Title: Coarse Phasing JWST using Dispersed Fringe Sensing and Dispersed Hartmann Sensing during Commissioning

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### 1.0 Introduction

Commissioning of the JWST telescope is envisaged to take place during the ~90 day transit from the vicinity of the Earth to L2, the outer co-linear Earth-Sun unstable Lagrangian equilibrium point near the Earth. In this time interval the primary mirror (PM) must deploy itself, its segments must be aligned to a common pointing (by an activity called coarse alignment), and the segments will need to be adjusted to conform to a more or less continuous surface, so that the segment wavefronts arriving at a focus interfere coherently with each other, thereby changing the Point-Spread Function (PSF) of JWST from an incoherent sum of individual segments’ PSFs, each of angular size $\lambda/D_{\text{seg}}$, to one whose size is of the order of the diffraction limit of the full mirror, $\lambda/D$. This latter activity is known as coarse phasing. After coarse phasing occurs, routine wavefront sensing and control operations (described in JWST-TM 2003-0011) perform fine phasing to bring the PSF within the specifications required by JWST’s science drivers.

This memorandum describes two possible ways this coarse phasing can be accomplished. We explain the manner in which coarse phasing is done with Dispersed Fringe Sensing (DFS) and Dispersed Hartmann Sensing (DHS), and we present a summary of operational issues pertinent to the two methods. Our purpose is to familiarize the STScI S&OC in the elements of the optical principles behind the two methods and to bring an operational perspective to the JWST Wavefront Sensing and Control Working Group discussions. We retain an operational perspective throughout the Memorandum: technical details of DFS and DHS are described in numerous Wavefront Sensing and Control Working Group presentations, and will be considered in depth in subsequent Technical Memoranda.

### 2.0 Assumptions

Our assumptions about the condition of JWST and its relevant subsystems are:
1. JWST primary mirror has unfolded, the secondary mirror positioned to within tolerance, and the segments coarse-aligned to a small fraction of the segment diffraction limit.

2. Segments have a common focus (within depth-of-focus and tracking limitations).

3. The JWST Attitude Control System (ACS) has enabled Fine Guidance Sensor (FGS) operation using the PSF after coarse alignment (a baseline assumption for DHS: FGS start-up with DFS is still being outlined).

4. Segment focus has been improved after initiating Fine Guiding.

5. An observing proposal to perform coarse phasing will have been prepared beforehand, and the Visits generated from the proposal are uploaded to Observation Plan Executive (OPE) running in the JWST Integrated Science Instrument Module (ISIM).

6. The OPE is capable of pausing at predetermined events to await commanding and data from the ground before continuing its execution.

7. Targets and guide star positions are contained in the Visit information.

8. The near infrared imaging camera in the ISIM, NIRCam has one functioning imaging channel with the appropriate coarse-phasing optical elements in its Pupil and Filter Wheels.

9. The science data link from NIRCam to the S&OC, and the JWST NIRCAM data pipeline is functioning.

10. Engineering data from the Command and Control Telemetry Stream (CCTS) is stored at the S&OC.

11. No data analysis is carried out on board JWST.

12. Sufficient calibration data for the required NIRCam data reduction and analysis to occur is available to the S&OC pipeline.

13. The Wavefront Sensing and Control Executive is operating at the S&OC, and can deliver PM actuator update command sets to the S&OC ground system software.

14. The S&OC ground system can uplink actuator update commands to the OPE

### 3.0 Data Downlink and Processing During Commissioning

The physical interface between the Observatory and Ground segments consists of two RF links, one operating in the X-band and one operating in the S-band. The Spacecraft Element provides a steerable high gain antenna (HGA) which can be used for X-band and S-band communications and two fixed low gain omni antennas (LGA) which are used for S-band communications only. The X-band link is uni-directional (downlink only) and the S-band link is bi-directional.

Communications with the Observatory will be provided by NASA’s Deep Space Network (DSN). During the complete 6 month commissioning phase, the DSN will provide 24 hours a day/7 days a week S-band coverage and 9 hours a day/7 days a week
X-band coverage (JWST-RQMT-000634 Revision B BA-516). Science data downlink via the X-band will happen during this contact period.

Pipeline data processing and collation of science data with engineering data occurs at the S&OC located at STScI. Data is required to be processed within 24 hours (JWST-RQMT-000634 Revision B BA-538). During deployment and commissioning WFS&C data will have higher priority than other science camera data on the downlink (JWST-RQMT-000634 Revision B BA-295), and possibly in the processing pipeline and retrieval from the data archive as well.

We assume that 24-hour omni-directional S-band contact with JWST is available for telescope commanding and engineering telemetry during commissioning. However, science data downlinking requires the high bandwidth X-band link, which utilizes the high gain antenna. There are no guarantees that the X-band link will be available for more than 8 hours per day during commissioning.

Coarse phasing activities will have to be designed with these operational constraints in mind. Data files from NIRCam will be described elsewhere.

4.0 Attitude Control During Commissioning

The telescope Attitude Control System (ACS) consists of fixed head star trackers, which are independent of the primary mirror, and a Fine Guidance Sensor (FGS) which uses the primary. Pointing with only the star trackers is guaranteed to place a target in a Science Aperture with a standard deviation of 7 arcseconds.

Each of the two FGS fields of view (FOV) are 2.3 x 2.3 arcminutes, and the FGS can access an area between 2 and 8 arcminutes of the center of the NIRCam FOV. The NIRCam short wavelength arm FOV is of the order of 2 arcminutes, assuming 4 2k x 2k detectors with minimal gaps, and a pixel size that is approximately the Nyquist spacing at a wavelength of 2 microns. The FGS pixel size is 68 mas on a side, and 3 x 3 or 4 x 4 pixel subarray reads will be used to provide an open loop frequency of 16 hz during routine operation. The FGS bandpass is 0.5 – 2.5 microns. During routine operations, the FGS will maintain pointing to 3 mas, using a guide star as faint as Jab = 20 (i.e. J=19, or K=18 for a spectral class G star).

If the FGS is used to control JWST’s attitude before coarse alignment, guiding may have to be performed using an individual PM segment PSF. Subarray read boxes will be larger than those used during routine science operations, and guide stars appropriately brighter, to enable such use. Larger subarray reads entail using a slower open loop rate in the guiding control loop. The FGS can be used to guide on the PSF after coarse alignment of the segments, using the larger subarray size to accommodate the incoherent individual segment PSFs stacked on top of each other.

A detailed study of expected drift rates due to the attitude control methods used during commissioning has yet to be performed. According to Liu (2003), the guide star limiting magnitude at its faint end is approximately Jab=15 in single-segment mode. The bright limit is set by the well-depth of the pixels, approximately 80,000 electrons.
5.0 Primary mirror segment actuation

The primary mirror segments possess 6+1 degrees of freedom: tip, tilt, x, y, rotation and piston, along with ROC control. The Ball Testbed Telescope illustrates JWST segment actuation, although relative sizes of segments and actuators differ from that of flight hardware.

Figure 1. This figure shows a single segment (of the Ball Testbed Telescope (TBT)) with a radius of curvature (RoC) actuator in place. The central leg is actuated, pushing or pulling the center of the mirror segment. Attachment is at three locations on the back of the segment (Kingsbury, 2003).

Figure 2. Left: a single actuator of the Ball TBT PM segment. Center: two actuators forming a bipod, attaching to flexures (shown on the right). The flexures attach to the back side of the PM segment, and to the rigid supporting structure (Kingsbury, 2003)
6.0 **Operations during Coarse Phasing**

Operating JWST entails some real time control. However, most of the operations are being planned as uplinked, autonomous activities, especially routine science camera exposures. Since JWST WFS&C uses science camera images as part of its sensing, having as much of the sensing as possible be in the ‘science operations’ mode reduces planning, development, operation, and calibration costs for the mission.

6.1 **Initial and Final Conditions**

After coarse alignment the full-mirror PSF at 2 microns is of the order of 0.3 arcseconds, with ~100 micron segment piston errors, and less than 200 nm Wavefront Error (WFE). The capture range for DHS or DFS is set by the grism resolution. Coarse alignment is assumed to attain 100 microns rms inter-segment piston and 200 nm rms WFE (Atcheson, 2003).

The final state after coarse phasing is required to be less than a micron rms WFE, and the telescope line of sight (LOS) jitter less than 8 mas rms (Atcheson, 2003).
6.2 Dispersed Fringe Sensing

After coarse alignment, piston error between two segments is within the depth of focus. DFS piston capture range is limited by the effective dispersion of the grism. Therefore DFS design should enable DFS to detect the piston error as large as the depth of focus of a single segment.

The PSF of a wavefront with a piston discontinuity (a step in phase across the wavefront at any particular wavelength) has a “dark band” in it. This band’s position within the PSF depends on the wavelength. Without a grism, PSFs of the different wavelengths in a broad bandpass are superposed to form a single broad band PSF – information on the wavefront piston (contained in the locations of the dark bands) is smeared out and lost.

Passing the light through a grism, with a dispersion perpendicular to the baseline between the two segments, enables the dark bands to be seen in broad band light. The term ‘baseline’ refers to the vector between the two segment centers (as is consistent with interferometric usage of the word). When the dispersion is parallel to the baseline between the two segments, there is no contrast in the dark bands. The sensitivity of DFS fringe contrast as the dispersion direction deviates from the perpendicular orientation is strongly dependent on the sparseness of the aperture formed by the two segments.

Consider the following illustrative example. When two segments of a mirror are completely co-planar at their edges, the PSF of the two segments will be centrally peaked, its overall shape being determined by the shape of the combination of the two segments. When there is a non-zero piston between the two segments, the resultant PSF is the single segment PSF multiplied by the square of a sinusoidal fringe pattern whose frequency in the image plane is directly related to the piston error in radians at the wavelength of light being considered. This fringe pattern is not detectable in a direct image’s PSF formed in broadband light, as the positions of the zeroes of the fringes are dependent on wavelength.

Figure 5 shows monochromatic PSFs from a circular aperture split into two equal D-shaped segments. The split occurs at the horizontal diameter across the aperture. In the far left PSF the segments are aligned. The PSF to the right of it has a 1 radian piston error (in the optical path difference, or OPD) between segments, and so on up to a 13 radian piston error on the far right. The location of the white light fringe is across the PSF center at a segment piston error of exactly at $\pi$ radians.
Figure 5. The same physical inter-segment piston error results in a wavelength-dependent phase error across the segments. When a broad-band PSF is dispersed horizontally, with a fixed physical segment piston error, the dark fringe will be located at a wavelength-dependent vertical offset from the PSF center (or the center line of the overall spectrum).

Figure 6: The Elements of Dispersed Fringe Sensing (adapted from WFS&C Working Group Quarterly presentation by Fang Shi et al.). Piston between two segments is reflected in sloping dark bands passing through a grism spectrum. Too great a piston results in bands that are so steep that the grism resolution does not separate them from each other clearly. As the piston gets smaller the bands’ slopes decrease, until, they disappear when co-phasing is achieved.
6.3 Dispersed Hartmann Sensing

The Dispersed Hartmann Sensor is an enhancement to the laboratory and field proven Dispersed Fringe Sensor for measuring relative piston errors between separate apertures. DHS operates on the principle of producing simultaneous dispersed fringe spectra from a family of segment configurations: its overall implementation is a balance between process duration and configuration accuracy.

DHS involves placing a prism over two segments, in a pupil plane, with a grating ruled on one side of the optic. The common tilt induced by the prism places the PSFs of the two segments (which are co-aligned to within a small fraction their diffraction-limit) at some specific location in the image plane. By choosing different prism angles, the PSFs of various pairs of neighboring segments can be separated from each other, to enable measurement of relative tilts without disturbing the segments themselves. (A grism, in contrast, has a prism angle chosen to let the light through without overall beam deviation).

Figure 7: The Conceptual Elements of Dispersed Hartmann Sensing (adapted from WFS&C Working Group Quarterly presentation by Scott Acton). Square prisms with gratings on one side are placed over a pupil image of the segmented primary, each square spanning two segments.
6.4 Operational Description of DFS

DFS requires two grisms with dispersions at right angles to each other in order to measure pistons between pairs of segments at the different orientations present in the JWST primary mirror.

After target acquisition and FGS lock is achieved, pairs of segments will be actuated to induce a common tilt between pairs (see Figure 8). Non-participating segments can be confined to a “parking lot” (a common pointing) while different pairs of segments are tilted to separate them from the herd for relative piston measurement. Simultaneous measurement of the relative piston of more than one pair is planned. After NIRCam data for one measurement is taken, the segments will need to be repositioned to measure other pairs against each other, and a second NIRCam exposure will have to execute. The optimal sequence of which sets of segments need to be measured against which other segment is being studied.

With two grisms and perfect actuators, a minimum of seven iterations of such visits (with ground-based data analysis by the WFS&C Executive software, and uplinked segment adjustments between each visit) will produce a coarsely phased 18-segment primary mirror. The presence of actuator errors may increase the number of iterations that DFS might require to co-phase JWST.

Figure 8: DFS for the 18-segment design (adapted from WFS&C Working Group Quarterly presentation by Fang Shi et al.) Square prisms with gratings on one side are placed over a pupil image of the segmented primary, each square spanning two segments.
Details of DFS procedures, actuator operational constraints, data volume considerations, using subarray reads, NIRCam pupil quality and chromatic aberration, guiding considerations, etc. will be presented in subsequent studies.

6.5 Operational description of DHS

DHS requires one or two elements in a NIRCam short wavelength camera pupil wheel.

A DHS visit consists of target acquisition and fine guiding lock, placement of one DHS element in the NIRCam pupil wheel, and image acquisition. Then, if the DHS algorithm mandates it, the second DHS element is rotated into position, and another image acquired. These data are downlinked for analysis by the WFS&C Executive, and actuator update commands are uplinked for subsequent assertion. With perfect actuation a single visit is required to co-phase the primary mirror. A second visit after actuator commanding will re-measure the segment co-phasing. The presence of actuator errors may increase the number of iterations that DHS might require. Preliminary studies by Acton indicate about 5 iterations combined with conservative actuator updates will produce a co-phased primary mirror.

Details of DHS procedures, actuator operational constraints, data volume considerations, NIRCam pupil quality and chromatic aberration, DHS element alignment requirements, using subarray reads, etc. will be presented in subsequent studies. Since the primary is not disturbed during DHS data acquisition, guiding considerations are simpler than those of DFS. The ability of DHS to be verified by ground testing will be addressed elsewhere.

7.0 Comparison of DFS and DHS from an Operational Perspective

Both DFS and DHS are possible from an operational perspective. Both of them require placing WFS&C elements in the NIRCam pupil wheel in the light path of one or two short wavelength cameras, and collecting data using pre-selected targets. DFS requires larger actuator moves, and more of them. DHS requires better pupil alignment. DHS measures piston without altering the PSF or using any PM segment actuation. With DFS the PSF of the telescope will be made scientifically unusable during the course of wavefront measurement.

One impact of the JWST operational strategy on DFS is on the ‘closed loop bandwidth’ of the control/sense cycle, given the number of iterations required to converge to a co-phased PSF. Using two grism elements with orthogonal dispersion directions in the NIRCam short wavelength camera, seven iterations are required if actuators behave exactly as commanded. Actuator error can increase the required number of iterations to twenty or more iterations.

DHS requires one visit for wavefront sensing, and one to check the results. The PSF of the telescope improves with each iteration. It is not altered during the wavefront sensing process itself because sensing does not require any segment motion.

Both DFS and DHS are adversely affected by segment tilt because of concomitant reduced fringe visibility. DHS can erroneously sense segment tilt as piston error. Studies by Acton indicate that such large tilts are not expected if PM components behave...
specifications. Furthermore, the methods used in routine fine phasing can be utilized during coarse phasing to sense the tilts of each segment without increasing the number of data downlinks required if the tilts are sufficiently small. Large tilts will reduce fringe contrast, and necessitate an iteration to correct them before the next fringe measurement.

7.1 Health and Safety of the PM segments

When segments are moved segment collisions must be avoided. If segment position or inter-segment gaps are measured, impending collisions can be detected. Methods of accomplishing this are a Pupil Imaging Lens (PIL) that can move into the light path in NIRCam, or edge sensors on the segment edges.

Images from a PIL require analysis to determine relative segment position. Assuming no data analysis is performed on board, this entails a downlink-analyze-uplink iteration, thereby increasing operationally induced latency in the control cycle. A risk associated with pupil imaging is that the lens assembly could block part of a NIRCam short wavelength detector. A benefit of having a pupil image is that phase retrieval algorithms become more reliable with better knowledge of the pupil.

The Keck telescopes use capacitive edge sensors to determine segment positions. Edge sensors do increase PM mechanical complexity, but can provide almost real-time information on relative segment positions over the low-bandwidth engineering telemetry stream from JWST.

Segment collision avoidance strategies are still being studied.

8.0 Conclusion

Both DFS and DHS appear to be feasible given our current operational ideas. The way operations will conducted will have an impact on the timelines of the two methods in view of the very different number of visits required by them. Risks of both methods need to be weighed carefully on technical grounds, taking the operational strategy of JWST into account, as well as pre-flight verification on testbeds, and predicted actuator behavior. DFS is a well-tested method in the lab, DHS is a new adaptation of the basic DFS strategy, and requires more study because of its potential operational benefits. Planning for the contingency that coarse phasing needs to be repeated during the mission will factor into the decision to use one or the other of these strategies.

9.0 References


