Operations Concept for Moving Target Observations with JWST

George Sonneborn
JWST Project Scientist for Operations
NASA/Goddard Space Flight Center

March 17, 2013

JWST Workshop
44th Lunar and Planetary Science Conference
The Woodlands, Texas

Topics

- Pointing control for moving target observations
- JWST focal plane and aperture geometry
- Event-driven science operations and observation scheduling
Moving Target Ops Concept in JWST Focal Plane

Guide Star Moving Target ephemeris

Guide Star moves along prescribed ephemeris path

Target remains fixed in SI FOV

Science Target Trajectory without Moving Target compensation
Recent Progress on Spacecraft Moving Target Capability

- **Mission requirements for moving target capability**
  - Capability to observe moving targets with apparent rates up to 0.030 arcsec/second
    - Includes Mars and beyond, but not all possible comets or near-Earth objects
    - Recent pointing stability simulations: <0.010 arcsec (1σ) for all rates

- **Non-linear ephemeris uplinked, stored by observation scripts, and executed by Attitude Control Subsystem**
  - Ephemeris defined by 5th order Chebychev polynomial derived from JPL HORIZONS

- **Commands/telemetry exchanged between observing scripts and spacecraft attitude control for autonomous execution of moving target observations.**

- **Critical Design Review for moving target capability will be in August 2013**
  - Will include simulations of moving target pointing performance using non-linear stability analysis with JWST observatory dynamics model

- **Moving target observations will be supported in first year of JWST observing**
  - Cycle 1 Call for Proposals in 2017
Moving Target Observation Sequence

- Moving target observation process (Same as Fixed Targets)/ (New for Moving Targets)
  - Step 1: Slew to ID Attitude; FGS ID/ACQ; Attitude Update
  - Step 2: Specify MT ephemeris
  - Step 3: Move guide star to Science Attitude for guide star tracking; Compute time when science exposure can start (guide star will be in position along ephemeris trajectory
  - Step 4: FGS guide star acquisition; Attitude Update; Zero Offset Maneuver
  - Step 5: FGS Track mode on guide star; Enable fine guidance control in ACS
  - Step 6: Enable MT Tracking of guide star; Start science exposure
  - Step 7: Stop science exposure; Disable fine guidance control; Update Attitude Command
  - For offset/dither slews, Go To Step 3
Schematic for Moving Target Observation

- MT offset command repositions Guide Star and initiates moving guide star tracking
- MT ephemeris defines guide star position such that science target is in SI aperture
- ACS iterates offset slew calculation and computes guide star position $P_3$ at time $T_3$
- ACS sends $T_3$ and $P_3$ to Scripts; Scripts sets up FGS for Track Mode
- ACS executes offset slew from $P_2$ to $P_3$ prior to $T_3$
- ACS waits until $T_3$ and then starts MT tracking of guide star
- Scripts starts science exposure

$T_s = \text{Start of Ephemeris}$

$T_e = \text{End of Ephemeris}$

1. Acquired GS position
2. Executed offset slew from P2 to P3
3. GS position $P_3$ at time $T_3$
4. 32x32 track box follows guide star
5. Science exposure starts
6. Science exposure ends

NOT DRAWN TO SCALE
- L2 halo orbit; no Earth or Lunar eclipses
  - Solar array power
- Thermal
  - Telescope and instruments passively cooled to T~40K in shadow of sun shield
    - Mid-IR instrument cooled to 6.7K by cryo cooler
- Communications
  - Two 4-hour DSN contacts per day for command uplink, real-time telemetry, and data downlink
- Attitude control – two control loops
  - Reaction wheel/gyro/star tracker observatory attitude control system
  - Fine guidance with focal-plane camera/tracker and focal-plane fine-steering mirror
  - Hydrazine/oxidizer propulsion system to maintain orbit and reaction wheel momentum
- On-board science operations are event driven, not absolute time commanded (more later)
  - Observation – Series of exposures with single instrument to achieve science objective
  - Visit – Exposure(s) obtained with one science instrument and a single guide star
    - An observation may be split into more than one visit (Visit is basic unit of scheduling)
## Spectroscopic Apertures and Slits

<table>
<thead>
<tr>
<th>Channel</th>
<th>Wavelength (µm)</th>
<th>Spatial Slice (arc sec)</th>
<th>Field of View (arc sec)</th>
<th>Number of Slices or Apertures</th>
</tr>
</thead>
<tbody>
<tr>
<td>NIRSpec IFU</td>
<td>0.6 – 5</td>
<td>0.1</td>
<td>3.0x3.0</td>
<td>30</td>
</tr>
<tr>
<td>NIRSpec Fixed Slits</td>
<td>0.6 – 5</td>
<td>0.2, 0.4, 1.6</td>
<td>0.2 x 3.3, 0.4 x 3.8, 1.6 x 1.6</td>
<td>3, 1, 1</td>
</tr>
<tr>
<td>NIRSpec Microshutters</td>
<td>0.6 - 5</td>
<td>0.2 x 0.46</td>
<td>200 x 200 4 x (97 x90)</td>
<td>~250,000 4 x 365(λ) x 171(X)</td>
</tr>
<tr>
<td>MIRI IFU 1</td>
<td>5 - 7.8</td>
<td>0.176</td>
<td>3.7 x 3.7</td>
<td>21</td>
</tr>
<tr>
<td>MIRI IFU 2</td>
<td>7.7 – 11.9</td>
<td>0.277</td>
<td>4.7 x 4.5</td>
<td>17</td>
</tr>
<tr>
<td>MIRI IFU 3</td>
<td>11.8 – 18.3</td>
<td>0.387</td>
<td>6.2 x 6.1</td>
<td>16</td>
</tr>
<tr>
<td>MIRI IFU 4</td>
<td>18.2 – 28.5</td>
<td>0.644</td>
<td>7.7 x 7.9</td>
<td>12</td>
</tr>
<tr>
<td>MIRI Low Res Slit</td>
<td>5 - ~14</td>
<td>0.6</td>
<td>0.6 x 5.5</td>
<td>1</td>
</tr>
</tbody>
</table>
IFU geometry for Uranus

Uranus image (Keck Observatory) from 12 July 2004, solar elongation 133°
Neptune image (Keck) from 27 July 2007, solar elongation 163°

0.2 x 3.3 arcsec slit
MIRI IFU geometry for Comet Tempel 1

5-7.8 µm channel
3.7x3.7 arcsec

HST Image (Feldman & Weaver)
NIRSpec Microshutter “Long Slit” Concept

Microshutter pseudo long slit

All shutters in column opened (~90 arcsec long in one quadrant)

Each shutter is 0.2x0.46 arcsec

Spectral dispersion

HST Image of Comet Holmes (2007)
Event-Driven Science Operations

- On-board scripts autonomously control the execution of the science timeline
  - Scripts respond to actual slew completion and command execution
    - Scripts also respond to interrupted or failed visit, moving on to next valid visit
    - Visits scheduled with overlapping windows to avoid idle time
  - Visit execution begins between earliest and latest start times within Visit window (nominally ~24 hrs)
- Increases observing efficiency by at least 10% (compared to fixed-time scheduling)
- Can switch instruments in adjacent visits (all instruments on, all the time)
- Supports time-critical observations, Targets of Opportunity (48 hour minimum response time)
Guide Stars for Moving Target Observations

- Event-driven operations provide flexibility in use of Guide Stars for moving targets
  - Multiple sets of guide stars defined to cover complete visit scheduling window
- Guide star selection software development at STScI nearly complete
- Observations with different instruments require separate guide stars (and visits)

\[\begin{align*}
\text{E} & \quad \text{L} & \quad \text{F} \\
& \quad \text{Visit} & \quad \text{Nominal Visit Scheduling Window}\\
& \quad \text{Guide Star 1 Window} & \\
& \quad \text{Guide Star 2 Window} & \\
& \quad \text{Guide Star 3 Window} & \\
& \quad \text{Guide Star 4 Window} & \\
& \quad \text{Guide Star 5 Window} & \\
& \quad \text{Guide Star 6 Window} & \\
\end{align*}\]

Visit Start Time, can use Guide Star 2 or 3 for tracking

\[E = \text{Earliest Start Time}, \ L = \text{Latest Start Time}, \ F = \text{Latest End Time}\]
Time-Critical Moving Target Observations

- Some observations need to execute in a narrow time window
  - Fully supported by JWST planning and scheduling system
  - Earliest and Latest Start Times define beginning of scheduling window
  - Latest End Time defines end of window

- Observations with different instruments require separate guide stars (and visits)
  - Back-to-back observations of a target with different instruments depends on GS availability

\[ E = \text{Earliest Start Time}, \quad L = \text{Latest Start Time}, \quad F = \text{Latest End Time} \]
STScI is nearly finished with three key ground system features for moving targets

- Guide star selection software
  - Multiple guide stars uplinked to cover entire plan window, but only one of these guide stars will be used for the visit (which one is determined in real time on board by scripts)

- Conversion of Moving Object Support System (MOSS) from Fortran to C++
  - MOSS has been a cornerstone of HST’s Solar System observation planning for over 20 years
  - Will be a major element of the MT observation planning for JWST

- Implement polynomial ephemeris in Visit Scheduling System, derived from JPL HORIZONS ephemerides
  - The ephemeris used by flight software to track the guide star will be a 5th-order polynomial.

Near-term work includes

- Update/define solar system use cases for operations development
  - Science planning, on-board scripts, target acquisition, science data processing
- Target acquisition for spectroscopic observations (fixed and moving targets)
- Proposer interface to define observations and to input observer-supplied ephemerides
Observation Planning and Time Accounting Philosophy

- Treat all observers equally
- Help observers craft programs that run efficiently on the Observatory
- The combination of exposure times plus computed and statistical overheads should reasonably describe the actual time for the Observatory to execute an Observation.
  - **Computed overheads** include all deterministic activities to acquire and setup a series of science exposures that form an Observation.
    - GS and target acquisitions, instrument mechanisms, offset slews, detector setup, etc
    - These overheads depend on the exact instrument configuration and type of observation.
    - Instrument internal overheads will be determined during cryo testing in 2014-15
    - Acquisition and offset slew times will be estimated by high-fidelity simulations
  - **Statistical overheads** include the major Observatory slew to the initial target attitude
  - There is no “moving target tax” applied to MT programs
- Policies not yet developed for how to handle other types of Observatory overheads
  - Activities not included in any observing program (e.g. momentum unloads, wavefront sensing & control, orbit maintenance, calibration observations)
  - Resource-intensive observations, such as rapid TOOs (e.g. SNs, GRBs,) or high data volume
BACKUP
<table>
<thead>
<tr>
<th>Object</th>
<th>Minimum rate (mas/sec)</th>
<th>Maximum rate (mas/sec)</th>
<th>Time to move 2 arcmin at min rate (hrs)</th>
<th>Time to move 2 arcmin at max rate (hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mars</td>
<td>2.5</td>
<td>28.6</td>
<td>13.3</td>
<td>1.2</td>
</tr>
<tr>
<td>Ceres</td>
<td>1.0</td>
<td>18.4</td>
<td>33.3</td>
<td>1.8</td>
</tr>
<tr>
<td>Jupiter</td>
<td>0.07</td>
<td>4.5</td>
<td>476</td>
<td>7.4</td>
</tr>
<tr>
<td>Saturn</td>
<td>0.04</td>
<td>2.9</td>
<td>833</td>
<td>11.4</td>
</tr>
<tr>
<td>Uranus</td>
<td>0.02</td>
<td>1.4</td>
<td>1667</td>
<td>24</td>
</tr>
<tr>
<td>Neptune</td>
<td>0.004</td>
<td>1.0</td>
<td>8333</td>
<td>34</td>
</tr>
<tr>
<td>Pluto</td>
<td>0.16</td>
<td>1.0</td>
<td>208</td>
<td>34</td>
</tr>
<tr>
<td>Haumea</td>
<td>0.35</td>
<td>0.89</td>
<td>95</td>
<td>37</td>
</tr>
<tr>
<td>Eris</td>
<td>0.22</td>
<td>0.56</td>
<td>152</td>
<td>59</td>
</tr>
</tbody>
</table>

Note: Times for some objects to move 2 arcmin at minimum rate (e.g. Uranus and Neptune) exceed the time when the object is moving at the minimum rate. However, durations are significantly longer than plausible observing windows (24-48 hours) for all objects except Mars when near minimum rates of motion.
### Spatial Resolution for a 2 μm Diffraction Limit (0.07")

<table>
<thead>
<tr>
<th>Object</th>
<th>Angular Diameter (arcsec)</th>
<th>Diameter (km)</th>
<th>2 μm Spatial Resolution (km)</th>
<th>IFU size (km) 3”x3”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mars</td>
<td>7</td>
<td>6800</td>
<td>68</td>
<td>2900</td>
</tr>
<tr>
<td>Jupiter</td>
<td>37</td>
<td>143,000</td>
<td>270</td>
<td>11,600</td>
</tr>
<tr>
<td>Saturn</td>
<td>17</td>
<td>120,000</td>
<td>490</td>
<td>21,180</td>
</tr>
<tr>
<td>Uranus</td>
<td>3.5</td>
<td>51,000</td>
<td>1020</td>
<td>43,700</td>
</tr>
<tr>
<td>Neptune</td>
<td>2.2</td>
<td>50,000</td>
<td>1590</td>
<td>68,180</td>
</tr>
<tr>
<td>Pluto @ 35 AU</td>
<td>0.1</td>
<td>2300</td>
<td>1600</td>
<td>72,000</td>
</tr>
</tbody>
</table>

Angular diameter shown for planet at quadrature
JWST attitude control system diagram

**Integrated Science Instrument Module (ISIM)**
- **Science Instrument (SI)** observes science target
- **Fine Guidance Sensor (FGS)** observes guide star

**FGS Control**
- Guide star centroid
- 16 Hz

**Spacecraft Bus**
- Star Trackers observe reference stars (roll control)

**Optical Telescope Element (OTE)**
- **Primary Mirror**
- **Secondary Mirror**

**Tertiary Mirror**
- **Fine Steering Mirror (FSM)**
- **FSM control**
- **FSM command to position guide star**
- **FSM offset to correct Observatory pointing**

**Fine Guidance Control**
- **Gyros**
- **Observatory Pointing Control**
- **Reaction Wheels**

**FGS**
- Focal plane

**FGS detector**
- Guide star centroid
- Commanded position

**Guide star subarray**
- Photons
- Reaction Wheels correct Observatory pointing
Photometric performance, point source

Limiting flux density (Jy) vs. wavelength (µm)

- HST
- JWST
- SOFIA
- Spitzer
- WISE
- Herschel
- ALMA Cycle 0

Flux of a 10σ detection in 10^4 s

Jane.R.Rigby@NASA.gov
Low resolution spectroscopy, point source

\[ f_v \text{ detected at } 10^\sigma \text{ in } 10^4 \text{s (Jy)} \]

\[ \text{m}_\text{AB} \]

\[ \text{wavelength (\text{\textmu m})} \]

- Spitzer IRS
- WFC3 grism
- ACS grism
- MIRI
- NIRSpec
R=600-2400 spectroscopy, emission line, point source

Line flux detected at 10 \sigma in 10^4 s (erg s^{-1} cm^{-2})

(wavelength (\mu m))

Keck, Gemini, VLT, SOFIA, Spitzer, MIRI, NIRCam, NIRSpect
- Observatory thermal design defines the allowed Solar orientations
  - Solar elongation 85° to 135° (like Spitzer)
  - Roll ±5° about line of sight

- JWST can observe the whole sky every year while remaining continuously in the shadow of its sunshield.
  - Field of Regard is an annulus covering 35% of the sky
  - The whole sky is covered each year with small continuous viewing zones at the Ecliptic poles
NIRSpec Microshutter “Long Slit” Concept

NIRSpec microshutter pseudo long slit
shutters opened on diagonal
Each open shutter is 0.2x0.46 arcsec

HST Image of Comet Holmes (2007)