JWST Solar System Capabilities

ESAC 2016 JWST Workshop

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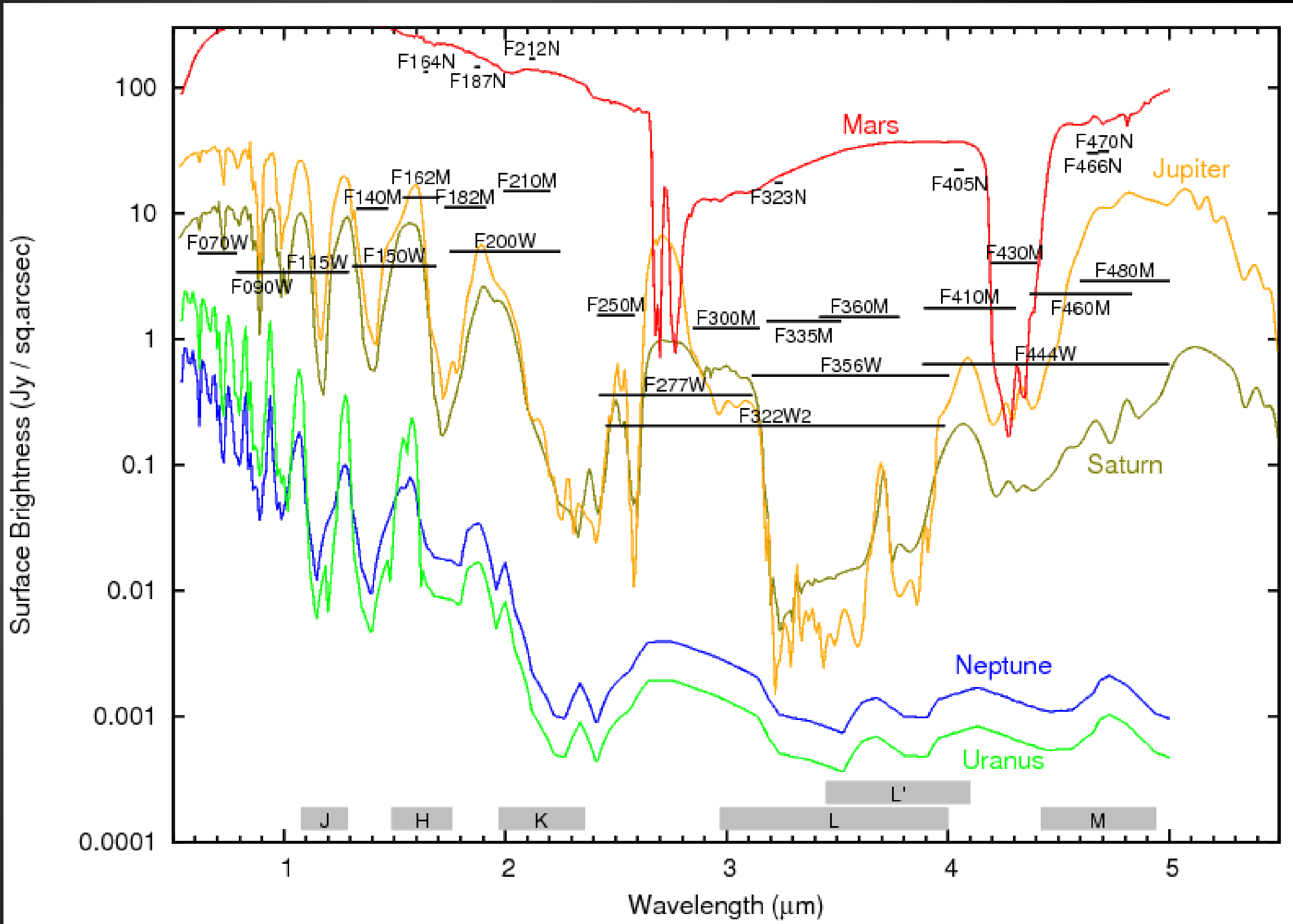
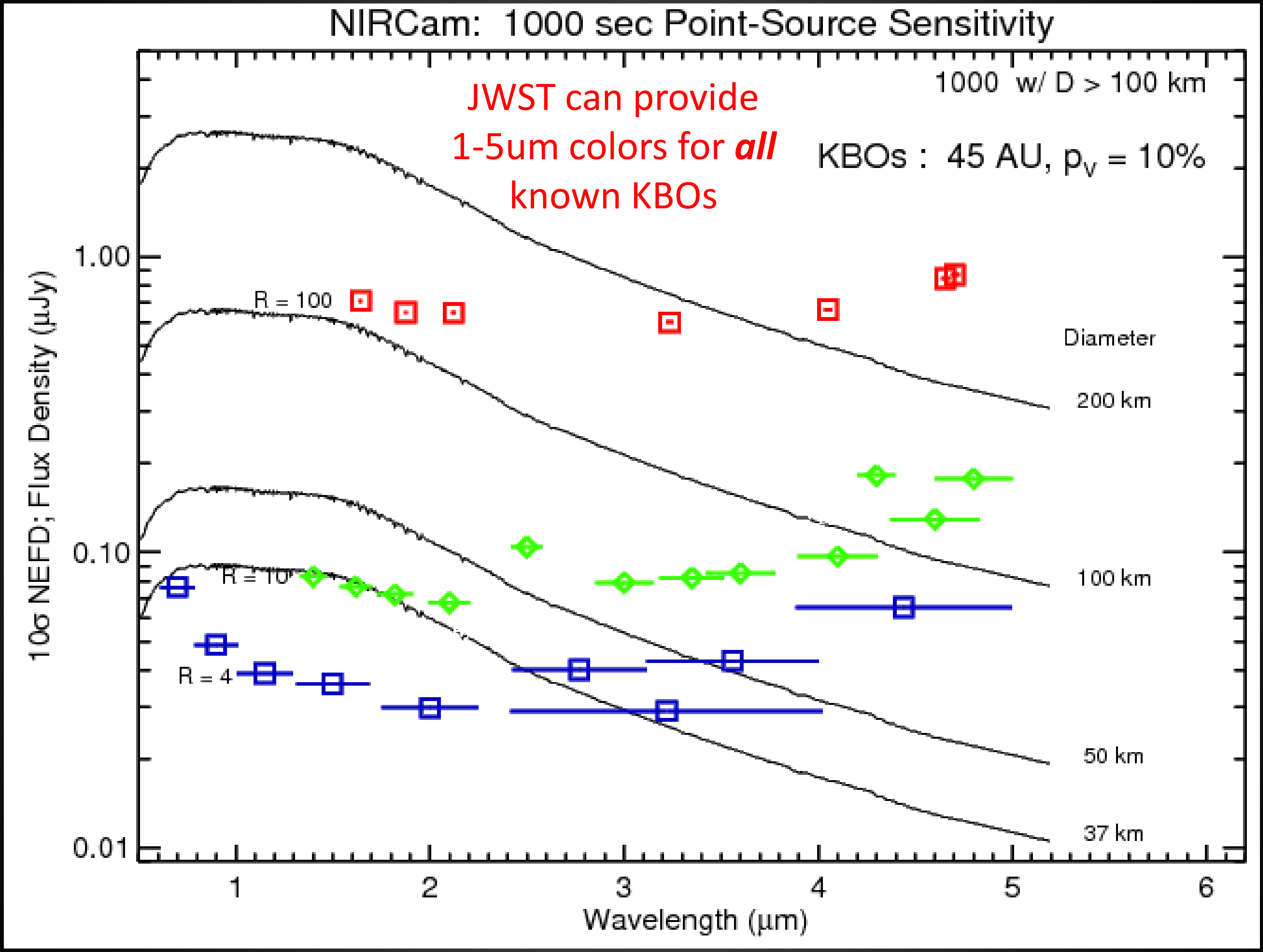
Solar System Science Highlights

Giant Planet Imaging with NIRCam

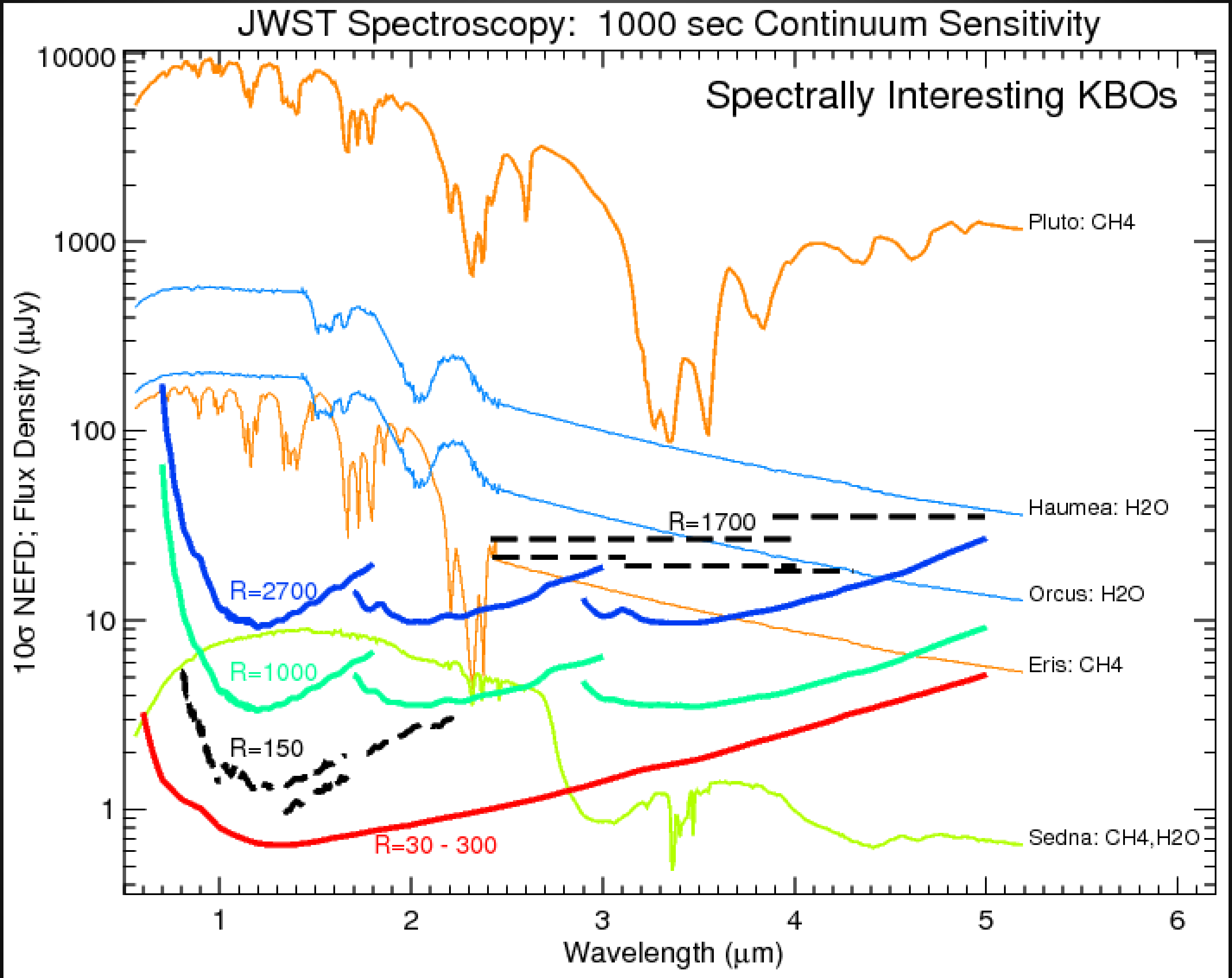
- Bright limits for 640x640 subarrays
- 160x160 limits are 15x higher



KBO Photometry with NIRCam

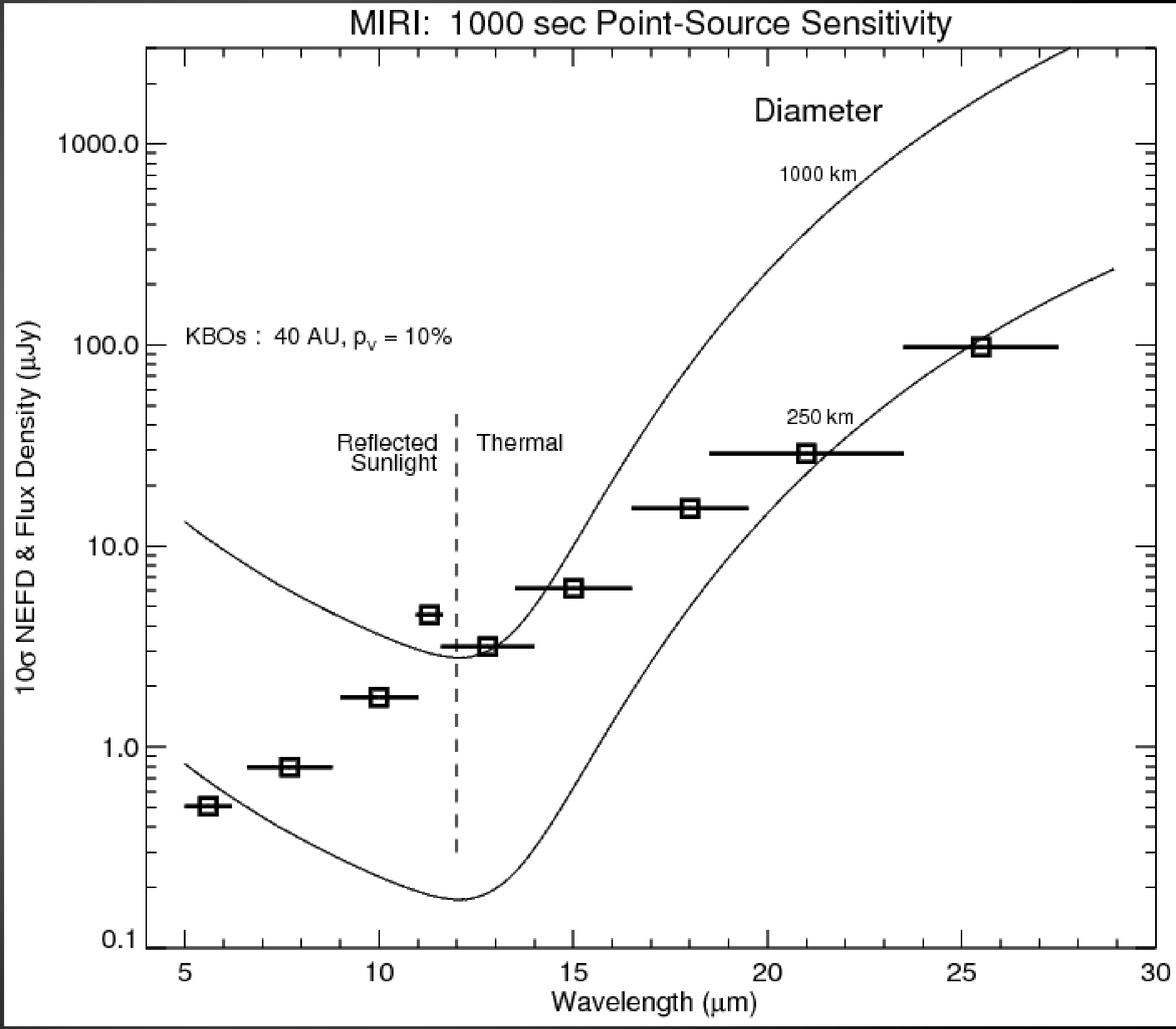


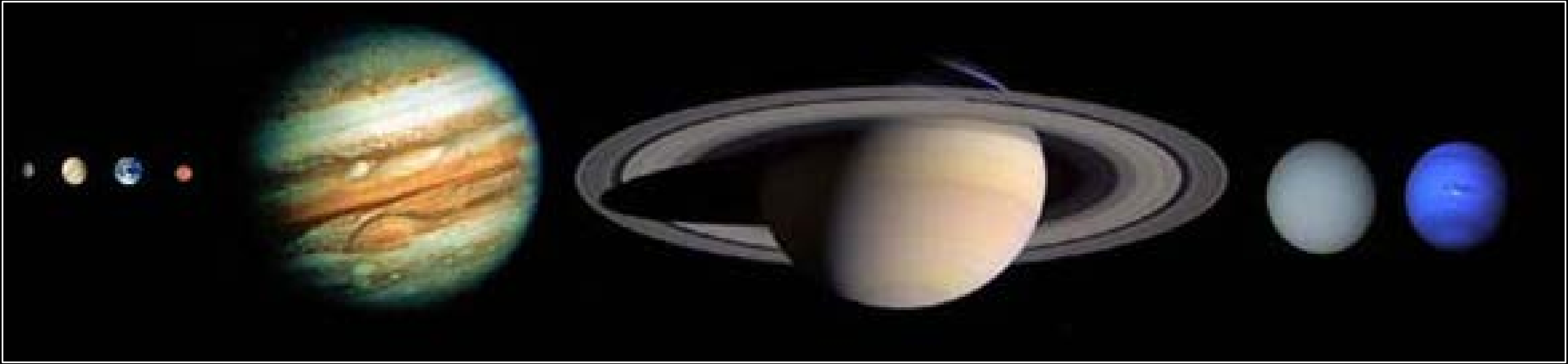
KBO Spectroscopy with NIRSpec



KBO Thermal Radiometry with MIRI

- MIRI can measure temperature distributions for quite small KBOs
- Sensitivity well matched to that of ALMA
- Valuable for
  - Thermal inertia
    - Composition
    - Regolith structure
  - Emissivity
  - Albedo
  - Diameter





PASP Special Issue

(Jan 4, 2016)

Innovative Solar System Science with the James Webb Space Telescope

Stefanie Milam, Special Editor

http://iopscience.iop.org/1538-3873/128/959

11 topical papers

http://iopscience.iop.org/1538-3873/128/960

1 high-level paper (Norwood et al.)

10 JWST Solar System Focus Groups

(and 11 papers! http://iopscience.iop.org/1538-3873/128/959

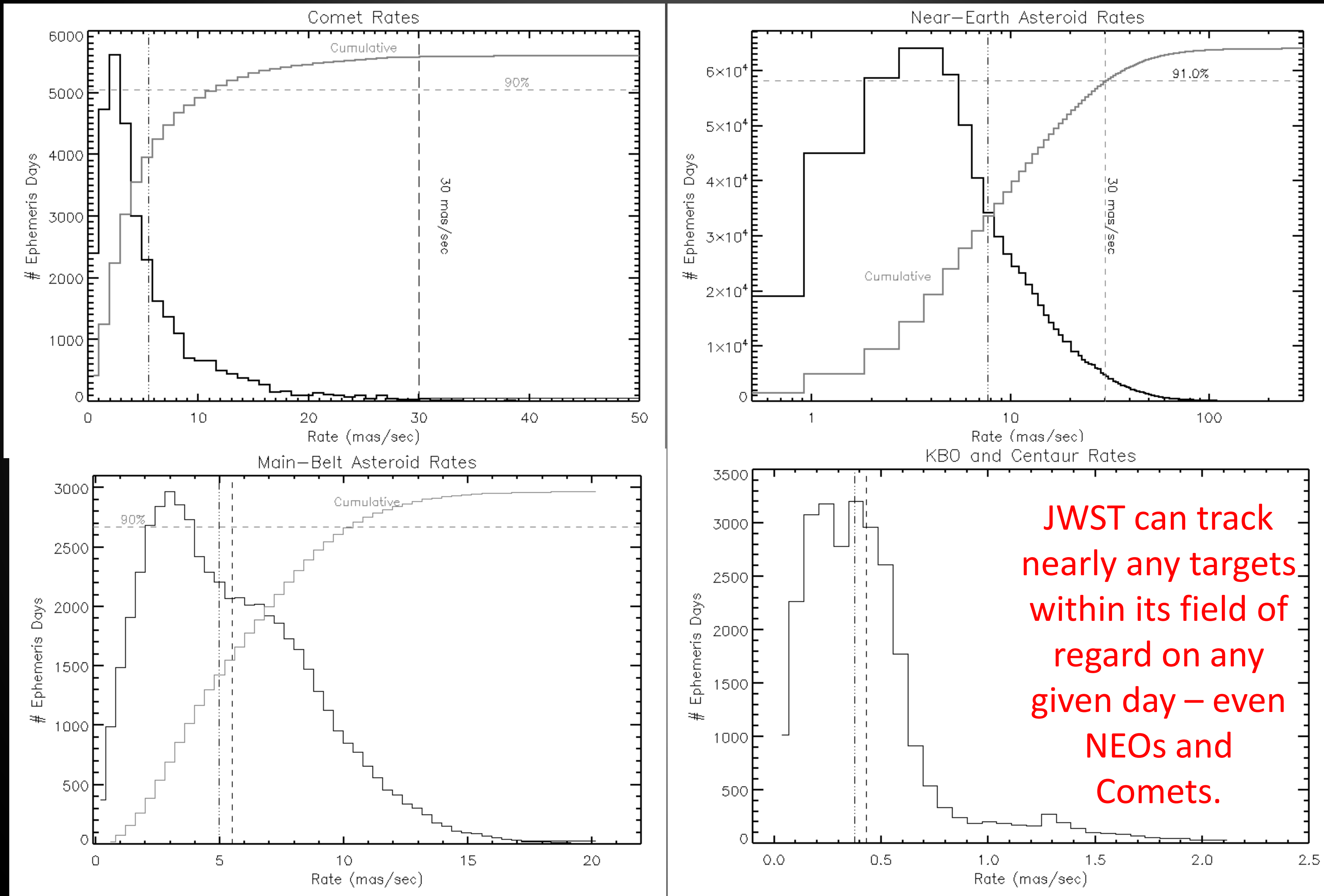
- **Asteroids** (Andy Rivkin, JHU/APL)
- **Comets** (Chick Woodward, U. Minnesota)
- **Giant Planets** (Jim Norwood, NMSU)
- **Mars** (Geronimo Villanueva, GSFC)
- **NEOs** (Cristina Thomas, GSFC)
- **Occultations** (Pablo Santos-Sanz, IAA-CSIC, Spain)
- **Rings** (Matt Tiscareno, Cornell)
- **Satellites** (Laszlo Kestay, USGS)
- **Titan** (Conor Nixon, GSFC)
- **TNOs** (Alex Parker, SwRI)
- JWST Solar System Capabilities (Milam, GSFC)

Performance Overview of JWST for Moving Targets

Moving Targets – Observatory, Flight Software

- Non-sidereal tracking – **Implemented**.
  - Rates up to 30 mas/s (108''/hr) supported (max rate of Mars)
    - Modeling shows excellent pointing stability (< 7mas NEA), ~same as fixed targs
  - The moving-target is fixed in detector frame while exposing
    - Dithers, mosaics supported (slightly higher overheads)
  - ~1 mag brighter guide stars required for moving targets
  - Long (~1hr+ tracks), and observations can use multiple guide stars

How Fast are Moving Targets Moving?

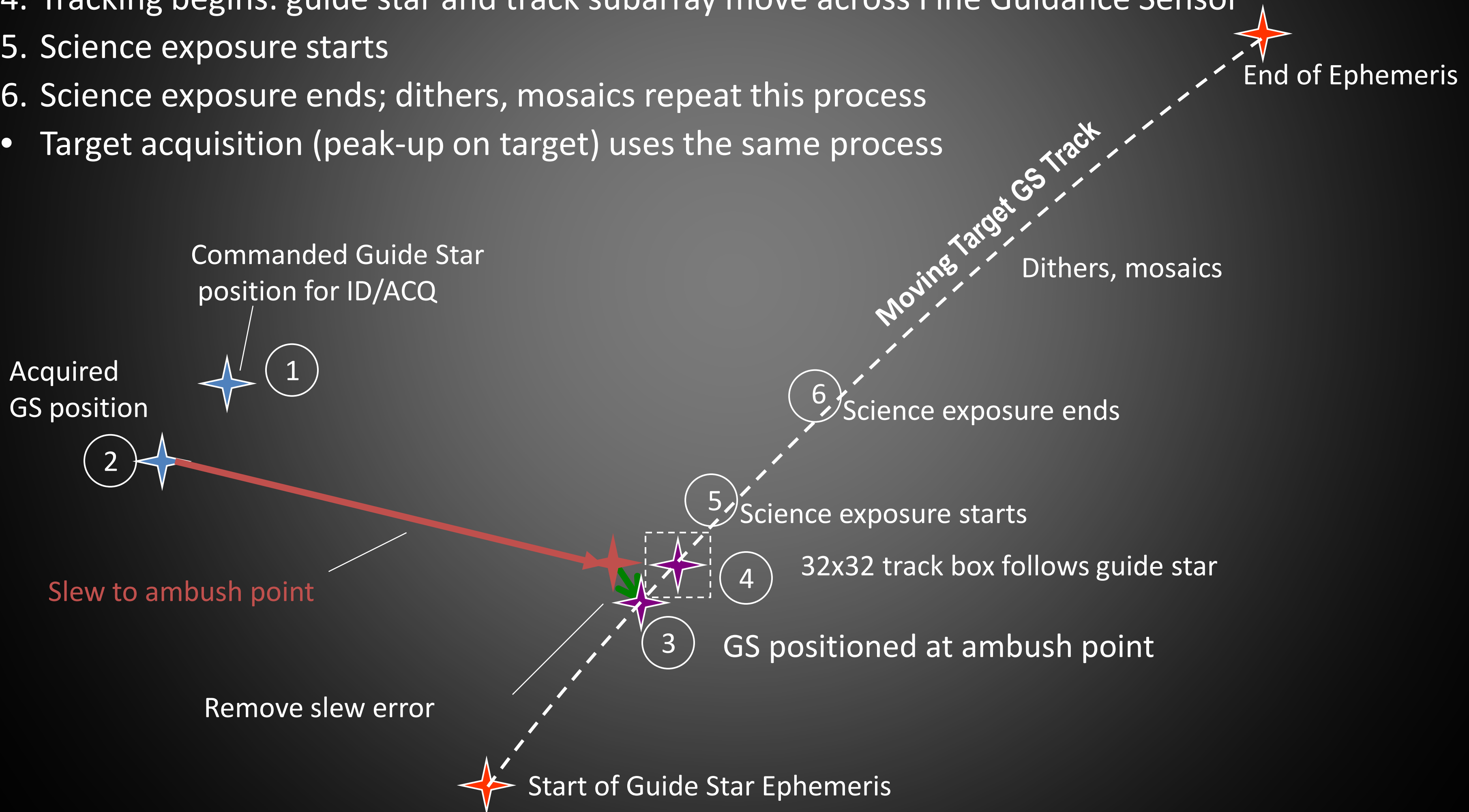


JWST can track nearly any targets within its field of regard on any given day – even NEOs and Comets.

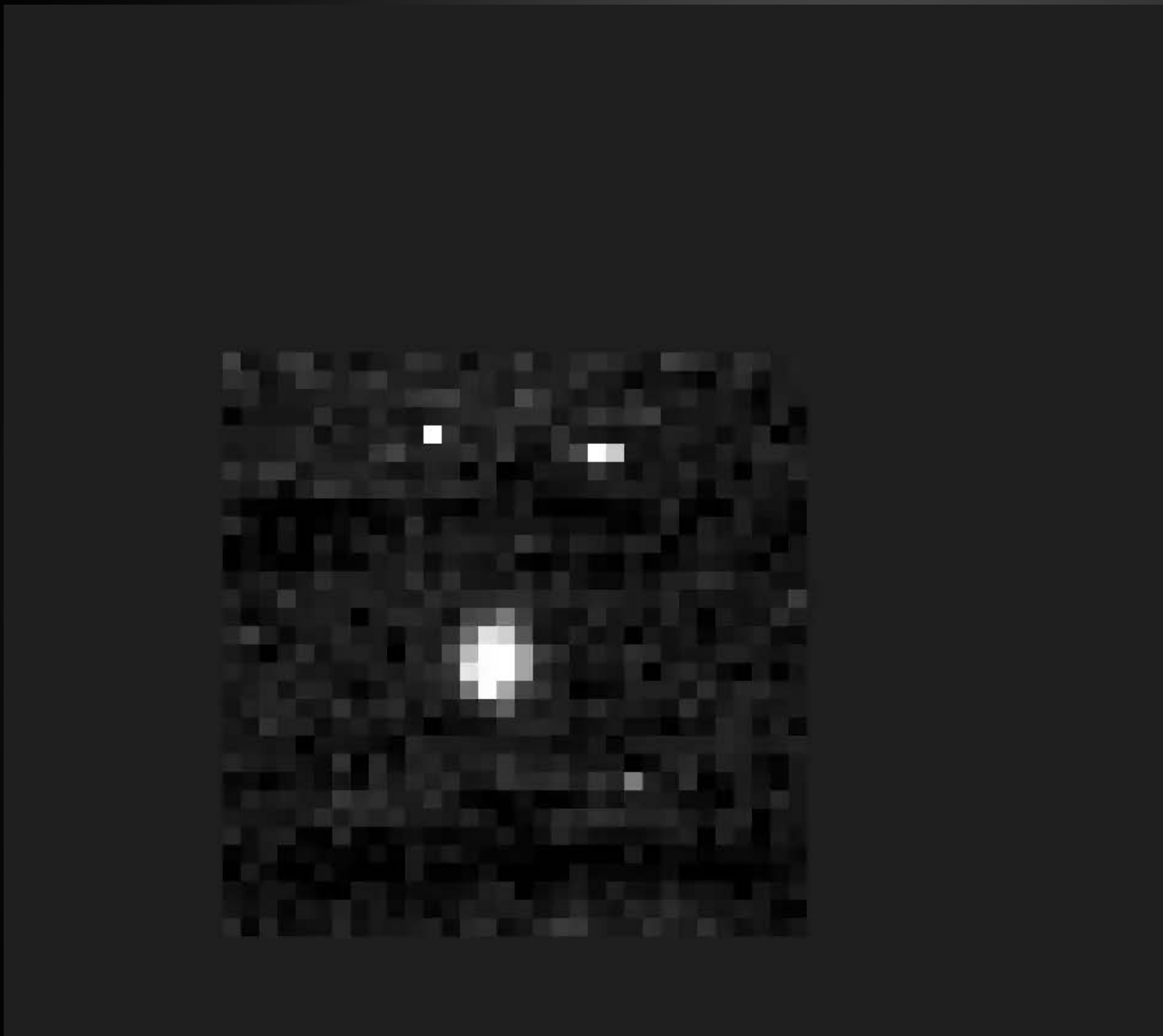
Schematic for Moving Target Observation

1. Usable guide star selected from candidate list, identified in field normally
2. Slew from acquisition point to target 'ambush point' computed and executed
3. Guide star position refined, system waits for tracking start time
4. Tracking begins: guide star and track subarray move across Fine Guidance Sensor
5. Science exposure starts
6. Science exposure ends; dithers, mosaics repeat this process

- Target acquisition (peak-up on target) uses the same process



Fine Guidance Sensor Moving Target T



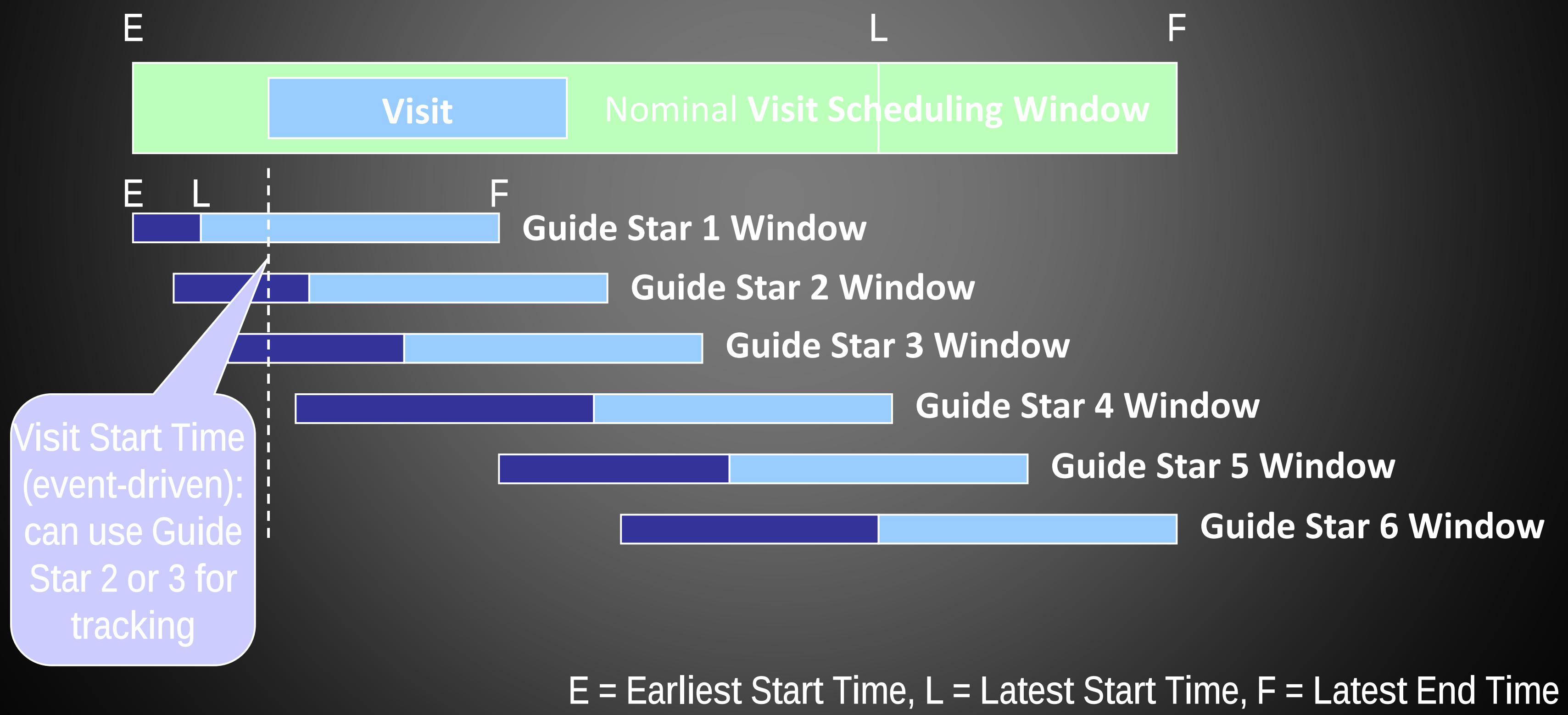
- FGS configuration
  - FGS ➔ TRACK
  - 32x32 track box (subarray)
  - Saved image data
  - Note hot pixels
- OSIM point source
  - Moderate illumination
  - ‘steps’ mimic GS motion on FGS detector
- FGS FSW
  - Centroids at 16 Hz
  - FSW moves track box to follow guide star
  - NOT quite the same as MT tracking...
    - For MT tracking Box moves in manner prescribed by the ephemeris

Moving Targets – Observatory, Flight Software

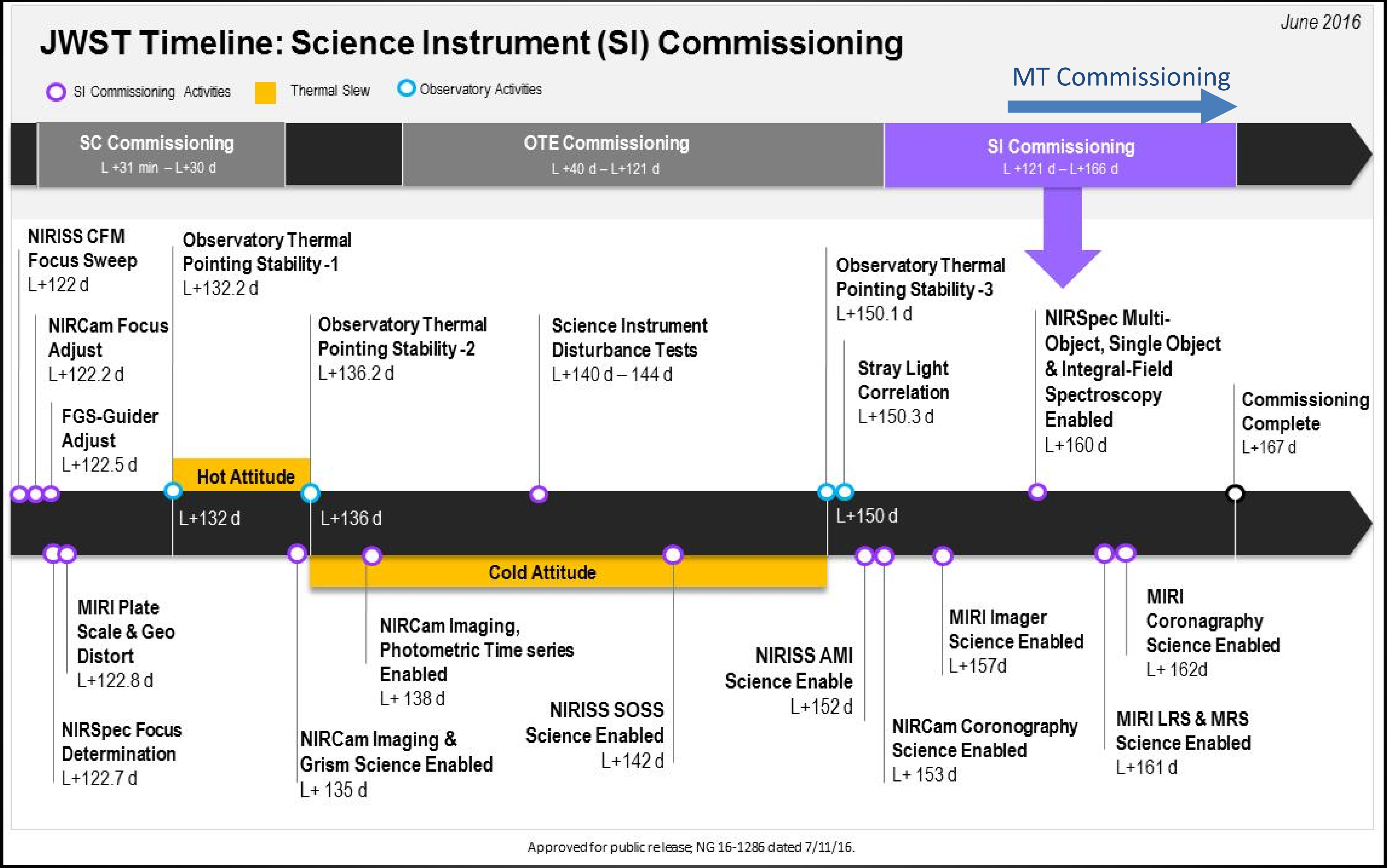
- Event-driven scheduling / operations
  - Each target has many possible guide stars, useable during different windows
  - At time of observation, 1st usable guide star selected, acquired normally
  - 5th O Chebyshev representation of guide-star track
    - **Primarily** enables guide-stars to be used at any time during target visibility window
    - **Secondarily** allows tracking targets with ephemeris accelerations
  - Time-constrained observations are supported

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
  - Typically 3 guide stars for any time within visit scheduling window
  - Up to 200 guide star candidates per moving target observation
- Observations with different instruments require separate guide stars (and visits)



Moving Target Commissioning



Moving Targets Commissioning

- Will start ~20 days before end of commissioning, after…
  - Complete commissioning of the telescope
  - Basic instrument commissioning
  - Guider to instrument astrometric solution updates
  - Target acquisition for fixed targets (NIRSpec)
  - Observatory ephemeris is fairly well understood
- Basic tracking checkout – NIRCam
  - 3 targets, rates of ~3, ~10, ~30 mas/sec
    - Executed in separated observations
  - Full-frame imaging, "bright" (15 < Kmag < 17)
  - Dithers and mosaics
  - 2 filter combinations
  - Observations long enough to allow ~30'' of target motion

Moving Targets Commissioning

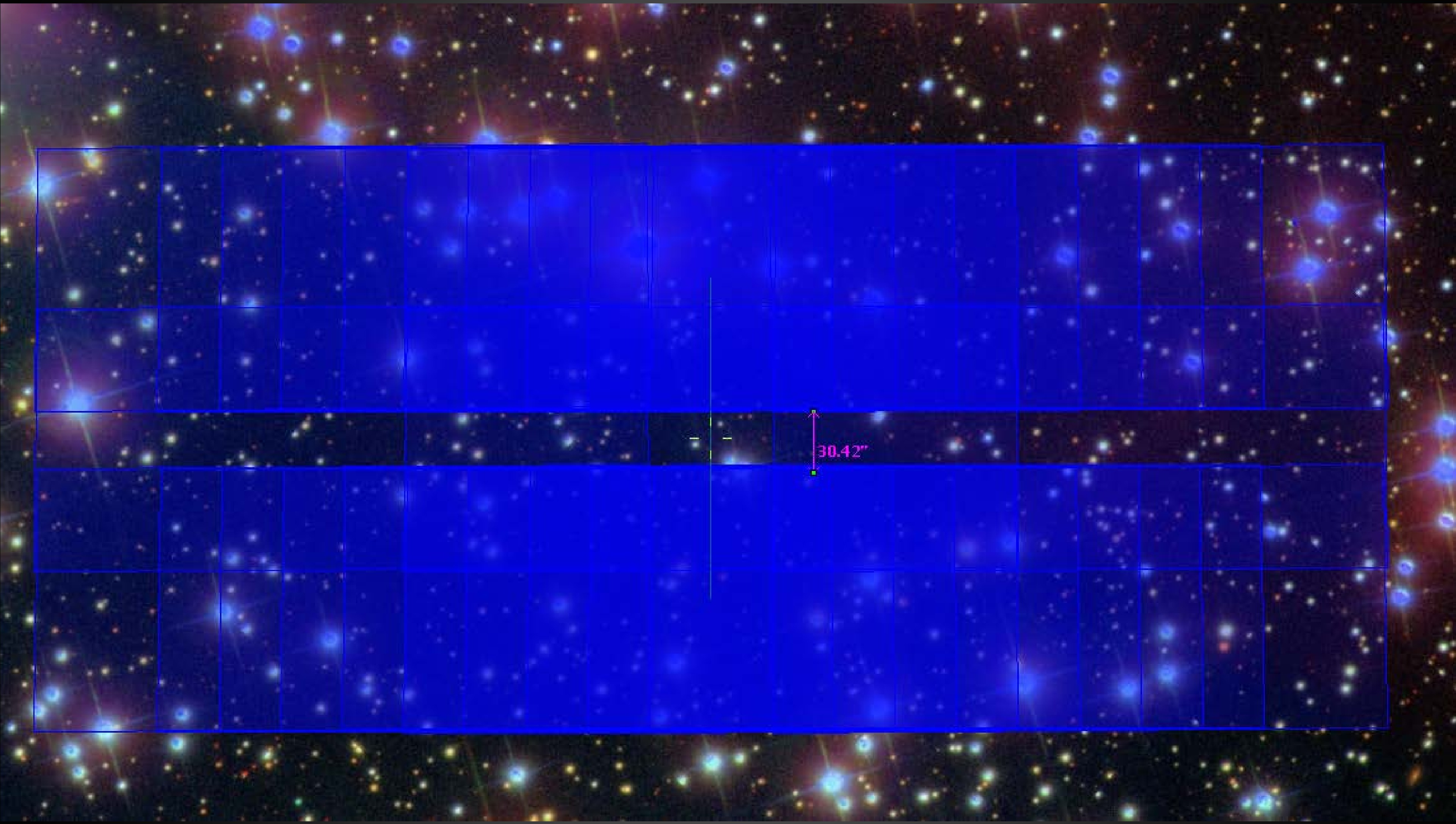
- Other instruments moving target checkout
  - Observations long enough to allow >~10’’ of target motion
  - MIRI, NIRISS
    - 1 target each, 10 – 30 mas/sec
    - Dithers and/or mosaics
    - MIRI imager and IFU
    - NIRISS AMI
  - NIRSpec
    - 1 target, 10 – 30 mas/sec
    - IFU point-and-shoot (no target acq), dithers, 2 grating settings
    - Target acquisition test
      - 1.6” aperture for TA
      - IFU for quick science observation/pointing verification

- Pipeline verification is a key goal for all of these tests

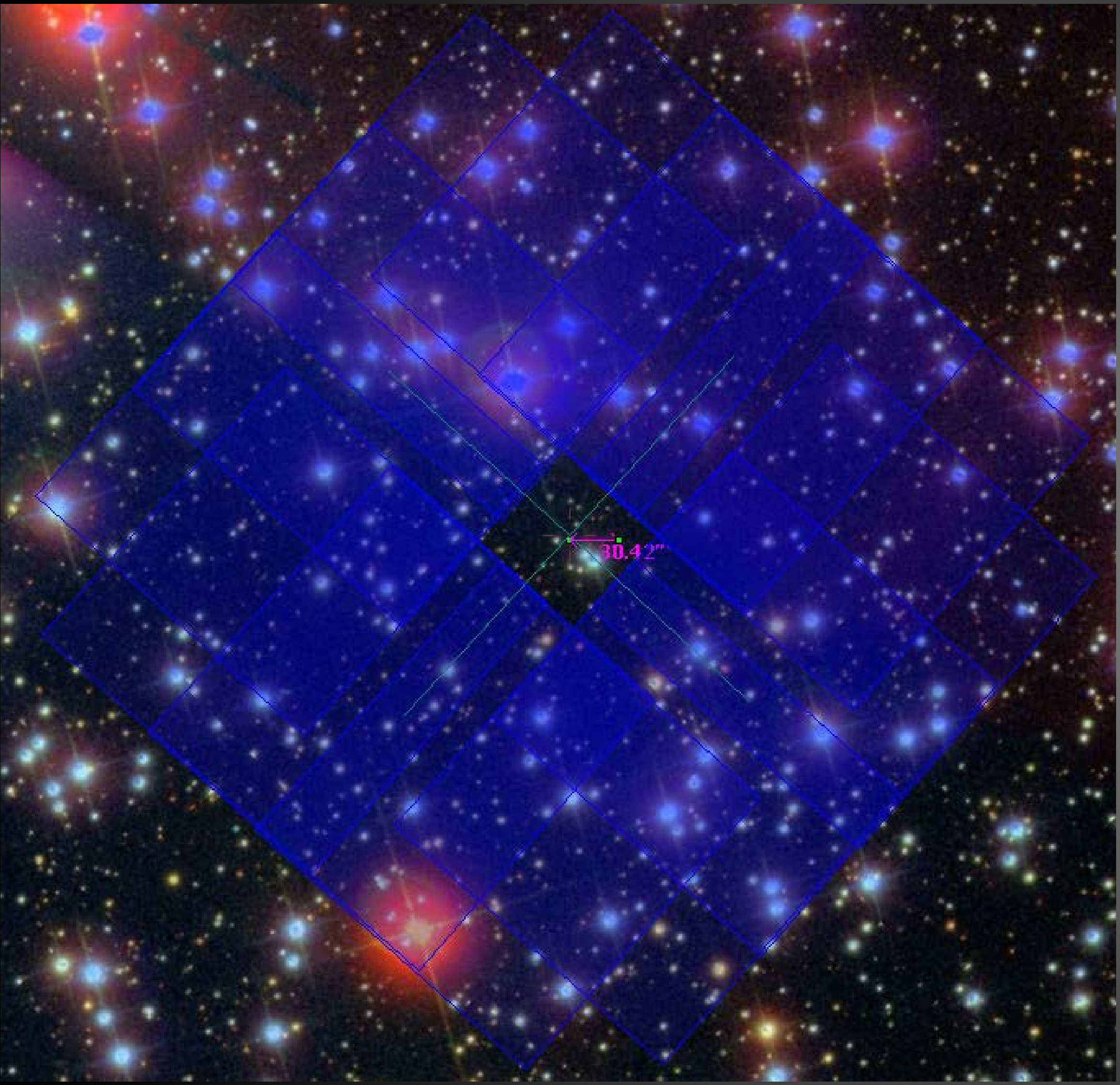
Moving Targets Commissioning

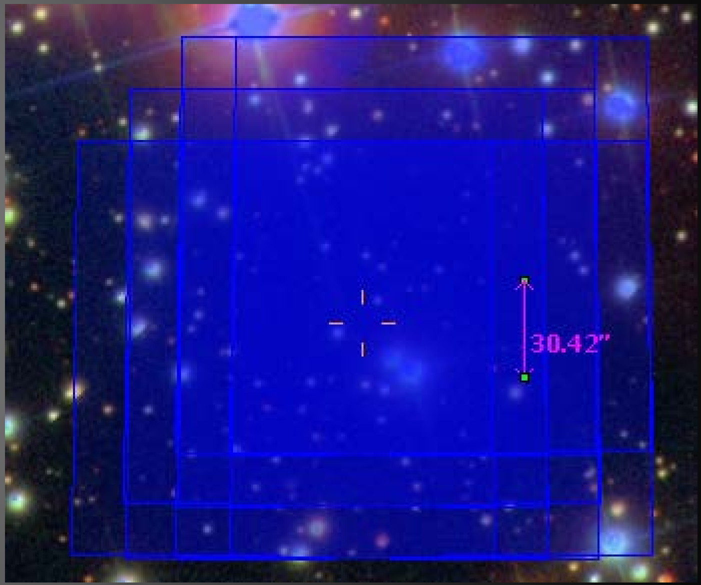
- Scattered Light checkout
  - Jupiter or Saturn as illumination source (assumes no big launch delay)
  - Use mosaic patterns to steer instrument FOVs around the source
    - NIRCam on-axis stray light will be checked (shortwave channel FPA mask)
  - Each SI will undergo this initial stray-light check
  - Checkouts will be a severe test of FGS guiding near a giant planet

NIRCam Stray-light Test Mosaic

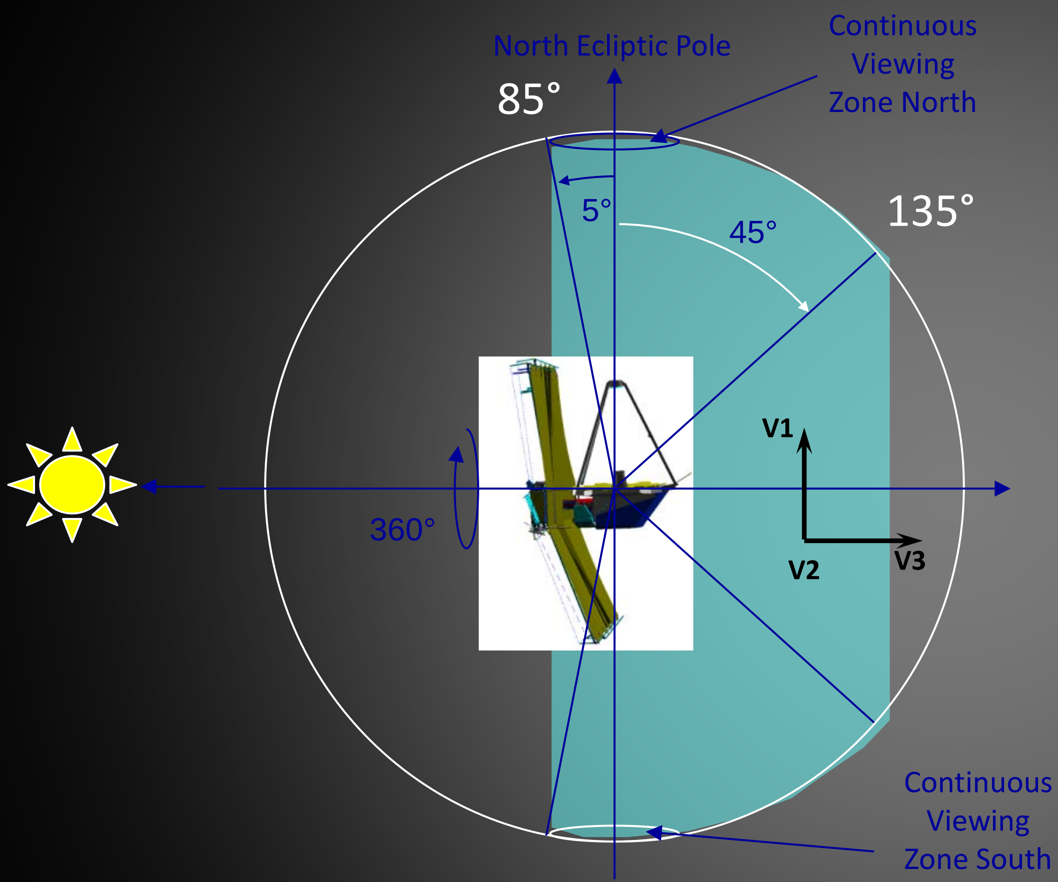


NIRSpec Stray-light Mosaic; NIRCam In-field Check





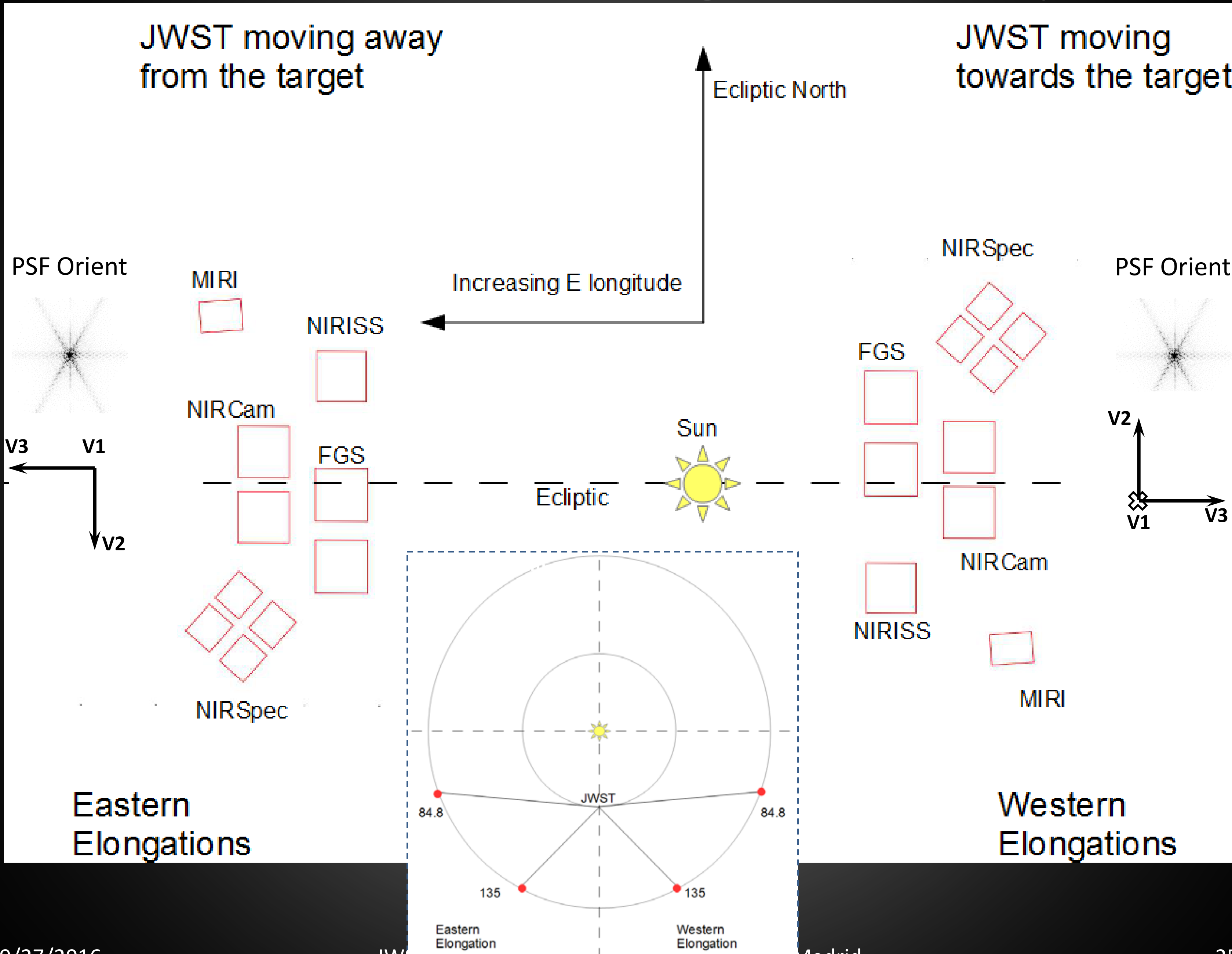
JWST Field of Regard



- Observatory thermal design defines the allowed Solar orientations
  - Solar elongation 85° to 135° (like Spitzer, Herschel)
  - Roll ±5° about line of sight
- JWST can observe the whole sky every year while remaining continuously in the shadow of its sunshield.
  - Instantaneous Field of Regard is an annulus covering 35% of the sky
  - The whole sky is covered twice each year with small continuous viewing zones at the Ecliptic poles

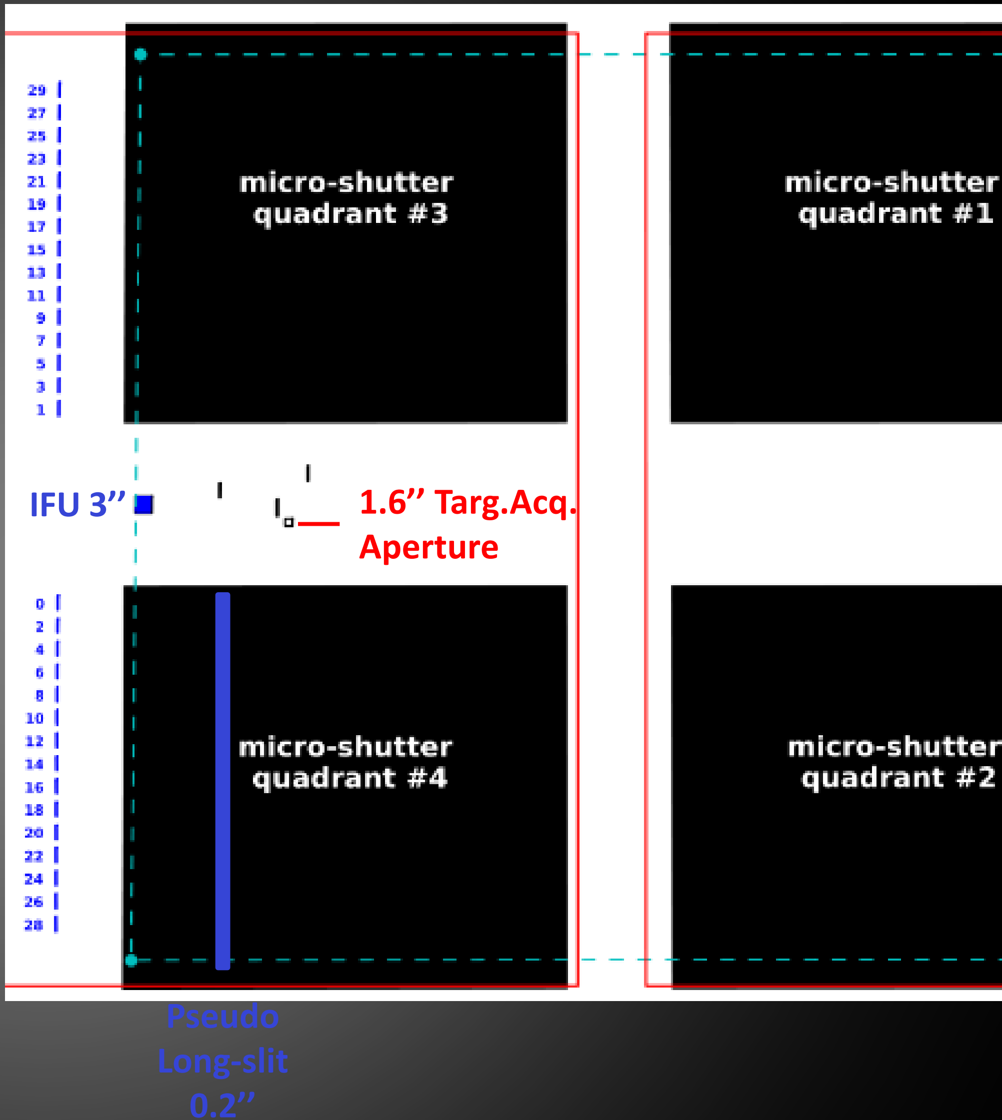
Solar System Targets: Observations occur near quadrature, not at opposition

JWST Instrument FOVs for Targets in the Ecliptic Plane



Target Acquisition: NIRSpec

- NIRSpec TA for moving targets is not easy
  - 1.6’’ square aperture
    - Ephemeris of target must be accurate!
  - Centroid calculated on-board
  - Target can be accurately (<10mas) positioned in the IFU, any of the fixed slits, or in a pseudo long-slit in the microshutter array



Data Pipeline for Moving Targets: GTO/Cycle-1 Baseline

Moving-target Pipeline Overview

- JWST high-level requirement for moving target data:

  "The data management system shall calibrate moving target data"

  - Calibration pipeline data product "levels":
    1. Data formatting, science-frame re-orientation, WCS information
    2. Calibrated single-exposure count-rate images; flux conversion
    3. Combine Level-2 products ➔ coadd exposures, mosaicking, etc.

- Moving Target baseline data processing (level 1):
  - WCS is expanded to include 4 MT keywords per integration + 2 per observation
    - Moving Target World Coordinate System (MTWCS)
      - CRVALMT1, CRVALMT2, RA_REF, DEC_REF – per integration
      - RA_REF0, DEC_REF0 – per observation
        - position of the target at observation mid-time
    - Dithers/mosaic offsets preserved
    - MTWCS creation triggered by moving-target flag created by APT

Moving-target Pipeline Overview (Baseline)

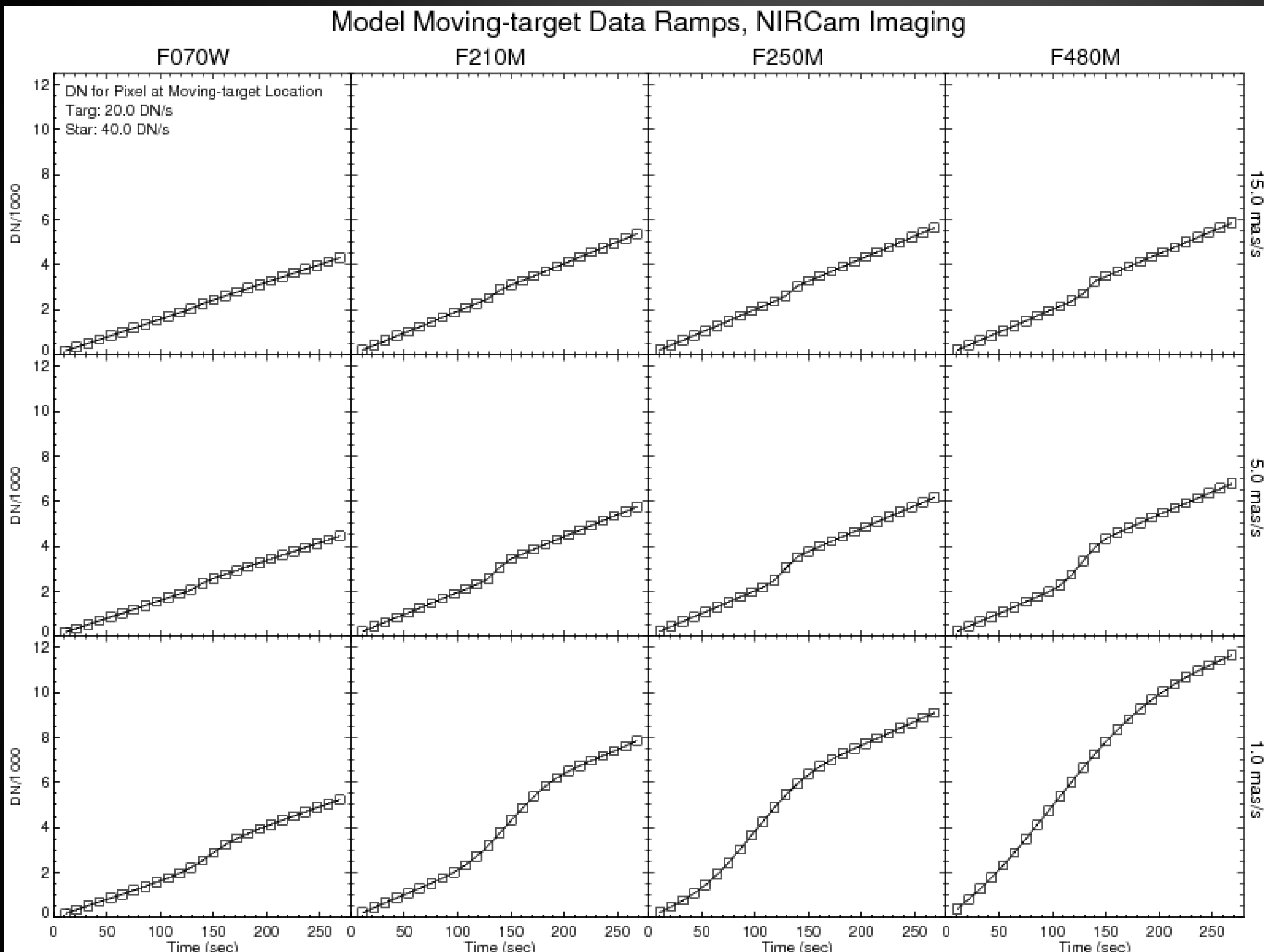
- Single-exposure calibration processing (level 2):
  - **Science target is 'fixed' in the detector frame (telescope tracking)**
    - **Detector-level calibration steps are very similar to those for fixed targets**
  - Stars trail through the scene
    - Stars cause transient increases in detected signal as they cross pixels
      - Cycle 1: Ramps-to-slopes treats these as cosmic ray hits
      - Future: enhanced treatment of transient signals from stars (Cycle-2 or later)
- Multi-exposure calibration processing (level 3):
  - **Coaddition of exposures occurs in the co-moving frame of the target**
    - Existing fixed-target algorithms will be used
    - Moving-targets WCS data is used instead of normal WCS
    - Triggered by APT moving-target flag
    - ***HST Pipeline has never done this***
  - Same approach used by Spitzer and Herschel
    - Works for imaging, spectroscopy

Moving Target Effects on Integration Ramps

- Stars move across pixels creating transient signal increases
  - Dwell time on a pixel (τ_*) depends on:
    - pixel scale, *S* (32 mas NIRCam SW – 110 mas MIRI)
    - Track rate, *R* (~0.1 mas/sec – 30 mas/sec)
    - PSF FWHM, *W* (45 mas @ 0.7µm – 1.6" @ 25.5µm)
  - Star-transient signatures have a characteristic time-scale:
    - $\tau_* = (S + W) / R$
    - 2.6 sec (NEO, Comet @ 0.7 µm) – 1700 sec (slow KBO @ 25.5µm)
  - Transient signal strength is proportional to τ_*

- JWST operates in a unique regime
  - Much smaller PSF and pixel scales than Spitzer, Herschel, WISE
  - Stars will be rejected by cosmic-ray detection module in many moving-target observations.

Moving Target Data Model: Results



- PSF Pixel sampling:
  - F070W, F250M: under-sampled
  - F210M, F480M: well-sampled
- Track rates increase from bottom to top
  - 1, 5, 15 mas/sec
- Signal-jump magnitude
  - Smaller for higher track rate
  - Increases as FWHM/pix_scale
- Signal-jump duration
  - Same dependencies as for jump magnitude

See Backup Charts for Data-model animation/demo

Pipeline Testing & Validation

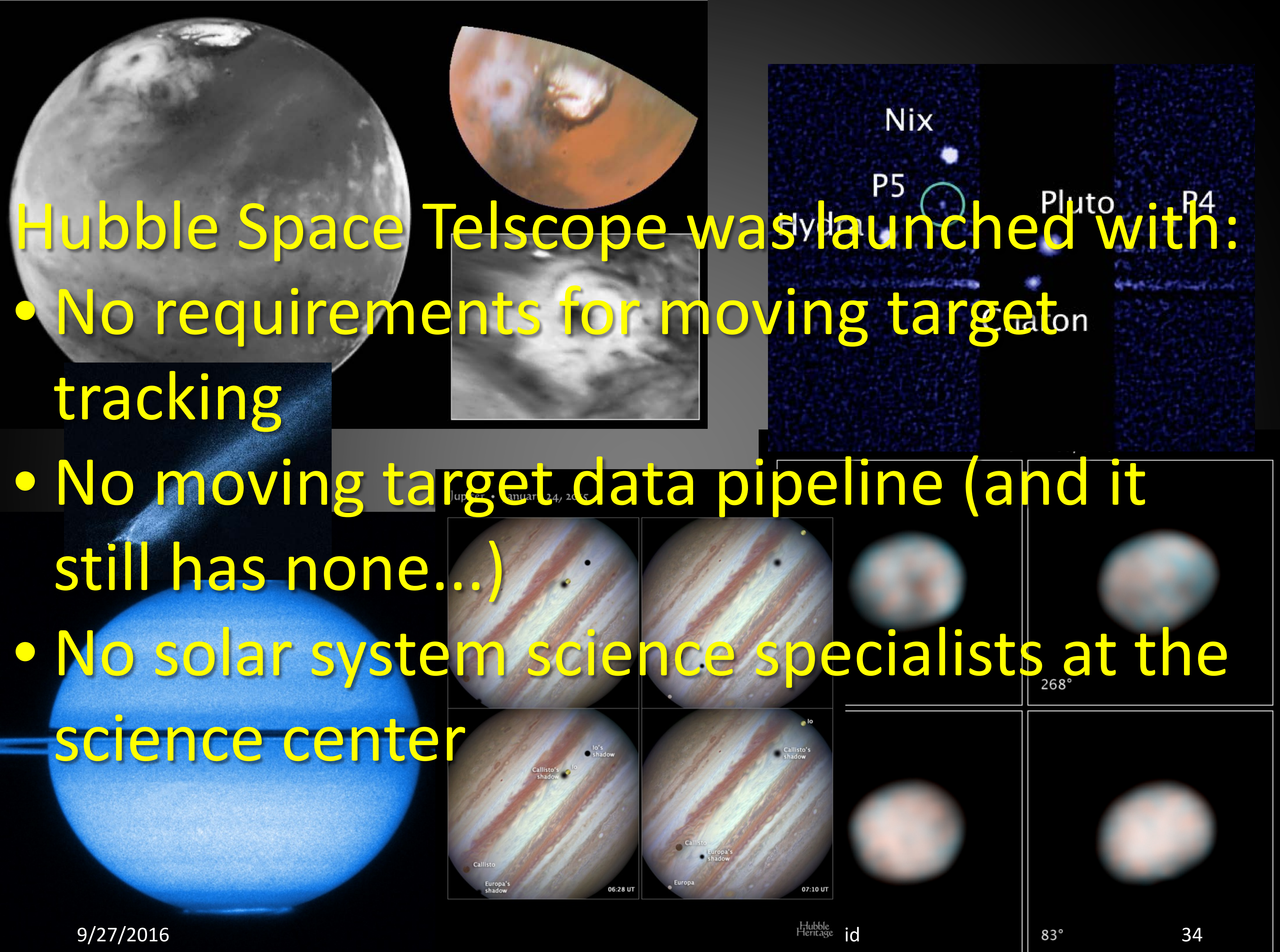
- ***Requires full-up spacecraft simulator software (EMTB, OTB)***
  - Version supporting moving targets (3.0) available late 2017
  - Also need full simulation of tracking, attitude control system:
    - Engineering Model Test-Bed (EMTB) available early 2017
- Exercises full ground system (***required*** *by pipeline system…)*
  - APT MT Proposal
    - Target data (ephemeris)
    - Scheduling system
    - Visit files
    - EMTB observation simulation ➔ SSR science data, pointing, complete telemetry, …
    - Pipeline requires this level of fidelity to operate…
      - Science data in the EMTB output to be replaced with output from a MT data model.

Moving Targets Pipeline Summary

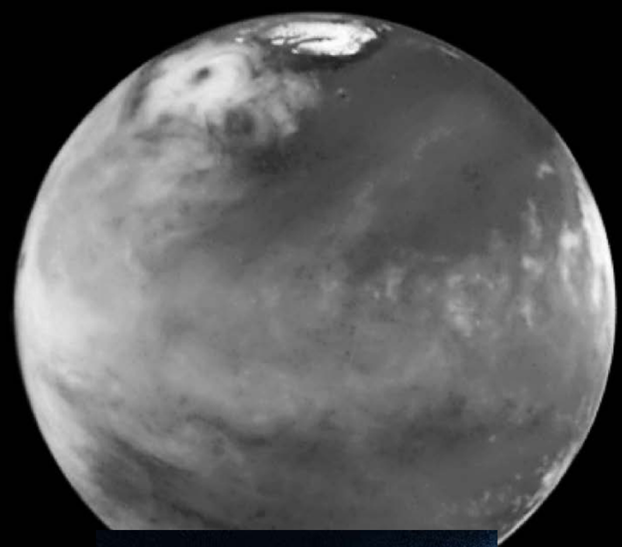
- Baseline calibration algorithms for moving targets are generally slight modifications to those used for fixed targets
  - When tracked, the ‘moving’ target is fixed in the detector frame, so calibrations applied at that level (up through level 2B) work well for both types of target
  - Stars trailing across the scene cause transient increases in signal levels in pixels they cross.
    - Level-2 processing flags these as cosmic rays if they are ‘fast’ regime
    - Level-2 enhancements to correct transient signals are possible, but are not planned for Cycle-1
  - Level-3 calibration steps only require use of modified world coordinate system (WCS) data that is in the co-moving frame of the target
    - Image stacking (non-dithered) and mosaicking will further reduce signals from fixed objects in the scene

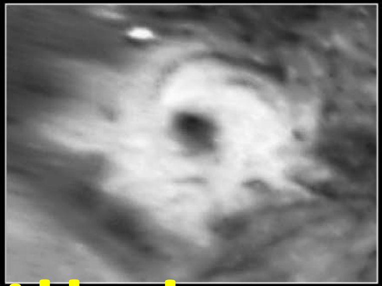
Hubble Space Telscope was launched with:

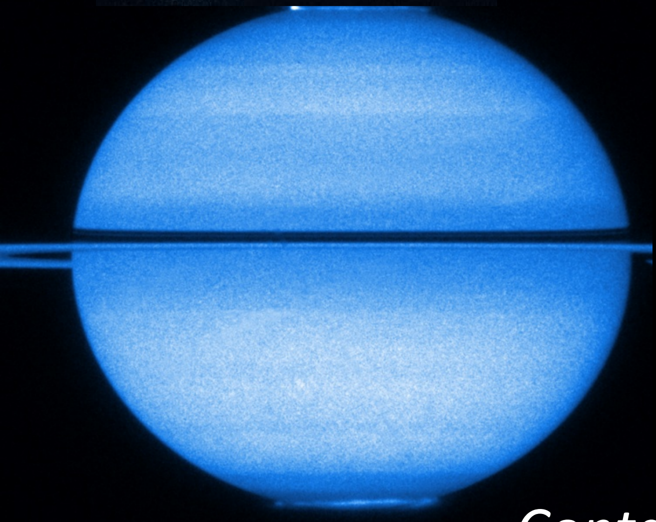
- No requirements for moving target tracking
- No moving target data pipeline (and it still has none…)
- No solar system science specialists at the science center

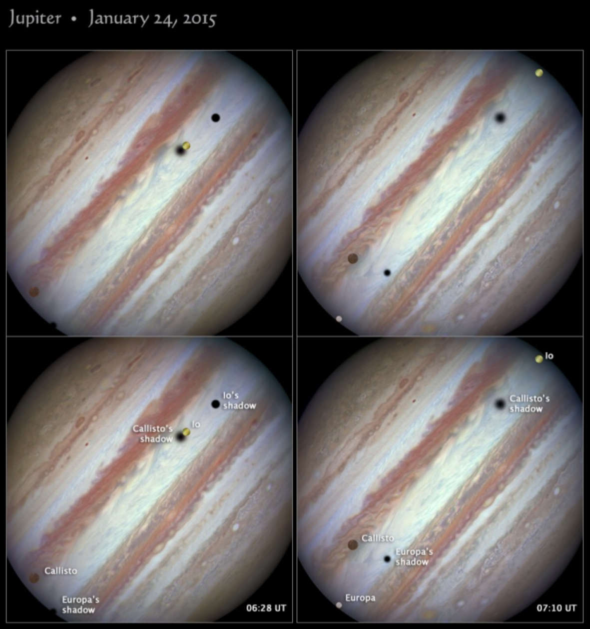


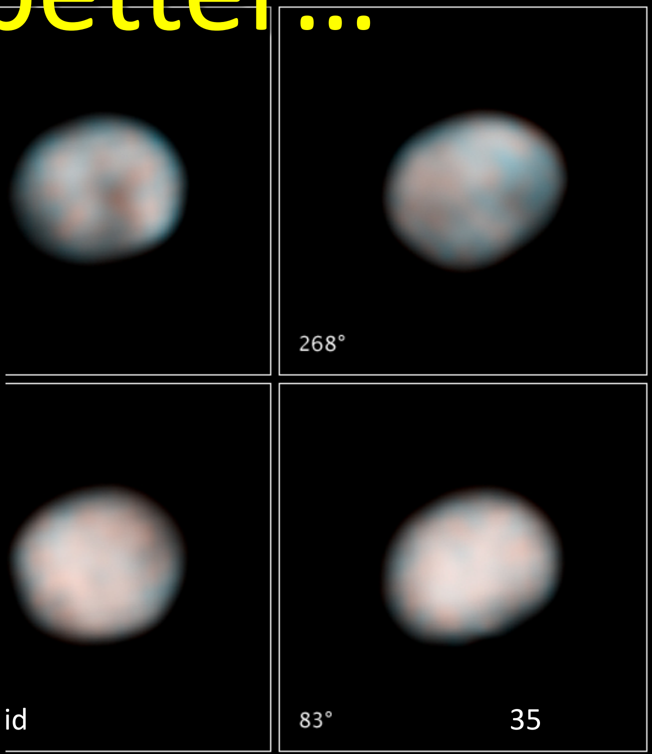
JWST will do even better…











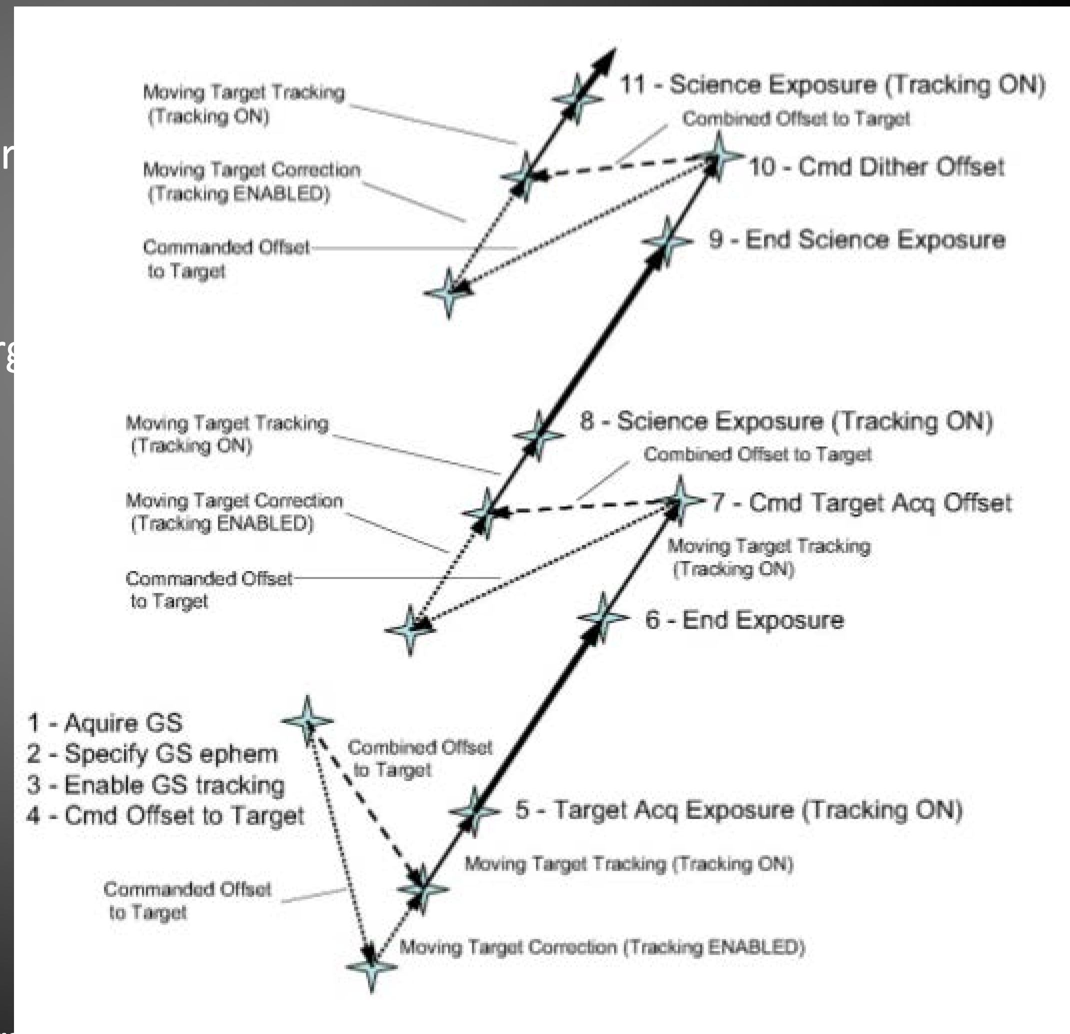
Contact: jstans@stsci.edu

Backup

ACS Operations Concept for Moving Targets

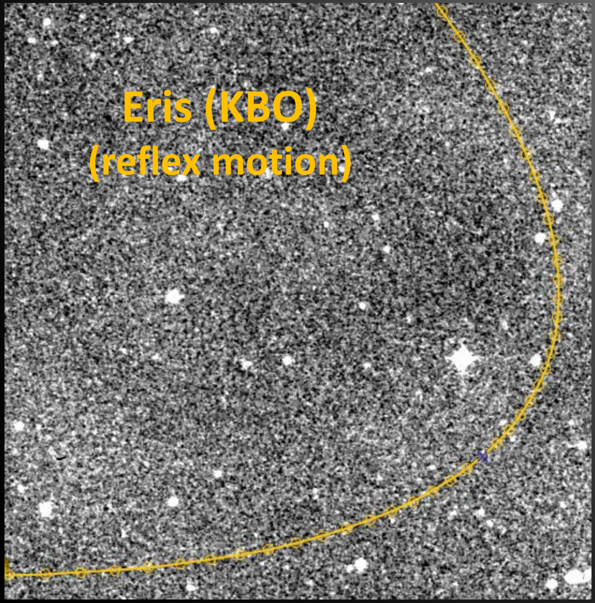
- On-board Scripts Subsystem (OSS) – Attitude Conctrol System (ACS) Interactions
  - Dithers, maps
    - Offset sent to ACS at end of exposur
    - ACS moves track box to offset + predicted ephemeris motion
    - Tracking starts at predicted time targ reaches the science aperture
  - Target-acq will also work for MT's
    - SI data analyzed by OSS
    - Offset sent to ACS
    - ACS moves track box to offset + predicted ephemeris motion

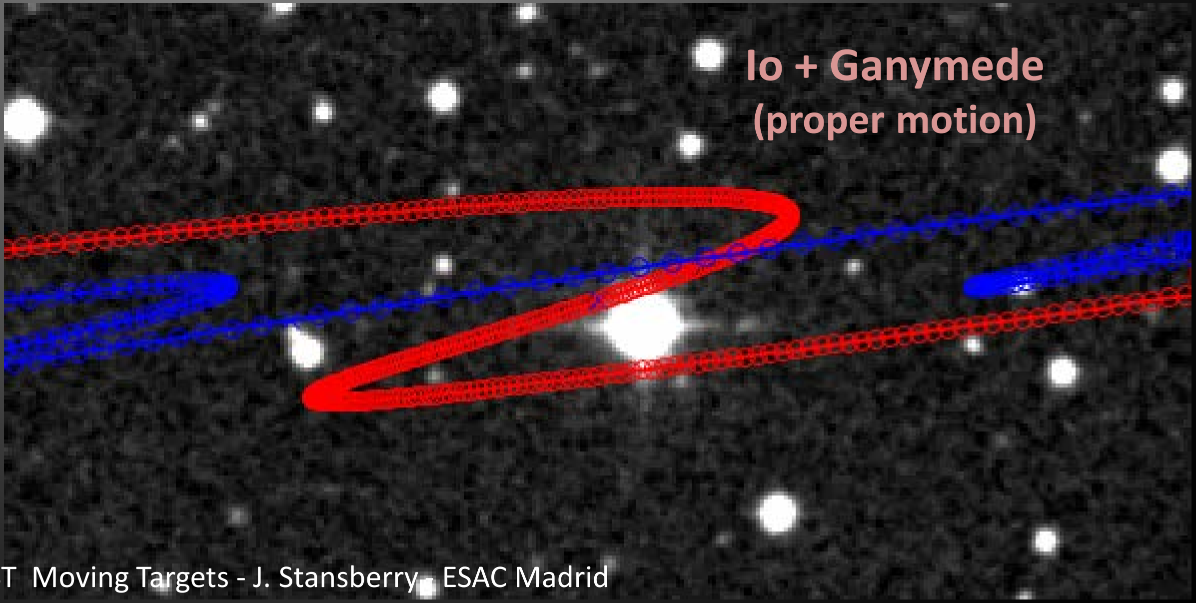
MT Target Acq and Dither Schematic
JWST-RPT-009982



Ephemeris Tracking

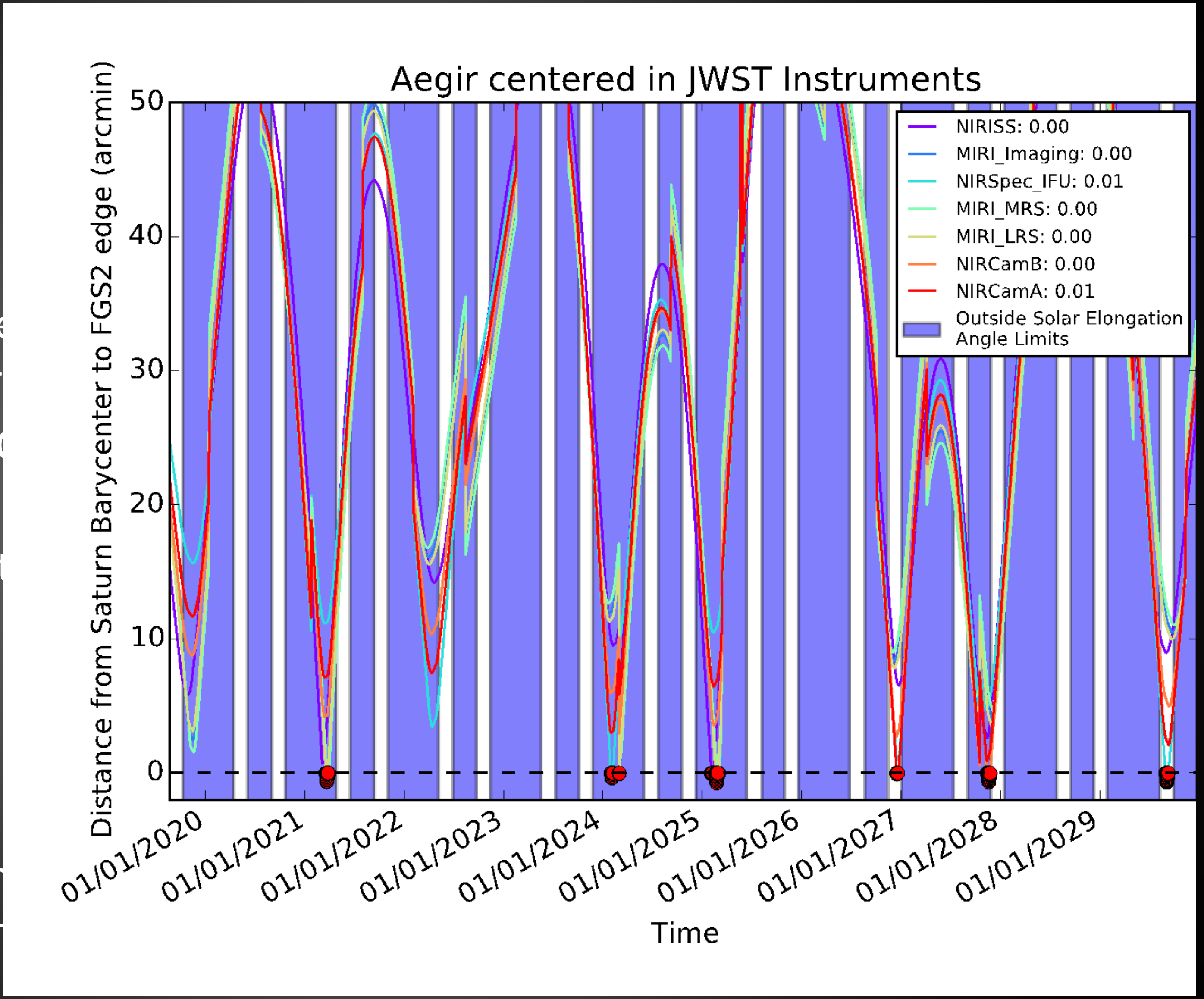
- Attitude Control System (ACS)
  - Autonomously tracks target by moving guide star & track box in FGS
    - OSS sends ephemeris to ACS
    - ACS corrects ephemeris for applicable SI
  - ACS notifies OSS that it is tracking, OK to expose
- Rates ≤ 30 mas/sec over arc of 30” (requirement)
  - Rates ≤ 60 mas/sec could probably be supported
- No requirement on acceleration
  - 5^{th} O polynomial ephemeris supports accelerations as well as event-driven operations





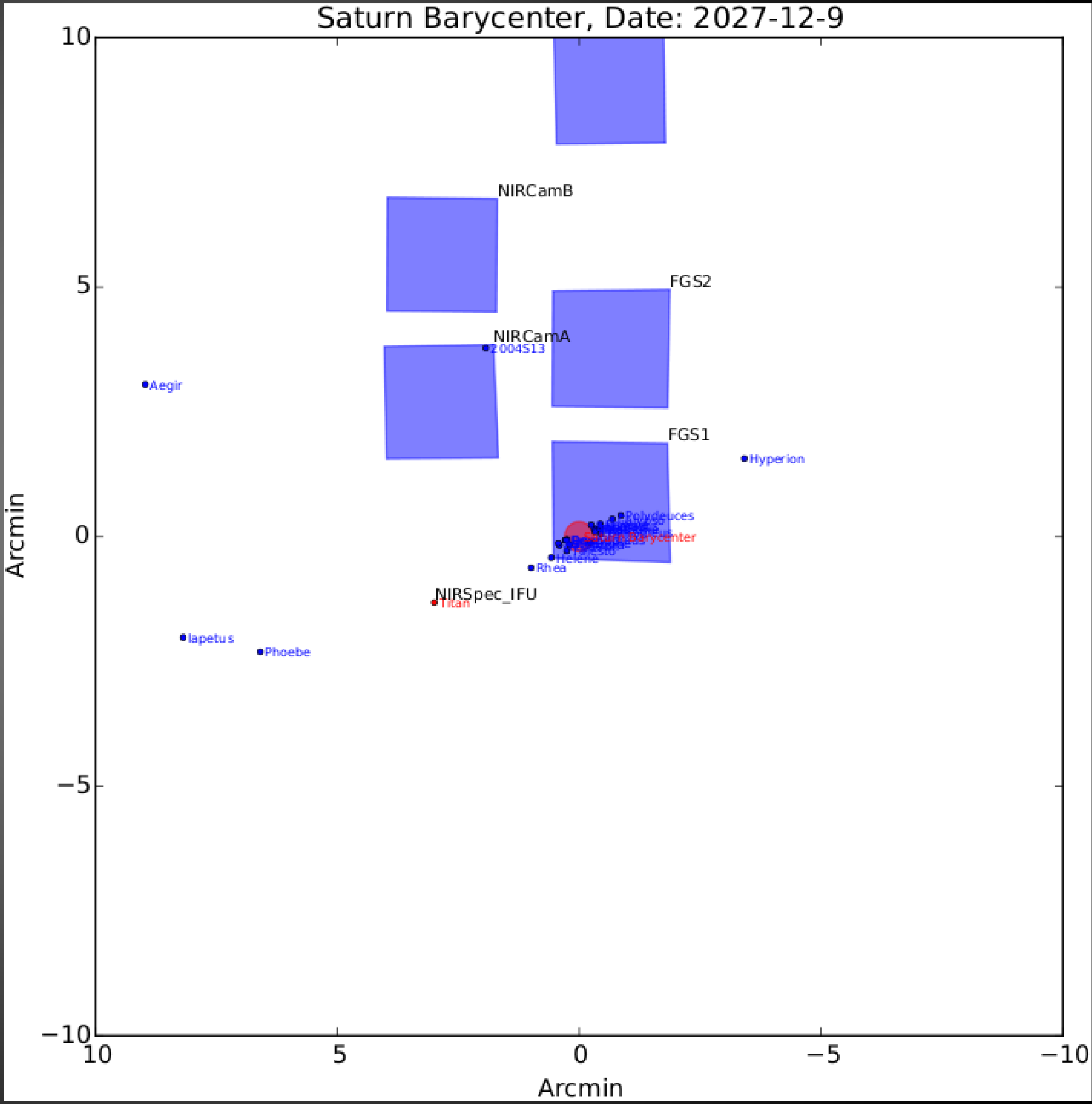
FGS Impingement by Planets

- 10 year ephemerides
- JWST as observatory
- Many (but not all) like
  SI apertures consider
- Planet within JWST F(
- Fixed focal plane
  orientation (V3 // to t
  ecliptic)
- All known satellites
  considered
- All analysis and graph
  done by Bryan Hilber

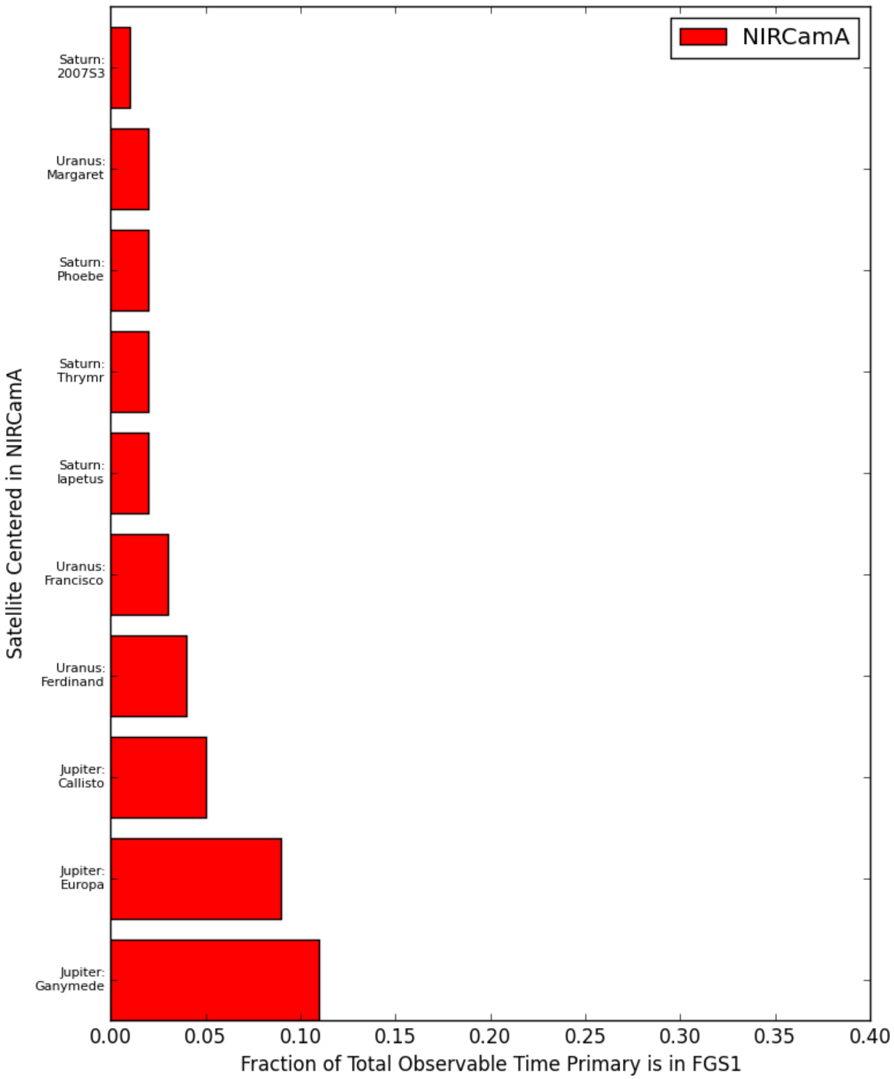


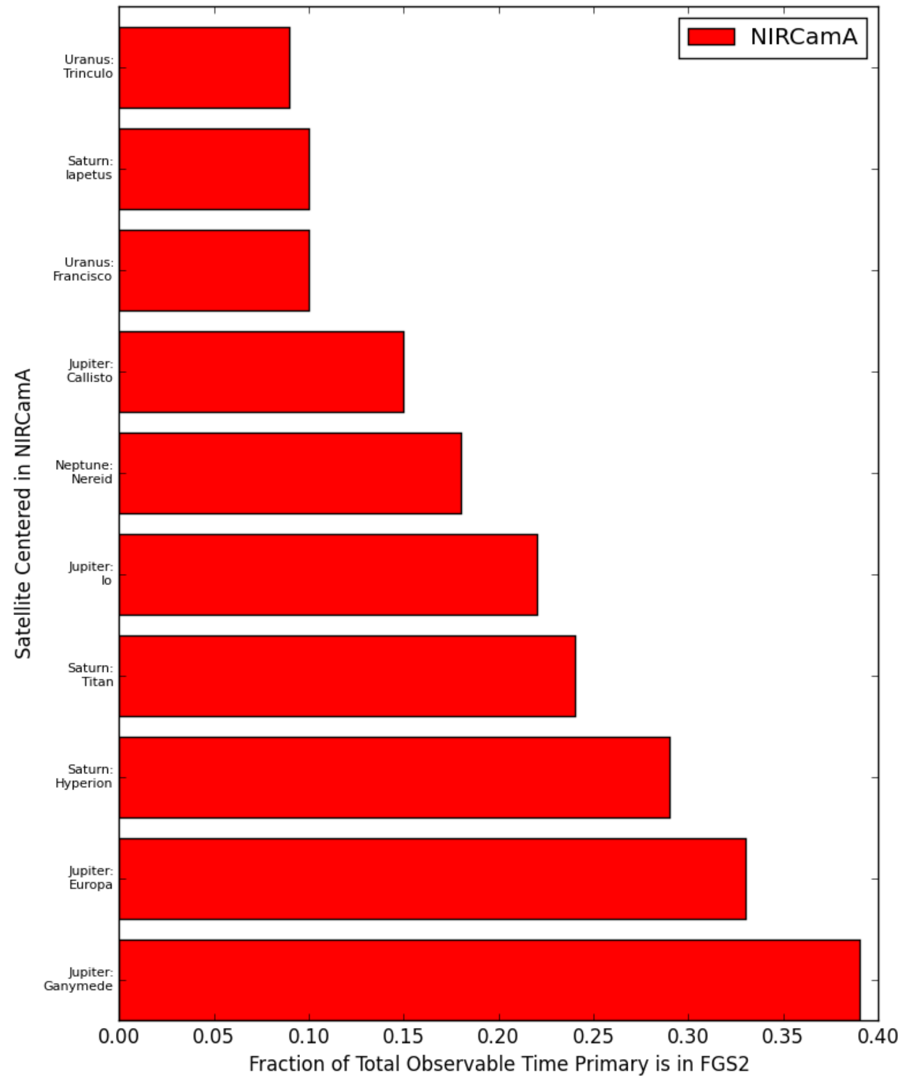
FGS Impingement by Planets

- "Impingement" is defined as the limb of the planet encroaching on the FGS FOV to any extent.
- Example is for Titan observed using the NIRSpec IFU

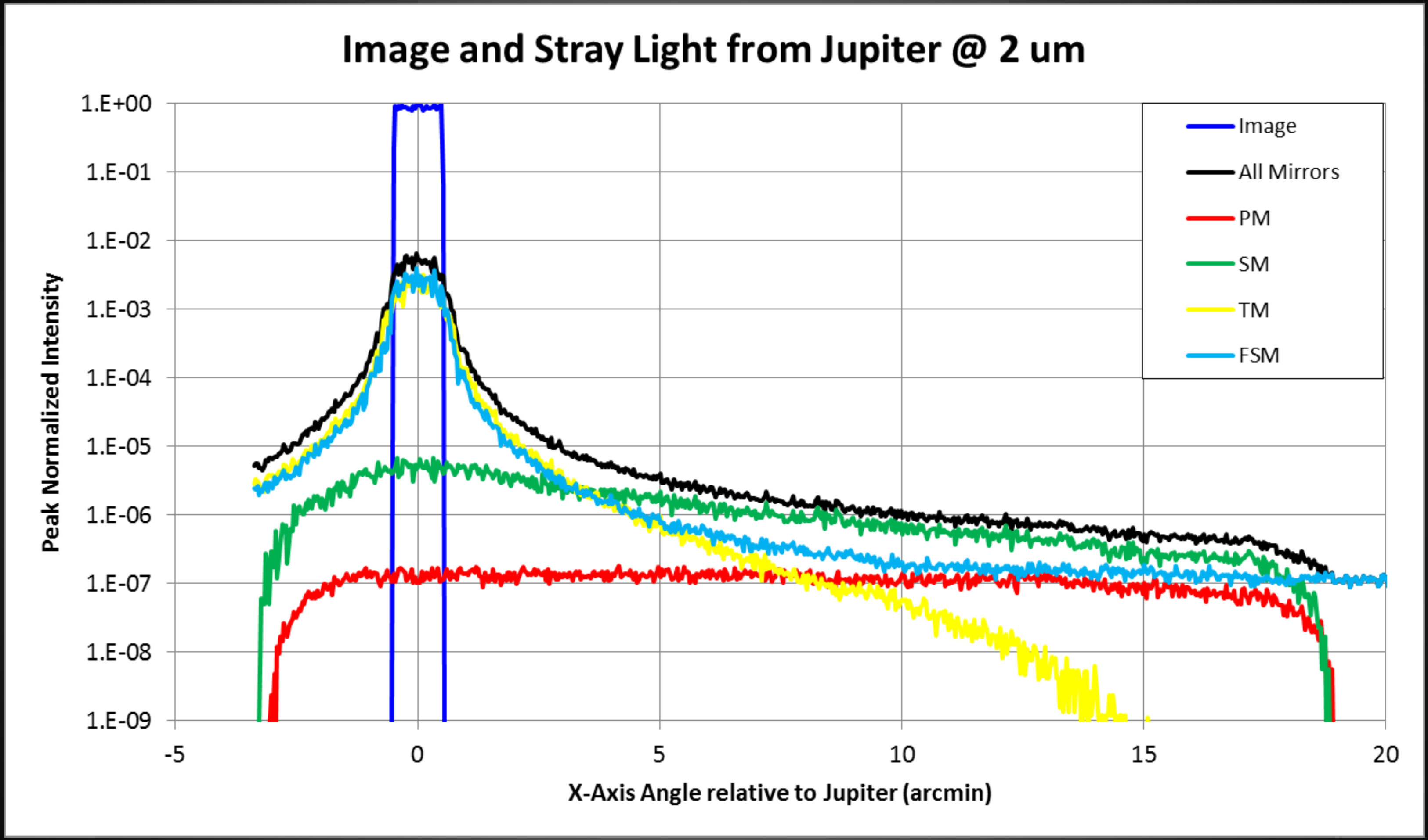


FGS Impingement: NIRCam Imaging – Mod A





Scattered Light: Jupiter, 2 μm



Coadding in the Co-Moving Frame

- Spitzer and Herschel pipelines were highly successful implementations
  - Rely on knowledge of target RA, Dec for each integration:
    - RA_REF, DEC_REF
  - Additional CRVAL data for moving targets
    - Pick RA_REF, DEC_REF reference (observation mid-time) values: RA_REF0, DEC_REF0
    - Compute CRVALs for integration # *i*, for use in co-moving mosaic:
      - CRVALMT1(*i*) = CRVAL1(*i*) + (RA_REF0 – RA_REF(*i*))
      - CRVALMT2(*i*) = CRVAL2(*i*) + (DEC_REF0 – DEC_REF(*i*))

        (see http://irsa.ipac.caltech.edu/data/SPITZER/docs/dataanalysistools/tools/mopex/mopexusersguide/18/)
    - Chebyshev polynomials express the *guide star* ephemeris in the guider
      - Requesting a similar set of polynomials expressing the *target ephemeris in RA, Dec* for use in creating MTWCS, locating target in images, etc.
  - Mosaicking algorithm must use the Moving-Target WCS (CRVALMT1, CRVALMT2), rather than the standard CRVAL data

Unique Aspects of Moving Target Data

- Coadding must account for target motion
  - Coadding in sky coordinates 'trails' the science target across the scene, destroying the benefit of telescope tracking (the HST pipeline way…)
  - Simple adaptation of WCS for moving targets allows standard mosiacking software to work

- Stars trail across images as the telescope tracks the target, causing:
  - Transient signal increases in integration ramps
  - Streaks in slope images if transients aren't corrected
  - Effectively higher and more structured 'background' due to stellar flux being spread out