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James Webb Space Telescope Calibration

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Abstract. The James Webb Space Telescope (JWST) is the planned successor to the magnificent Hubble Space Telescope and the smaller but remarkably powerful Spitzer Space Telescope. It will extend the Hubble and Spitzer science in many areas, ranging from the first stars and galaxies, to the current formation of stars and planets, and the evolution of planetary systems to conditions capable of supporting life. The JWST is a NASA-led project in partnership with the European and Canadian space agencies. The deployable cooled 6.5 meter telescope will cover the wavelength range from 0.6 to 28 μm with imaging and spectroscopy. With diffraction-limited image quality at 2 μm and and zodiacal background-limited camera sensitivity for $\lambda <$ 10 μm, the JWST will be the most powerful space observatory yet constructed. To enable the huge telescope to fit into the rocket fairing, it is very carefully folded up for launch. It has a primary mirror with 18 segments, each one able to be positioned with 6 degrees of freedom and a radius of curvature adjustment. While it is quite well protected from thermal variations, it is nevertheless expected that the JWST primary mirror may be readjusted on the order of every two weeks. This design enables a primary mirror larger than the rocket fairing, but also leads to very interesting calibration issues. In the years since JWST was conceived, the potential scientific benefits of greatly improved calibration and stability have become apparent. Now the challenge is to find ways to achieve those improvements with hardware that has already been designed. In this paper, I outline the basic issues and some strategies to pursue.

1. Introduction

Even before the launch of HST, a conference was held in 1989 at the STScI to consider possible successors, and the proceedings are very informative (Bély et al. 1989). The Next Generation Space Telescope (NGST) was NASA's response to recommendations of the report "HST and Beyond" (Dressler et al. 1996), which called for an IR-optimized telescope with an aperture of 4 m or more, along with equipment to study Earth-like planets around Sun-like stars. The NGST project was initiated in October 1995 with small studies that showed the amazing potential benefits of a large radiatively-cooled telescope operating far from the Earth. When NASA administrator Dan Goldin told the American Astronomical Society that NASA would build the recommended telescope but even larger, he received a standing ovation. The NGST was described along with the scientific motivations in the Black Book (Stockman et al. 1997). In 2000, the National Academy's Decadal Survey ranked NGST as top priority among large space missions. In 2002, The NGST was named for NASA's second Administrator James E. Webb to honor his leadership of NASA as we prepared the Apollo mission. For further details on the JWST history, please consult the web site: http://www.stsci.edu/jwst/overview/history/index_html.

More recent documentation includes the science team's report (Gardner et al. 2006), and the Arizona conference proceedings (Thronson et al. 2009). Many additional documents are available on line at http://www.jwst.nasa.gov and http://www.stsci.edu/jwst/, and in white papers (Google "JWST white paper"). Some early technical papers are at STScI (http://www.stsci.edu/jwst/externaldocs/technicalreports), and Casertano et al. (2001) gives an initial view of JWST calibration. See also SPIE articles (Google JWST NGST calibration SPIE). After more than two decades of calibrating HST, there are many good tools available that can be augmented and updated for JWST.

2. Instruments

The JWST carries four instruments and a fine guidance sensor sharing the focal plane. Some calibration, such as dark current measurements, will be done in parallel to science observations. The Near Infrared Camera (NIRCam) covers wavelengths from 0.6 to 5 μm in two bands separated by a dichroic filter. It has two modules providing side-by-side 2.2 arcmin square fields of view; the short wavelength channels are Nyquist-sampled at 2 μm, and the long wavelength channels at 4 μm. NIRCam is provided by the University of Arizona (M. Rieke, PI) with support from Lockheed Martin. NIRCam is also used for wavefront sensing, using thin lenses and diffraction gratings in the filter wheels, and using a special pupil-imaging lens. Detectors are 2048^2 pixel arrays of HgCdTe from Teledyne, with different cutoff wavelengths for the short and long wavelength channels. NIRCam provides coronagraphic spots using a thin wedge in the filter wheel.

The Near Infrared Spectrometer (NIRSpec) provides spectroscopy over the same wavelength range, using gratings and grisms to obtain spectral resolutions of 100, 1000, and 3000. NIRSpec uses a microshutter array located at an image plane to select up to 100 objects for simultaneous observation in a field of view of 9.7 square arcmin. Over 250,000 shutters are individually addressable by ground command. In addition, NIRSpec provides fixed slits and an integral field capability using image-slicing mirrors. The NIRSpec is provided by ESA with support from Astrium; the Project Scientist is P. Jakobsen. NASA provides the microshutter array (S. H. Moseley, PI) and the detector arrays (B. Rauscher, PI). These detectors are also from Teledyne.

The Mid IR Instrument (MIRI) provides imaging, integral-field spectroscopy, and coronagraphic capability from 5 to 28 μm over a field of view of 1.4×1.9 arcmin. The optical system is provided by a European consortium of many institutes, led by G. Wright of the UKATC, and the detector assembly is provided by the Jet Propulsion Laboratory using Raytheon Si:As detectors. G. Rieke (Arizona) co-leads the team with G. Wright. MIRI requires active cooling to about 7 K for detector operation.

The Fine Guidance Sensor (FGS) and the Tunable Filter Imager (TFI) are provided by the Canadian Space Agency. The FGS provides two modules with adjacent 2.3 arcmin square fields of view and generates position information for guide stars in its field of view. The TFI includes a tunable Fabry-Perot interferometer with a spectral resolution of about 100, covering the range from 1.6 to 4.9 μm.

The instruments are housed within the Integrated Science Instrument Module (ISIM). All of the instruments are in final preparation and are expected to arrive at Goddard Space Flight Center by October 2011 for integration into the ISIM.

3. Telescope

The JWST telescope uses a 3-mirror anastigmat design, to provide a much larger diffraction-limited field of view than a Cassegrain telescope. Its 6.5 m aperture produces a final f/20 image that is diffraction-limited at 2 μm after deployment and adjustment on orbit. The primary mirror is made with 18 hexagonal beryllium segments, lightweighted by removing 92% of the material to leave a triangular rib structure on the back of each piece, with the remaining material of order 2 mm thick. At the time of this writing, all of the primary mirror segments have been polished at room temperature, all have been measured cold, and one has been polished to final form and coated with gold. All the mirror segments, the secondary and tertiary mirror, and the fine steering mirror will be completed by September 2011.

4. Observatory and Orbit

The observatory combines the telescope, the ISIM, the spacecraft bus, and a giant sunshield to enable passive cooling of the telescope and instruments to about 40 K. The sunshield, roughly the size of a singles tennis court, uses 5 layers of metallized plastic to obtain a Sun Protection Factor of $>10^6$. The selected shape allows observation for lines of sight between 85° and 135° from the Sun, so that 35% of the sky is accessible at any one time. Telemetry to the Earth is handled by K_A band transceivers and a small parabolic dish, to relay 464 Gbit/day of data. Onboard command processors allow event-driven observations, following a sequence rather than absolute times, to improve efficiency of operations. Primary pointing is provided by applying torque to large momentum wheels in the spacecraft bus. The spacecraft bus also carries the compressors to operate a helium pulse-tube cooler for the MIRI.

The selected orbit is a large loop centered on the Sun-Earth Lagrange point L_2, about 1.5×10^6 km from Earth. This point, first found by Euler in 1750, moves around the Sun once a year with the Earth. The JWST avoids the shadow of the Earth. JWST will near its desired orbit about 2 months after launch, about the same time that the telescope and instruments reach equilibrium temperature. The orbit is unstable, so small jets are fired every few weeks to maintain it. The jets are also used to remove accumulated angular momentum (due to solar radiation pressure torques) from the wheels. Fuel is provided for 10 years of scientific observations.

5. Wavefront Sensing and Control

The JWST is deployed and focused after launch. There are many steps leading to final alignment, and all have been demonstrated through simulation and using a 1/6 scale telescope model. The final fine adjustment uses the same mathematics as were used to repair the HST. Stellar images are taken in focus and out of focus, and least-squares-fit algorithms compute the required mirror adjustments. The fitting algorithms use the fact that the electric field of an image is analytic in three dimensions, so that phase errors in the focussed image are related to amplitude changes in the out-of-focus images. The NIRCam provides the needed capabilities for this fine adjustment, but the earlier stages require the use of data from the other instruments as well, to ensure that large-scale (low-order) aberrations such as field curvature and field tilt are within specifications.

Periodic adjustment of the mirrors will be needed because the temperatures change slowly with time, with time constants of weeks to respond to changes of orientation relative to the Sun. In addition, as the orbit is 1.7% eccentric around the Sun, there is a 7% (peak-to-peak) variation of the incident solar radiation through the year. It is conceivable that experience will show us how to adjust the mirrors better and better, or that we could decide to optimize the focus for one instrument or another, according to the scientific objectives. Calculations suggest that optimizing the focus for just one point in the NIRCam field of view could give diffraction-limited imaging at 1 μm near that point, but this optimization could make the imaging significantly worse for the other fields of view.

6. Calibration Challenges

The JWST requirements for calibration accuracy were set several years ago. Photometric accuracy for NIRCam, MIRI, and TFI were specified at 5%, and spectroscopic flux accuracy was set at 10% for NIRSpec and 15% for MIRI. Much work has already been completed, generating error budgets to enable the construction of the needed tools and procedures. Calibration algorithms and data are to be provided by the instrument teams, and the STScI is to convert them into tools that run routinely on the flight data.

Since the JWST was conceived in 1995, the importance of calibration has dramatically increased. The discovery of the accelerating universe was based on a discrepancy of about 20% in the brightness of distant supernovae of type Ia. While this may seem to be a large effect, the proof requires comparison of extremely faint and redshifted objects with bright local standards at different wavelengths, and many types of non-ideal instrument behaviors must be calibrated or bounded. Also, the observation of transiting Earth-like planets around Sun-like stars requires exceptional (10 parts per million) photometric stability over the period of a day or so. The Kepler mission has achieved such stability, but it was custom-designed with that requirement foremost. The HST was designed without such a requirement, but has nevertheless been used to observe exoplanet transits and detect various atmospheric constituents.

A paper by Cohen (1998) says that there is a network of standard stars with $\pm 3\%$ accuracy, and outlines the problems to be overcome. The ACCESS sub-orbital mission will set up several NIST-traceable bright standard stars with $\pm 1\%$ accuracy (Kaiser et al. 2010.) There are some effects that can not be measured on the ground, others that can not be measured in flight, and some things that ought to be measured and usually are not. Papers by the Spitzer MIPS team (e.g. Engelbracht et al. 2007) give calibration factors based on standard stars, but with differences between approaches that are of order 1-2%. Can JWST achieve this or better photometry? That depends on addressing many challenges, such as:

- Faint target stars and galaxies. As JWST can observe fainter objects than any other telescope, by definition there is no experience in finding or utilizing a network of standards down to the 1 nJy level.

- Residual images. Tests show that the JWST detectors do have residual images after observations of bright objects, but they are much better behaved than many earlier IR detectors. Nevertheless the effects might be important after slews, or after intentional observation of bright objects. We do not know whether the residual images would have any effect in using dithered observations, where each dither pointing will still have a small after-image from the previous one.

- Detector nonlinearity. Our detectors store charges on capacitive pixels until they are read out, and each pixel may have its own linearity correction. These effects are substantial but presumably measurable through study of the time-dependence of the signals as we sample up the ramps.

- Detector reciprocity failure. This is a different effect, one in which the rate of arrival of the photons matters, instead of the total number in the pixel well. It can limit the ability to compare faint and bright objects, and it can make the response to a point source depend on the background light from zodiacal dust or stray light.

- Detector pixel response functions. While the JWST detectors are well-behaved there are detectable photometric effects based on where exactly a star is located relative to the pixel boundaries. These effects, if significant, might also differ across the face of each detector, or differ with wavelength.

- Detector sampling sequence. It is not unlikely that the calibration factors are detectably different if we change the timing of the sampling of the detectors; hence, the smaller the number of choices, the less work is involved in calibrating them.

- Cosmic ray removal. As we send back multiple samples of the detector signals through each integration period, we have the ability to recognize cosmic rays in the data and remove them. But we do not know whether the corrected data will have the same quality as those from pixels that are not hit by cosmic rays. There are possible nonlinear effects caused by the cosmic rays themselves, that might act as after-images and decay over long periods of time.

- Detector degradation with time. Our detectors are exposed to much higher doses of cosmic rays than those used in low Earth-orbiting telescopes. On the other hand, those in the Spitzer Space Telescope have held up well. Unlike CCDs, which suffer changes in charge transfer efficiency, all the JWST detectors operate with an amplifier for every pixel. Hence, cosmic ray damage is expected to be localized in the form of "hot pixels".

- Point spread function variation in time. We have an official specification: "SR-13: Encircled Energy Stability. The total encircled energy of an image of a point source over the FOV of the Near-Infrared Camera within a circle of 0.08 arc-second radius and at a wavelength of 2 micrometers shall be stable to better than 2.0% over a period of 24 hours without intervention by ground command." Proving that we will meet this specification has been very challenging, and it is possible we will have to loosen this specification to match what can be built and promised. On the other hand, the worst case variations probably occur very infrequently, and typical performance may be much better than this specification. Temperature variations or other effects may change the telescope image quality over week time scales, and periodic adjustments to optimize the image quality may divide the calibration data files into many subsets. The image quality also varies strongly across the field of view of each instrument, and with wavelength. While this part of the problem may be well modeled by physical optics, we must certainly account for it, and users must be aware of it.

- Multi-slit spectroscopy with microshutters. No microshutter instrument has been built before NIRSpec, so we have no practical experience with the challenge of hundreds to thousands of slit functions for every observation. We are also not able to place each target in the middle of a slit, so we must learn to cope with this by observing strategies (dithering, etc.), modeling, or inclusion of slit-loss errors in the analysis.

- Spectral response functions. All the filters in the instruments have been measured before they are integrated into the instruments, but some may change with age, launch vibration, or cryo-cycling. The gratings and grisms are supposed to be well understood, but we will have to know how close the spectral responses are to the calculated ones. Spectral stray light (spectral purity) might be an issue with our complex optical systems.

- Vibrations. The JWST spacecraft bus contains momentum wheels and refrigerator compressors that run all the time, along with the telemetry antenna, which is adjusted occasionally, and the jets, which fire infrequently but cause significant disruption of observations. The wheel vibrations change with time as the wheels change speed, and at some speeds the vibrations will be amplified by mechanical resonances in the spacecraft or telescope. Although the effects on the point spread function are required and predicted to be small most of the time, they may be detectable sometimes. These vibrations may limit the ability of the JWST to do transit spectroscopy on exoplanets.

- Fine (fast) steering mirror. This small flat mirror, located at the image of the primary mirror formed by the tertiary mirror, is the core of the pointing control system. It responds immediately to the error signals from the fine guidance sensor. Its range of motion is small, but there is one important effect: differential image distortion. The mirror servo acts to keep the guide star on its required location in the FGS field of view, but all other parts of the telescope field suffer tiny residual motions. While the specifications show that this effect must be extremely small, there may be observations where the effect can be detected. There is another effect as well: noise from the fine guidance sensor is partially tracked by the fine steering mirror, and hence the effect on the PSF depends on the brightness and color of the guide star.

- Steep off-axis optics. The focal surfaces of the instruments are significantly curved and tilted, the plate scale (arcsec/pixel) is not constant across the fields of view, and circular images become ellipses. While this is purely geometrical optics and well understood in principle, we can anticipate that some studies of weak lensing and cosmic shear might still suffer from errors in this area.

- Optical contamination. We do not expect signifiant changes of the dust coverage or condensed volatile materials during the JWST mission, because the sources are all supposed to be on the warm side of the sunshield, with no way to reach the telescope or instruments. Nevertheless we will need to be alert to changes. Micrometeoroid pits on the primary and secondary mirrors will increase gradually with time but are predicted to cover only 0.1% of the primary mirror after 10 years.

- Stray light and zodiacal light. These sources of light are not supposed to influence the point source photometry, but they do influence the noise and if the detectors are nonlinear, or have reciprocity failure, they might also affect the calculated source brightness. We need to look for this possibility by comparing photometric fields taken under different stray and zodiacal light levels. We also have to be alert to structure in the stray light, due to some undesired path like the "rogue path" in which unfocused light from the sky goes past the baffles all the way to the detectors.

7. Astrometry

Much work has already gone into plans for astrometric calibration for JWST. Good astrometry is essential to placing spectrograph slits or coronagraph spots in the right place. Astrometric reference fields have already been calibrated by HST and will be ready for use by JWST. The stability of the astrometric calibration for JWST can be readily checked, and there are no known factors expected to make it change much. There is significant potential for scientific discovery based on JWST astrometry: follow-up of microlensing planet observations may be able to measure image deflection as well as amplification, proper motion studies of newly discovered brown dwarfs, etc.

8. Summary and Conclusions

We are preparing to calibrate the JWST, both photometrically and astrometrically, but there are many interesting effects due to the extreme sensitivity (ability to observe sources that are far fainter than any calibration standards), and the potentially variable PSF due to changes in the temperature of the segmented primary mirror.

9. Acknowledgments

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