IMAKA
Imaging from Mauna Kea
with a 1 square degree atmosphere corrected imager

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Context

- CFHT call for ideas, new instruments for 2012+ period:
  - Post Golden Age Plan, Pre-TMT/E-ELT.
  - Can CFHT still remain viable?

- Older, smaller telescope (3.6m, 1980)

- Reputation for excellent image quality.

- CFHT: Wide-field community
  - Increase field? (lots of competition!)
  - Or somehow improve resolution?
  - Latter more difficult => unique!
2012 Landscape

LSST, Pan-Starrs, HyperSuPrimeCam, ODI.

All will have larger $A \Omega$. But may be this is not the right metric?

At the very least, should be $A' \Omega$ where $A' = ITR.A$ (Integration Time Ratio, gain in SNR)

Cannot compete against LSST in photon limited regime,

But in crowded source confusion regime?

Also, astrometric gain... (all points to <0.3")

GLAO on Gemini, ESO all have fields <10'

Limited by telescope.
Ground Layer AO

CFHT User’s Meeting 2007, McLaren, Richer floated idea of FA limited wide field imager.

GLAO: measure and correct turbulence common to the entire field, That is: turbulence at pupil.

Simplest way: average wavefront measurements, as high altitude is completely decorrelated over large FoV

Do not get diffraction limited performance

But improved seeing mode.

Improvement (performance) depends on how much turbulence is at ground/dome ($C_n^2$ refractive index structure constant)
Ground Layer AO
Mauna Kea Turbulence

- Started collaboration with UBC/HIA to study GLAO for CFHT.
- Mark Chun & collaborators at IfA similar idea, led to joint proposal.
- Gemini GLAO study, led by M. Chun, R. Avila
- Use of SLODAR/LOLAS to characterize vertical profile of turbulence above Mauna Kea.
- Found very thin ground layer (70m)
  - with median equal and uncorrelated ground layer/free atmosphere, 0.65"
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Gray zone

Geometrically, the gray zone (Tokovinin) is the altitude/volume of turbulence that can be corrected when guide stars in different directions are averaged.

Or in other words, the thinner the ground layer, the wider the corrected field of view.

Mauna Kea’s thin ground layer should allow for very large fields to be corrected!

Gray zone: \( H_{\text{max}} \sim \frac{\lambda}{\beta \theta_0} \). \( \lambda \) is wavelength (700nm), \( \beta \) is goal resolution (0.3") so if \( H_{\text{max}} \sim 70 \text{m} \), \( \theta_0 \sim 30' \) (radius)!
Gray zone
Basic expected Performance

Starting point: Let us integrate the site characteristics to the instrument design.

Assume we can correct 70 meter thick Ground Layer.

Controlling dome & telescope seeing also becomes part of instrument design. Questions as to how we do this, but....

In theory, should allow to get impressive performance:

- ~0.3” FWHM at 700nm over 1°x1°

Fed this performance to astronomers (Carlberg, Richer et al.)

Very compelling Science Cases...
Example science cases!

- **Solar System:**
  - Kuiper Belt 30km size objects, formation and collisional evolution
  - Jupiter’s moons

- **Extra-solar planets**
  - by transit, in dense star fields. Need millimagnitude accuracy...

- **Stellar physics**
  - High proper motion accuracy
  - Search for exotic stellar objects in the field.

- **Galaxy formation & Evolution**
  - Large area at 0.2”~0.3” in red is good tool to discriminate z~6 objects that will be routinely probed by JWST and ELTs
  - Morphological galaxy survey up to z~1
  - At low redshift (up to Virgo cluster), star formation history from multi-band photometry on resolved stellar population.

- **Cosmology**
  - Equation of State parameter, \( w \) at redshift 1.2 from supernovae
  - Strong lensing of distant supernovae (improved through resolution)
Can it be designed?

At prime focus?

Packaging problem for AO relay, intermediate focal plane...

Idea to use MegaCam at Cass with ASM

But detector “too small”! (need 36000 x 36000 for proper sampling)

AO relay at Cass with new detector?

DM tilted with optical axis turns out to be a problem for DM conjugation and pupil shear with field angle.

Size & Cost of optics to provide 0.1” resolution over 1 degree (at F/5.7, focal plane ~ 358mm)
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ASM for CFHT?

ASM may turn out to be only feasible optical design!

Camera at Cassegrain (or Gregorian)

For comparison, current F/8 is 8.6m above primary
conjugated -23.3m
but 1.5m in diameter!

For comparison, MMT ASM is 640mm (with 336 actuators)

ESO ASM~ 1.2m asphere.

And not cheap...
Because of very large field, DM conjugation is actually much more critical...

And so is image quality

Working with extremely talented and creative optical designers (John Pazder - HIA, Harvey Richardson - retired) to try to solve issue.

Need all the talent we can get!
ASM is not easy!
Diffraction limited design over full 1 degree field.
DM is tertiary, concave.
7 element corrector...
DM is convex secondary, a little smaller.
4 element corrector...

DM is convex secondary, 1m, -46m conjugate.
3 element corrector...
Wavefront sensing?

NGS versus LGS?

- Rayleigh LGS ideally suited
  - Low level turbulence is sampled
  - LGS provides fixed constellation
  - Laser much cheaper than sodium
  - LGS separated spectrally (especially if at UV)
- Multiple or Rotating Rayleigh LGS?
- But, cost, complexity!
Wavefront sensing?

NGS versus LGS?

But with such large field, probability of finding enough natural stars becomes quite large!

\[ P(m, n) = 1 - \sum_{i=1}^{n} \mu(m)^i \frac{e^{-\mu(m)}}{i!} \]

- 50% sky coverage at NGP if 6 stars with \( m < 11 \)
- 95% sky coverage at NGP if 6 stars with \( m < 12 \)

Near IR WFS, with dichroic beamsplitter?

Moveable mirrors to pick up light and send to WFS

On chip pyramid wavefront sensing?
Wavefront sensing?

\[ P(m, > n) = 1 - \sum_{i=1}^{n} \mu(m)^i \frac{e^{-\mu(m)}}{i!} \]
Wavefront sensing?

- NGS versus LGS?

  - But with such large field, probability of finding enough natural stars becomes quite large!

| $P(m_n > m)$ | = | $1 - \mu(m)$ |

On chip pyramid wavefront sensing?
Performance

Many simulations, using PAOLA, simul.pro and yao

Problem of Monte Carlo simulations is size of arrays.

- at 10km, 1° is 175m,
- >2000 pixels if a few pixels/r₀

PAOLA (analytical PSF model) has similar problem.

- due to aliasing (poorly sampled low frequencies at high altitude as field increases)

But confirm we can get 0.44”, 0.38” and 0.35” at V, R and I respectively...
Simulation results

- Yao an simul.pro tested side by side

- With $3e^{-}$ read noise, need magnitude 12 or brighter

- Although with $0.5e^{-}$, can gain up to 2 magnitudes

- Followed by extensive Yao simulations

- Trade study, number of guide stars

- Order of AO system

- Sampling frequency, atmosphere
Simulation results

Atmospheric Limited PSF

Diffraction Limited PSF

FWHM and rms (370nm)

FWHM and rms (500nm)

FWHM and rms (700nm)

FWHM and $\sigma_{\text{rms}}$ (0.370$\mu$m)

FWHM and $\sigma_{\text{rms}}$ (0.500$\mu$m)

FWHM and $\sigma_{\text{rms}}$ (0.700$\mu$m)

FWHM and $\sigma_{\text{rms}}$ (0.900$\mu$m)

Guiding Star Mag (V)

PSF only

No GLAO

N_g = 8

N_g = 6

N_g = 4

N_g = 10

No GLAO
PSF uniformity

Yao simulations also used to trace PSF uniformity

But 9000 steps (1msec = 9 second exposure) is still limited by atmosphere residual variations.

How do we know we are correcting Ground layer?

Changing size of 10 guide star constellation does not change PSF uniformity,

until constellation small enough to start correcting 1000m layer.
Fundamental limits

Previous simulations assume 0.65” (50th percentile) seeing/profile.

But seeing/performance is a probability distribution...

Work done By David Andersen, HIA

Look at 7000 $C_n^2$ profiles,

compute free atmosphere seeing as limit of GLAO performance,

assuming that all the turbulence below 600 or 70m can be corrected.
Fundamental limits

Credit: Mauna Kea site testing data obtained and processed by: Remy Avila, Mark Chun and Richard Wilson. GLAO simulations performed by D. Andersen using PAOLA (Jolissaint & Véran 2002).

Based on observations obtained at the Gemini Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under a cooperative agreement with the NSF on behalf of the Gemini partnership: the National Science Foundation (United States), the Particle Physics and Astronomy Research Council (United Kingdom), the National Research Council (Canada), CONICYT (Chile), the Australian Research Council (Australia), CNPq (Brazil) and CONICET (Argentina)
But still shy from 0.3’’!

Enter the OTCCD! (Tonry et al. Collaboration Cuillandre/UH)

PanStarrs camera: 1.3 Gpixel with orthogonal charge transfer

With 0.1’’ pixels, field=1 degree...

And orthogonal charge transfer allows to correct local (i.e. de-correlated, which means high altitude) tip-tilt.

From 0.75 to 0.5’’ on sky tip-tilt improvement

If using LGS, also get average tip-tilt for free

Fast read time (6sec) and “cheap” clone of PS1...

MIT/DALSA chip: 0.1c/pix (x 1.3 \(10^9\)pix ...)

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Final performance

- Used YAO to first simulate GLAO module.
- High altitude simulated by a few layers at 4, 5km
- Took performance of that and fed into new YAO simulation of tip-tilt only and (scaled) vertical turbulence profile with zero ground layer.
- Would still like to simulate end-to-end in one round.
- But these preliminary results encouraging...
Final performance

GLAO + OTCCD, 0.65” seeing

GLAO + OTCCD, 0.50” seeing

seeing
- OTCCD on-axis
- OTCCD 10’ off-axis
- GLAO
- GLAO + OTCCD on-axis
- GLAO + OTCCD 10’ off-axis
Feasibility study

Feasibility study to be completed in two weeks (!)

Feasibility versus:

Instrument design, cost,

we have a pretty good idea - not cheap, but unique capability, funding agencies will have to make strategic decision

Science cases & interest (well established!),

and expected performance.

Because of very strong dependence on strength of ground layer, will require more simulations, measurements and experiments.
If successful...

To get hard data, in situ (on telescope itself), LOLAS experiment using MOS

- Measure telescope, dome seeing. Confirm turbulence profile, strength of GL, and hence performance
- Refine trade study, design of AO system, parameters, architecture
- Refine optical design
- ASM...
New and bold ideas will help this older, smaller telescope remain at the forefront of research. Better understanding of site characteristics and including them as integral part of instrument design may pave the way to the… next generation of ground based imaging!
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