Overview of James Webb Space Telescope and NIRCam's Role

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ABSTRACT

The James Webb Space Telescope (JWST) is the scientific successor to both the Hubble Space Telescope and the Spitzer Space Telescope. It is envisioned as a facility-class mission. The instrument suite provides broad wavelength coverage and capabilities aimed at four key science themes: 1)The End of the Dark Ages: First Light and Reionization; 2) The Assembly of Galaxies; 3) The Birth of Stars and Protoplanetary Systems; and 4) Planetary Systems and the Origins of Life. NIRCam is the 0.6 to 5 micron imager for JWST, and it is also the facility wavefront sensor used to keep the primary mirror in alignment.

Keywords: NIRCam, James Webb Space Telescope, JWST, near-infrared

1. INTRODUCTION

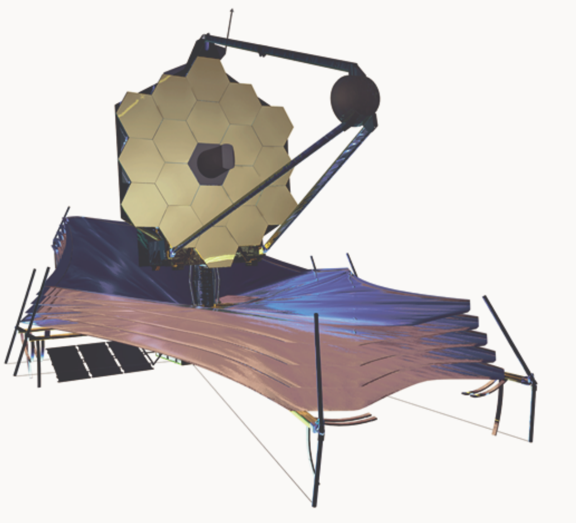

Figure 1: Deployed view of JWST.

The James Webb Space Telescope (JWST), named for the NASA Administrator who directed the agency during the Apollo era, has been conceived as the scientific successor to both the Hubble Space Telescope (HST) and to the Spitzer Space Telescope. To answer the scientific questions posed by these two antecedent missions requires a very capable telescope. A large collecting area is needed to probe beyond the limits reached by Spitzer and Hubble. Available launch vehicles cannot carry a sufficiently large primary mirror unless the mirror can be folded, which has led to an innovative, segmented design for JWST's primary mirror. The mirror must be aligned on-orbit. To achieve the sensitivity required for its science goals, JWST must operate near 35K which in turn requires an orbit far from Earth and a large sun shield. Figure 1 shows the fully deployed JWST, including its sun shield. The instruments are mounted to the Integrated Science Instrument Module (ISIM), which is located behind the primary mirror.

1.1. JWST's Science Program

1) First Light: The first science goal to be defined for JWST is that of finding the light from the first objects to coalesce after the Universe has cooled after the Big Bang[1]. The potential of JWST for studying distant sources has prompted a number of theoretical studies predicting the properties of the first stars, which may be quite different from stars forming today because of the lack of any elements heavier than helium[2]. These calculations show that a plausible JWST cannot literally detect an isolated first star -- it misses by a least a factor of a 1000 in sensitivity. However, if stars form in clusters or small galaxy sized aggregates, then a realistic JWST with a suitable imager should readily detect such objects. The telescope and instruments must be designed to detect objects whose output is but a few nJy (1 nJy = 10^{-35} Watts/m^2/Hz). Another requirement placed on the telescope and its instruments by this goal is that of being an infrared

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telescope. The first galaxies formed at an early time, perhaps only a few 100 hundred million years after the Big Bang. The expansion of the Universe shifts light to redder wavelengths as more distant objects are observed, and consequently, to observe the first galaxies, one must observe at wavelengths longer than one micron. A complicating factor is absorption by hydrogen atoms along the line of sight to distant galaxies, which absorb photons at wavelengths shorter than Lyman α at 0.1216 μm. Galaxies have now been found at redshifts as high as 7 so observations at wavelengths longer than 0.97μm are needed to counter this effect. The first galaxies may lie at redshifts of 10-15 so proportionately longer wavelengths must be used, and wavelength coverage beyond 5μm is required to prove that an object is indeed a first light object. Broad wavelength coverage will be needed to characterize these source whose properties can be predicted to some extent if they are comprised of stars, but whose spectral energy distributions could have several components if they harbor black holes.

The first light objects may be the light sources that reionized the hydrogen gas leading to the state of the Universe we see today. Current data from WMAP and Sloan Survey quasars suggest that the Universe may have been reionized twice, once around z~20 and again around z~7-8. JWST will be needed to find such objects. See Loeb and Barkana[3] for a review of the early galaxy population and reionizing sources. Definition of when reionization occurs is most easily done using spectroscopy so JWST should be equipped with both imaging and spectroscopic capabilities.

2) Assembly of Galaxies: The same observational drivers that define the first light search also support detailed study of how galaxies are assembled **--** in other words, how do galaxies change from first light objects to the suite of morphologies and galaxy types that we see today. This study also imposes a requirement for high spatial resolution to distinguish when the shapes of galaxies are established. The geometry of the Universe imposes a nearly constant conversion between linear size and angular scale at redshifts above ~1, with a linear size of 1 kiloparsec, a typical scale length for structures in galaxies, translating to 0.1 arc sec. The Airy limit at 2μm of a telescope with a 6.5-meter mirror is 0.077 arc sec so this requirement sets a lower limit on the primary mirror diameter.

To understand how today's galaxies have evolved from first light objects requires more knowledge than can be provided by imaging alone. Spectroscopy will be needed for a sample of galaxies spanning the redshift range from today back to the first galaxies that can be identified. The sample will also need to cover the range of galaxy sizes and characteristics in each redshift bin. These requirements imply that JWST needs to take many galaxy spectra simultaneously or such a survey would take a prohibitive amount of time. JWST's spectrometer needs a multi-object capability and must have sufficient spectral resolution to separate diagnostic spectral lines used for estimating heavy element content and star formation rates, R~1000. If possible, adequate resolution for measuring masses from velocity dispersions would be extremely valuable, R~3000.

3) The Birth of Stars and Protoplanetary Systems: A good framework is in place for understanding how stars form and how they may form planetary systems, but a number of key steps in the process are not understood. JWST will work to unravel the birth and early evolution of stars, from infall onto dust-enshrouded protostars to the genesis of planetary systems. JWST needs to provide high sensitivity and high spatial resolution over a span of wavelengths that can penetrate the clouds enveloping the early stages of star formation and that can penetrate large column densities along the lines of sight through our galaxy.

Physical parameters such as the density profiles of collapsing clouds have yet to be determined unambiguously because submillimeter wavelengths are sensitive only to the dust emission. JWST will be able to measure dust absorption optical depths through the centers of the densest cloud cores by observing background stars shining through the cloud. The prime wavelengths for this type of study are from 3μm to 10μm.

Another area where our understanding of the star formation process is deficient is in understanding how clouds fragment. The fragmentation process determines the initial mass function (the distribution of stars over mass). A number of parameters such as chemical composition, dynamical state of the cloud, and clumpiness may determine this function. Current data sets have probed a limited range of conditions in our own galaxy and have only been able to measure the initial mass function for the most massive stars in other galaxies. JWST will be able to measure the initial mass function to much lower masses than have been reached previously in other galaxies and will be able to measure the full initial mass function anywhere in the Milky Way. In addition, JWST will be able to probe the distribution of masses for sub-stellar objects, which should shed light on the connection between brown dwarfs and bonafide planets.

Other issues in the star formation process such as how early protostars collapse, how the formation of massive stars affects their environment, how protostars form disks, and how the star formation process is linked to the chemical evolution of a cloud are also ripe for study. A common thread to these issues is the need for high spatial resolution data in the 5-28μm range, both imaging and spectroscopy. Another common thread is the desire to take advantage of the windows in the dust absorption in the Milky Way near 7μm and near 15μm.

4) Planetary Systems and the Origins of Life: Recent discoveries of many exosolar planets lends impetus to programs designed to characterize them. Equally important is developing an understanding of how planetary systems form, and what determines the numbers and arrangements of planets in a system. Spitzer discoveries of how debris disks, the likely remnants from planetary system formation, decay with time [4] is a good illustration of how the observation of these disks tie in to the solar system and hence to planetary systems in general. JWST will be an excellent platform for studying these low surface brightness objects with a high sensitivity mid-infrared imager. JWST will also provide a wealth of information on the surface compositions and albedos for Kuiper Belt Objects in the solar system, which will facilitate comparing what happens in debris disks with what is seen very locally. Imaging and spectroscopy in the near infrared are needed to measure absorption features from a variety of ices, and mid-infrared observations are needed to image the disks.

Figure 2: JWST folded up for launch inside the Ariane V shroud. Part of the folded sunshield is not shown to permit viewing of the telescope.

Burrows et al. have illustrated that Jupiter-size and larger planets will have a distinctive ratio of fluxes at 2.7μm to that at 4.6μm, with planets being much brighter at the longer wavelength[5]. Thus, coronagraphic imaging at these two wavelengths should be very efficient at finding planets. Background stars will be easy to differentiate from planets because most stars will be brighter at the shorter wavelength. Coronagraphy at longer wavelengths may be even more powerful because of the better contrast ratio between planet light and star light. A JWST planet search program will begin to answer questions about the frequency of giant planets, their orbital characteristics, and the nature of the planets themselves.

1.2. Launch and Deployment

JWST will be launched using an Ariane V rocket provided by the European Space Agency. Figure 2 shows the telescope inside the launch shroud. JWST's final orbit is to be at L2, an acceptable compromise between a cold thermal environment and the need to telemeter large amounts of image data to the ground. After launch, JWST and its sunshield will be deployed while the spacecraft is still relatively warm[6]. During the cruise phase to L2, the telescope and instruments will cool to reach their eventual operating temperature of ~35 K. The first steps in aligning the telescope may be done before the telescope and instruments are fully cold. The steps of locating images from the 18 separate segments does not require good image quality and only modest stability.

1.3. JWST Operating Environment

As described in Section 1.1, the science goals for JWST dictate that it be an infrared telescope. High performance detectors for the 0.6 - 5μm range need to be cooled below 40 K to reduce dark current and read noise. An L2 orbit and a good sun shield will allow passive radiators to cool the ISM enough that active cooling is needed only for detectors operating at wavelengths longer than 5μm. The performance of the sun shield and the cooling of the outer shell of Spitzer validate the prediction that JWST detectors can be cooled to ~35 K passively.

The radiation environment at L2 has been probed by both the WMAP satellite and essentially by Spitzer. Appropriate levels of shielding are needed to reduced the cosmic ray flux to ensure the survival of both detectors and electronics.

2. JWST INSTRUMENTS

To pursue the science goals described in Section 1 requires a broad suite of instrument capabilities. Table 1 gives the characteristics of the four JWST science instruments. Two of the instruments, NIRCam and FGS/TF, also have facility roles. The FGS/TF is the fine guidance sensor in addition to providing R~100 imaging through tunable filters and its role in guiding is described in Section 2.3. NIRCam is described in Section 3 and its role in wavefront sensing is described more in Section 4.

Instrument	Wavelength Range (µm)	Spectral Resolution ($\lambda/\Delta\lambda$)	Field of View (arc minutes)	Detector Type	Comments
NIRCam	0.6-5	4, 10, 100	2 x 2.2'x2.2'	HgCdTe 2Kx2K	Facility Wavefront Sensor Dichroics used to observe 2 λs simultaneously
NIRSpec	0.6-5	100, 1000, 3000	3.4' x 3.6'	HgCdTe 2Kx2K	Mulit-object spectroscopy provided by programmable slit mask
MIRI	5-28	~5, ~2000	1.9' x 1.4'	Si:As 1Kx1K	Imager and spectrometer Cryocooler used for detectors
FGS/TF	1-5	1.5, 100	3 x 2.2'x2.2'	HgCdTe 2Kx2K	Dichroics used to observe 2 λs simultaneously

Table 1: Characteristics of JWST Instruments

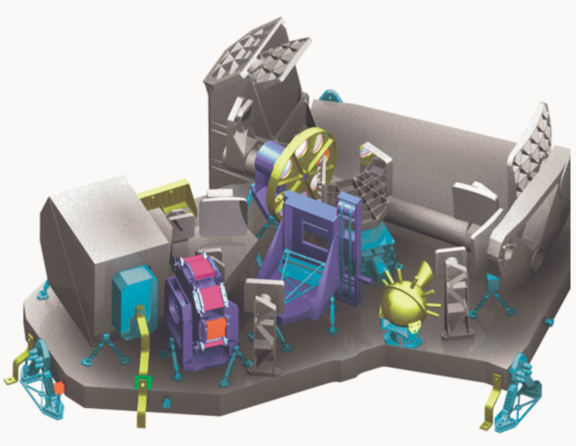

Figure 4: A view of NIRSpec with its outer shroud removed. The grating wheel is visible on the left while the MSA and feed optics are in upper right.

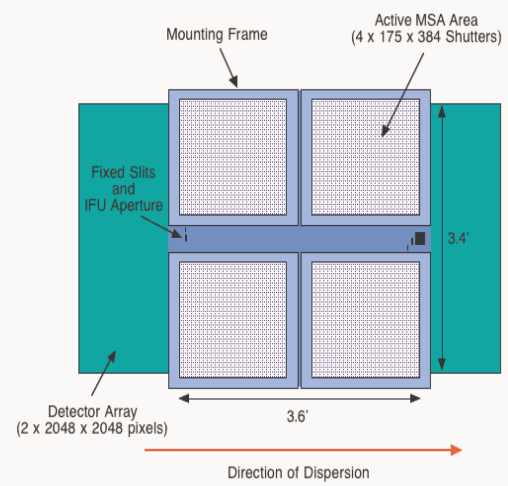

Figure 3: Arrangement of the multi-slit assembly and fixed slits in NIRSpec.

2.1. NIRSpec

Near infrared spectroscopy for JWST is provided by NIRSpec, which is being developed by the European Space Agency (ESA). Detectors and the slit selector are being supplied to ESA by Goddard Space Flight Center. A driving requirement for NIRSpec is the need to acquire >100 spectra at once. Groundbased spectrometers typically use fibers and positioners or drilled plates, one per field, for such a multi-object capability. Neither of these choices is satisfactory for space use so a programmable array of microshutters has been developed[7].

NIRSpec provides a choice of two spectral resolutions in multi-object mode, R~100 and R~1000. The higher resolution mode is the optical choice for the study of the assembly of galaxies. NIRSpec will also have an R~3000 mode in an integral field unit with a field of view ~2"x2". This will enable measurement of galaxy masses. NIRSpec also includes fixed slits to be used either as a back-up or for dim objects close to brighter objects where the microshutter array may not provide adequate rejection of scattered light. Figure 4 shows the slit layout for NIRSpec.

2.2. MIRI

Mid-infrared imaging and spectroscopy are provided for JWST by MIRI. MIRI is being developed jointly by a European consortium led by the United Kingdom Astronomy Technology Center which has responsibility for the optical bench and the Jet Propulsion Laboratory which has responsibility for the detectors and cooler. MIRI's detectors need to operate below 7K so more cooling is needed than can be achieved with a passive radiator system, and the extra cooling will be supplied by a cryocooler.

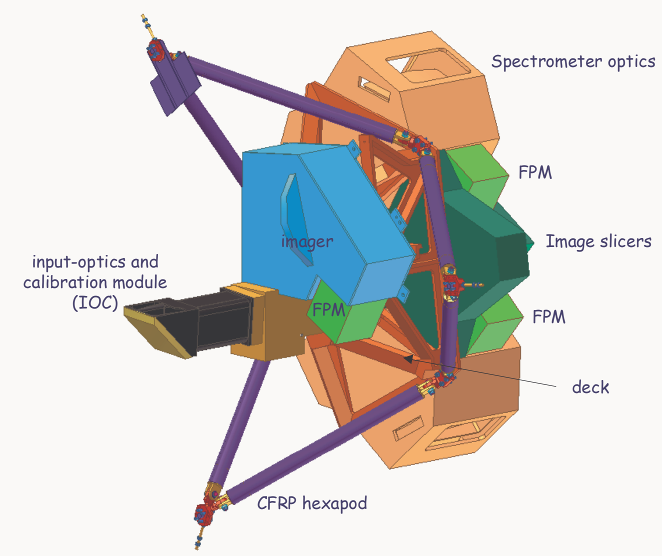

Figure 5: The MIRI instrument including its struts for mounting in the ISIM. The detectors are located in the boxes labeled FPM, Focal Plane Module.

Figure 5 shows the layout of MIRI with its imager on one side of its deck and the spectrometer modules on the other. MIRI's spectrometer is configured as four integral field units to cover the spectral range from 5 to 28μm. The field of view scales from 3.5"x3.5" at the short wavelength end to 7"x7" at the long wavelength end.

Planet detection is an important science program for MIRI and it will be equipped with two types of coronagraph, a traditional focal plane mask and a phase mask[8]. The phase mask has the advantage of being able to observe closer to the central source in the region where the traditional mask is opaque. It has the drawback of working over only a limited spectral range so MIRI will have several phase masks to provide a wavelength choice.

2.3. FGS/TF

The Fine Guidance Sensor/Tunable Filter (FGS/TF) is being provided by the Canadian Space Agency. Because JWST is a large and not very rigid structure, tracking targets to the accuracy required for diffraction limited imaging cannot be accomplished through changing the pointing direction of the entire structure. The optical train of the telescope is configured as a three-mirror anistigmat which provides a location for a fine steering mirror at a pupil. Tracking is achieved by imaging a guide star with the FGS on an array identical to the ones used in NIRCam and NIRSpec. A centroid is measured and an error signal is generated and fed to the fine steering mirror. The spacecraft's body pointing is updated as needed to keep the mirror within its range of travel.

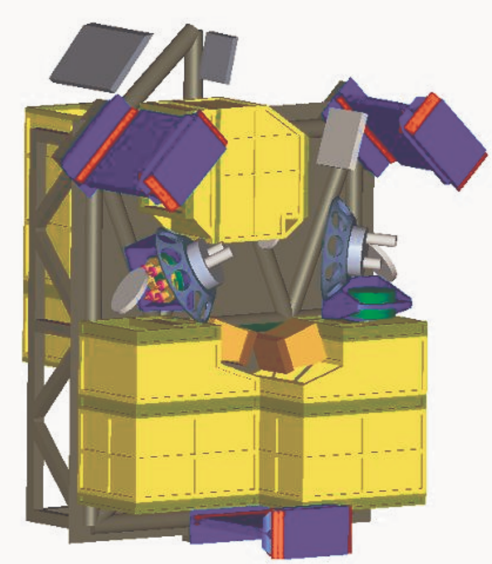

Figure 6: A view of the tunable filter side of FGS/TF. One of the TFs is visible on the right adjacent to a filter wheel.

The other half of the FGS/TF is shown in Figure 6. This portion of the instrument has the same field of view as one half of NIRCam. A dichroic is used to view this field by using short wavelength and long wavelength tunable filters simultaneously. These filters have R~100 and also include a coronagraphic capability. The etalons of the tunable filters are controlled by a piezoelectric drive[9]. The matching of field of view with NIRCam and the ability to select a wavelength of interest enables a search for high redshift galaxies with large equivalent widths in Lyman-α that might not otherwise be readily distinguished. By observing a field in NIRCam and one with the FGS/TF, a robust survey for first light and re-ionizing sources can be carried out. The long wavelength channel of the FGS/TF will be used to study redshifted H-α in galaxies to learn the spatial distribution of star formation within galaxies, one of the keys to understanding galaxy assembly. The long wavelength channel of FGS/TF and its coronagraph will be very useful for discovering and characterizing extra-solar planets, which are relatively bright at these wavelengths[5].

3. NIRCAM'S ROLE AS A SCIENCE INSTRUMENT

NIRCam's imaging from 0.6-5μm supports the four JWST science themes in a variety of ways. A common element in NIRCam's usage is ensuring that the diffraction limited output of the telescope is recorded with minimal degradation. Another common thread is the need to cover some area on the sky -- not square degrees but large enough areas to avoid cosmic variance when executing extragalactic surveys and large enough to cover star clusters efficiently for star formation surveys. Figure 7 presents the layout of one half of NIRCam: the other half is a mirror image, and the two halves are bolted together. Key elements for science imaging are a dichroic beamsplitter to enable imaging of one section of sky at two wavelengths simultaneously, filter wheels with 12 slots each, and focal planes with 4Kx4K pixels in the short wavelength arm and 2Kx2K pixels in the long wavelength arm. Fewer pixels are needed at the longer wavelengths for proper sampling of the diffraction limit.

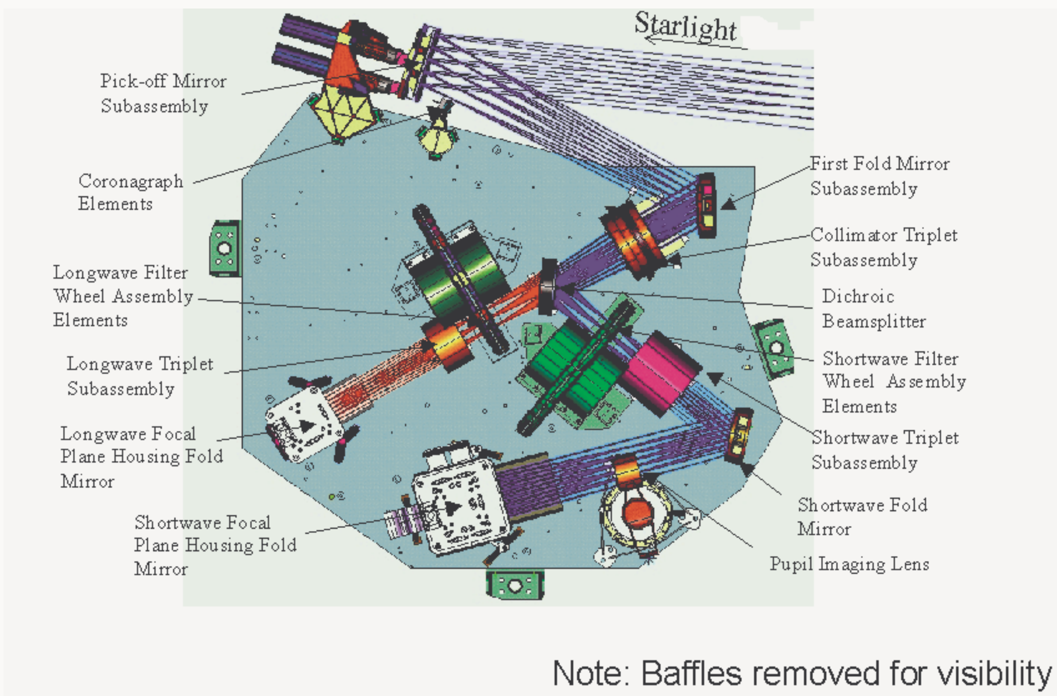

Figure 7: Optical layout of NIRCam. The instrument consists of two of these assemblies bolted together.

NIRCam's tasks for each of the science themes can be summarized as follows. For the End of the Dark Ages: First Light and Reionization, NIRCam's principal activity is executing deep surveys of the sky with enough wavelength coverage to estimate photometric redshifts. Section 1 shows that high sensitivity is paramount if “First Light” galaxies are to be detectable. If the first light objects that are within JWST’s light grasp are rare, then a premium is also place on field of view to ensure surveying enough area to find such objects. Photometric redshifts rely on using enough filters that fitting of the spectral energy distribution will yield the redshift. NIRCam’s filter selection has been optimized for redshift measurement.[10] For the Assembly of Galaxies, NIRCam must find galaxy samples that can be defined well enough in terms of redshift, morphology, and luminosity that spectroscopic surveys can be executed efficiently. The requirements for this task overlap those for first one with the addition of high spatial resolution for categorizing galaxy morphologies.

For the Birth of Stars and Protoplanetary Systems theme needs data on stars in stellar clusters and on forming stars in cloud cores. To achieve the science goals described in Section 1.1 requires that NIRCam have high sensitivity, especially at wavelengths longer than 3μm. A field of view large enough to cover most of a star cluster or dark cloud core in one exposure will maximize efficiency, at least 2 arc minutes is required. NIRCam must also have a high dynamic range to cope with the range of brightnesses seen in a star cluster. A range of filters including medium and narrowband are needed for characterization of conditions in star formation regions, in circumstellar disks, and in jets emanating from protostars.

For Planetary Systems and the Origins of Life, NIRCam will use its coronagraphic images to characterize disks and planets, and it will classify surface properties of Kuiper Belt Objects. To gather the data required for this theme, NIRCam's coronagraphic mode must be able to use a selection of filters. NIRCam will also need filters capable of determining which ices dominate on the surfaces of outer solar system bodies as well as in debris disks.

4. WAVEFRONT SENSING AND PRIMARY MIRROR ALIGNMENT

As mentioned earlier, the need for a large area primary mirror combined with launch restrictions has dictated that JWST employ a segmented primary mirror. The mirror consists of 18 beryllium hexagons each of which is equipped with actuators for controlling tip, tilt, focus, x position, y position, and limited radius of curvature control. The telescope will be aligned and phased using imagery from NIRCam. Routine maintenance of the telescope figure will also rely on NIRCam imagery.

4.1. Basic Strategy

The JWST primary and secondary mirrors must be aligned after launch [11,12]. The primary mirror will be unfolded and the secondary mirror tripod extended within a few days of launch following sun shield deployment, while the structure is still warm. After the mirrors are in their basic positions, the next step in alignment will happen after the structure and instruments have cooled substantially. The first step in the process is to locate all 18 images from the 18 primary mirror segments. This step can take place before the final operating temperature is reached as good image quality is not needed. Once all 18 have been found and identified, the mirror segments will be commanded to place the images in a predefined pattern. Once the mirrors and NIRCam are close enough to operating temperature, the secondary mirror can be moved to the best average focus. The individual mirror segments will then be moved to optimize their focus settings.

The goal of the wavefront sensing process is a primary mirror that functions as though it were a monolithic mirror with a wavefront error as seen though NIRCam of no more than 150nm to ensure diffraction-limited performance. To achieve this performance, the mirror segments must be positioned so their wavefronts are phased. The phasing is done in two steps. The coarse phasing step uses grisms[13] to measure the interference between the wavefronts from two mirror segments. Pairwise measurements produces a primary mirror alignment adequate for the next step. The final or fine phasing step uses focus diverse phase retrieval to determine the segment motions needed to reduce the wavefront error below the 150nm requirement. The fine phasing step is repeated at intervals as needed.

4.2. NIRCam's Role as a Wavefront Sensor

NIRCam must record all images needed for the alignment process described in Section 4.1.The short wavelength arm of NIRCam will be used for wavefront sensing. It must include any grisms, filters, and lenses needed for the alignment steps and must be able to position these elements accurately enough and repeatably enough into the optical train that the 150nm wavefront can be produced. The aggregate of these requirements demands that NIRCam have two wheels for optical elements: a pupil wheel carrying grisms and some weak lenses and a filter wheel carrying band limiting filters for the grisms and an additional weak lens. The weak lenses are used for the focus diverse phase retrieval[14]. NIRCam's wheels also need higher positioning accuracy than usual in an astronomical camera. NIRCam's own optical train must have a wavefront error that is either very small or sufficiently stable and known that it can be removed from the wavefront correction process. If these conditions are not met, NIRCam's wavefront error will be imprinted in reverse on the primary mirror, and although this would produce well-correct images for NIRCam itself, the other instruments would see a worse wavefront.

NIRCam includes two additional features to aid in alignment and wavefront correction. As shown in Figure 7, NIRCam's pick-off mirror has a three degree-of-freedom mechanism that moves the pick-off mirror in focus, tip and tilt.

This mechanism will aid in aligning NIRCam's pupil with the exit pupil of the telescope, important both for sensitivity and wavefront sensitivity. Figure 7 also shows that NIRCam can insert a pupil imaging lens to record pupil illumination patterns and to check alignment – either between NIRCam and the telescope or of elements in NIRCam's wheels. Last, NIRCam's role as the facility wavefront sensor and its use to align the telescope initially requires that NIRCam have a high degree of reliability. This reliability has been assured by NIRCam's being comprised of two identical modules, either of which can act as the wavefront sensor.

5. SUMMARY

JWST aims to achieve science goals that can never be reached from even the largest envisioned groundbased telescopes. It will be equipped with four instruments capable of studying the 0.6 to 28μm region using both imaging and spectroscopic techniques. NIRCam will serve as a wavefront sensor to align the large, segmented primary mirror needed for the sensitivity and spatial resolution demanded by JWST's science goals.

Acknowledgements

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References

1. A. Dressler et al., "HST and Beyond, Explorations and the Search for Astronomical Origins: A Vision for Ultraviolet- Optical- Infrared Space Astronomy", AURA, 1996
2. Bromm, V. and Larson, R. B., "The First Stars", Annual Review of Astronomy and Astrophysics, Vol. 42: 79-118 , 2004
3 . Loeb, A. and Barkana, R., "The Reionization of the Universe by the First Stars and Quasars",Annual Review of Astronomy and Astrophysics, Vol. 39: 19-66, 2001
4. Rieke, G. H.; Su, K. Y. L.; Stansberry, J. A.; Trilling, D.; Bryden, G.; Muzerolle, J.; White, B.; Gorlova, N.; Young, E. T.; Beichman, C. A.; Stapelfeldt, K. R.; Hines, D. C., "Decay of Planetary Debris Disks", ApJ, Vol. 620: 1010-1026, 2005.
5. Burrows, A., Sudarsky, D., and Lunine, J. "Beyond the T Dwarfs: Theoretical Spectra, Colors, and Detectability of the Coolest Brown Dwarfs", ApJ, Vol. 596: 587-596, 2003.
6. Deployment video available at http://ngst.nasa.gov/Multimedia/.
7. Li, Mary J. et al. ,"Microshutter Array Development for the James Webb Space Telescope", Proc. SPIE, Vol. 5650: 9-16, 2005.
8. Boccaletti, A., Riaud, P., Baudoz, P. Rouan, D., Baudrand, J., and Lagage, P.O., "Observations of Exoplanets with JWST/MIRI", 35th COSPAR Scientific Assembly, p.2123, 2005.
9. Scott, Alan D., Norman, Rodney, and Zhou, Liping, "Tunable Etalons and Other Applications of Low-Voltage Piezoelectric Instrument Control Electronics", Proc. SPIE, Vol. 5492: 1755-1762, 2004.
10. Rieke, M. Baum, S., Beichman, C., Crampton, D., Doyon, R., Eisenstein, D., Greene, T., Hodapp, K.-W., Horner, S., Johnstone, D., Lesyna, L., Lilly, S., Meyer, M., Martin, P., McCarthy, D., Rieke, G., Roellig, T., Stauffer, J., Trauger, J., Young, E., "NGST NIRCam Scientific Program and Design Concept", Proc.SPIE, Vol 4850: 478-485, 2003.
11. Redding, D. C., Basinger, S. A., Cohen, D., Lowman, A. E., Shi, F., Bely, P. Y., Bowers, C. W., Burg, R., Burns, L. A., Davila, P. S., Dean, B. H., Mosier, G. E., Norton, T. A., Petrone, P., Perkins, B. D., Wilson, M., "Wavefront Control for a Segmented Deployable Space Telescope", Proc. SPIE, Vol. 4013: 546-558, 2000.
12. Atcheson, P., Towell, T., Quigley, P., "Segmented Aperture System Wavefront Error Sensing and Correction Experiments At BATC", Proc. SPIE, Vol. 3785: 38-47, 1999.
13. Shi, F., Chanan, G., Ohara, C., Troy, M., Redding, D., "Experimental Verification of Dispersed Fringe Sensing as a Segment Phasing Technique using the Keck Telescope", Applied Optics IP, Vol. 43: 4474-4481, 2004.
14. Atcheson, P., Acton, S., and Lightsey, P., "Instrument-level Phase Retrieval Wavefront Sensing and Correction for Astronomical Telescopes", Proc. SPIE, Vol. 4839: 228-239, 2003.