Optical-InfraRed Design Considerations

Luc Simard
National Research Council of Canada

Dunlap Institute Instrumentation
Summer School 2018
Luc’s Career in One Page (“Trust your instinct”)

- Observed Moon on Halloween at age seven through a 50mm Tasco refractor - bought it for $30 when neighbor lost interest
- Bought 2nd telescope (150mm reflector) at age eleven with paper route money
- Went to the most awesome astronomy camp in Port-au-Saumon, QC
- Built a backyard radio-telescope (helical antenna; 400 MHz; Crab nebula)
- Went to Queen’s University to become a radio astronomer (1987-90)
- Went to the University of Victoria for grad school (1990-1996)
- Postdocs at UC Santa Cruz and University of Arizona (1996-2001)
- Joined NRC in 2002 with the Canadian Astronomy Data Centre
- Joined TMT in November 2005; Science Instruments Group Leader 2009-2017
- Became Director of Astronomy Technology at NRC in 2017
Why do an Observatory and its instruments look the way they do?
Outline

• From science to requirements
  • How do I know what to build?

• From requirements to technical design
  • How do I link my science to my design?

• Fundamental design trade-offs
  • What do I need to pay attention to?
Flow your Science into your Observatory/Instruments
Very demanding science case

Micro-arcsecond astrometry over 10-year timescale

Incredible instrumental stability

Figure 14. Upper panels: A 0".8 x 0".8 (0.027 x 0.027 pc) region centered on the Milky Way’s supermassive black hole (SMBH), as imaged at 2.1 μm with the current Keck + AO system (Strehl = 0.3; left panel), and with TMT/IRIS with a multiple laser AO system (Strehl = 0.7; right panel). Lower panels: Implications for short-period star orbits (note that a different scale and a different point in time has been chosen, meaning the stars are at different positions). Overlaid are all known orbits and examples of expected orbits with periods less than 23 years that are detectable both astrometrically and spectroscopically (14<K<16, yellow; K<17, green; K<18, cyan; K<19, magenta; K<20, tan). TMT/IRIS will not only increase the number of measurable short period orbits by an order of magnitude, but should also find systems that orbit the SMBH much deeper in the central potential, with orbital periods that are a factor of 5 smaller. These systems are particularly helpful for measurements of post-Newtonian effects (GR and extended mass distribution).
Orbits at the Galactic Center – A Real Image

Challenge: To determine minimum field-of-view needed to get as many positional reference sources (masers) on the same image for astrometry.

Figure 17. A Keck/NIRC2 22” x 22” mosaic of the Galactic Center. The circled sources are SiO masers that are used for the construction of an absolute reference frame. The red cross marks the SMBH. A large enough field-of-view is therefore crucial to get into a stable reference frame for proper motion studies.
Orbits at the Galactic Center – Simulating Real Results

TMT IRIS Simulation of the Galactic Center (Meyer et al.)

17” × 17” subsection

100,000 stars down to K = 24 in a 20-second exposure

10 micro-arcsec astrometry

Figure 16. Astrophysical experiments with Galactic Center stellar dynamics measurements. Left panel: constraint on the extended mass distribution obtainable with IRIS/TMT. Shown are the 68%, 95%, and 99.7% confidence levels on the enclosed mass and slope of an extended matter distribution, assuming an astrometric limit of δθ = 0.5 mas and a spectroscopic limit of δν = 10 km s⁻¹. The input models have power-law slope of γ = 1.5 and 2 and an input enclosed mass of 6000
Orbits at the Galactic Center – Observing Scenario

6.5.5. Example Observing Scenario: Testing General Relativity at the Galactic Center

Science case: Monitoring the orbits of short period stars around the SMBH in the Galactic Center to test General Relativity in an unprecedented regime.

Targets: The nuclear star cluster of the Milky Way.

Desired Observations: Diffraction-limited imaging at K-band and spectroscopy with spectral resolution of $R \sim 8000$ around the Brγ line for high-precision astrometry ($\sim 30$ μarcsec) and radial velocities ($\sim 5$ km/s). A plate scale of 4 mas/sec is required for accurate centroiding of point sources. In order to construct a stable reference frame, maser sources at a distance of $\sim 20$ arcsec from the SMBH need to be imaged in the same field of view. High Strehl ratios are crucial because of the extreme crowding in the field. IRIS should be able to obtain a spectroscopic $S/R = 50$ for a $K = 21.5$ source after five hours of integration. For broadband imaging at a 4 mas sampling scale, a point source with $K = 23.5$ can be observed to S/N=600 in an hour. Astrometric measurements should scale as $1/\sqrt{t_{\text{int}}}$ as this is the limit of atmospheric noise. Individual exposure times will be short in order to avoid saturating the brightest stars in the field.

Calibration: Flat fields, darks, background skies, and telluric standard stars will be necessary for calibrations. Astrometric fields and a grid are required to calibrate the plate scale. Currently, globular clusters observed with HST have been used at Keck to calibrate the instrumental plate scale and orientation. A device like a fiber source will be useful to calibrate instrumental PSF spatial variability effects.

Challenges: In order to do sub-milliarcsec astrometry over a field of view of 30 arcsec, the spatial stability of the PSF needs to be maximal or very well understood. Low spatial order systematic changes in the field distortion can be fit out (translation, rotation, plate scale), but high spatial order systematic changes should also be limited to $\sim 30$ μarcsec (see also Star Formation science case). Due to short individual exposure times low detector read noise is required.

Similar to writing an actual observing proposal!
Calibration requirements should never be overlooked!
Orbits at the Galactic Center – Derived Instrument Requirements

### Table 18: Major Requirements for the Galactic Center

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>[REQ-2-IRIS-0710]:</td>
<td>Wavefront error less than 30 nm. The best possible astrometric accuracy (&lt;&lt; 100 mas) is required to map the orbits of stars in the Galactic center well enough to test general relativity.</td>
</tr>
<tr>
<td>[REQ-2-IRIS-1310]:</td>
<td>Distortion correctable to 50 μas.</td>
</tr>
<tr>
<td>[REQ-2-IRIS-0730]:</td>
<td>FOV at least 15x15 arcsec for imaging mode. The largest possible field is required to tie the coordinate system of the Galactic center to other frames, and to follow stars out to larger radii.</td>
</tr>
<tr>
<td>[REQ-2-IRIS-0780]:</td>
<td>Sampling at 0.004 arcsec/pixel for imaging. The best possible sampling is required for accurate centroiding of stars in the Galactic center. We would like to have 4 samples per diffraction-limited element. H and K are the optimal filter for astrometry depending on the precise AO performance.</td>
</tr>
<tr>
<td>[REQ-2-IRIS-0790]:</td>
<td>R=2-5 for imaging mode, to 300 in selected bands. Broad-band and narrow-band imaging may both be used to maximize astrometric sensitivity.</td>
</tr>
<tr>
<td>[REQ-2-IRIS-0810]:</td>
<td>The instrument should not increase the (inter-OH) background by more than 15% over natural sky + telescope background. One major advantage of TMT over other instruments is IRIS’s ability to detect a much larger number of very faint stars. The sensitivity of the instrument is of key importance to the groundbreaking science goals.</td>
</tr>
<tr>
<td>[REQ-2-IRIS-0830]:</td>
<td>Detector dark current and read noise should not increase the effective background by more than 5% for an integration time of 2000s. One major advantage of TMT over other instruments is IRIS’s ability to detect a much larger number of very faint stars. The sensitivity of the instrument is of key importance to the groundbreaking science goals.</td>
</tr>
<tr>
<td>[REQ-2-IRIS-0800]:</td>
<td>(Goal) The total efficiency of the internal optics and components for the imager and spectrograph in IRIS will be greater than 42% and 35%, respectively.</td>
</tr>
<tr>
<td>[REQ-2-IRIS-0780]:</td>
<td>Spectral resolution at the smallest pixel scale of R=4,000 or better that covers a field of view of roughly 0.5 x 0.5 with a spectral range of at least 5%. Radial velocity precision of 10 km/sec or better is required for stars that have radial velocities that range from 0 to a few times 10,000 km/sec. The stars of interest will reside within a region that is roughly 0.5 x 0.5. Higher spectral resolution is desirable as it would deblend the Br gamma from the nearby He line, reducing systematic error. We note that spatial and spectral coverage can be increased with a loss of observational efficiency.</td>
</tr>
</tbody>
</table>

Unique label for each requirement

Levels:

0 = “Prime Directive”
1 = “Observatory”
2 = “Instrument”
3 = “Subsystem”
Objectives, Observations and Requirements

• **Science Objectives:**
  
  • Should be exciting!
  
  • Should be broad in scope to exercise all aspects of your design
  
  • List should still be manageable

• **Observations:**
  
  • Should be end-to-end: Preparation/planning, execution, calibrations and reductions
  
  • Should covered all important variables: depth, field-of-view, angular/spectral resolution, wavelength range, baseline and cadence

• **Requirements:**
  
  • A requirement is **NOT** a specification!
  
  • A good requirement should be traceable **AND** testable!
  
  • Definition can include a goal and a discussion
Cosmology and Fundamental Physics

• **Science objectives:**
  • Dark matter on large and small scales
  • First measurement of a Kerr spacetime
  • Dark energy density versus cosmic time
  • Variations of fundamental constants over cosmological timescales

• **Observations:**
  • Proper motions in dwarf galaxies and microarcsec astrometry
  • Wide-field spectroscopy
  • Transient events lasting > 30 days
  • High-res observations of quasars/AGNs

Stellar orbits around Galactic Center with Keck

- $\lambda = 0.31$-0.62$\mu$m, 2-2.4$\mu$m
- $R = 1000$ - 50,000
- Very efficient acquisition
- 0.05 mas astrometry
- Stable over 10 years
- SL Field of view = 20'
- AO field of view = 15’’ (w/ stable PSF)
Galaxy Formation and the IGM

- **Science objectives:**
  - Baryons at epoch of peak galaxy formation
  - Velocity, star-formation rates, extinction and metallicity maps of galaxies at $z = 5.5$
  - IGM properties on scales $< 300$ kpc

- **Observations:**
  - Optical/IR multiplexed spectroscopy of distant galaxies and AGNs
  - Spatially resolved spectroscopy

- **Line-of-sights through the Inter-Galactic Medium (IGM):**
  - $\lambda = 0.31-2.5 \mu m$
  - $R = 3000-30,000$
  - Very efficient acquisition
  - Multiplexing factor $> 100$
  - Field of view $= 20'$
Formation of Stars and Planets

- Science objectives:
  - Origin of stellar masses
  - Architecture of planetary systems
  - Pre-biotic molecules in disks
  - First direction of reflected-light Jovians
  - Exoplanetary atmospheres (oxygen)

- Observations:
  - High precision, crowded field photometry
  - Very high Strehl ratio imaging
  - Diffraction-limited, high-resolution, mid-IR imaging and spectroscopy
  - High-res optical and IR spectroscopy
  - $\lambda = 1\text{-}25 \, \mu m$
  - $R = 4000,30000\text{-}100,000$
  - Low telescope emissivity
  - and PWV $< 5 \, \text{mm}$
  - Fixed gravity vector
  - Strehl ratio $> 0.9$ and
  - Contrast ratio of $10^{8\text{-}9}$
Solar System

• Science objectives:
  • Composition of Kuiper Belt objects and comets
  • Monitoring weather, vulcanism and tectonic activity

• Observations:
  • Diffraction-limited, spatially resolved spectroscopy
  • Diffraction-limited, high-resolution, near-IR and mid-IR spectroscopy

Volcanic Plume on Titan

- λ = 1-10 µm
- R = 1000 -100,000
- Non-sidereal tracking
- Fast response time
Multiplexing versus Discovery

• Requirements:
  • Wavelength range, field of view slit length, spectral resolution

• Impact:
  • Multiplexing:
    • Tomography of the Inter-Galactic Medium
    • Topology of reionization
    • Rest-frame UV and optical properties of distant galaxies
  
  • Discovery:
    • Identification and diagnostic spectroscopy of transient phenomena (e.g., supernovae/GRBs/tidal flares)
    • Metal-free star formation in First Luminous Objects
    • Pre-biotic molecules

Galaxy velocity fields from SINS survey
Observing Efficiency

- **Requirements:**
  - Acquisition, calibration, downtime, fast response and weather

- **Impact:**
  - Large programs (# observations > 500)
    - Tomography of the intergalactic medium
    - Jovian exoplanets
    - Doppler detection of planetary systems
  - Time-critical programs
    - Supernovae/Gamma-ray Bursts
    - Weather and volcanic activity in the outer solar system
    - Exoplanetary transits
Image Quality

• Requirements:
  • Resolution (telescope aperture) and sampling (detector size versus field of view)
  • Strehl ratio (AO performance)
  • Contrast ratio (wavefront control, speckle suppression, segment coating and cleaning)

• Impact:
  • Test of General Relativity at the Galactic Center
  • Proper motions in the Local Group of galaxies
  • Star formation histories of nearby (D < 16 Mpc) galaxies
  • Direct detection and characterization of exoplanets
  • Surface physics of planets and satellites
After Repeating for Many Science Cases …

Table 7: Flow-down of Science Case Requirements

<table>
<thead>
<tr>
<th></th>
<th>White dwarfs</th>
<th>Metal Poor Stars</th>
<th>Resolved populations</th>
<th>Dark matter mapping</th>
<th>IGM Tomography I</th>
<th>IGM Tomography II</th>
<th>z~ 2 – 5 Galaxies</th>
<th>QSO Pairs</th>
<th>Transients</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slits/mask</td>
<td>140</td>
<td>&lt; 10</td>
<td>140</td>
<td>140</td>
<td>20</td>
<td>90</td>
<td>20</td>
<td>20</td>
<td>1</td>
</tr>
<tr>
<td>Masks/night</td>
<td>2</td>
<td>5</td>
<td>2.5,7</td>
<td>6</td>
<td>2</td>
<td>10</td>
<td>2</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Slit width [arcsec]</td>
<td>0.6</td>
<td>0.75</td>
<td>0.8</td>
<td>0.75</td>
<td>0.75-1.0</td>
<td>0.75-1.0</td>
<td>0.75</td>
<td>0.75</td>
<td>0.75</td>
</tr>
<tr>
<td>Typical integration time/exposure [s]</td>
<td>1800</td>
<td>1200</td>
<td>1200</td>
<td>1800</td>
<td>1800</td>
<td>1800</td>
<td>1800</td>
<td>1800</td>
<td>1800</td>
</tr>
<tr>
<td>Typical integration time/mask [ks]</td>
<td>15</td>
<td>7.2</td>
<td>9.3</td>
<td>3.6</td>
<td>14.4</td>
<td>3.6</td>
<td>14.4</td>
<td>14.4</td>
<td>3.6</td>
</tr>
<tr>
<td>Resolution (blue/red)</td>
<td>2000</td>
<td>8000</td>
<td>8000</td>
<td>2000/5000</td>
<td>5000</td>
<td>1000</td>
<td>5000</td>
<td>8000</td>
<td>1000-8000</td>
</tr>
<tr>
<td>Maximum wavelength (blue/red) [nm]</td>
<td>550</td>
<td>550/800</td>
<td>550/900</td>
<td>550/900</td>
<td>550/750</td>
<td>550/800</td>
<td>550/1000</td>
<td>550/1000</td>
<td>550/1000</td>
</tr>
</tbody>
</table>

- ECH mode needed?
  - Need very precise flux calibration?
  - Needs very precise sky subtraction?
  - Uses blue and red arms at same time?

TMT Wide-Field Optical Spectrograph (WFOS)

The resulting requirements shown in this table impact all aspects of the instrument design all the way from optical design to robotic mask exchange systems!
## Linking Science to Requirements

### Science Flowdown Matrix Parameters

<table>
<thead>
<tr>
<th>Domain</th>
<th>Parameter Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Configuration</td>
<td>Observing Mode</td>
</tr>
<tr>
<td></td>
<td>Wavelength range</td>
</tr>
<tr>
<td>Spectral Parameters</td>
<td>Spectral Resolution</td>
</tr>
<tr>
<td></td>
<td>Flux/radial velocity</td>
</tr>
<tr>
<td>Spatial Parameters</td>
<td>Image quality</td>
</tr>
<tr>
<td></td>
<td>Geometry</td>
</tr>
<tr>
<td></td>
<td>Astrometry</td>
</tr>
<tr>
<td>Multiplexing</td>
<td>Sample size</td>
</tr>
<tr>
<td></td>
<td>Number of observations</td>
</tr>
<tr>
<td>Tracking</td>
<td>Rate</td>
</tr>
<tr>
<td>Synoptic Signature</td>
<td>Baseline Cadence Duration</td>
</tr>
</tbody>
</table>

Energy, position and geometry and time ...
## TMT Science Flowdown Matrix

### Linking Science to Requirements

<table>
<thead>
<tr>
<th>Science Program</th>
<th>Resolution (mas)</th>
<th>Strehl (S) / Contrast (C) ratio</th>
<th>SRD/ORD Requirement(s)</th>
<th>Total Areal Coverage (sq. arcmin)</th>
<th>Field of view / observation (sq. arcmin)</th>
<th>Field overlap (0-1)</th>
<th>SRD/ORD Requirement(s)</th>
<th>Relative/absolute</th>
<th>Precision (mas)</th>
<th>Stability timescale (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multiplexed spectroscopy of distant galaxies: rest-frame optical DSC 5.4</td>
<td>200</td>
<td></td>
<td>SRD-0070, 0075, 0100, 0105, 0110, 0115, 0120, 0145, [0405-0420], [0455-0470], [0555-0580], 1115</td>
<td>&gt; 350</td>
<td>3.5</td>
<td>0.00</td>
<td>SRD-{0220-0230}, 0250, 0260, 0265, 0805, 0815, 1105, 1120, 1140, 1305, 1315, 1320, 1330</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spatial dissection of forming galaxies DSC 5.5</td>
<td>8</td>
<td>S = 0.5</td>
<td>SRD-0045, 0070, 0075, 0100, 0105, 0110, 0115, 0120, 0145, [0405-0420], [0455-0470], [0555-0580], [0820-0830], 0915, 1015, 1025, 1030, 1035, 1310</td>
<td>275 $^{166}$</td>
<td>25 $^{160}$</td>
<td>0.00 $^{160}$</td>
<td>SRD-{0220-0230}, 0250, 0260, 0265, 0270, 0280, 0805, 0850, 0885, 0890, 0905, 0910, 0920, 1005, 1010, 1030, 1035, 1310, 1320, 1330</td>
<td>Relative $^{160}$</td>
<td>100 $^{160}$</td>
<td></td>
</tr>
<tr>
<td>IGM: Core samples during galaxy formation epoch DSC 5.6</td>
<td>800 $^{165}$</td>
<td></td>
<td>SRD-0070, 0110, 0120, 0145, [0455-0470], [0555-0580], 1220, 1225, 1230, 1275, 1715, 1720</td>
<td>4 $\times$ 4032</td>
<td>40.3 $^{167}$</td>
<td>0.01</td>
<td>SRD-0050, 0220, 0225, 1205, 1230, 1705, 1710, 1720</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Epoch of galaxy formation in 3D DSC 5.7</td>
<td>800 $^{165}$</td>
<td></td>
<td>SRD-0070, 0110, 0120, 0145, [0455-0470], [0555-0580], 1220, 1225, 1230, 1275</td>
<td>4 $\times$ 4032</td>
<td>40.3 $^{167}$</td>
<td>0.01</td>
<td>SRD-0050, 0220, 0225, 0250, 0255, 0265, 1205, 1230</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SMBHs in nearby galactic nuclei DSC 6.1</td>
<td>10 $^{16}$</td>
<td>S = 0.5</td>
<td>SRD-0045,0070, 0075, 0100, 0105, 0110, 0115, 0120, 0145, [0405-0420], [0455-0470], [0555-0580], [0820-0830], 1015, 1025, 1030, 1035</td>
<td>&lt; 10.2 $^{167}$</td>
<td>&lt; 0.03 $^{160}$</td>
<td>0.00</td>
<td>SRD-{0220-0230}, 0250, 0260, 0265, 0805, 0850, 0885, 0890, 1005, 1010, 1030, 1035</td>
<td>Relative $^{162}$</td>
<td>2 $^{162}$</td>
<td></td>
</tr>
</tbody>
</table>

Color traces provenance of information
Mapping Science Cases in “Discovery Space”

(Credit: TMT)
Mapping Instrument Capabilities in Discovery Space

(Credit: TMT)
Planning for the “Unknown Unknowns” (!)

Source: Figure 8.6, LSST Science Book
From Science to Subsystems

Transients - GRBs/supernovae/tidal flares
Fast system response time

NFIRAOS fast switching science fold mirror

Articulated M3 for fast instrument switching

Fast slewing and acquisition
From Science to Subsystems

Doppler exoplanet detection
Fixed instrument gravity vector and thermal control for long-term stability

HROS
(W=11m, H=4m, L=10m)
From Science to Subsystems

IGM tomography
Covering large FoV in seeing-limited mode → Large instruments

WFOS (D=4m)

+X Nasmyth structure

Fast slewing and acquisition

-X Nasmyth structure
From Science to Subsystems

Direct imaging of exoplanets
High-contrast imaging

Minimizing pupil obstruction area and complexity

Planet Formation Instrument
Alignment and Phasing System

Filled aperture + segment surface errors, coating, and cleaning
From Science to Subsystems

**Galactic Center**
High Strehl w/ stable PSF over 15'' → MCAO

- LGSF asterism generator + launch telescope
- LGSF beam transfer
- NFIRAOS + IRIS
From Science to Subsystems

Spatial dissection of distant galaxies in formation
Multiplexed, MOAO-assisted, spatially-resolved spectroscopy

LGSF asterism generator + launch telescope
LGSF beam transfer

IRMOS (~160 VLT nights/night)
30m M1 to overcome photon starvation + FoV ≥ 5’

1” (8 kpc)
Some Instrument Trade-offs

- Imaging versus spectroscopy
- Seeing-limited versus adaptive optics - assisted
- Optical versus near-infrared versus mid-infrared

- “Workhorse” instruments:
  - Aimed at a broad community of users
  - Maximizes synergy with other facilities
  - On-going science observations

- “Niche” instruments:
  - Aimed at a specific science mission with a high impact
  - Unique by definition
  - Limited useful lifetime

- Proven or new technologies?
Impact of Distributed Design

- Instrument projects often require teams that are located at different sites
- Design should therefore be modular
- Interfaces should be very well-defined ("clean") and very well-controlled (under "Change Control")
Multiplexing versus Wavelength Range

• Science detectors are expensive. Must make optimal use of a limited number of pixels (“detector real estate”)

Multi-Object Spectroscopy (MOS)
• Can now achieve several hundreds of spectra in a single exposure through the use of band-limiting filters

Echelle spectroscopy:
• Full wavelength coverage in a single exposure
• Single object
Seeing-limited Instruments

- Resolution of a seeing-limited spectrometer depends on the ratio of the collimated beam diameter incident on the grating to the telescope diameter $D_{\text{grating}}/D_{\text{tel}}$

- To preserve a fixed resolution, larger telescope diameter $\rightarrow$ larger collimated beam $\rightarrow$ larger instrument

- ELT-class instruments can become as big as small buildings

TMT Wide-Field Optical Spectrograph (WFOS)
Diameter = 4m

Some versions were 8m in diameter – same size as the Gemini telescopes(!)
Slit Width versus Resolution

• Resolution of a seeing-limited spectrometer scales linearly with slit width:

• Narrower slits yield higher spectral resolutions but lead to higher light losses

• Solution: Slice it!

Example - Durham Advanced Image Slicer Concept:

1. Optimum use of detector pixels

2. Correct spectral sampling with loss of spatial resolution in dispersion direction

3. Diffraction is only a 1D issue
Optical Elements

• Minimize number of elements to maximize throughput and simplify alignment

• Pay attention to the manufacturability of your elements:
  • Challenging polishing – Avoid if possible!
  • Fragile coating – Avoid if possible!
  • Maximum size (e.g., largest lenses are ~1m in diameter)
  • Homogeneity (e.g., CaF2 polycrystals) – can impact image quality

• Pay attention to the availability of material:
  • Do not assume that a type of material will always be available
  • Avoid “sole source” design options

• Pay attention to mounting and handling
Stability under Gravity

• Mechanical flexure is the enemy!

• How is the orientation of the instrument changing with respect to the gravity vector?

ESO VLT - Nasmyth focus:

• Less stringent constraints
• Horizontal instruments (but could be vertical w/ one more mirror)
• Instrument must follow field rotation

Gemini Telescope - Cassegrain focus:

• Strong constraints on space envelope, mass and center-of-gravity
• Compact and stiff instruments
Thermal Stability

Example: Gemini High-resolution SpecTrograph (GHOST; AAO/NRC/ANU/Gemini)

Fiber-fed, high-resolution spectrograph for the Gemini South telescope

One science goal is precise radial velocity measurements (~1 m/s)

Measurements require a very thermally stable instrument – 10 mK

Entire instrument enclosed in an active thermal enclosure, i.e., a totally isothermal box

Each enclosure panel senses local temperature and actively cools/warms as needed
Cryogenic Instruments

- Science may drive you to the near-infrared or mid-infrared
  - Emissivity of instrument itself can swamp faint astrophysical signals – transition is between H-band (1.8 μm) and K-band (2.2 μm)
  - Instrument must be cryogenically cooled down to 20-120K typically

- Increased complexity and cost
  - Off-the-shelf and custom-designed components must work at low temperatures
  - Various parts of the instrument will change size and shape with lower temperatures
    - Must be modelled very carefully

- Multiple cool-downs will be required during integration and testing
  - Typically takes many days to cool-down and many days to warm up

- Cryo-coolers are an unwanted source of vibrations – bad for AO!
On the Importance of Adaptive Optics

Seeing-limited observations and observations of resolved sources:

\[ \text{Sensitivity} \propto \eta D^2 \quad (\sim 14 \times 8 \text{m}) \]

Background-limited AO observations of unresolved sources:

\[ \text{Sensitivity} \propto \eta S^2 D^4 \quad (\sim 200 \times 8 \text{m}) \]

High-contrast AO observations of unresolved sources:

\[ \text{Sensitivity} \propto \eta \frac{S^2}{1 - S} D^4 \quad (\sim 200 \times 8 \text{m}) \]

where sensitivity \(\equiv 1 / \text{time required to reach a given S/N ratio,} \)
\(\eta \equiv \text{throughput,} \quad S \equiv \text{Strehl ratio and} \quad D \equiv \text{aperture diameter} \)
Adaptive Optics and Vibrations

- Vibrations are the enemy of adaptive optics instruments
  - Major source of vibrations are cryocoolers
  - Pretty much every AO instrument has suffered from this!

- Case Study: Gemini Planet Imager
  - Phase map w/ Cryo on
  - Phase map w/ Cryo off

Hard to understand given that vibrations from cryocooler was measured in the lab and found to have a “clean” signature at 60 Hz as expected

After a lot of hard investigative work, it was found that the instrument cryocooler was exciting vibrational modes in the telescope primary mirror itself!
Access and Maintenance

Need to consider:
- Doors
- Lifts, walkways, rails (!), stairs
- Cranes

TMT Narrow-Field InfraRed AO System (NFIRAOS; Canada)

Enclosure (blue) is 11 m long
Cost and Schedule (perhaps not the most exciting part but essential!)

- **Cost**
  - You must be able to afford to build your design - De-scopes are very painful ...
  - Need to include labor, materials, travel and contingency
  - Bases of estimates: Off-the-shelf catalog items, vendor quotes, historical data, “Parametric scaling” and “engineering estimates”
  - Ideally a detailed “bottom up” estimate with a “top down” sanity check

- **Schedule**
  - List of tasks, people assigned to each task, time estimate for each task
  - Linking all the tasks with a logic that captures the workflow is key
  - Changes are unavoidable but must be tracked to make the right decisions
  - Do not underestimate time for team interactions and document preparation!
Some Final Thoughts

• Excellent instruments are born out of excellent science

• Pay attention to science, technical complexity and readiness, cost and schedule

• Team structure will have an impact on the design itself

• Instrumentation is hard. Very hard. (Did I say it was hard?)

• It often requires a vision that is not always immediately shared by future users.

• It is driven by a powerful mixture of creativity, passion, knowledge, tenacity, patience, tears, sweat and exhilaration

  • Stick with it!!

• First and foremost, HAVE FUN!
Discussion

• So, what do YOU think the keys to success are?
  • Telescope aperture?
  • Instruments?
  • Proven versus new technologies?
  • Timing?
  • Others?

• How would YOU approach instrument design?