JWST Fine Guidance Sensor Calibration

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Abstract. The primary function of the Fine Guidance Sensor (FGS) is to provide continuous pointing information to the Observatory. The FGS will image two separate regions of the JWST field of view onto two independent 2k x 2k infrared focal planes arrays, which will cover a wavelength range of 0.6 to 5 μm. Once in fine guiding, the FGS will provide continuous pointing information to a precision of ≤ 5 milli-arc seconds at an update rate of 16 Hz for $J \simeq 18.5$ magnitude stars. In order to fulfill its functions, i.e., Identification, Acquisition, Track, and Fine Guide, the FGS will require calibration. In this paper, we present a brief overview of the FGS design, its operations, and its calibration.

1. Introduction

The Fine Guidance Sensor (FGS) is an near-infrared (NIR) instrument that will provide the data for fine pointing and attitude stabilization to the James Webb Space Telescope (JWST) Attitude Control System (ACS). By measuring and providing accurate positions of a guide star to the ACS, the FGS will be used to stabilize the line of sight in order to achieve the pointing stability that is required by the science instruments on board JWST. The Canadian Space Agency (CSA) is contributing the FGS to the JWST Observatory in collaboration with COM DEV Space Systems of Ottawa Canada which is CSA's prime contractor. CSA is also contributing a NIR narrow band imager called the Tunable Filter Instrument (TFI) that will be part of the JWST science instrument collection (see Martel et al., these proceedings). We describe in this paper the design of the FGS and its operations, and present some aspects of its calibration.

2. FGS Optical Design

Figure 1 illustrates the optical layout of the FGS with respect to the Optical Telescope Element (OTE). The FGS is located behind the primary mirror where it is mounted on the Integrated Science Instrument Module (ISIM) structure. The FGS pick-off mirror, which is
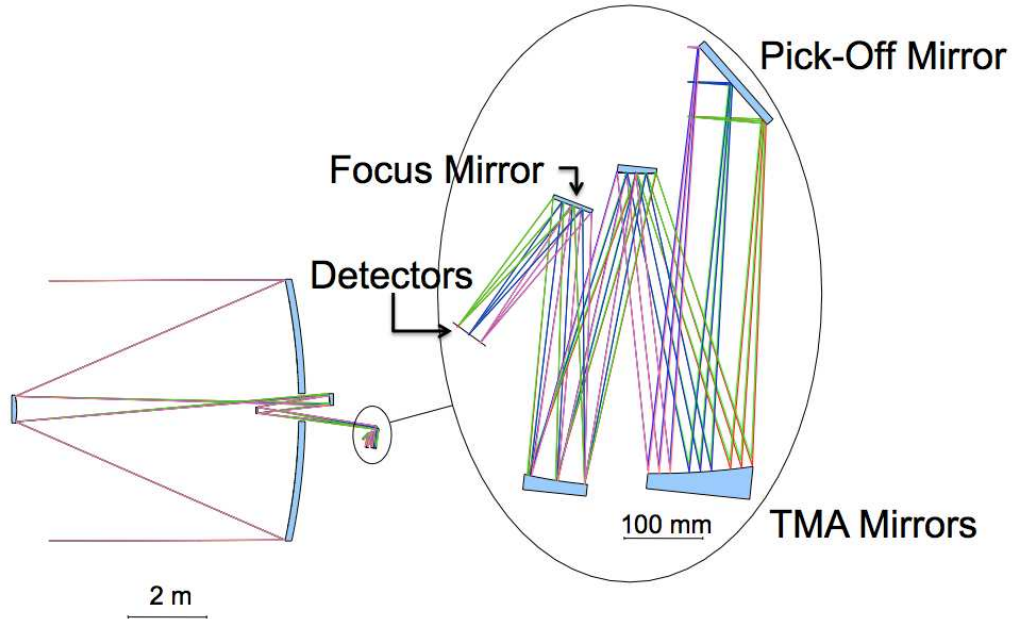
Figure 1: FGS optical layout diagram with respect to the OTE. (Courtesy of COM DEV Space Systems of Ottawa Canada.)

placed just past the OTE focus, picks up the light that comes from two adjacent fields of view (FOV) and feeds it to the relay Three Mirror Assembly (TMA). The light is collimated by the TMA and is then focused by a fold mirror onto two NIR detectors. Both FOVs cover $2.3' \times 2.3'$ each.

Figure 2 shows a drawing of the FGS optical assembly and illustrates the optical subsystem components that are mounted on the FGS aluminum bench. The bench is attached to the ISIM structure via three bipod kinematic mounts. The TFI optical assembly is underneath the FGS optical assembly and shares the same optical bench (see Figure 1 of Martel et al., these proceedings). In Figure 2, the baffles are not drawn in order to show clearly the pick-off mirror, the Fine Focus Mechanism (FFM) with its fold mirror, and the detector assembly. The FGS focus is adjusted after the TMA by moving a fold mirror mounted on the FFM. A calibration lamp is located behind a small aperture in the center of the tertiary mirror of the TMA and provides a light source that can illuminate both detectors.

The FGS Focal Plane Arrays (FPA) consist of two 2048×2048 pixels 5 μm cutoff HAWAII-2RG HgCdTe detectors from Teledyne Imaging Systems (TIS) (see, e.g., Loose et al. 2007). Four rows and columns surrounding the detectors are not sensitive to light and are used as reference pixels. This leaves a total of 2040×2040 sensitive and active pixels that can detect light spanning a wavelength range of 0.6 μm $\leq \lambda \leq$ 5 μm (Rowlands et al. 2008). TSI also provides two application specific integrated circuits (ASIC) that control the FPAs. Each ASIC is paired with an FPA. The ASICs, dubbed SIDECAR, for System for Image Digitization, Enhancement, Control and Retrieval, are placed on the FGS bench next to the detector assembly.
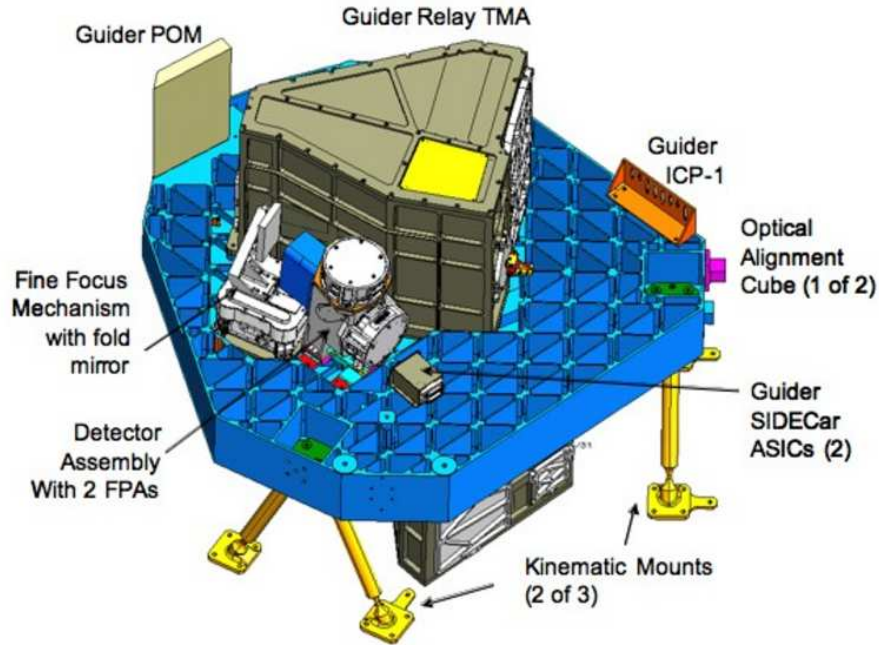
Figure 2: FGS optical assembly. The baffles have been removed in order to see the pick-off mirror, the fine focus mechanism, and the detector assembly. The TFI optical assembly is underneath the FGS optical assembly (see Martel et al., these proceedings). (Courtesy of COM DEV Space Systems of Ottawa Canada.)

3.   FGS Operations

3.1.   FGS Functions

The FGS Flight Software (FSW) uses the FGS for taking full frame and sub-window images in order to provide data to the ACS, which will position science targets within the FOV of a science instrument and stabilize the line-of-sight during an observation. During normal science observations, a sequence of functions is executed by the FGS FSW under the control of the Activity Description (AD) scripts that are running on the ISIM Command & Data Handling Unit. For instance, here are the four functions that the FGS will execute after the Observatory has slewed to and settled to a desired attitude:

IDENTIFICATION: During this process, the FGS FSW takes full frame images, extracts the positions of stars observed in the FOV, compares them to the positions of known stars that were uploaded from the ground, identifies the guide star, measures its position and reports it to the AD.

ACQUISITION: First, a 128×128 sub-window ($\sim 8.7'' \times 8.7''$) is placed on the guide star and a series of images are taken. The images are passed to the FGS FSW that measures the average position of the guide star. Then a 32×32 sub-window ($\sim 2.2'' \times 2.2''$) is centered on this new guide star position and a second series of images are taken in order to measure the position of the guide star more accurately.

TRACK: The AD commands the FGS FSW to center a 32×32 sub-window on the guide star. This time the sub-window is continuously read out and the FGS FSW computes the centroid of the guide star. These centroids are passed to the ACS at a rate of 16 Hz for line of sight stabilization of the spacecraft. The guide star location is continuously reported such that the sub-window location is updated in case the guide star is still moving across the FOV. Once the jitter and drift have been reduced, an 8×8 sub-window ($0.54'' \times 0.54''$)

is centered on the guide star and the FGS FSW computes more accurate centroids that are passed to the ACS at a rate of 16 Hz.

FINE GUIDING: The AD commands the FGS FSW to transition directly from Track to Fine Guiding by using a fixed window size of 8×8 pixels centered on the guide star. The FGS FSW computes the guide star's centroids and sends them to the ACS every 64 msec. Once in Fine Guiding, the image motion that is expected over a typical duration of science observation should be < 7 mas.

3.2. Guide Star Selection

The ground system will select guide stars and reference objects for JWST observations. Guide stars are used for fine guiding the telescope and reference objects are used in on-orbit pattern matching to identify the guide star. Stars with $12.1 \leq J \leq 18.6$ will be used as guide stars for fine guiding; reference objects may be even fainter. Up to three guide star candidates will be selected for each visit, dramatically reducing the risk of guide star acquisition failure. Guide stars and reference objects will be selected from the Guide Star Catalog II (GSC-II) and the Two Micron All Sky Survey (2MASS) Point Source Catalog (see, Lasker et al. 2008 and Skrutskie et al. 2006).

Although the GSC-II is based on a photographic survey, it has been selected as one of the best sources of guide stars for the JWST mission, because it is the deepest and most complete all-sky survey available. GSC-II contains approximately a billion objects (~ 0.3 billion stars) that were observed in three photographic pass bands: B_J ($\lambda_{eff} = 0.47$ μm), R_F ($\lambda_{eff} = 0.64$ μm), and I_N ($\lambda_{eff} = 0.85$ μm). As for the 2MASS point source catalog, it contains 0.47 billion objects over the entire sky in the J (1.25 μm), H (1.65 μm), and K_S (2.16 μm) band passes and is complete down to $J \simeq 16$. The resolution (≥ 2 arcseconds) of the 2MASS data is not sufficient to ensure that all objects are truly point sources. Sources at the bright end of the catalog ($J < 12.1$) are too bright for guiding and the faint limit of the catalog ($J \simeq 17$) is brighter than the expected faint limit for JWST FGS guide stars ($J \simeq 18.5$).

The on-board guide star identification and acquisition process uses a small star table provided by the ground system containing the positions and predicted detector count rates of the guide star and reference objects expected to be in the FGS FOV. As the FGS is a broadband camera with a wavelength range of ~ 0.6 μm to 5.0 μm, the magnitudes of the GSC-II objects, B_J, R_F, and I_N, must be transformed into J, H, K_S if 2MASS magnitudes are not available, and then extrapolated from K_S to 5 μm. These optical and NIR magnitudes are then convolved with the telescope aperture, the FGS throughput, and detector response to derive the predicted electron count rate.

Transformations of the GSC-II optical magnitudes into the near infrared J, H, and K_S have been derived from color-color diagrams for stars common to both GSC-II and 2MASS (Chayer et al. 2006). At high galactic latitudes ($|b| > 45$ degrees), where only 48% of GSC-II stars have 2MASS matches within 1.75 arcseconds, the effects and variations of reddening are negligible, and consequently, the magnitude transformations are fairly accurate (Holfeltz et al. 2009). At low galactic latitudes ($|b| < 30$ degrees), where highly variable reddening hinders accurate magnitude transformations and the GSC-II catalog is subject to confusion, 87% of GSC-II stars have 2MASS matches within 1.75 arcseconds, eliminating the need to predict their NIR magnitudes.

4. FGS Calibration

The calibration of the FGS affects many more aspects of the observatory than the accuracy and precision of pointing. The FGS must be calibrated in order to plan and schedule visits, select guide stars, optimize operational parameters, and execute spacecraft maneuvers, in addition to guiding JWST. The characterization and calibration of the FGS started during

instrument assembly, integration and ground testing. These measurements and analytic calculations will serve as the initial calibration database. These initial calibrations will be verified or updated during on orbit commissioning. Some calibrations may only be possible on orbit; initial data for these will likely be obtained during the commissioning phase. During routine on orbit operations, after commissioning is complete, the calibration plan is likely to consist mostly of periodic calibration monitoring and updating of the calibration database and operational instrument settings. Below is a partial list of the planned FGS calibrations. For more information, the reader is referred to the FGS Calibration Plan prepared by Nelan 2007 for CSA.

PSF CHARACTERIZATION: The effective point spread function (PSF) and its variation across the FGS field of view will be characterized; (the FGS PSF is under-sampled and cannot be directly measured). This calibration is needed for the geometric distortion correction and to verify the centroid non-linearity correction applied to the measured guide star position. Calibration data will be obtained by dithered observations of an astrometric field in the Large Magellanic Cloud (LMC). Dithering compensates for the under-sampled FGS pixels. This process will be iterative, since the commanded sub-pixel dithers cannot be actualized before the effective PSF in the guiding FOV is calibrated.

PHOTOMETRIC CALIBRATION: The magnitude transformations predicting FGS count rates from GSC-II and 2MASS magnitudes will be calibrated. Relatively accurate predicted FGS count rates are needed to select and identify guide stars. Predicted count rates are used in the guide star selection process to determine if a candidate is bright enough to serve as a guide star. Predicted count rates are used on orbit to pattern-match the predicted and observed scenes, and identify the guide star. To obtain the necessary calibration data, we will bootstrap from NIRCAM observations of the astrometric LMC calibration field.

GEOMETRIC DISTORTION: The geometric distortion will be determined across the FGS FOVs to ≤ 5 mas. Knowledge of the geometric distortion is needed to support fine pointing and accurate offset maneuvers. Calibration data to determine the geometric distortion across the FGS FOV will be obtained by dithered observations of the astrometric LMC field at various orientations.

SPACECRAFT TO FGS ALIGNMENT: The alignment of the star tracker coordinate frame relative to the FGS coordinate frame will be measured. Knowledge of the relative alignment is needed to place guide stars in the FGS FOV for identification & acquisition and set the orientation of ISIM focal plane. First, the star trackers must be aligned relative to each other by comparing catalog and observed positions of stars in the Bright Star Catalog (BSC). Next, the alignment of the star trackers with respect to the FGS is determined by simultaneously observing several BSC stars in the star trackers and LMC stars in the FGS.

ISIM TO FGS ALIGNMENT: The relative alignment of each ISIM instrument with respect to the FGS will be measured. Knowledge of the relative alignments is needed to fine point the instruments and support accurate offsets. The initial ISIM-to-FGS alignment will be measured on the ground during ISIM assembly. Accurate on-orbit calibration data will be obtained by simultaneously observing the astrometric LMC field with the FGS and each science instrument at selected positions and rolls.

FLAT FIELD: The FGS flat field will be determined. Knowledge of the pixel-to-pixel non-uniformity is needed for accurate measurement of guide star positions in the FGS field of view. Limited flat field data will be collected during ground tests. On-orbit flat field calibration data will be collected from observations of star fields and the internal flat lamp.

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