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HST Observations in Support of JWST Calibration

James E. Rhoads[1]

Space Telescope Science Institute

Abstract. The James Webb Space Telescope will be NASA's flagship observatory in the next decade. Optimum science return on JWST will require high quality calibration. The Hubble Space Telescope offers unique capabilities that will be essential in achieving such a calibration of JWST. We outline a three-pronged approach for establishing JWST calibration targets using HST. First, ACS astrometry of a dense stellar field in the Large Magellanic Cloud will yield a set of faint astrometric standards that will always be in the JWST field of regard, allowing astrometric calibration whenever it may be needed. Such calibration will certainly be required during on-orbit shakedown, and may also be needed after JWST's periodic primary mirror figure adjustments. Second, new NICMOS spectrophotometry of K giants and main sequence A stars will be combined with existing NICMOS observations of DA white dwarfs and solar analogs to establish a diverse set of sepctrophotometric calibrator stars. These stars will serve as the basic flux calibrators for the JWST NIRSPEC instrument. Finally, NICMOS photometry of solar analog stars in nearby clusters will allow rapid photometric calibration of the JWST NIRCAM shortly after launch. The overall program is currently in implementation, using 19 orbits of HST time.

1. The James Webb Space Telescope

The James Webb Space Telescope (hereafter JWST) is an infrared-optimized, 6.5m diameter telescope with a planned launch date sometime in the next decade. JWST has an effective collecting area of 25m^2. The primary mirror is articulated to fit inside the launch vehicle. This requires a segmented mirror design which unfolds during early on-orbit checkout. The mirror figure can be adjusted by moving the mirror segments independently, and such adjustments may be carried out monthly or even more frequently depending on the realized stability of the mirror figure in orbit.

JWST will have four science instruments:

- NIRCAM, the Near Infrared Camera. NIRCAM is an imaging camera with wavelength coverage $0.7\mu m \leq \lambda \leq 5\mu m$. NIRCAM has two redundant modules, each covering a $2.2' \times 2.2'$ field of view. The fields of the two modules are approximately adjacent on the sky. Each module has two channels, a short wavelength channel ($\lambda < 2.5\mu m$) and a long wavelength channel ($\lambda > 2.5\mu m$). The channels are split by a dichroic, so they share the same field of view. NIRCAM has a selection of broad, intermediate, and narrow band filters, with resolving powers $5 \leq R \leq 100$. The NIRCAM short wavelength channel is critically sampled at $\approx 2\mu m$, and the long wavelength channel at $\approx 4\mu m$. NIRCAM has coronagraphic capability.

[1]Present address: Arizona State University

- NIRSPEC, the Near Infrared Spectrograph. NIRSPEC provides spectra over the range $0.7\mu m \leq \lambda \leq 5\mu m$. There are three separate dispersing element options, with resolving powers $R = 100$, $R = 1000$, and $R = 3000$. NIRSPEC has a microshutter array allowing simultaneous observations of many targets. Additionally, there are fixed slit and IFU options. The NIRSPEC field of view is about 3'.

- MIRI, the Mid Infrared Instrument. MIRI is a very flexible instrument, offering $5\mu m < \lambda < 27\mu m$ imaging, $5\mu m < \lambda < 14\mu m$ spectroscopy with R 100, and $5\mu m < \lambda < 27\mu m$ integral field unit spectroscopy with R 3000. The imaging channel offers coronagraphic capability in four channels, each optimized for a separate wavelength.

- FGS-TF, the Tunable Filter module on the Canadian Fine Guidance Sensor. The tunable filter module provides tunable narrowband imaging with $R \sim 100$ over a $2.3' \times 2.3'$ field, with a wavelength range $\sim 2\mu m < \lambda < 4.8\mu m$. It is critically sampled at $\approx 4\mu m$.

JWST poses some unique calibration challenges. For (spectro)photometry: JWST's wavelength coverage is very broad, and little of it is accessible from the ground. Saturation comes early (especially for sources that can be well observed in the mid-infrared with Spitzer).

For Astrometry: JWST has a "floppy" architecture: its astrometric solution may change comparatively quickly. Moreover, JWST has tight roll angle constraints. Combined, these factors mean that self-calibration of an astrometric field may not be possible with JWST: The best astrometric calibrations depend on observations taken at roughly perpendicular roll angles. Obtaining data at two such roll angles would require $\gtrsim 60$ days delay between epochs with JWST, and in that time, the geometry of the JWST detectors may have changed appreciably.

2. Astrometric Calibration Plans

JWST Astrometric Calibration Requirements:

- Field Distortion must be corrected to 5 mas accuracy, for all Science Instruments and the guider.

- Pixel scale for NIRCAM = 0.032 arcsec, i.e., finer than the ACS-WFC.

- There are also requirements on knowing relative placements of instruments in the focal plane. If HST can help address these, it will be with archival data that spans a wide field of view (e.g. GOODS, GEMS, or COSMOS).

JWST Field of Regard: JWST is a passively cooled telescope. A large sun shade prevents sunlight from falling on the telescope and instruments. The orientation of the sun shade with respect to the telescope is fixed. Thus, the requirement that the telescope always remain in shadow translates to restrictions on the JWST Field of Regard (i.e., the portion of sky accessible to the telescope at any given time). The net result is a minimum sun angle of 85°, and a maximum sun angle of 135° (i.e., a 45° exclusion zone around the anti-sun). Since JWST will be in an L2 orbit, the ecliptic poles become the continuous viewing zone; that is, any point within 5 degrees of either ecliptic pole will always be in the field of regard.

Suitability of Existing ACS Fields:

- Arbitrary ACS-WFC fields achieve accuracies of 5 mas (milliarcseconds) easily.

- < 2 mas is achievable if the ACS distortion is itself properly calibrated. The best way to verify this is by observations at multiple roll angles. (See, e.g., Pirzkal et al 2005, for astrometry of stars in the Ultra Deep Field.)
- Existing extragalactic deep fields: The UDF and similar fields are too sparse.
- Existing globular cluster fields are few, none are in the JWST CVZ, and they have other issues- brightness, stellar density gradients.
- Requirements for JWST astrometry fields: Stellar density (high!); Stellar brightness (faint!); Proper motions (small!); and Continuous availability a major plus.
- Conclusion: We need a well calibrated ACS field in the JWST CVZ.

Astrometric Observations Overview: We will establish a new astrometric field in the Large Magellanic Cloud, using 7 orbits of ACS WFC observations. The LMC offers several advantages. The stellar density is high, the field can be in the JWST continuous field of regard, and the distance to the stars is sufficiently large that proper motions between the time of the HST observation and the JWST launch will be negligible (or nearly so).

To get a suitable density of stars at a suitable brightness, it is necessary to go near the peak projected surface density of LMC stars. This is about 4° from the south ecliptic pole. Observations with a JWST integration time of a few minutes will then reach the depth required for optimum astrometry. This depth is just below the crowded field astrometry regime, where stars with measured signal to noise $s/n \gtrsim 100$ have a typical separation of order $\sim 10\times$ larger than the point spread function. The target flux level, $V \sim 23$, is also near the "knee" in the observed LMC luminosity function (Geha et al 1998). This minimizes the confusion effects due to stars too faint to be used as astrometric standards themselves (I.e., the number of stars at $V > 23$ is fewer than the extrapolation of the $V < 23$ number-magnitude relation for the field.)

The field will be observed at two roll angles, separated by about 90°. At the first roll angle, we will use a cross-shaped pattern with an edge-to-edge extent of 2 ACS fields. The second roll angle will cover just the central ACS field of view. Within each orbit, the ACS will be dithered on small to intermediate steps. In net, then, we will have sampled each point in the central ACS field of view with essentially every quadrant of the ACS WFC detectors, and at two widely separated roll angles, and with offsets of intermediate scales too. This will allow a lot of redundancy in solving separately for the celestial coordinates of stars and the distortion terms in the ACS WFC. The ACS WFC distortion information will be used to help achieve our ultimate goal, which is good astrometric data on the star field.

The precise field selected needs to account for the desired stellar density. It also needs to avoid stellar density gradients, dust, and edge of CVZ.

3. Spectrophotometric Calibration Plans

Overview:

- HST uses White Dwarf and Solar Analog calibrators.
- Spitzer/IRAC uses K giants and main sequence A stars.
- Spitzer finds a discrepancy between K and A stars (Reach et al 05).
- Planned observations will allow calibration of JWST using a wide range of spectral types, including primary standards for both HST and Spitzer.

- HST observations of 8 stars from Spitzer's primary standard and candidate standard lists will cross-calibrate HST and Spitzer.
- Including the Spitzer standards will also make the HST/NICMOS calibration more robust by broadening its base.

JWST Photometric Calibration Requirements: There is a requirement that JWST be capable of achieving data calibration into physical units with absolute accuracies shown in table 1.

Instrument	flux % (imaging)	flux % (coronagraphy)	flux % (spectroscopy)	wavelength (% of resolution element, spectroscopy)
NIRCAM	5	5	NA	NA
NIRSPEC	NA	NA	10	12.5
MIRI	5	15	15	10
FGS-TF	5	10	NA	10

Table 1: Photometric calibration requirements for JWST.

Suitability of Existing Spitzer / HST Data:

- Absolute spectrophotometric accuracy of Spitzer IRS is 5 to 10% (at launch + 1 year).
- This is adequate (just) for JWST spectroscopy, but not for photometry.
- Model spectra tied down by a suite of IR to optical (or UV) data can do better.

Overall Strategy for Spectrophotometric Calibration:

- Take calibrated models as "ground truth."
- Use multiple stellar types to overcome systematic uncertainties in models for any one stellar class: White dwarfs, solar analogs, K giants, A dwarfs.
- Use HST, Spitzer, and ground based data to (i) Select the best model for each star; (ii) show that there are no significant discrepancies between the stellar spectrum and this model; (iii) Adjust the instrument model if necessary, then iterate.
- Stellar astrophysics and detector physics suggest separate lists of standards for MIRI and NIRSPEC. All stars have nearly Rayleigh-Jeans spectra in the mid-IR, so that MIRI fluxes will be much lower than NIRSPEC fluxes. Moreover, MIRI will have a higher sky background, since zodiacal dust emits strongly at $\lambda \geq 5\mu m$.
- We want $\sim$ 16 spectrophotometric calibrators in total: (4 stellar classes) * (4 stars per class).
- Why 4 stars per class? To cover variations of T_{eff} , log(g), abundance patterns, reddening, etc. within each class.
- MIRI calibrators? Used over the wavelength range $5\mu m < \lambda < 28\mu m$. Hence, there is no urgent need for new data at $\lambda < 2.5\mu m$ here.
- FGS-TF calibration? Can use a combination of NIRSpec and NIRCam calibrators; a separate list probably not needed.

Planned Observations for NIRSpec Spectrophotometry:

- We have selected calibration targets from Spitzer IRAC calibrators and HST calibrators. These have suitable fluxes for NIRSpec.
- We need good calibration from optical to 5 microns, not beyond.
- HST NICMOS grism spectra have high priority here.
- Spitzer IRAC (3.5, 4.5, 5.8, 8 micron photometry) is vital too.
- Spitzer MIPS (mid-IR photometry) and IRS (mid-IR spectra) are optional.
- DA white dwarfs and solar analogs: HST spectrophotometric standards furnish 3 of each; no new HST data needed here.
- Calendar coverage about 80-85% with existing WD and solar analogs.
- A dwarf and K giant calibrators: Spitzer IRAC calibrators furnish ¿ 4 of each, in the JWST CVZ.
- NICMOS grism: $<$ One orbit/target gives $s/n > 100$ from $0.8\mu m$ to $2.5\mu m$. So, 8 orbits total for 8 targets.

The selected stars are all from the Spitzer standard stars listed in Reach et al 2005. All are in the JWST continuous viewing zone. They were chosen to have magnitudes $K_s \gtrsim 11$, and (within reason) to span a range of surface temperature for both the A dwarfs and K giants. The A star IDs (Reach et al) are 1740346, 1805292, 1743045, and 1812095. Those of the K giants are KF08T3, KF01T5, KF06T1, and KF06T2.

4. Photometric Calibration Plans

Ultimately, we would like to tie calibration of JWST imagers to the spectrophotometric calibration via JWST spectrophotometry of fainter sources, but that is a long-term process. It begins with calibration of the JWST spectrographs using the spectrophotometric standards described above, continues with using the JWST spectrographs to observe new standards that are too faint for HST and Spitzer, and ends with obtaining photometric observations of those new standards with the JWST imagers. (Note, the JWST imagers saturate on the spectrophotometric standards described above, and will saturate on anything that can be properly observed with the HST and Spitzer IR spectrographs.)

Meantime, we want some calibrated standard star fields that we can use for rapid on-orbit calibration of imagers.

Our program consists of 4 orbits of NICMOS photometry, to observe four Galactic clusters as calibration targets for JWST NIRCam. At least two of these will be observed with Spitzer IRAC, allowing cross-calibration among the three observatories.

Strategy for Photometric Calibration: Advantages of clusters:

- Many targets per field, hence, efficient.
- Clusters have uniform metallicity, age, distance, reddening =¿ Relevant model spectra are a one-parameter family.

Approach:

- Take good optical and IR photometry;

- Determine the spectral class of each cluster member;
- Use model spectra appropriate to cluster members to predict their fluxes in JWST passbands.

Role of HST and Spitzer:

- HST offers high photometric precision and stability.
- Spitzer offers, in addition, mid-IR wavelength coverage.

Existing and Planned Data for Photometric Calibration Clusters: NIRCam candidate calibration clusters include NGC 2420, NGC 2506, NGC 6791, and Melotte 66. These are good solar analog clusters: Their age is comparable to that of the Sun; their distance is large enough that a solar analog will not saturate NIRCAM in a minimal 10 second exposure, and their metallicity is also approximately solar.

Spitzer observations of NGC 6791 and Melotte 66 were planned last spring (George Rieke, private communication). NGC 6791 was observed, while Melotte 66 was not, due to a Spitzer safing event. At least one of these two clusters is always in JWST field of regard.

At present, ACS F606W and F814W data exist for NGC 6791, and WFPC2 F555W and F814W exist for NGC 2420.

Planned observations: Photometry One orbit of NICMOS photometry gets one or more field at $s/n \gg 25$ for Vega magnitude = 22 in F110W and F160W. So 4 orbits total would give a small set of faint standards suitable for early NIRCam calibration in each of these clusters. NIC2 will be the primary camera, due to its combination of adequate sampling and good photometric stability (Roelof De Jong, personal communication). This photometry will also improve NIRCAM-NICMOS cross calibration.

5. Summary

HST observations will play a key role in meeting JWST calibration requirements.

- HST astrometric observations are essential for JWST calibration.
- HST spectrophotometric and photometric observations will establish a stronger basis for JWST calibration.
- An affordable investment of HST time will save JWST observing time and reduce schedule risk in JWST commissioning.
- The planned observations will cross-calibrate HST, Spitzer and JWST; and can help make HST calibration more robust.

The total orbit budget allocated to this work is 19 orbits. Of these, Astrometry is 7 orbits with ACS, Spectrophotometry is 8 orbits with NICMOS, and photometry is 4 orbits with NICMOS. The observation planning is largely complete for astrometry and spectrophotometry, and is in progress for photometry. As the present author has now left STScI, the final stages of photometric calibration planning are being carried forward by Rosa Diaz-Miller and Ralph Bohlin. Observations for all programs should be obtained within the coming year.

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