Infrared Camera Design Issues

- Considerations for camera design
  - field of view, wavelengths, pixel size
  - operating temperature
  - instrument volume
  - system throughput

- Example cameras
  - Murphy et al., 1995, PASP, 107, 1234

S-FTM16 / CaF2  Achromat
Camera Design Considerations - Wavelength

- Wavelength choice is certainly science driven, but constrained by the practicalities of
  - detector response
  - available detector format
  - field of view
  - cryogenics
  - optical materials
  - ambient backgrounds
  - atmospheric transmission
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  - atmospheric transmission
The infrared opacity of the atmosphere is dominated by molecular absorption -- particularly water and CO2.

Water is abundant only in the Earth's troposphere while CO2 is well mixed to higher altitudes.

Atmospheric Transmission Data

Fig. 2.1. Transmittance of 1000 feet horizontal air path at sea level containing...
Infrared Atmospheric Transmission

- Since water vapor is confined to the troposphere, infrared transmission through the atmosphere improves with altitude (at some wavelengths).

- Transparency can be so wavelength specific that for narrowband observations the Doppler shift due to the Earth's orbital motion can be used to observe an otherwise obscured spectral line.
Infrared Atmospheric Transmission

- Classical infrared passbands have been defined by atmospheric transparency "windows"
- The magnitude system was extended to these bands by assuming that Vega is "zeroth" magnitude at all bands.

<table>
<thead>
<tr>
<th>Band</th>
<th>Wavelength</th>
<th>Bandpass</th>
<th>Jy at Mag 0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y</td>
<td>1.04</td>
<td>0.2</td>
<td>?</td>
</tr>
<tr>
<td>J</td>
<td>1.25</td>
<td>0.3</td>
<td>1600</td>
</tr>
<tr>
<td>H</td>
<td>1.65</td>
<td>0.3</td>
<td>1000</td>
</tr>
<tr>
<td>K</td>
<td>2.16</td>
<td>0.4</td>
<td>630</td>
</tr>
<tr>
<td>L'</td>
<td>3.8</td>
<td>0.6</td>
<td>290</td>
</tr>
<tr>
<td>L</td>
<td>3.5</td>
<td>1.2</td>
<td>250</td>
</tr>
<tr>
<td>M</td>
<td>4.8</td>
<td>1</td>
<td>160</td>
</tr>
<tr>
<td>N</td>
<td>10</td>
<td>5</td>
<td>41</td>
</tr>
<tr>
<td>Q</td>
<td>20</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

Definition of Y-band (Hillenbrand et al. 2002)
Infrared Atmospheric Transmission

- Classical infrared passbands have been defined by atmospheric transparency "windows".
- The magnitude system was extended to these bands by assuming that Vega is "zeroth" magnitude at all bands.
Field-of-View is certainly also science driven, but, once again practicalities limit the implementations.

Most imagers aim to provide the largest field of view possible. Limiting factors include:

- array format (cost / existence)
- modulated by adequately sampling the seeing
- optics size (cost)
- bigger fields require bigger optics and more aberration control
- vignetting by telescope
- cassegrain telescopes, for example have a field limited by their secondary size and the size of the hole in the primary.
Optimal Image Sampling

- Astronomers frequently point to the Nyquist condition as a pre-requisite for optimal sampling of an image.
- In time series or spatial sampling, the Nyquist condition states that the sampling rate should be twice the maximum frequency of interest in order to avoid aliasing (seeing a frequency masquerade as another frequency).

http://www.ecs.soton.ac.uk/~km/imaging/course/resolutionandsampling.html
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Optimal Image Sampling

- Images should be optimally sampled at $\frac{1}{2}$ the spatial scale which retains meaningful information.
- Astronomers frequently, and incorrectly, cite the Nyquist sampling criteria as $\frac{1}{2}$ the image Gaussian FWHM.
- In reality, significant information exists at higher spatial frequencies.
- The Fourier transform of a Gaussian is another Gaussian -- a star image has spatial information out to high spatial frequency (but of vanishingly small amplitude).
- Sampling the FWHM with three pixels is a reasonable compromise.

http://www.starizona.com/ccd/advtheorynyq.htm
Image Quality – Diffraction and Seeing

- Diffraction restricts the optimum image quality delivered by the telescope to an Airy disk with FWHM of 1.22(\lambda/d).
- For a 10 meter telescope operating at 2.2\,\mu\text{m} the Airy disk FWHM is 0.055 arcseconds.
- For large telescopes operating at short wavelengths, seeing usually thwarts diffraction limited imaging.

http://www.gemini.edu/sciops/instruments/uhaos/uhaosIndex.html

http://www.chipchapin.com/CDMedia/cdda3.php3
Today's laser guide star technology combined with the emerging technology of “multi-conjugate” adaptive optics promises to provide diffraction limited focal planes of large angular scale. Suppose Keck could deliver diffraction-limited images at 2μm over a 10'x10' field of view.

- an appropriate pixel scale would be 20 mas/pixel – 50 pixels/arcsecond.
- 30,000 x 30,000 pixels could adequately sample the focal plane.
- 200 2048x2048 detector arrays would do the job (at a present day cost of about $100 million dollars).
Seeing

- Seeing arises because of refractive index variations in air due to turbulence.

- Since this turbulence is sub-sonic there can be no significant pressure gradients – the refractive variations are thermally generated.
  
  - rapid response differential temperature sensing can predict seeing

- The turbulence can be characterized by a single spatial scale, \( r_0 \), the “Fried parameter”
  
  - \( r_0 \) is the typical scale over which phase variations are 1 radian
  
  - the “seeing disk” scale is set by diffraction through an aperture \( r_0 \) in size.
The number of “speckles” in an image is proportional to the number of Fried cells within a telescope aperture.

- If r0 is comparable to the telescope aperture size, the image is near diffraction limited – one speckle.

The coherence time is the time it takes a blob of atmosphere to cross the Freid length (and thus related to the wind speed).

r0 is 10cm for 1” seeing at 0.5um

- r0 scales as \( \lambda^{1.2} \), thus seeing varies as \( \frac{\lambda}{r_0} = \lambda^{-0.2} \)

- seeing improves toward longer wavelength
- at the same time diffraction increasingly degrades images
  - telescopes become diffraction limited at mid-infrared wavelengths
  - “tip-tilt” image motion correction becomes an effective form of adaptive optics.
Seeing Variation

- Seeing is time variable and optimal camera parameters derive from long-term seeing statistics.
Differential Image Motion Monitors -- DIMMs

- Detect relative image motion at two positions in an aperture.
- Convert to seeing \( r_0 \) based on dispersion.

http://www.astro.virginia.edu/~cp8h/dimm/
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S-FTM16 / CaF2 Achromat
Las Campanas IR Camera (1992)

- Refractive near-infrared camera for 128x128 NICMOS2 array.
- Three available platescales
  - Scale change achieved through interchangeable camera modules.
  - Camera and collimator based on Petzval design
Las Campanas IR Camera (1992)

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Las Campanas IR Camera (1992)

- The Petzval collimator consists of four lenses while the cameras contain four, and in one case five.
- Sixteen/eighteen optical surfaces require first class anti-reflection coatings.
Las Campanas IR Camera (1992)

- Achromatic design requires good material choices based on partial dispersion and Abbe number.
- BaF2 / SiO2 used here
Las Campanas IR Camera (1992)
Fan Mountain Infrared Camera

- Achromatic doublet collimator
- Near-Petzval camera
- BaF2 / SiO2 (Infrasil) design
Palomar 60” Near-infrared Camera (1995)

- Offner re-imaging optics for a 256x256 NICMOS3 array.
- 1.0-2.5 µm wavelength coverage.
Offner Optical Design

- All reflective - achromatic
- All spherical – inexpensive
- Aberration free! Even avoids spherical aberration due to symmetry around the pupil stop.
- M1 is concave. M2 is convex with a focal length equal to the vertex separation between M1 and M2
  - The system pupil stop is thus located near M2.
  - Note that the image of the telescope primary IS aberrated.
- M1 and M2 are concentric about a point in the focal plane, C.
The actual implementation is a variant on the Offner design
- M1 is broken into two independent mirrors (sections of the original monolithic M1)
- Having two separate elements provides more degrees of freedom permitting optimization of the pupil image.
- A cold focal plane stop protects against stray light reflecting from M1 directly to the array.

Although locating the pupil stop at M2 is practical, it is not feasible to mount the filters at this “standard” location.
- Instead the filters lie at a non-ideal location close to the focal plane
- Different stars see different parts of the filter.
### Table 1

<table>
<thead>
<tr>
<th>Surface</th>
<th>Radius (mm)</th>
<th>Displacement (mm)</th>
<th>Thickness (mm)</th>
<th>Glass</th>
<th>Index (^d)</th>
<th>Dia. (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tel. Primary (^f)</td>
<td>-7619.977</td>
<td></td>
<td>2827.918</td>
<td>mirror</td>
<td></td>
<td>1524.0</td>
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<tr>
<td>Tel. Secondary (^g)</td>
<td>2750.003</td>
<td></td>
<td>3407.316</td>
<td>mirror</td>
<td></td>
<td>454.6</td>
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<td>Dewar Win. W</td>
<td>-</td>
<td></td>
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<td>Sapphire</td>
<td>1.74446</td>
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<td>Air Space</td>
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<td>28.565</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Focal Plane (F_1) and Stop</td>
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<td></td>
<td>157.209</td>
<td></td>
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<td>Flat (M_0) (^h)</td>
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<td>56.70</td>
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<tr>
<td>Mirror (M_1) (^i)</td>
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<td>174.601</td>
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<td>71.40</td>
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<td>Mirror (M_2)</td>
<td>171.86</td>
<td>45.000</td>
<td>168.810</td>
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<td>23.90</td>
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<td>Mirror (M'_1) (^i)</td>
<td>-344.491</td>
<td>90.000</td>
<td>312.414</td>
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<td>65.80</td>
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<td>Filter FLTR ((K_3))</td>
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<td>90.000</td>
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<td>Silicon</td>
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<td>Air space</td>
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<td>Focal plane (F_2)</td>
<td>-</td>
<td></td>
<td>91.680</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^a\)Negative radius indicates concave surface.
\(^b\)Displacement of the surface vertex off-axis.
\(^c\)Denotes distance to subsequent surface.
\(^d\)Index of refraction at \(H\) (1.65 \(\mu m\)).
\(^e\)Full aperture.
\(^f\)Asphere with conic constant \(-1\) and sag\(=\(-6.5617 \times 10^{-5}\) y^2\+(1.835 \times 10^{-14}) y^4\) mm.
\(^g\)Asphere with conic constant \(-1\) and sag\(=\(-1.818 \times 10^{-4}\) y^2\+(1.743 \times 10^{-11}) y^4\) mm.
\(^h\)'Folds beam 90°.'
\(^i\)Surfaces \(M_1\) and \(M'_1\) are tilted 7.387° about their vertices towards \(S_5\) (toed-in).
Las Campanas Infrared Survey Camera (2002)

- Reflective Offner design for Quad 1024x1024 HAWAII-1 arrays
- 1.0-2.5μm; Wide field – 0.2”/pixel  560”x560” field of view
- Refractive corrector needed to mitigate aberrations from the telescope.
Las Campanas Infrared Survey Camera (2002)

- All-invar space frame support structure produces a modular optical assembly.
Las Campanas Infrared Survey Camera (2002)

- Pupil mask blocks thermal radiation at M2.
- Position actuator shifts mask in real time