FGS/TFI instruments

- Two redundant guider fields
- Tunable Filter Imager (TFI) instrument
- Mounted on opposite sides of single optical bench
- Separate operations and pickoff mirrors
- Provided by CSA as JWST partner hardware contribution
- Principal contractor ComDev Ltd, Ottawa
- John Hutchings (NRC Canada) Guider PI
- Rene Doyon (U de Montreal) TFI PI
JWST instrument layout on the sky

Two guider fields of view

Coronagraph spots

MIRI

Two fields of view

NIRSPEC

Elixir June 2010
The FGS Science team

- R. Doyon (U. Montréal)
- J. Hutchings (HIA)
- R. Abraham (U of Toronto)
- L. Ferrarese (HIA)
- R. Jayawardhana (U of Toronto)
- D. Johnstone (HIA)
- D. Lafrenière (U. Montréal)
- M. Meyer (ETH, Zurich)
- J. Pipher (U. Rochester)
- M. Sawicki (St-Mary’s University)
- A. Sivaramakrishnan (AMNH → STScI)
Guider

Top level requirements

- 2 Fully redundant fields of view
- Guide star position updated at 16 Hz
- Guide star centroid (NEA) 3.5mas or better
- 95% probability of GS, any place in the sky
Guider performance drivers

NEA depends on

- Guide star brightness and SED
- Optical throughput and pixel scale
- Image quality/focus
- Detector QE and read noise

*Dark current not an issue – rapid reads*

*All these combine to require ~5 arcmin field of view to have 95% chance of useable GS present*

*No filter – all photons from 0.8 to 5 microns used*
Other guider tasks

• Guiding with detector latency, dead pixels
• Target identification by pattern/brightness matching
  *Crowded and sparse fields, extra stars, double stars, compact galaxies*
• Tracking on moving targets
  *9mas NEA moving up to 30mas/sec*
• Guide on images during primary mirror focus, alignment, phasing
  *Range of image quality, flux, and focus*
• Focus sweep images for wavefront sensing
  *Modelling images, tracking to interpret the results*
• Full field imaging (science!) in non-guiding FOV
  *JWST’s deepest images*
• Calibrated boresight movement with guider/OTE focus
• Stable, known position wrt other instruments to 5mas
Fully integrated ETU
Guider signal depends on the detector selected.

Guide star signal mostly at short wavelengths

Estimates for the presently-considered PFM and flight detectors F022 good choice for guider.
Conversion from visible to J band magnitudes
Colour distribution and number counts of guide stars at the Galactic pole

Distribution of available guide stars at Galactic pole
Available guide stars and catalogues

SDSS stars to FGS limit per single FGS field at galactic pole: 6.3
   to $J_{AB} = 18.0$ 3.9
10 degrees off this direction, to FGS limit 7.1

GSC2 useable stars are estimated to be 2.6 per single FGS field.
Total stars to GSC2 limit are about 10 per single FGS field at pole

FGS can guide on double stars and compact extended objects
Above SDSS numbers will likely include some of those

Need for J-band catalogue of stars near galactic poles
But need good spatial resolution: HST or ground-AO
Guide star limiting counts and magnitudes

NEA with GS signal

1000 counts is $J_{AB} \approx 19.4$

Read noise estimates crucial

Number of GSC2 stars per FOV

Nominal FOV is 10% larger
3 stars per field is ~95% prob

SDSS point sources $J$ mag

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Guider: NEA vs signal from lab data

Heavy line is model for similar centroid window and noise, flight centroid algorithm
Guiding on double stars

Sep ~100mas
Flux ratio 4

Limiting magnitude 0.7 brighter for this case

Detector pixels
NEA variation with OTE focus and WFE

Top – models

Lower – measures from ETU
Intra-pixel sensitivity systematically offsets centroids

Model of pixel sensitivity for NEA calculation

Map of intra-pixel variations
JWST detector intra-pixel sensitivity

*HIA lab results at 2.2microns*

Response corrected for charge spread

Raw response within pixels
Guider: CNL measured from lab data
Systematic centroid offsets from pixel-sampled data

X-direction cuts through different places within detector pixel
This will be corrected for in reporting guider centroids

Signal 900e, 1.5 microns
Signal 5000e, 3.2 microns

Verification of modelled performance, plus pixel-to-pixel non-uniformities, ongoing
Centroid offsets moving across pixels

Min signal vs centroid error with window size

Centroid max systematic error (pixels)

Min signal for 3.5 mas NEA

4x4

K star

M star

8x8
Angular rates of Solar System objects seen by JWST

<table>
<thead>
<tr>
<th>Object</th>
<th>Min. Rate (mas/sec)</th>
<th>Max Rate (mas/sec)</th>
<th>Distance Traveled in 10 hrs at Min Rate (asec)</th>
<th>Time to Travel 1° at Max Rate (hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mars</td>
<td>2.5</td>
<td>28.6</td>
<td>90.0</td>
<td>0.6</td>
</tr>
<tr>
<td>Jupiter</td>
<td>0.070</td>
<td>4.5</td>
<td>2.5</td>
<td>3.7</td>
</tr>
<tr>
<td>Jupiter, Io</td>
<td>0.004</td>
<td>10.2</td>
<td>0.14</td>
<td>1.6</td>
</tr>
<tr>
<td>Saturn</td>
<td>0.040</td>
<td>2.9</td>
<td>1.4</td>
<td>5.7</td>
</tr>
<tr>
<td>Uranus</td>
<td>0.020</td>
<td>1.4</td>
<td>0.7</td>
<td>17</td>
</tr>
<tr>
<td>Neptune</td>
<td>0.004</td>
<td>1.0</td>
<td>0.14</td>
<td>24</td>
</tr>
<tr>
<td>Pluto *</td>
<td>0.160</td>
<td>1.0</td>
<td>5.7</td>
<td>24</td>
</tr>
<tr>
<td>KBO</td>
<td>0.002</td>
<td>0.5</td>
<td>0.07</td>
<td>48</td>
</tr>
</tbody>
</table>

*Adopted: linear tracking over FGS FOV at max 30mas/sec*
Galactic coordinates of all known KBOs

Compared with galactic poles:
At $b=60$ star counts up by $x1.6$
At $b=50$ star counts up by $x2.1$

From $J=19.4$ to $18.0$ star counts down by $x1.6$

For almost all KBOs we have $>95\%$ probability of GS giving 6mas in 32x32 guide box.

Extending the observing window by $\sim$hours (FGS field crossing time) will double the GS numbers again.
ETU on DFL Vib table Oct 21
ID and acq issues

- Full field is read in strips to create ID map
- Spacecraft is drifting, so strips should overlap to avoid losing stars
- CRs are several times the GS faint limit signal
- Double-reads needed to eliminate CRs
- Pixel-to-pixel variations larger than star signals
- Require CDS reads, and avoidance of first-frame settling
- All this easily breaks original timing budget of 45 secs – up to 83 secs
- Can reduce number of strips (i.e. FOV) and overlap to save time
- Tradeoff between time and success rate

- There are several non-GSC stars and compact galaxies per FOV
- Can guide on close doubles and compact galaxies, unlike HST
- All above affect the ID success rate and/or observing efficiency
- Plan Monte-Carlo runs for ID success stats by FGS team at STScI
Wavefront Sensing and Control (WFSC)

- WFSC must capture and correct the initial post launch state of the OTE,
- It must sense the WFE of the Secondary and PMSA to 10 nm of WFE each
- It must unambiguously correct the Low Spatial Frequency WFEs of the OTE to within 19 nm over the FOV of the OTE
Steps in primary phasing

Guiding performance modelled for all cases.

Little difference between G0 and M5 guide star types.

Require isolated star of mag \(\sim 14.5\)
TFI design

- All reflective optics, except etalon & blocking filters
  - 79 nm rms wave front error
- Dual wheel for blocking filters and masks
Optical Subsystem – TFI Layout

- Light from JWST Telescope
- TFI Pickoff Mirror
  - Focus Mechanism
  - Coronagraphic Masks
- Camera
  - TMA
- Etalon Volume
- Dual Wheel Volume
- Kinematic Mounts
- Collimator TMA
- TFI Optical Assembly
TFI at a glance

• FOV: 2.2’x2.2’
  – 65 mas pixel sampling (Nyquist at 4.0 μm)
  – 2048x2048 pixels (Hawaii 2RG)
• Wavelength range: 1.6-2.6 and 3.2-4.9 μm
  – (actually 1.5-2.7 μm and 3.1-5.0 μm)
• Resolving power of ~100 (80-120)
• Sensitivity, 10σ 10x1000 s

• Operating modes
  – Normal imaging
  – Lyot coronagraphy
    • 4 occulting spots, 3 lyot masks
  – Non-Redundant Masking interferometry (NRM)

<table>
<thead>
<tr>
<th>Wavelength (μm)</th>
<th>Sensitivity (nJy)</th>
<th>Sensitivity (mag)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>149</td>
<td>24.8</td>
</tr>
<tr>
<td>2.0</td>
<td>139</td>
<td>24.3</td>
</tr>
<tr>
<td>2.5</td>
<td>119</td>
<td>24.1</td>
</tr>
<tr>
<td>3.5</td>
<td>110</td>
<td>23.5</td>
</tr>
<tr>
<td>4.0</td>
<td>136</td>
<td>23.1</td>
</tr>
<tr>
<td>4.5</td>
<td>142</td>
<td>22.8</td>
</tr>
</tbody>
</table>
Spectral Resolution

![Graph showing spectral resolution over wavelength (nm)]
Filter is defined \((\lambda_c, \Delta \lambda)\) so that …

- Transmission is maximized over the working interval
- Contamination from other orders is minimized
Spectral/spatial uniformity

~0.1% wavelength shift at edge of field

~4% drop in flux at edge of field for perfectly monochromatic source
Coronagraphy (Lyot coronagraph)

- 4 occulting spots engraved on pick-off mirror
  - Diameters of 0.58", 0.75", 1.5" and 2.0"
- 3 lyot masks
  - Transmissions of 71%, 66% and 21%
  - Robust against pupil shear of up to 4%

C71
- 0.58" and 0.75"
- <1"

C66
- 1.5"
- 1"-2"

C21
- 1.5" and 2.0"
- >2"

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Coronagraphy contrast limits
(3% pupil shear)

These contrasts can be improved further with PSF subtraction

<table>
<thead>
<tr>
<th>Sep (&quot;)</th>
<th>Contrast (mag)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>6.9</td>
</tr>
<tr>
<td>1.0</td>
<td>7.9</td>
</tr>
<tr>
<td>1.5</td>
<td>9.2</td>
</tr>
<tr>
<td>2.0</td>
<td>10.0</td>
</tr>
<tr>
<td>2.5</td>
<td>10.9</td>
</tr>
<tr>
<td>5.0</td>
<td>12.3</td>
</tr>
</tbody>
</table>

- Small separations: C71N + 0.58", 0.75"
- Medium separations: C66N + 1.5"
- Large separations: C21N + 1.5" (orange), 2" (blue)
Differential imaging with TFI

- Reference star PSF subtraction
  - Narrow-band relieves requirement of similar spectral shape within band (speckles are chromatic)
  - May perform better than for other instruments
- SDI (Spectral Differential Imaging)
  - Unique to TFI
  - Can be used in addition to reference star PSF subtraction
  - Simpler than roll subtraction (which other instruments may require)
  - There are several spectral features suitable for SDI in exoplanet spectra
Case for 4-5 \( \mu m \) \( \lambda \) coverage: Exoplanet SEDs

- Identification and statistics of extrasolar planets: direct observation
- Scan through wavelengths of maximum planet/star contrast
- The combination of coronagraphy and TFI wavelength scanning is ten times more sensitive than other JWST fixed filter observations.

TFI planet detection simulation:
Monochromatic PSF movie: 4 to 5 \( \mu m \)

Planets are bright at 4-5 \( \mu m \)
Etalon: design, lab and flight models

U de Montreal lab model

Flight design test

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Find Charlie! (fake companion added)

U de Montreal lab results

Subtraction from two adjacent wavelengths

Companion 10000 fainter
Summary: TFI can achieve excellent contrast

- Contrast of \( \sim 10^{-5} \) possible at >1"

Simulation: M. Beaulieu

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HR 8799 seen with TFI

- Example shown with SDI
  - $3\lambda$
- Could use reference star PSF subtraction instead

Without coronagraph

With coronagraph

With SDI

Simulation: M. Beaulieu
Non-Redundant Masking interferometry

- **Better resolution** Two sources can be resolved for a separation of 0.5 $\lambda/D$
- **Better contrast at small separations** Wave front phase errors have little effect on closure phase

\[
\phi(2-1) = \phi_0(2-1) + \psi_2 - \psi_1 + \epsilon_{12} \\
\phi(1-3) = \phi_0(1-3) + \psi_1 - \psi_3 + \epsilon_{13} \\
\phi(3-2) = \phi_0(3-2) + \psi_3 - \psi_2 + \epsilon_{32}
\]

Measured = true + phase error + meas. error

Sum these (closure phase) and phase errors cancel out
TFI Non-Redundant Mask

- 7 apertures
  - 5.28 m longest baseline
  - 1.32 m shortest baseline
- Throughput
  - 15%
- Resolution ($\lambda/2B_L$)
  - $\approx 75$ mas at 4.6 µm
- Nominal FOV ($\lambda/2B_S$)
  - $\approx 0.4$” at 4.6 µm
- Contrast sensitivity
  - $\approx 10$ mag
TFI/NRM defines unique capability

NIRCam & MIRI contrast from Beichman et al. 2010

TFI curve assumes only a modest PSF subtraction performance
TFI/NRM will be a powerful tool for finding young planets within 30 AU

Beichman et al. (submitted)
A note on solar system planets

• TFI could be the only instrument on JWST for (spectral) imaging without saturation – rapid subwindow read and narrow bandpass
High-Redshift Science with TFI

- TFI wins by detecting line emission in faint objects.
- Lyman Alpha Emission can be up to 20x as bright than the continuum for a Lyman Alpha Emitting (LAE) galaxy.
- \(\lambda\alpha\) is redshifted into the TFI \(\lambda\) range for \(z\sim 10-30\), covering the era from the dark ages to first light where the universe becomes reionized.

- Its relatively small bandpass yields higher S/N than NIRCam broadband filters, reaching fainter flux sensitivity for line emission.
Efficient detection of first-light Lyman alpha emitters

TFI unique science example

NIRCam bandpass

TFI bandpass
High-Redshift Science with TFI

- Predictions of Lyman Alpha emitting galaxies at \(z=12, 15, 30\) are highly speculative
- Can make a guess by using the parameters (IMF, metallicity, photon escape fraction) defined by population of LAEs at \(z=6.5\) Kashikawa et al (2006)
- However, **THIS IS EXPLORATORY SCIENCE**, TFI is the best and if the sources of *First Light* are very faint, it may be the only option

- A single 2.7 hour pointing is sufficient to detect an LAE in the more optimistic, but plausible scenarios. Multiple pointings probe more volume and lead to higher possible detections.

- Can ‘tune’ TFI to redshifts of suspected galaxy overdensities soon to be predicted from high-z 21 cm mapping of neutral hydrogen, increasing chances even more.
TFI can map the ionisation bubble evolution

MAPPING NEUTRAL HYDROGEN DURING REIONIZATION WITH THE Lyα EMISSION FROM QUASAR IONIZATION FRONTS

SEBASTIANO CANTALUPO, CRISTIANO PORCIANI, AND SIMON J. LILLY

Ly alpha emission from bubble boundaries

Scanning through wavelengths (redshift) maps bubble sizes and density through reionisation Epoch

Sizes should match TFI field at z>10
Example Object

- A dusty quasar in the field of cluster Abell 478
- Discovered by its large sub-mm emission
- Redshift ~2.8 from Keck spectroscopy
- Gravitational lens effects are small (~1.3x)
- Scaling this object to other redshifts gives:

<table>
<thead>
<tr>
<th>Redshift</th>
<th>CIV Emission Line</th>
<th>FGS-TF Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>wavelength</td>
<td>Flux (W / m²)</td>
</tr>
<tr>
<td>2.8</td>
<td>0.6 µm</td>
<td>4.6 x 10^-18</td>
</tr>
<tr>
<td>7.0</td>
<td>1.24 µm</td>
<td>2.3 x 10^-20</td>
</tr>
<tr>
<td>15.0</td>
<td>2.48 µm</td>
<td>1.5 x 10^-20</td>
</tr>
<tr>
<td>20.0</td>
<td>3.26 µm</td>
<td>4.9 x 10^-21</td>
</tr>
</tbody>
</table>
Thank you

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