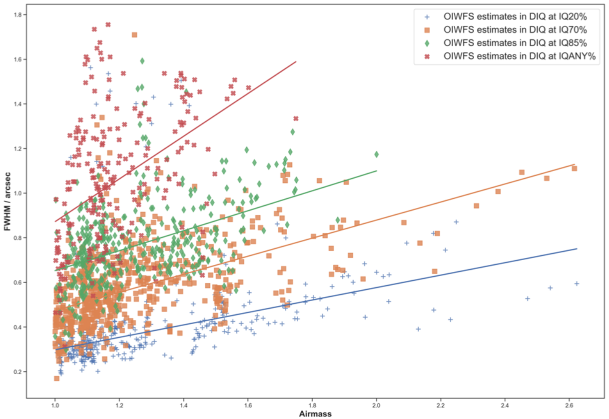
DIQ vs. Wave Front Sensors (continued)

Case 2: GMOS OIWFS

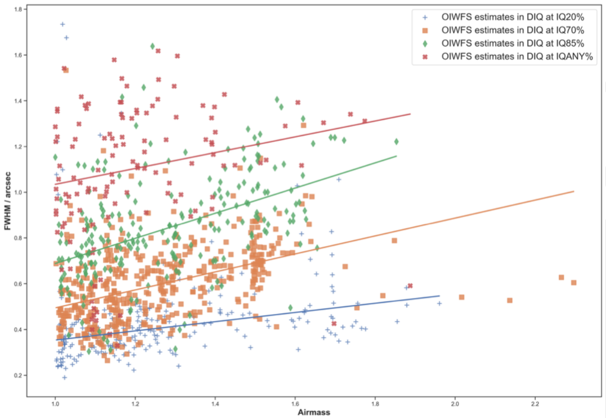
$IQ(X)=IQ(zenith)*X^{0.6}$



Guiding rate – 200Hz



Guiding rate – 100Hz



Guiding rate – 50Hz

GMOS OI estimates better seeing than the DIQ measured in IQAny at airmass higher than 1.2 (X>1.2).

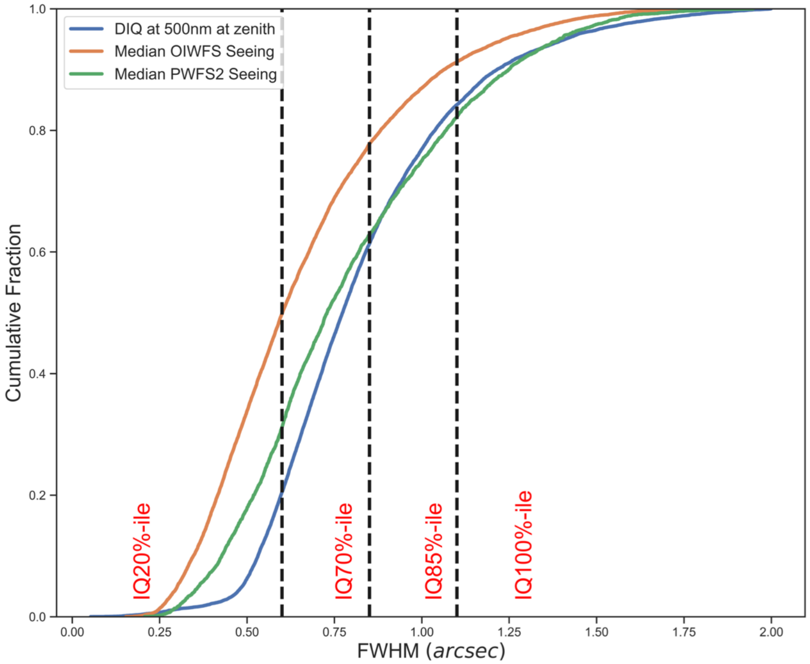
GMOS OI estimates are in agreement with the DIQ measured for all IQ bins

GMOS OI estimates are in agreement with the DIQ measured for all IQ bins

DIQ vs. Wave Front Sensors Statistics

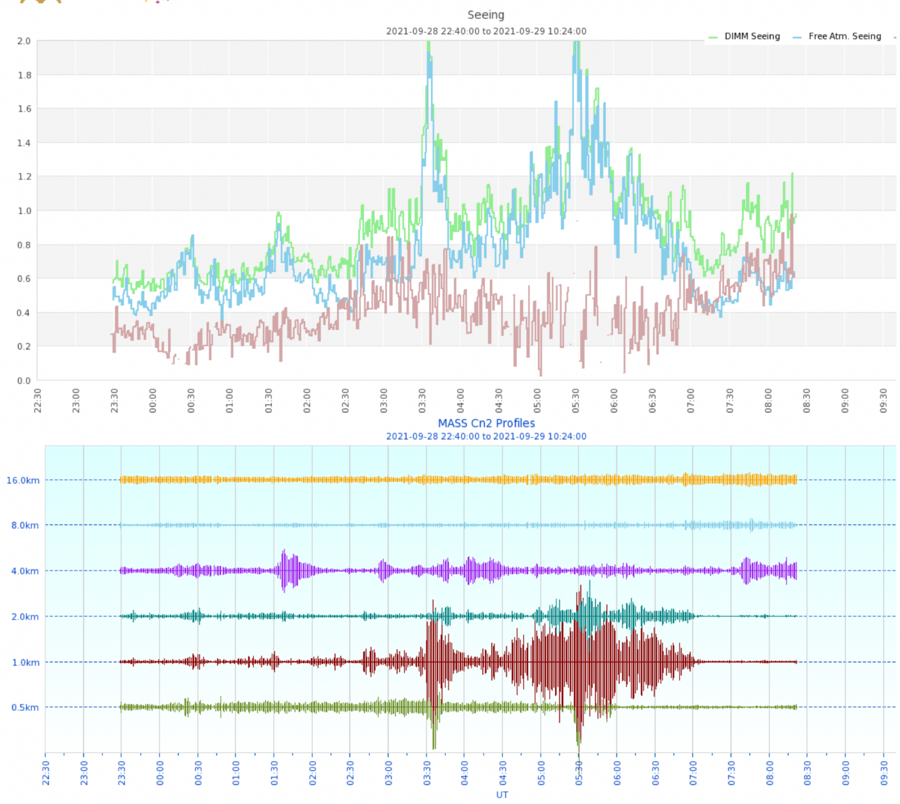
Percentile	DIQ	OIWFS	PWFS2
10	0.53″	0.35″	0.43″
25	0.63″	0.45″	0.56″
50	0.77″	0.60″	0.73″
Average	0.83″	0.76″	0.92″
75	0.98″	0.82″	1.00″
90	1.21″	1.06″	1.25″
Total number of samples	15,948	12,121	3,827

Cumulative statistics of FWHM of long–exposure stellar images obtained from GMOS images and GMOS WFS (OI/P2) over 8 years (2014-2022).



Cumulative distribution of the GMOS Instrument Wave Front Sensors (OI/P2) and DIQ FWHM (2014-2022).

DIMM and MASS

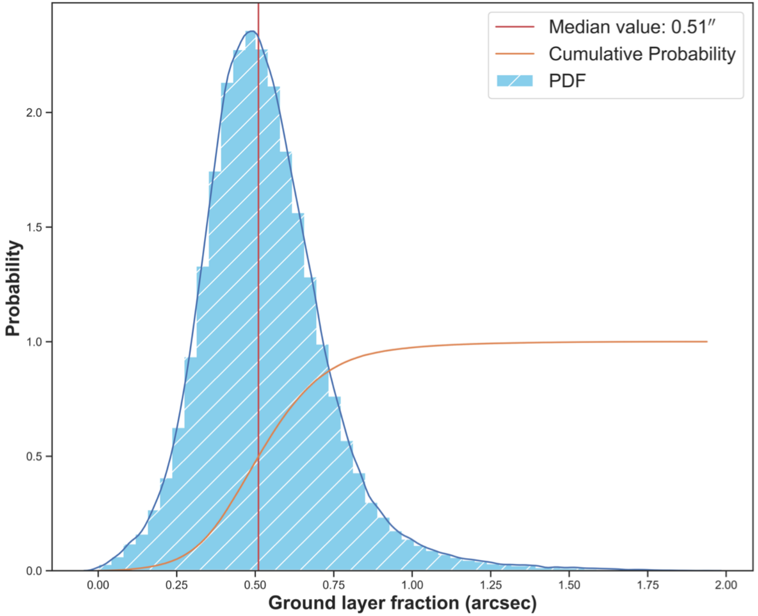


Percentile	ϵ_{DIMM} (arcsec)	ϵ_{MASS} (arcsec)	ϵ_{GL} (arcsec)	$\theta_{0,MASS}$ (arcsec)	$\tau_{0,MASS}$ (ms)
10......	0.55	0.28	0.31	3.12	8.20
25......	0.64	0.34	0.40	2.56	6.75
50......	0.76	0.46	0.51	2.01	5.09
75......	0.91	0.64	0.64	1.54	3.63
90......	1.10	0.90	0.77	1.20	2.75

Cumulative statistics of the Turbulence parameters of Cerro Pachón.

A typical night (Sept. 28–29, 2021) of DIMM – MASS data.

Ground Layer

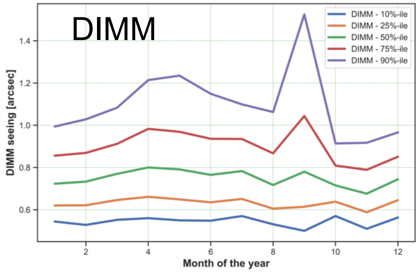


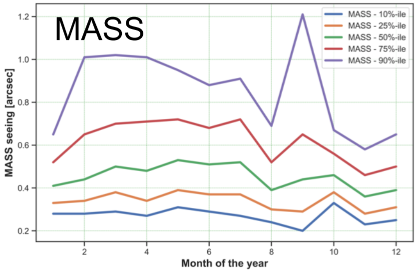
The fraction of the turbulence below ~500m contributes typically about 51% to the total integral seeing.

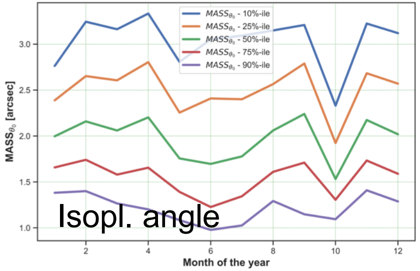
Tokovinin et al. (2005) computed that the GL contributes typically about 61% to the total integral and a median seeing of 0.77 arcsec for Pachón.

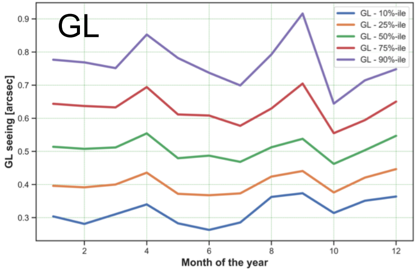
Probability density function (PDF, filled dashed area) and cumulative probability of the Ground–Layer (GL) fraction, as measured from the MASS–DIMM in CP between 2017 and 2021.

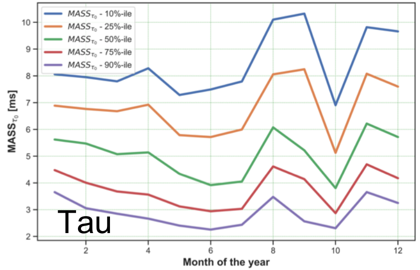
Seasonal variations and turbulence strength:

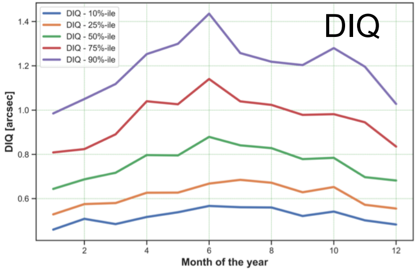


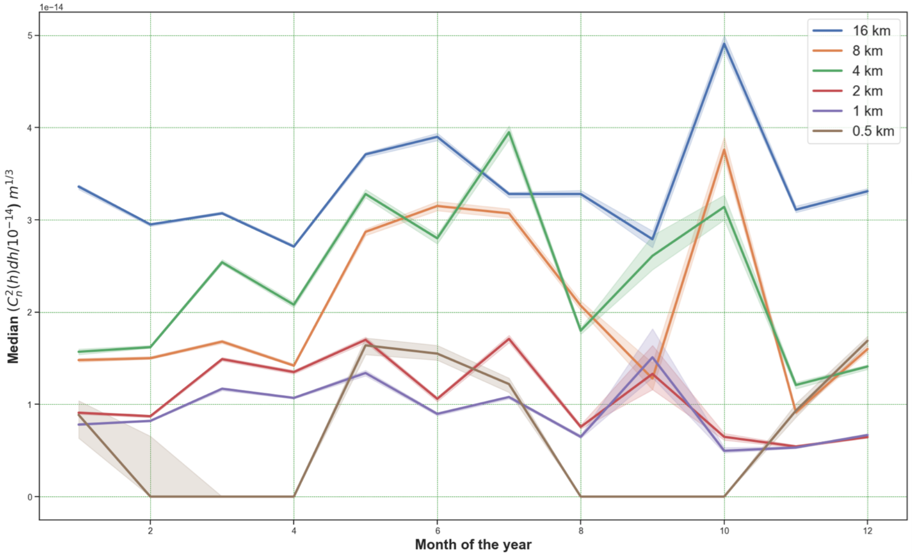












Median turbulence strength $C_n^2(h)dh$ of the individual MASS layers during the year.

Astronomical conditions at the Observatories in Chile

Site	Median (ε_0) Seeing [arcsec]
Pachon (Gemini South)	0.76 (2017-2021)
VLT / La Silla (ESO)	0.82 (1998-2002) / 0.89 (1999-2002)
Tololo (CTIO)	0.95 (2002) / 0.75 (2004-2008)
Magellan (Las Campanas)	0.67 (2007-2008)

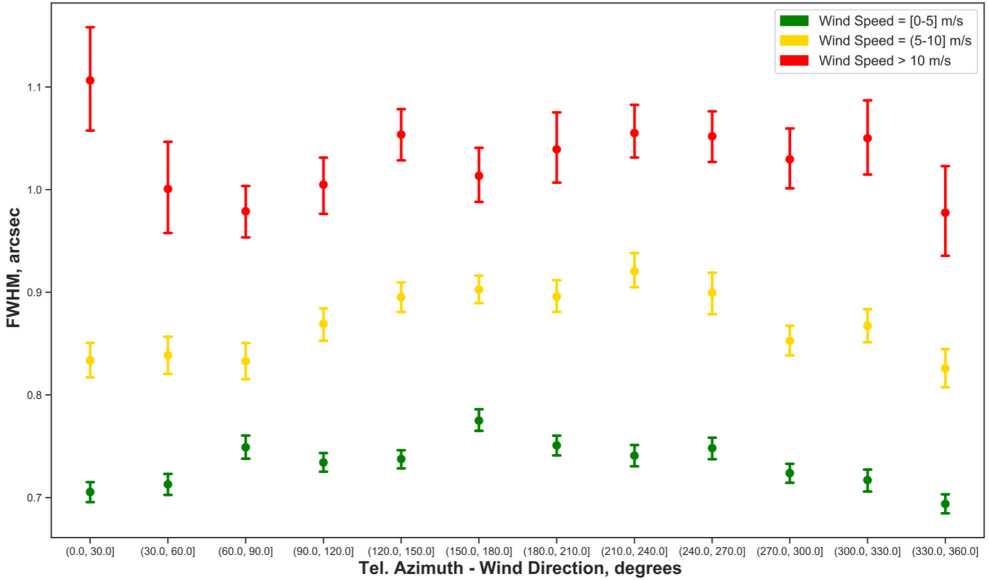
Environmental conditions at Gemini South

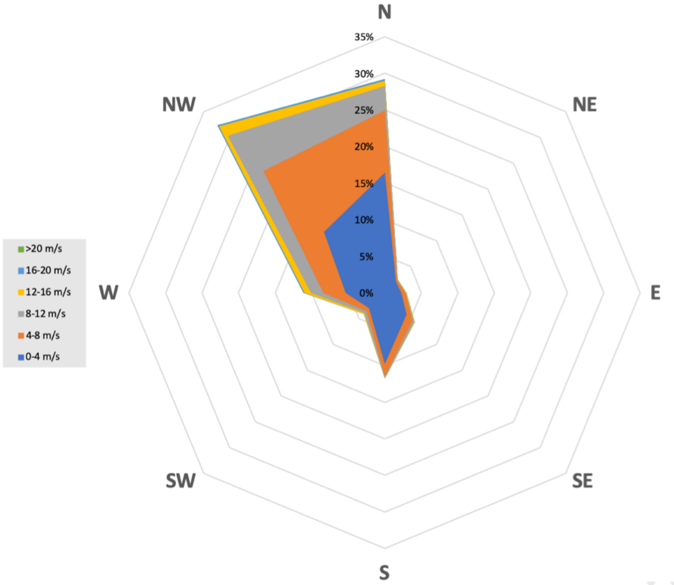
Variables

- Winds
- Temperature

DIQ vs. Weather (WINDS)

- Wind speed and direction influence on the DIQ:

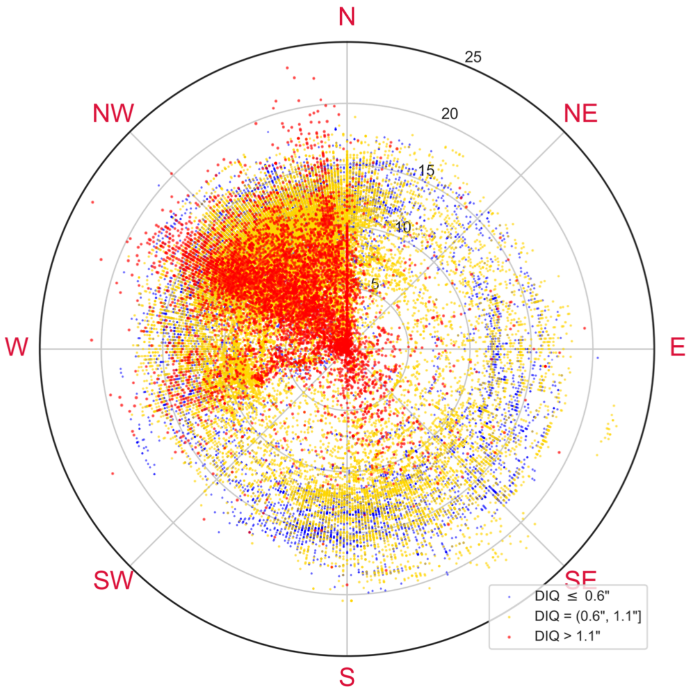


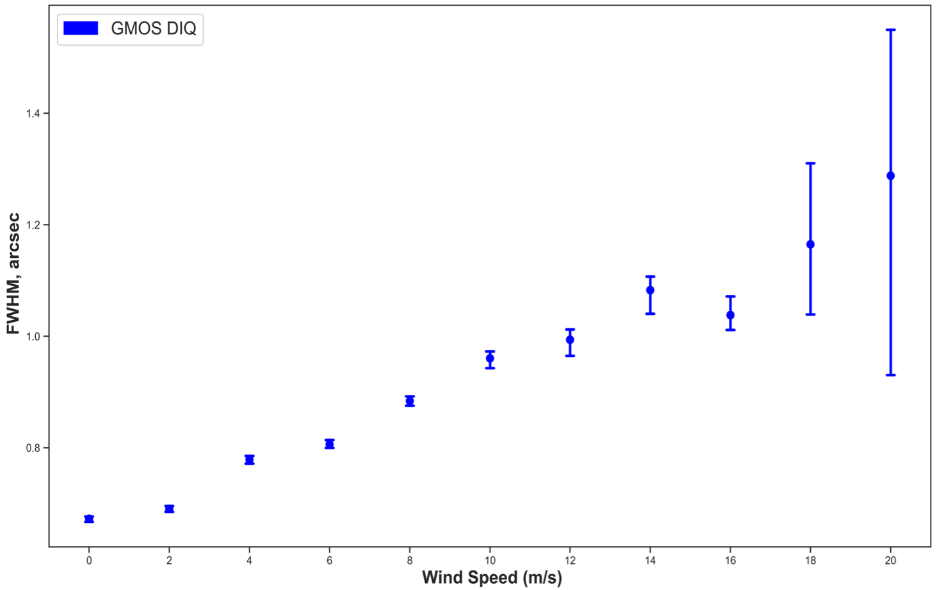


The DIQ as a function of the telescope azimuth position, incoming winds and their strengths.

On CP summit, the prevailing wind is coming from NW (~30% of the time during night time) and the most common wind speed is between 4 to 8 m/s. August and June are the windiest months of the year.

DIQ vs. Weather (WINDS)





TEMPERATURES

- Inside Temperature
- Outside Temperature
- M1 Temperature

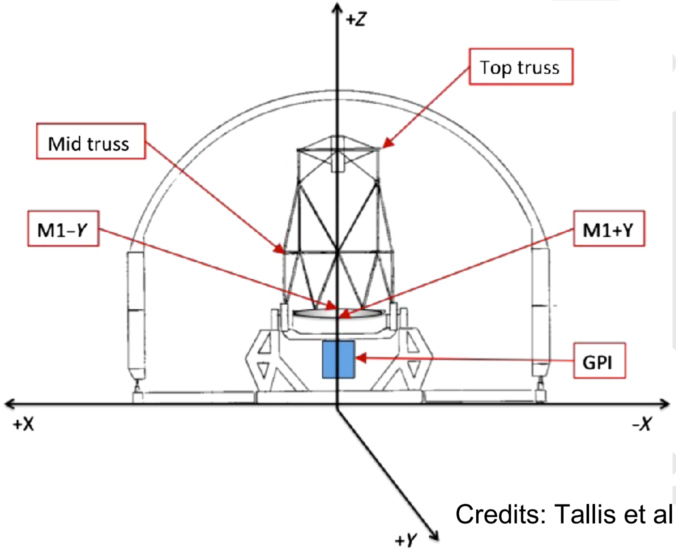
TEMPERATURES

- Inside and outside temperatures (2011-2022)

- We retrieved readings from the inside air temperature from lower-truss sensor.
- Outside air temperature, wind speed and direction were obtained from the weather station.
- M1 temperature sensors revealed significant offsets. We applied corrections as described in Tallis et al. (2020). Temperature offsets for GS temperature sensors (Tcorrected=T0+offset).

Sensor	Offset (°C)
M1+Y	3.5
M1-Y	2.1

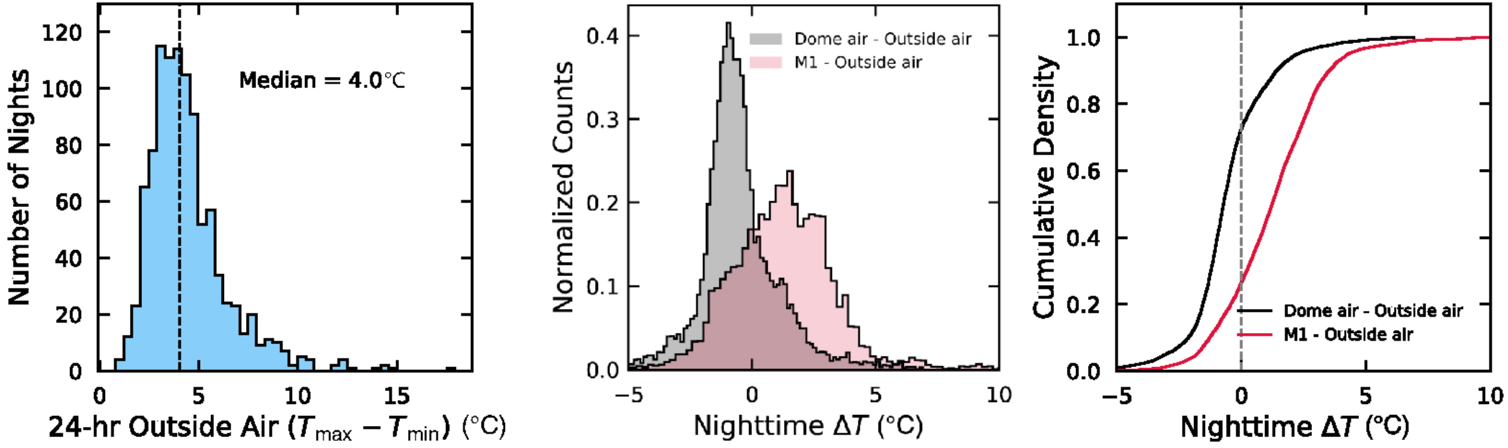
- To produce an instantaneous M1 temperature. We averaged the two corrected M1 sensors.



Credits: Tallis et al.2020

Schematic of Gemini South telescope and observatory dome. Arrows mark the locations of temperature sensors.

Data: Jan 1, 2014- Dec 31, 2018



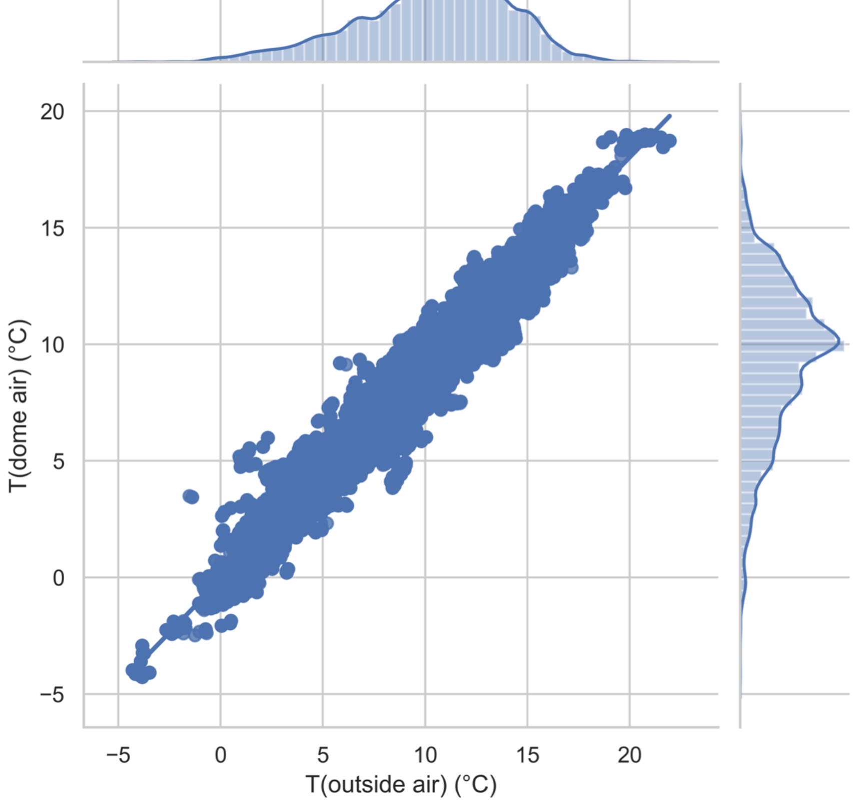
(a) (b) (c)

Credits: Tallis et al.2020

Figure 4. Temperatures at the Gemini South observatory. (a) Histogram of the daily min-max range of outside air temperatures. (b) Histogram of instantaneous temperature differences between dome air or M1 and outside air at night, for those nights when GPI was observing, with DC offset corrections as described in Section 3.1. (c) Cumulative density plot of the data in (b)

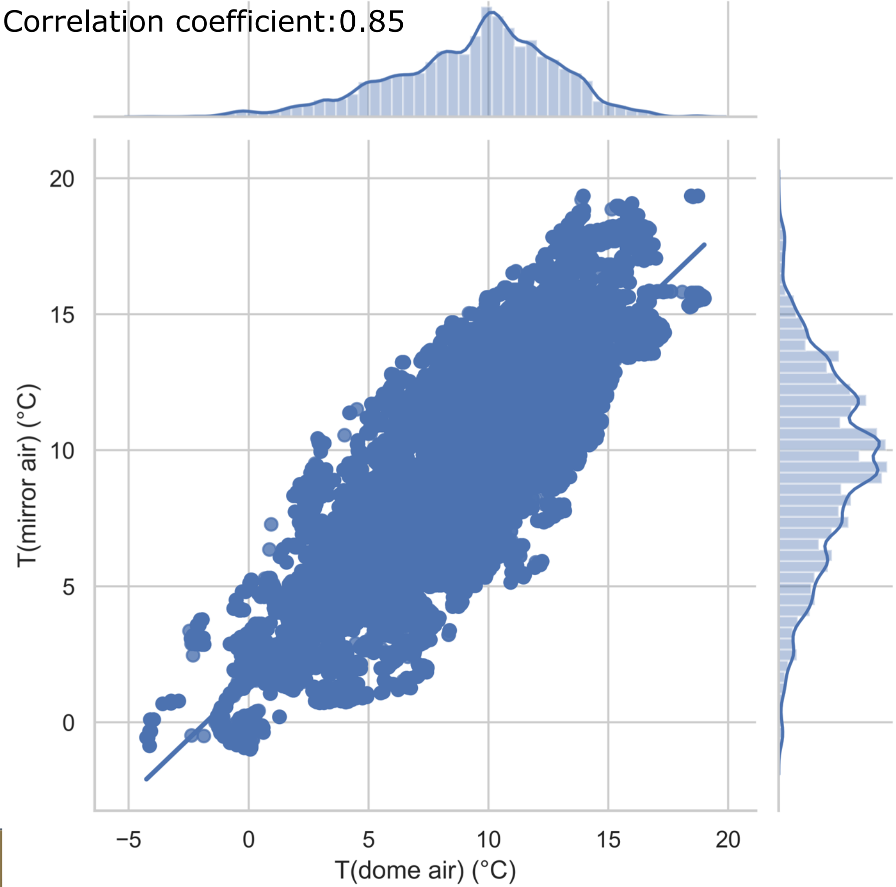
Median Tempe. Difference (Dome air-Outside air): -0.7 °C

Correlation coefficient:0.98

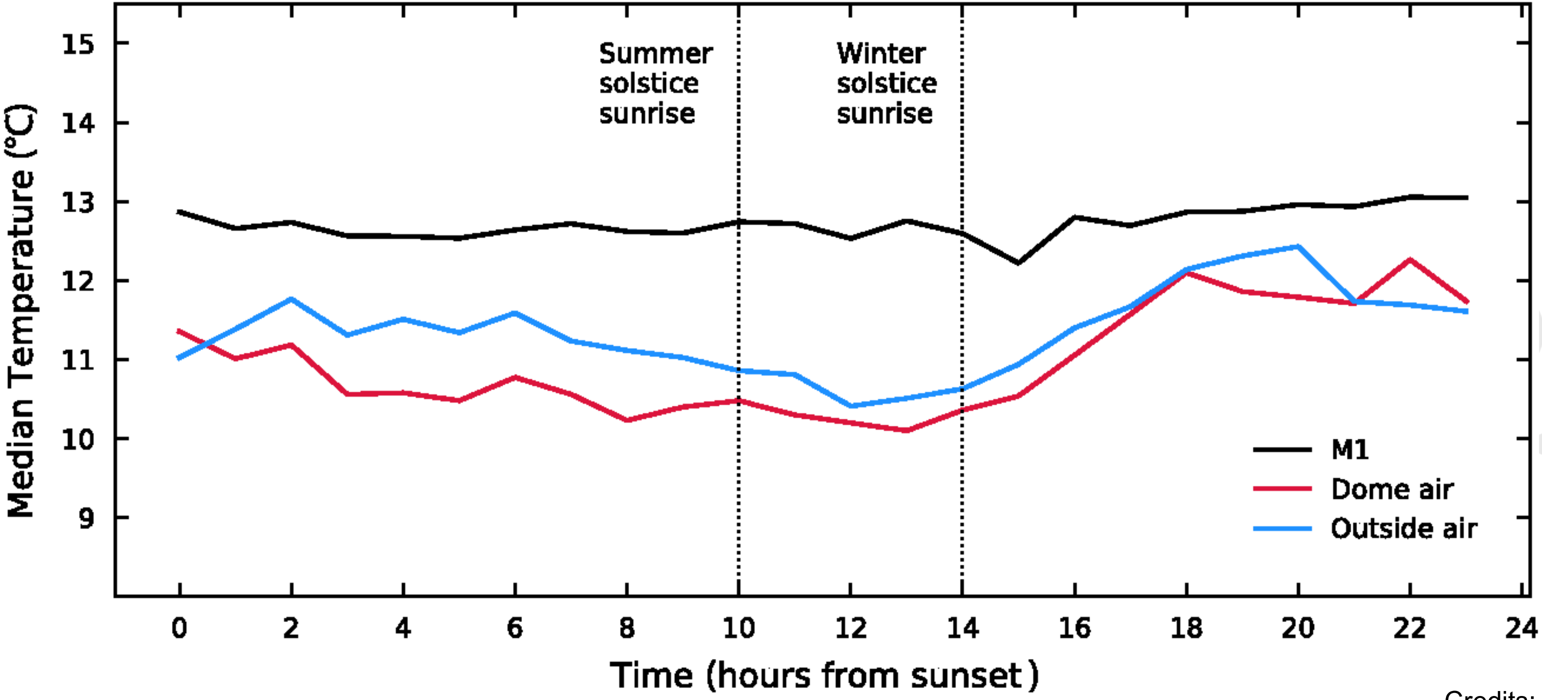


Median Tempe. Difference (M1-dome air): +0.06 °C

Correlation coefficient:0.85



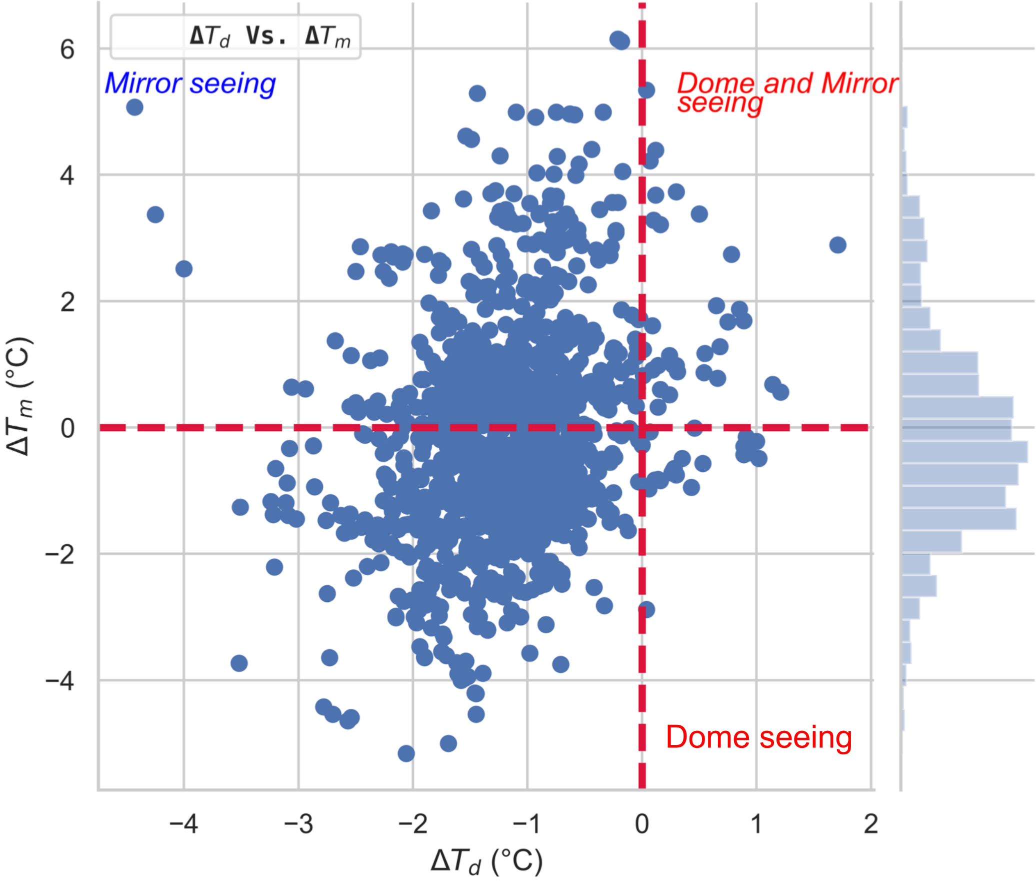
TEMPERATURES



Credits: Tallis et al.2020

The median 24-hr temperature profile of M1, dome air, and outside air.

Diagnostic Temperature plot

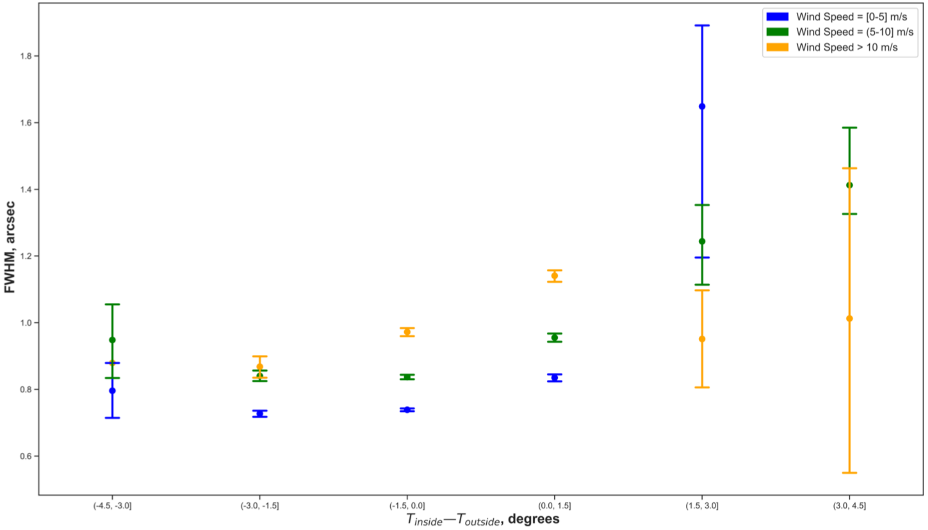


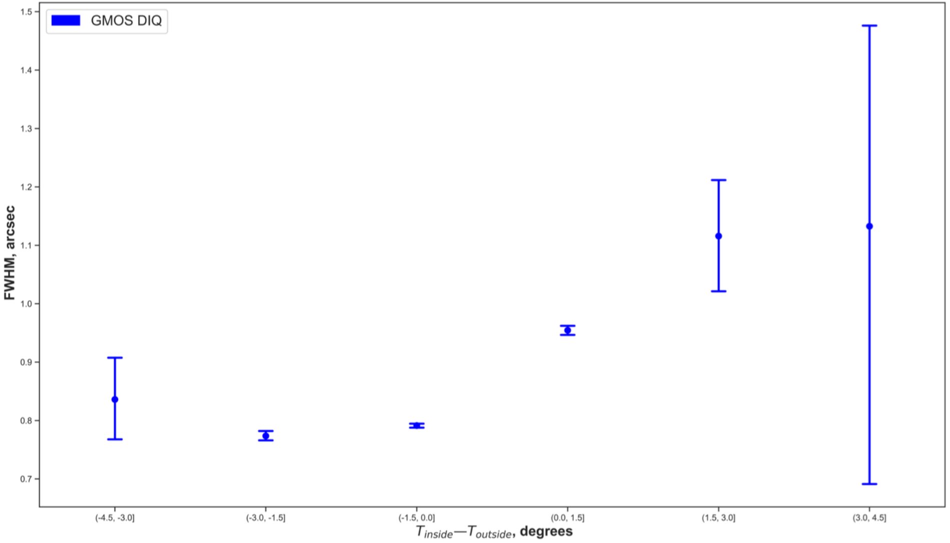
$\Delta T_m = T_{mirror} - T_{dome}$: This measures the temperature excess of the primary mirror above air in the dome and should be correlated with "mirror seeing".

ΔT_d = (compelling): This is an indication of the temperature difference between dome air and outside air and should be correlated with "dome seeing".

Positive ΔT_m or ΔT_d correspond to convectively unstable conditions and should be expected to produce air turbulence and IQ degradation.

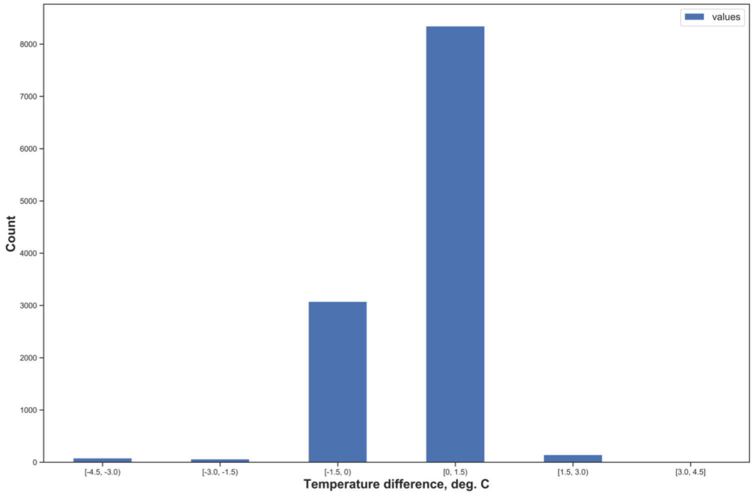
DIQ constrained by Temperatures + wind speed





Temperature difference between dome and ambient temperature constrained by wind speed ranges Vs DIQ

Temperature difference between dome and ambient temperature Vs DIQ



Histogram of temperature differential between outside and inside

Conclusions and recommendations

- The median **Delivered Image Quality (DIQ)** at the focal plane of long-exposure GMOS-S imaging airmass corrected at 500-nm is 0.75 arcsec.

- Summer time and spring are the best seasons to get good IQ from imaging data.

- Both **Gemini WFSs** (OI/P2) report underestimated atmospheric seeing when compared to the IQ measured on GMOS images.
- The OIWFS follow the IQ trends throughout the time, but the P2WFS does not for all target's airmasses. We suggest to use the seeing trends reported by the OIWFS only if MASS-DIMM are not available.

- **DIMM and MASS** data indicate a median seeing of ε_0 = 0.76 arcsec and a median free − atmosphere seeing ε_f = 0.46 arcsec (all layers above 500 m) at **Cerro Pachón (CP)** . This result is in agreement with the median ε_0= 0.75 arcsec and ε_f = 0.50 arcsec as measured by DIMM and MASS in Cerro Tololo Inter-American Observatory (Els et al. (2009)).

- The **MASS data** indicate that a strong annual variation of high-altitude turbulence with the weakest turbulence encountered while approaching the southern summer months.
- The **Ground Layer** (GL) seeing contributes typically about 51 percent to the total integral.

- We find that the **DIQ** starts to deteriorate when the **wind speeds** are above 10 m/s and slightly affected when the telescope is pointing towards southerly directions.

- We show that the **DIQ** significantly degrades when the **inside air temperature** is higher than 1.5˚C with the **outside air temperature**.

Future prospective

- 22B semester: Finish the paper about these results (Fuentes-Lettura et al. (in preparation)).
- 23A semester: Start the same study for GN using all this experience to consolidate knowledge.

Acknowledgments

- Pedro Gigoux for extracting and facilitating the MASS-DIMM data from seeing monitors database.
- Tom Hayward for facilitating the scripts for extracting GEA environmental data, WFSs and DIMM data.
- Ariel Lopez and Fredrik Rantakyrö for advisory and sponsoring this project.
- Pablo Prado for providing suggestions to improve this work.

References

1. Els, S. G. et al. 2009 PASP 121, 922.
2. Tokovinin, A., 2002, PASP 114, 1156.
3. Tokovinin A. & Travouillon T., 2006, MNRAS, 365, 1235.
4. Martinez, P. et al. 2010, A&A, 516, A90.

Questions?