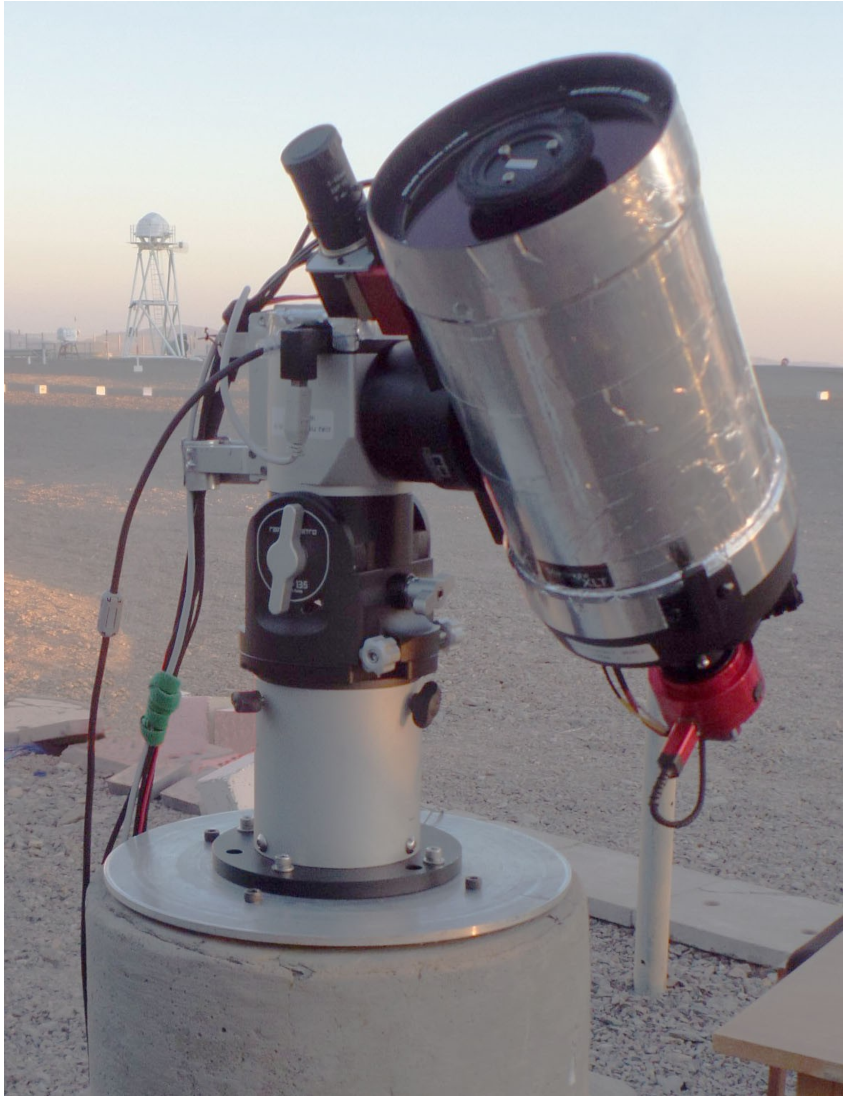
Portable turbulence profilers: from MASS to RINGSS



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– NSF's NOIRLab

Outline

- Path to a solid-state upgrade of MASS
- Principle and theory of the RINGSS method
- RINGSS instrument
- First results at Cerro Tololo and Paranal

New animal in our Zoo!

Turbulence profilers

- Crossed beams: SCIDAR, SLODAR, MCAO, Lunar limb
- Scintillation of Sun/Moon (low layers only)
- Single-star scintillation (MASS, FASS, SHIMM, RINGSS)

Spatial scale: Fresnel radius $\sqrt{(\lambda z)}$ = 1.5…10cm (0.5-20km)

Time scale: 20m/s*1ms = 2cm => exp. time 1ms or less

Photon flux: star ~2mag, texp=1ms, S=1cm^2
Band 100nm, QE 0.5 => 80 electrons

Need fast, low-noise detectors: PMTs, EM CCDs, CMOS

Signal-to-noise vs. aperture in DIMM

- Image motion in DIMM (signal) ~D (turb. spectrum)
- Centroid photon noise $(\lambda/D)*N_{ph}^{-0.5} \sim D^{-2}$
- S/N ~ D^3 !

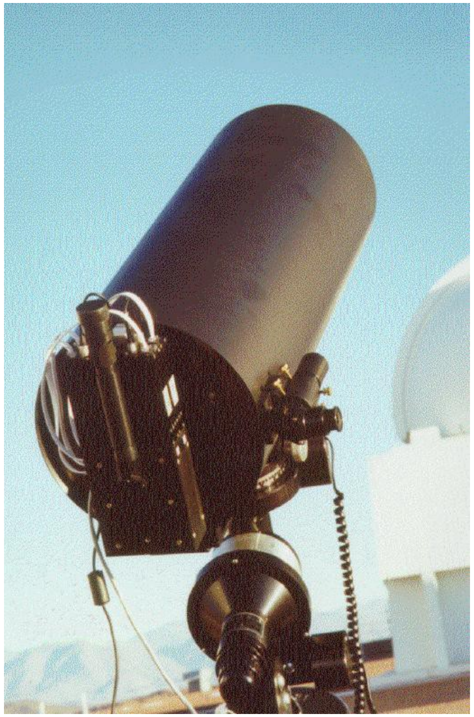
DIMM uses telescopes of 25-35 cm

Propagation is important for d<10cm

Small aperture is a challenge, needs efficient use of photons. Advantage: portability and low cost

The first MASS (1998-2002)

Victor Kornilov
(1953-2021)
Nicolai Shatsky
Olga Vozyakova
Marc Sarazin

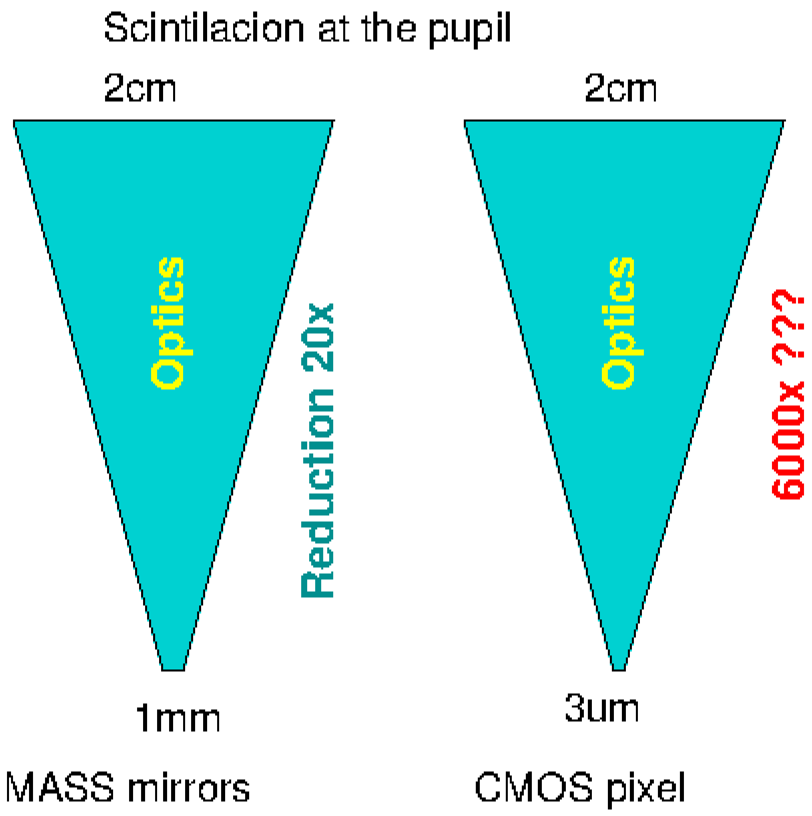


15-cm off-axis reflector
(custom-made)

MASS = theory + instrument + software

How to modernize MASS-DIMM?

- The PMT technology is obsolete → CCD? CMOS?
- Use commercial components (cheaper)

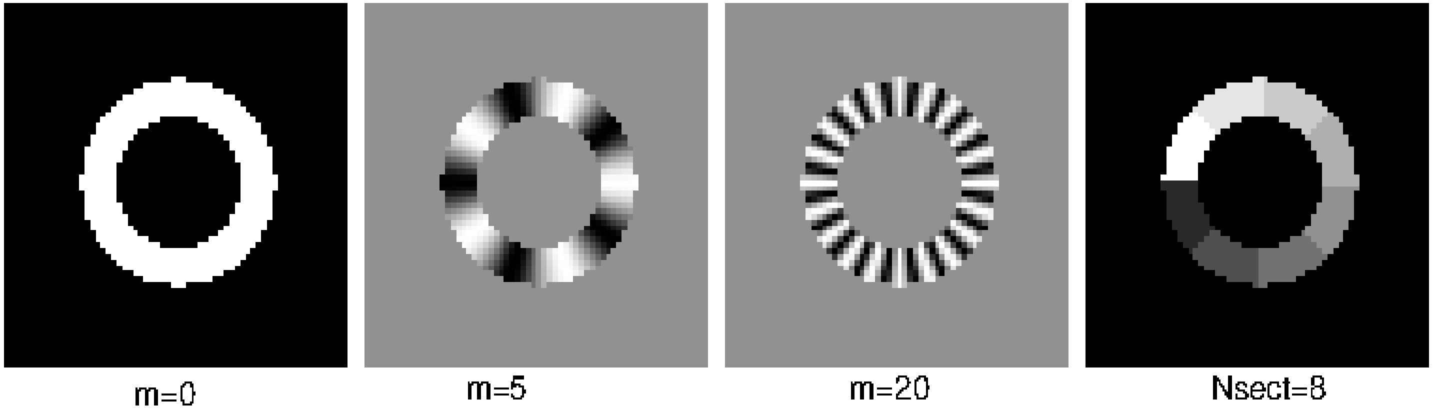


Replacing mirrors
in MASS-DIMM
by a CCD or CMOS
does not work!

It is easier to work in the
image plane than at pupil

Ideas and solutions

- CMOS emulator with binning (LBT prototype, failed)
- EM-CCD with binning (FASS = Full-Aperture Scintillation Sensor), A.Guesalaga (PUC, Santiago)
- Defocused image (ring) → RINGSS
- Fourier transform over angle (FASS), otherwise - aliasing
- SHIMM (Paris, Durham, Moscow, Tokyo): use lenslets



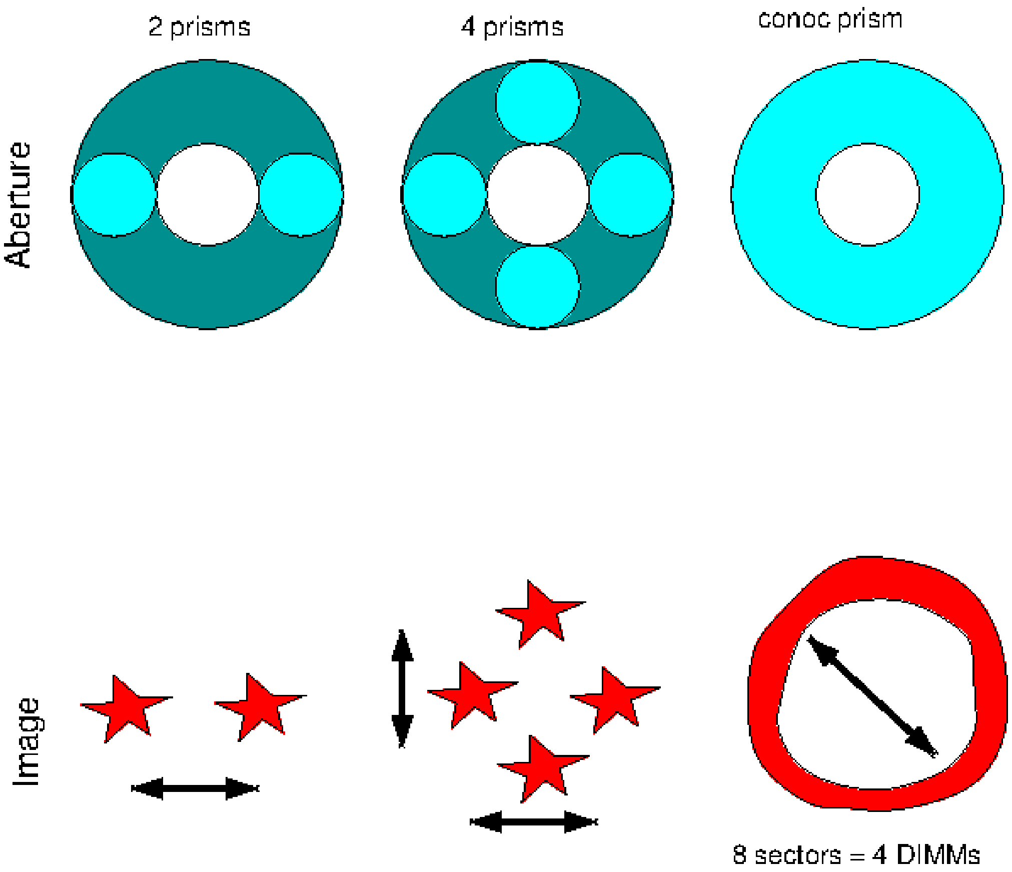
Paper: 2021, MNRAS, 502, 794

Why ring image?

- Conic wave-fronts are easy to make (defocus+spherical = cone).
- Compared to pure defocus, light is more concentrated (wins over detector noise). But defocus is OK, too.
- Simultaneous seeing measurement by 4 equivalent DIMMs (differential sector motion).
- Rotational symmetry → wind and AO time-constant measurement.
- Use all the light efficiently, can reduce aperture size

Ring seeing monitor has been tested at Tololo in 2007 (A.Kellerer, FADE)

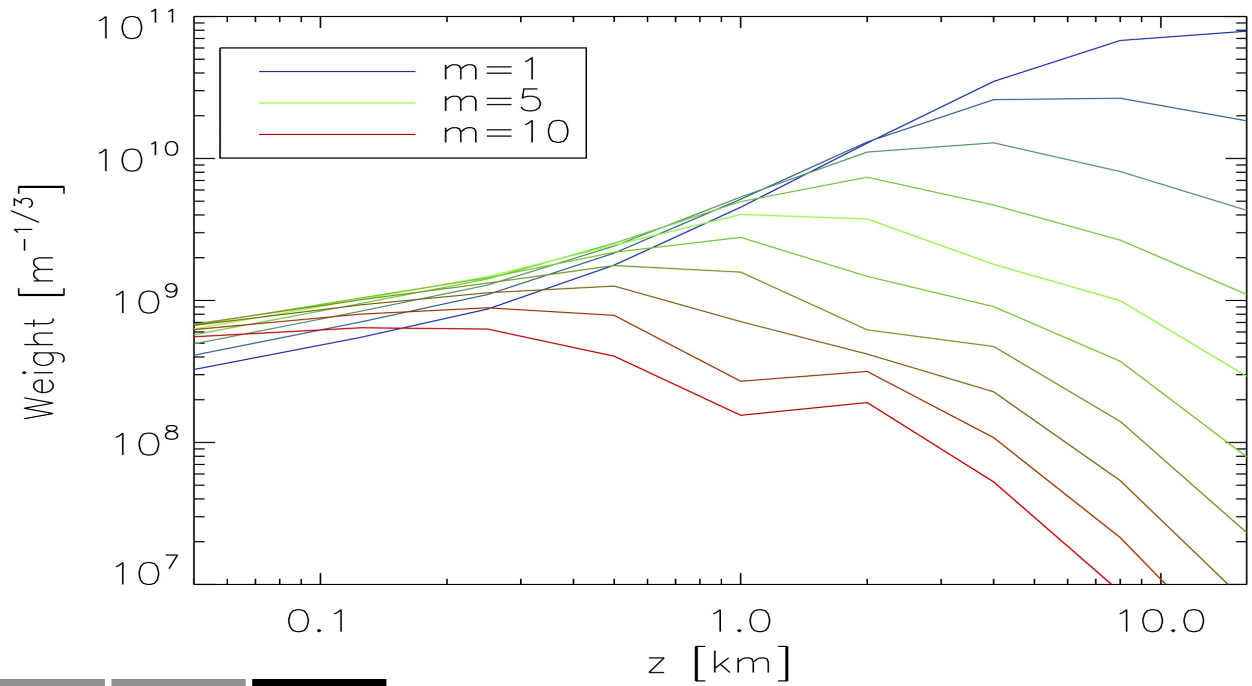
Relation between DIMM and RINGSS

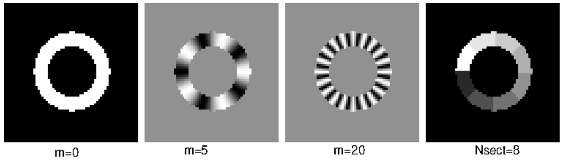


- Conic lens → ring image (replace 2 prisms of DIMM by a conic prism, use full pupil)
- Fluctuations of intensity in the ring serve to measure the scintillation
- Radial distortions of the ring measure the seeing as in DIMM

Theory of RINGSS

- The ring image is not an exact copy of pupil intensity
- Needs modification of the theory to measure turbulence profile. Sensitive to the ground layer (but also to aberrations)
- Verification of analytic theory and code by simulations





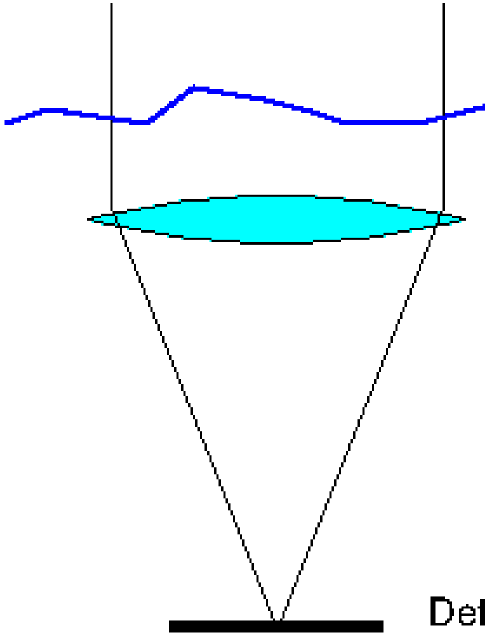
Calculation of weighting functions

- 2007 MNRAS, 381, 1179

"signal" S = Image*Mask

$\Delta S = \int F_\varphi \varphi + \int F_\chi \chi$

$\langle \Delta S^2 \rangle \rightarrow | F_\varphi + F_\chi |^2 \rightarrow$ WF



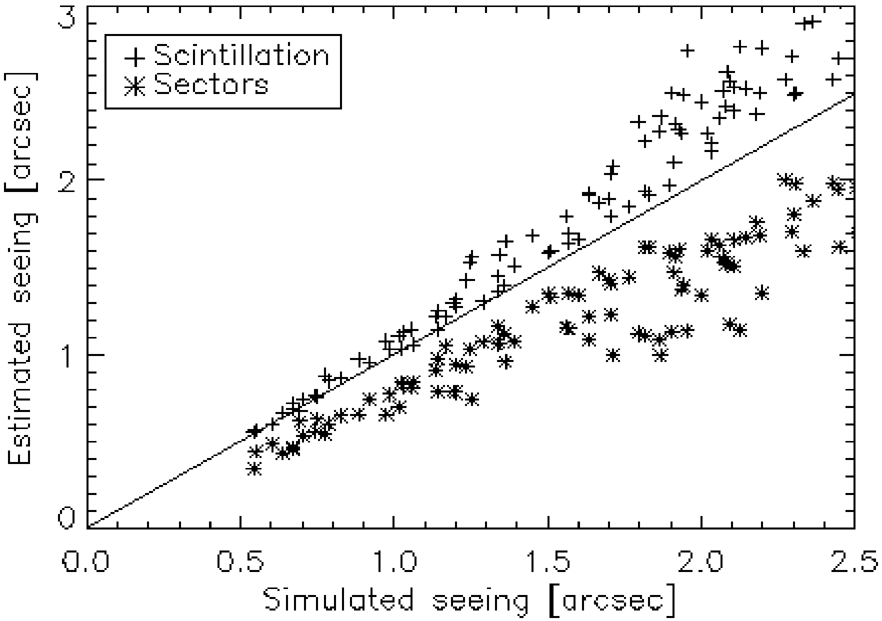
DIMM: centroid mask → reaction to defocus etc.

RINGSS: sin/cos(mθ) mask + conic → WF(m)

FASS: sin/cos(mθ) mask + defocus → WF(m)

Biases

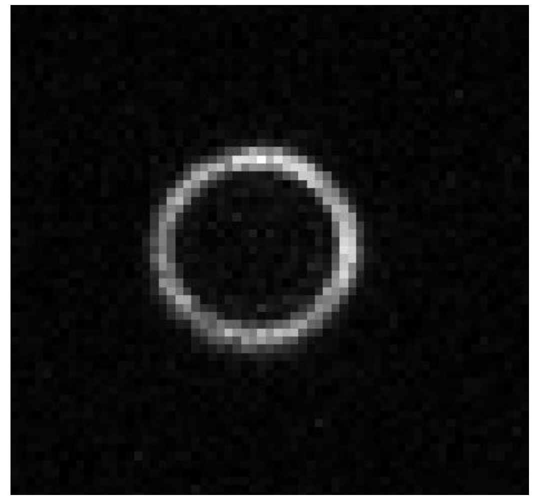
- Noise: calibration (el/ADU) and analytic calculation
- Exposure time: extrapolate to texp=0 using covariance
- Saturation: simulation-based correction of power spectrum (use machine-learning instead?)
- Aberrations: measure from ring and modify the WFs.



These biases must be accounted for in all single-star profilers

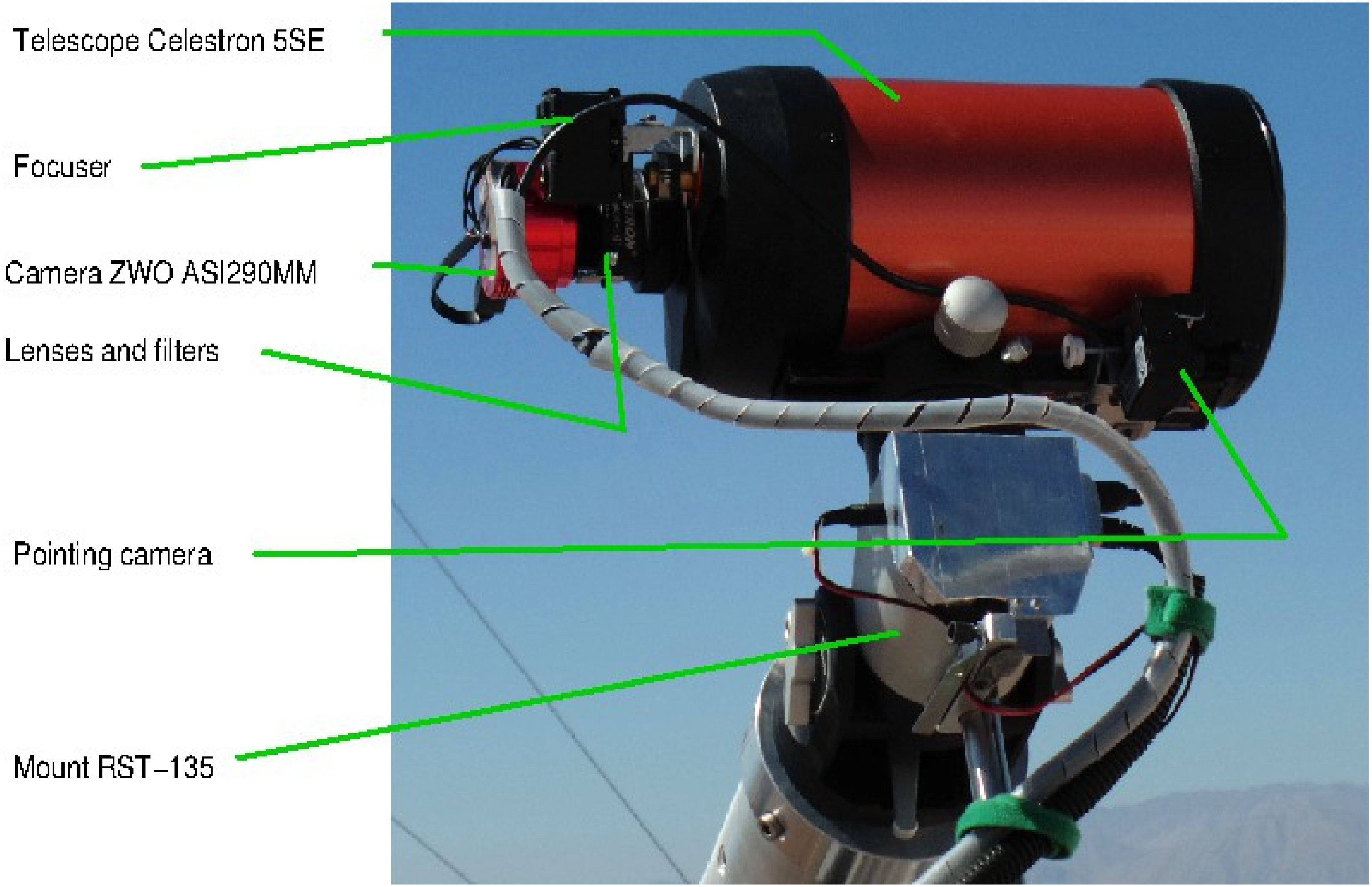
The advantages of RINGSS

- Commercial components: easy to replicate (except enclosure), modern technology (CMOS)
- Telescope smaller than in MASS-DIMM
- Wide field, easier to point the star
- Better data (QE, more pixels, 4 DIMMs)

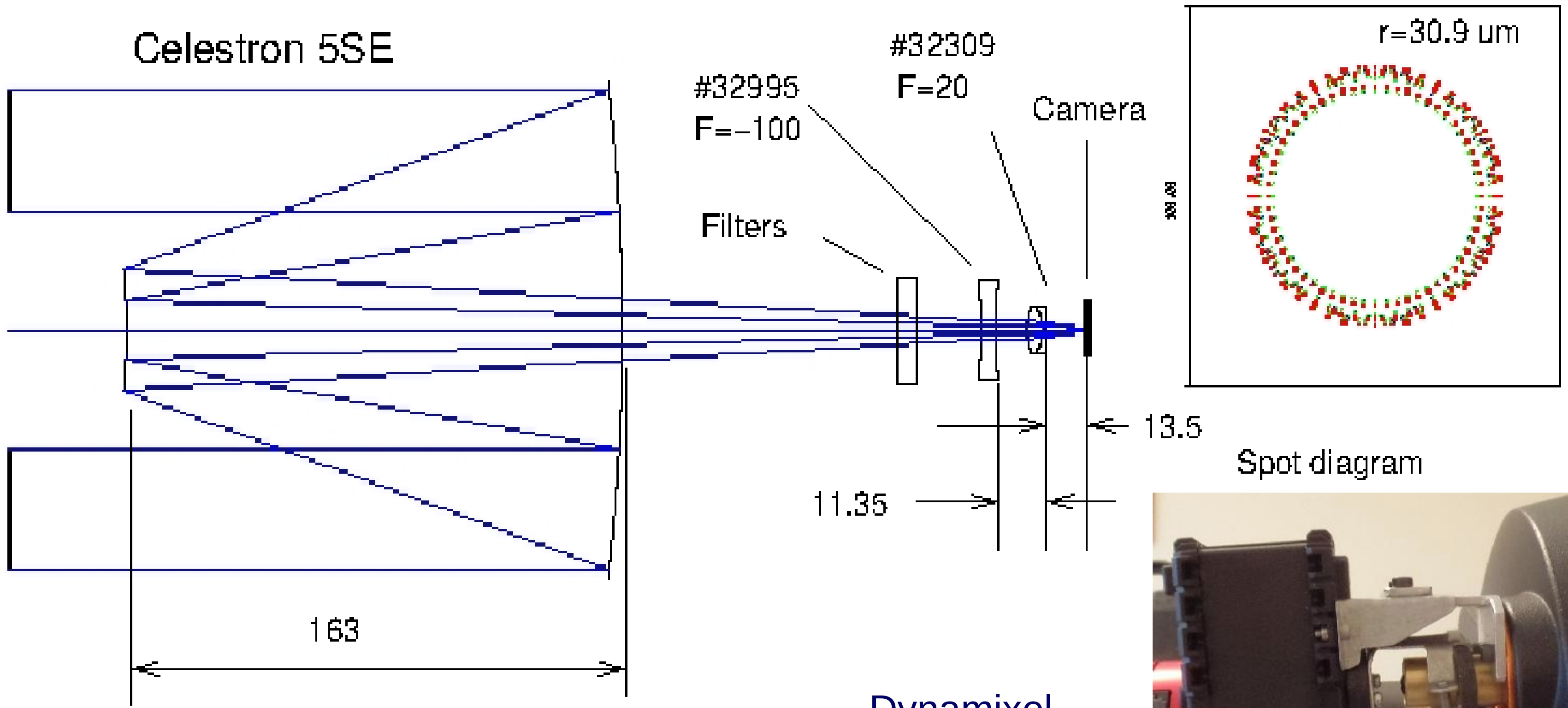


RINGSS is being replicated in Australia and at LBT.
The signal-processing software is publicly available.

The instrument



Optics and focuser

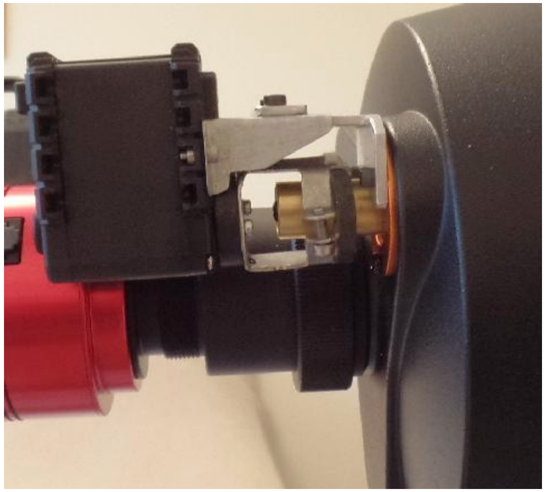


Pixel scale 1.7”

Ring radius 10 pixels

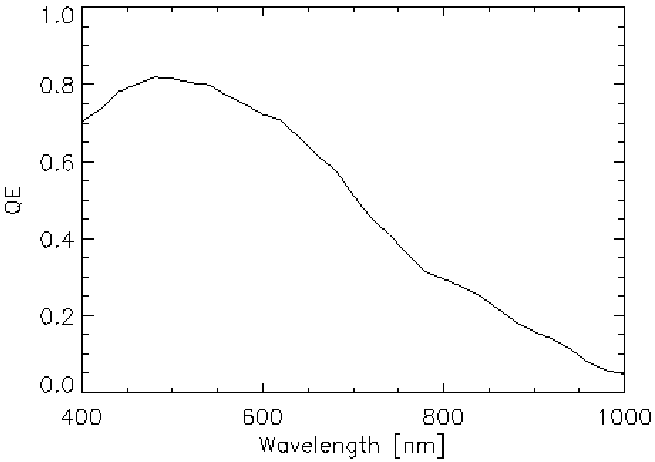
Full field ~0.5 deg

Dynamixel AX-12A attached to the focus knob



The CMOS detector

- ZWO ASI 290MM (China) used in astro-photography
- Format 2Kx1K pixels, 2.9 um/pixel
- Quantum efficiency ~80%, noise 1 electron
- Interface USB, rapid enough
- Cost <$400 USD!
- Studied in Feb. 2020 (L.Peige, M.Bonati, B.Cancino)



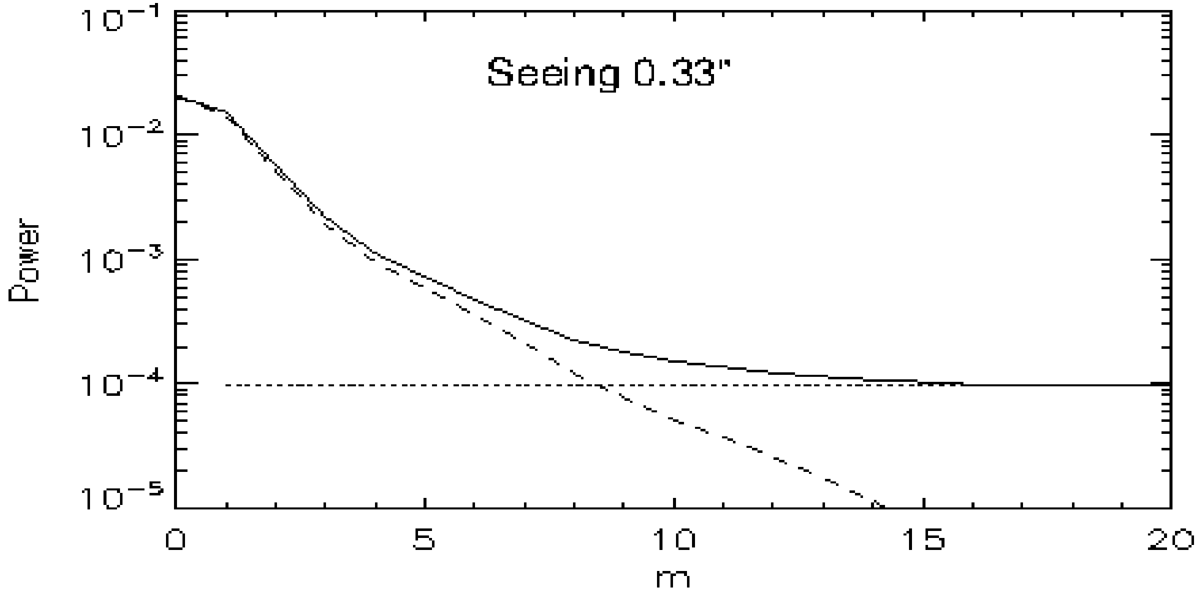
Classic CCD is too slow and noisy, EM CCD is expensive (>25K USD)

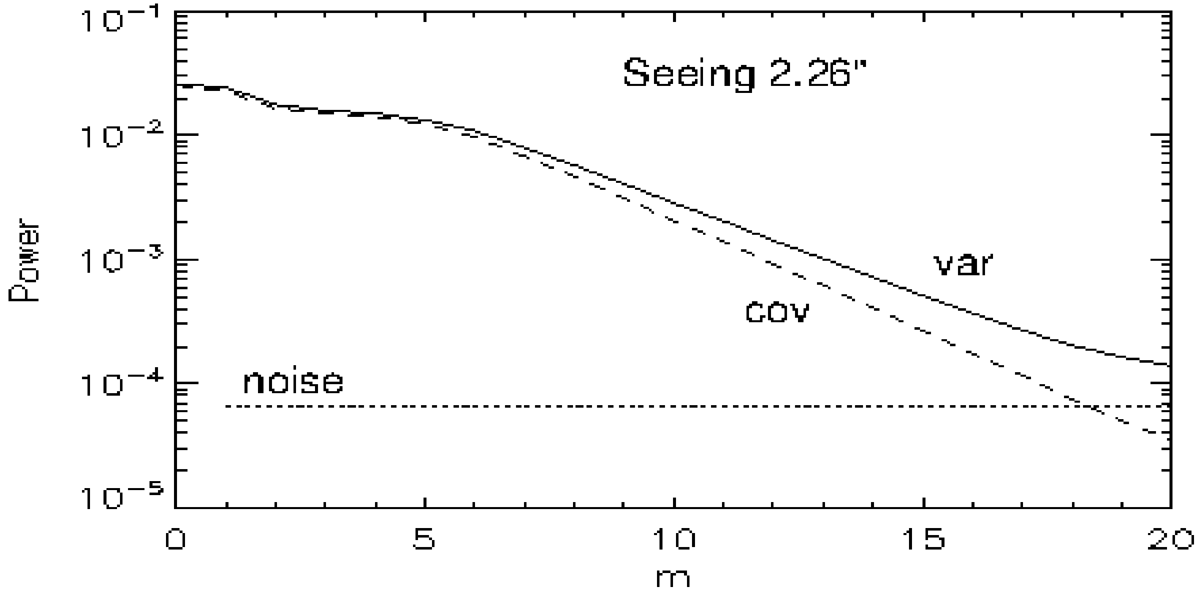
Signal processing

- Determine ring radius and width
- Prepare the sine/cosine/sector masks up to m=20
- Multiply each frame of the cube by masks → “signals”
- Signal variance → angular spectrum and sector motion
- Average spectrum over ten 2-s data cubes
- Restore profile using pre-computed polychromatic weighting functions (star color matters)
- Measure wind speed and AO time constant (Kornilov 2011)

Signal processing is coded in IDL and python, extensively tested.
Code posted at http://www.ctio.noirlab.edu/~atokovin/ringss/

Angular power spectrum



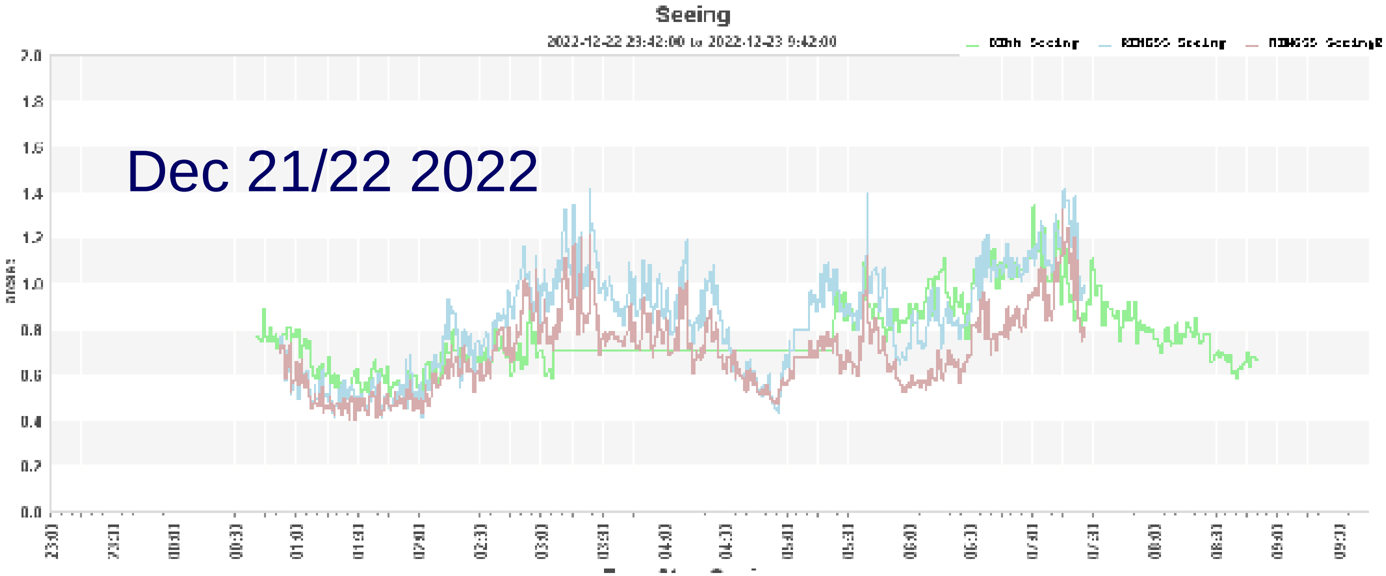


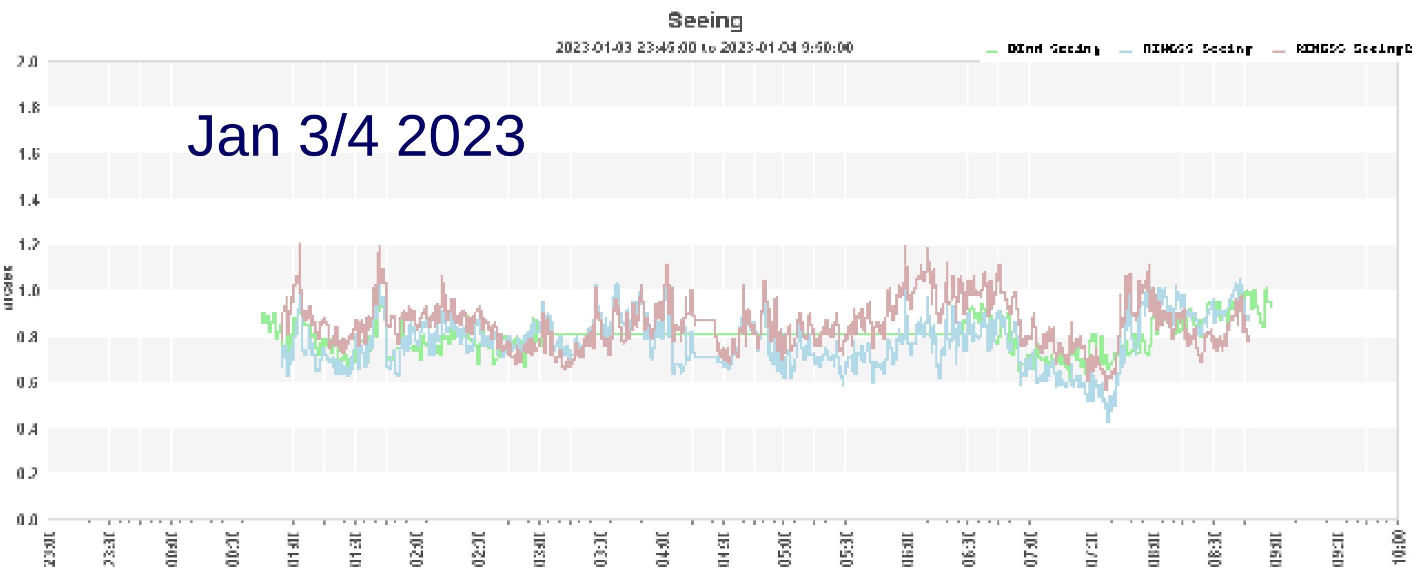
Paranal, March 2023

RINGSS-1 on the Halfmann tower

RINGSS on the Halfmann tower at Cerro Tololo
October 2022

RINGSS-1 on duty (robotic)

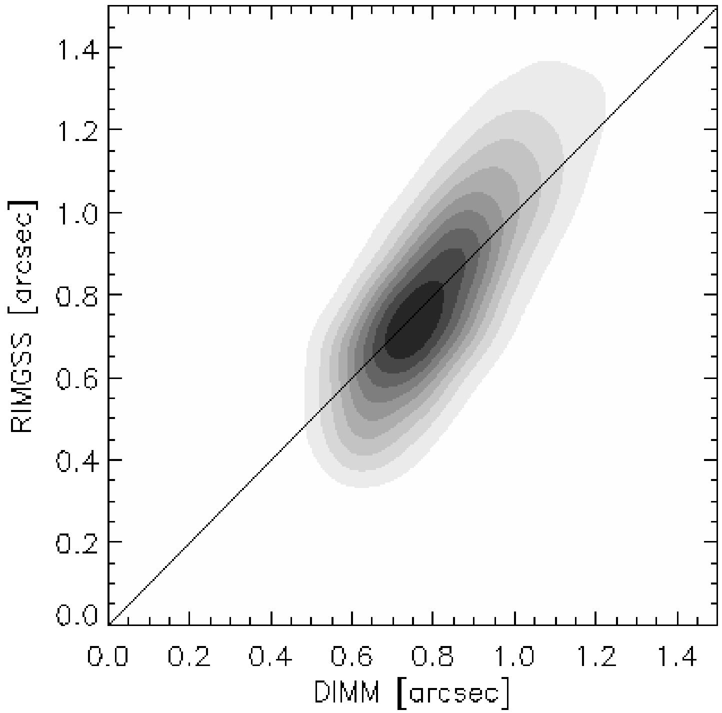


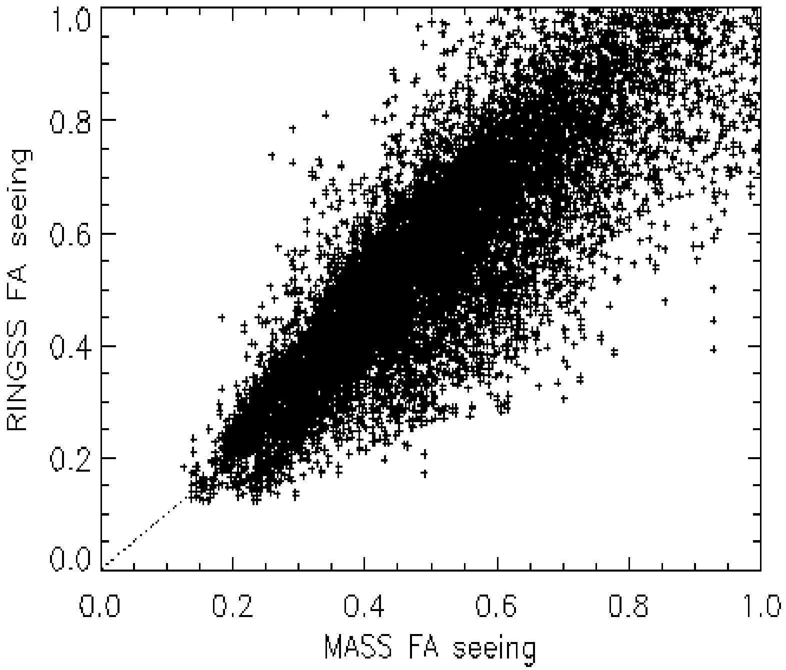


green: DIMM
blue: scintillation
red: sectors

RINGSS vs. MASS-DIMM at Tololo (1)

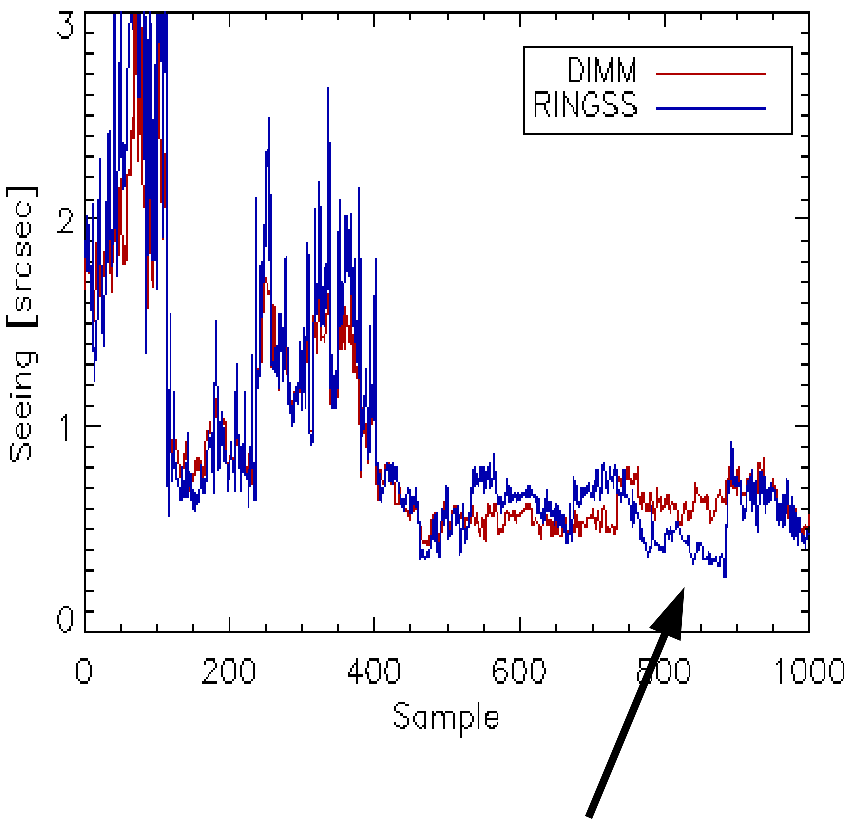
- Nov. 2022-Feb. 2023: 18,900 matched measurements
- Full report: on the RINGSS web page

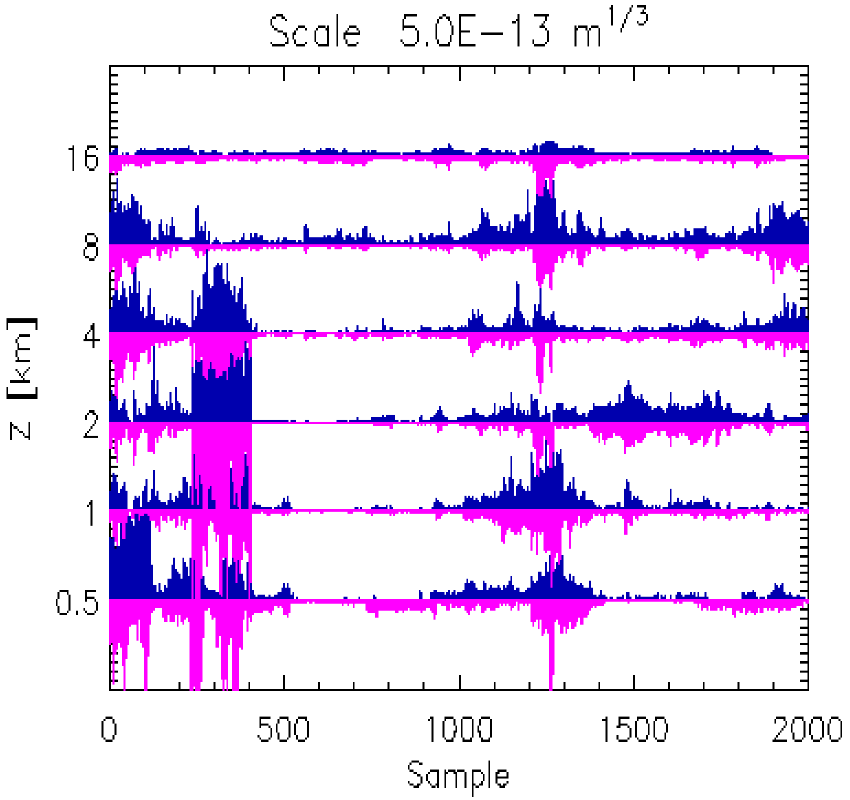




RINGSS = -0.27 + 1.36*DIMM

RINGSS vs. MASS-DIMM (2)





"Good seeing" problem:
DIMM over-shoots

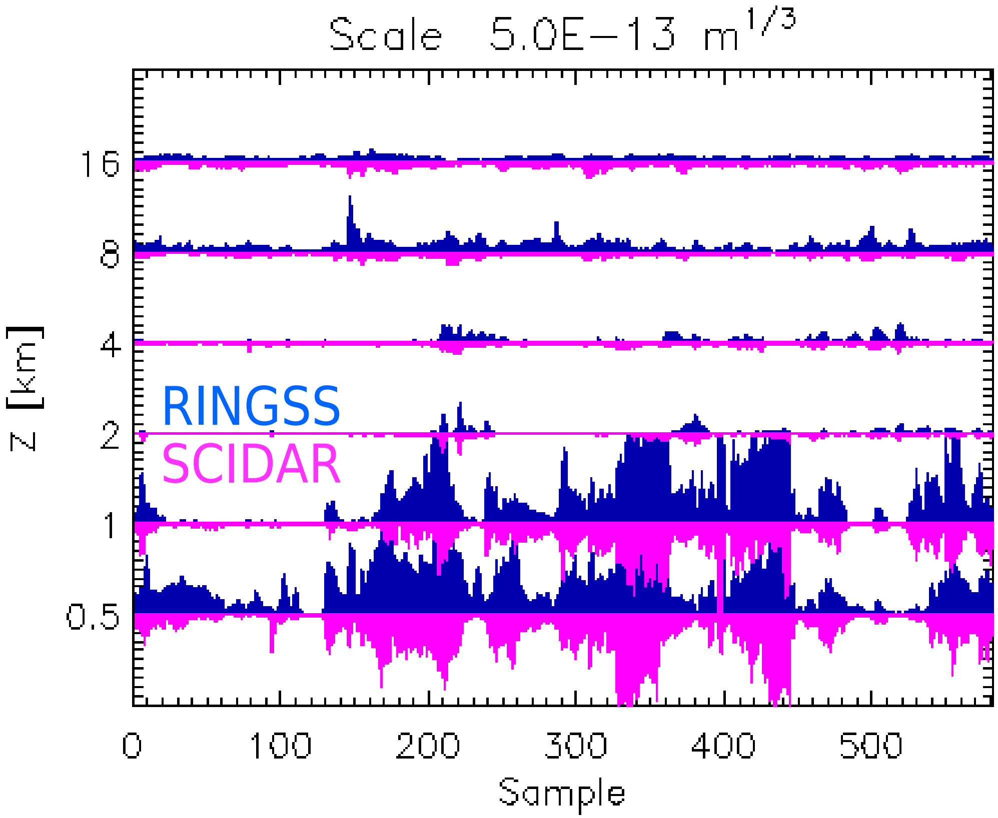
RINGSS: blue-up bars
MASS: pink-down bars

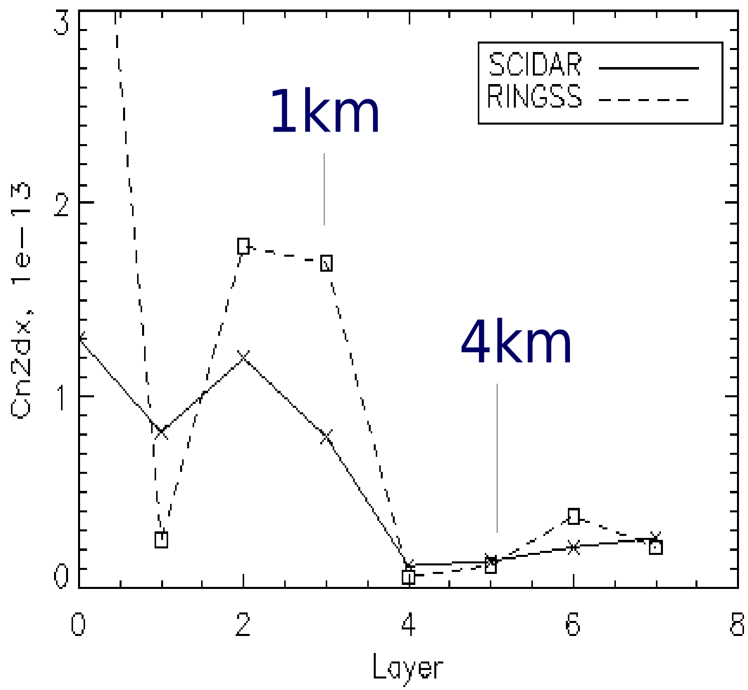
RINGSS-2 at Paranal

- Campaign Feb 28 – March 4 organized by ESO
- SHIMM, RINGSS, FASS plus MASS-DIMM and SCIDAR

RINGSS vs. SCIDAR

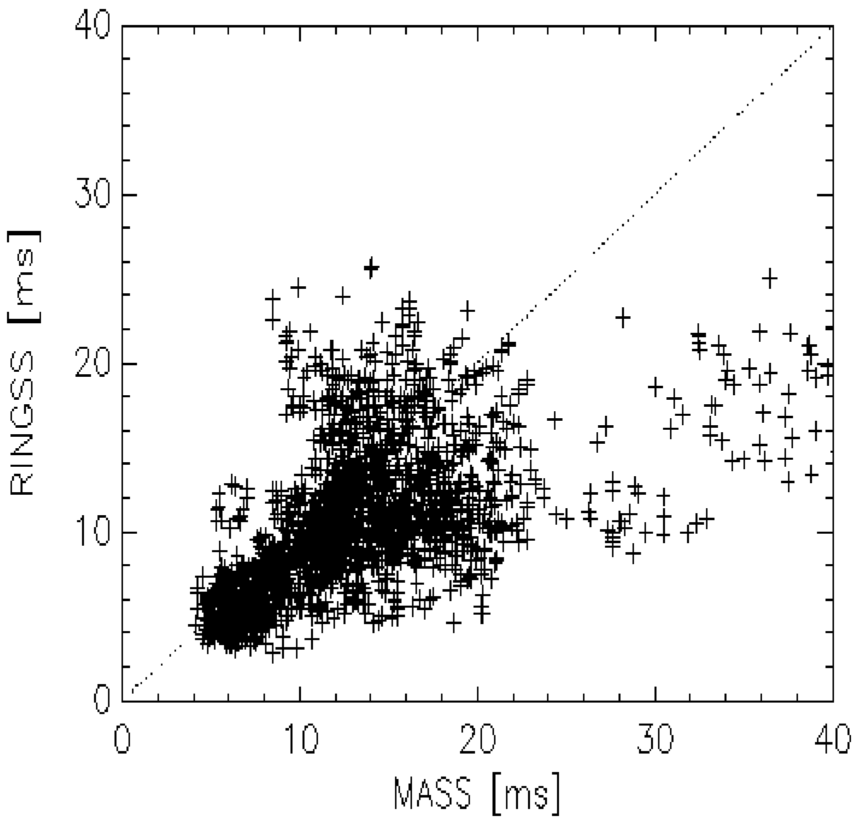
- Credit: T. Butterley (data proc.), J. Velasquez (obs.): 611 profiles with 2-min. resolution during 5 nights.

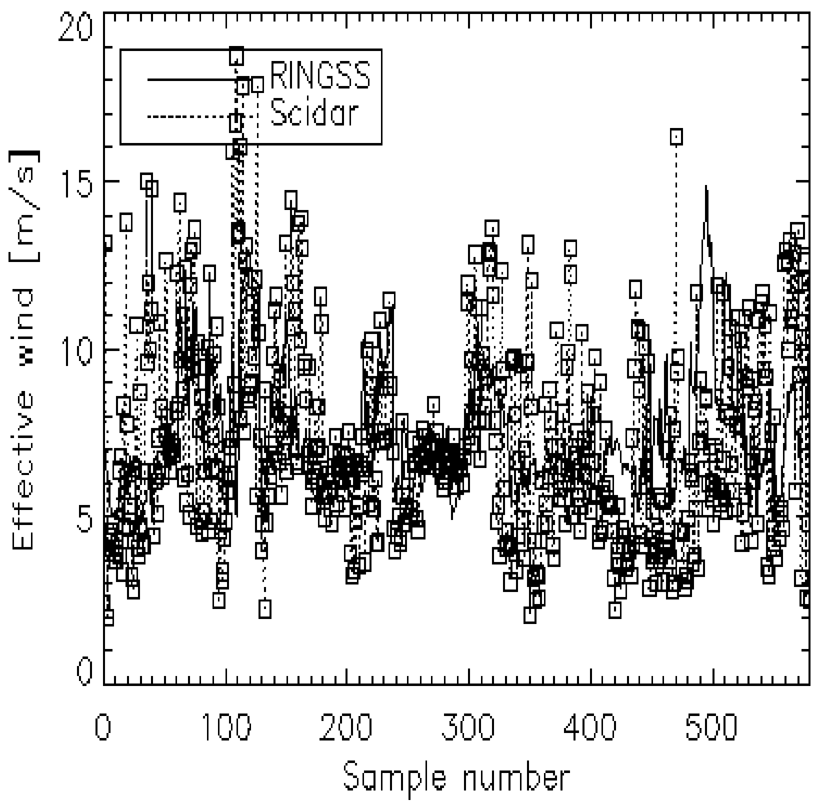




Mean prof.

Wind and time constant





SCIDAR: two methods to compute V_0.

Compact enclosures for RINGSS

- Cylindrical equatorial shell (Tololo)
- Compact box for Alt-AZ (simpler, home-made)
- No enclosure: protect only optics and mount?

RINGSS fits in
2 suitcases
(without enclosure)

Summary

- The RINGSS concept is new but mature, anchored in the MASS experience and theory
- The instrument works in robotic mode and gives correct results
- Ready for replication or modification.

RINGSS method and data processing: public
RINGSS instrument operation: proprietary