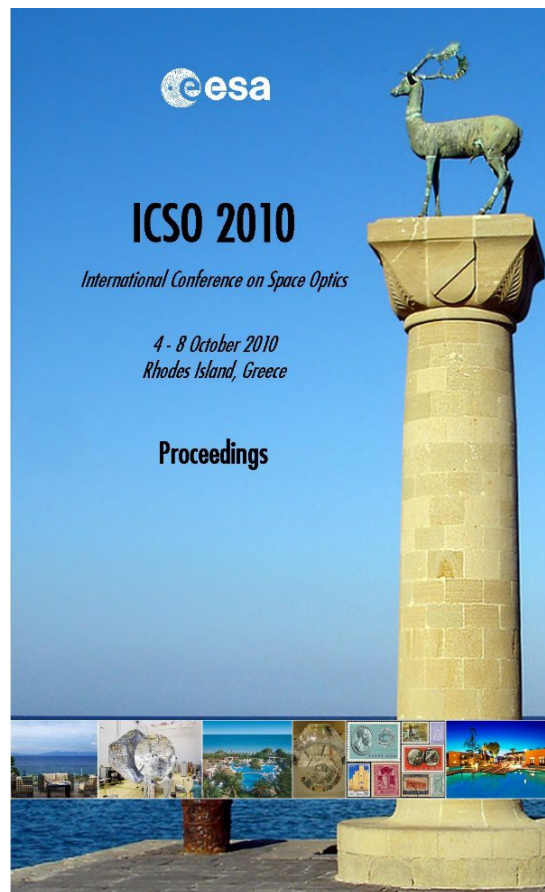


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## *James Webb space telescope (JWST): fine guidance sensor and tunable filter imager optical design overview and status*

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## JAMES WEBB SPACE TELESCOPE (JWST) - FINE GUIDENCE SENSOR AND TUNABLE FILTER IMAGER OPTICAL DESIGN OVERVIEW AND STATUS

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### I. JAMES WEBB SPACE TELESCOPE (JWST) OVERVIEW

The James Webb Space Telescope (JWST) is a successor of the Hubble Space Telescope and the Spitzer Space Telescope to be launched in 2015 for 5 years long (10 years goal) science mission.

JWST large collecting are of  $\sim 25\text{m}^2$  and spectral range are designed to exceed goals beyond those achieved by Hubble and Spitzer. The project is lead by NASA (Goddard Space Flight Center) with contributions from the European Space Agency (ESA) and Canadian Space Agency (CSA).

The JWST will be placed at the L2 Earth-Sun Lagrangian point about 1.5 mln km from Earth. That location and a large sun shield are to ensure operating temperature of 35K of the passively cooled observatory. The Optical Telescope Element (OTE) consisting of the deployable primary and secondary mirrors, part of the off-axis Three Mirror Anastigmat (TMA) design, must be aligned on orbit. Each of the 18 segments of the primary and secondary mirrors is actuated in six degrees of freedom and the primary has additionally an adjustable curvature. The tertiary mirror and the fine steering mirror (FSM) are located in the aft optical system from which light is directed to the four science instruments whose Pick-off Mirrors (POM) are close to the focal plane of the telescope. The instruments are:

Near Infrared Camera (NIRCam) from University of Arizona, Near Infrared Spectrograph (NIRSpec) from ESA, Mid-Infrared Instrument (MIRI) from JPL/ESA and Fine Guidance Sensor/Tunable Filter Imager from CSA. They are mounted on the Integrated Science Instrument Module (ISIM), which is located behind the primary mirror. The prime contractor for FGS/TFI is ComDev Ottawa. The principal investigators are John Hutchings (Herzberg Institute of Astrophysics) for the FGS and René Doyon (Université de Montreal) for the TFI.

### II. FINE GUIDING SENSOR (FGS-Guider) OVERVIEW

The JWST is a large and not very rigid structure requiring. As a result tracking target stars with accuracy of a diffraction limited imaging cannot be accomplished by orientation of the entire observatory. Instead, the fine steering mirror located at the pupil of the telescope, fed by the error signal of guide star centroid data produced by the FGS-Guider, provides the line of sight pointing and stabilization. For the redundancy the imaging is achieved on two, Teledyne manufactured HgCdTe 2048x2048 detectors with  $18\ \mu\text{m}$  pixel size of the same type as used in NIRCam and NIRSpec.

A typical operation sequence will consist of Identification, Acquisition, Tracking (moving target observation) and Fine Guiding with 16Hz centroid data update rate. Table 1 summarizes current FGS-Guider parameters [1]. The optical layout of the FGS-Guider portion of the instrument is shown in Figure 1. The first optical element is the POM, which redirects a portion of the Optical Telescope Element (OTE) focal plane to the FGS-Guider's TMA assembly which in turn reimages the field onto the detectors. There is one optical path for both FGS-Guider fields of view. The detectors are packaged separately and are electrically and mechanically independent of each other.

Table 1

FOV (arcmin)	Pixel Scale (milli-arcsec)	Spectral range ( $\mu\text{m}$ )	Wavefront Error (nm) -Guider only	Sensitivity ( $\mu\text{Jy}$ at $1.25\mu\text{m}$ )	Noise Equivalent Angle (milli-arcsec)	Optic mass (kg) Guider and TFI
2.34x2.34	67.3	0.6-5	90	52.3	4 Guide star brightness of $58\ \mu\text{Jy}$	82.4

A fold mirror (part of the detector assembly) separates the combined optical paths for each detector. An actuated Fine Focusing Mirror (FFM) provides a focus adjustment for the FGS-Guider.

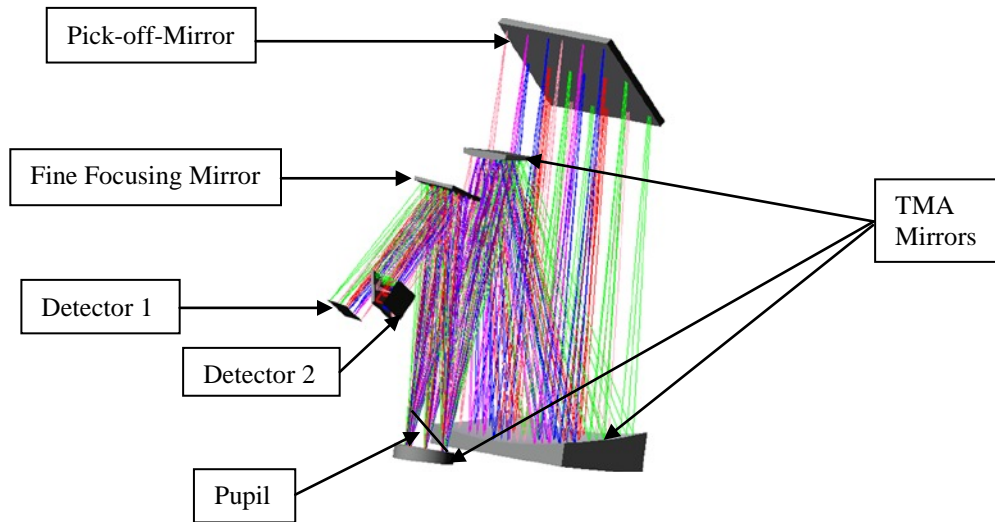


Fig.1. FGS-Guider Optical Lay-out

The OTE produces fairly well corrected image on a curved surface just in front of the POM. The FGS-Guider optical system corrects the image curvature and local tilt to produce a plane, correctly focused image on the detectors. The FGS-Guider also provides some corrections for the remaining OTE aberrations and the resulting correction at the detectors is very good. The POM and some nearby baffles provide a good approximation for a field stop. They limit the FGS-Guider light input to the instrument FOV and form first line of defence against stray light. In addition a local aperture stop located at the perimeter of the tertiary mirror provides the further attenuation of the stray light. Despite pupil inclination its aberrations are well controlled with best corrected part at the tertiary mirror where a fiducial is located. A small, plane Pupil Reference Mirror machined at the centre of the tertiary will be used during FGS-Guider integration with the other instruments. The tertiary mirror accommodates also in its centre a calibration lamp intended for an on-orbit detector characterization. The FGS-Guider and the FGS-Tunable Filter Imager and the optical bench are all aluminum with exception of focus mechanisms and filter wheel made of titanium and are interfaced to the composite material made ISIM with three titanium bipod kinematic mounts.

### III. FGS -TUNABLE FILTER IMAGER (FGS-TFI) OVERVIEW

The FGS-TFI is packaged with the FGS-Guider on the other side of the optical bench. The function of the FGS-TFI is to provide JWST with narrow-band, continuously tuned imaging capability. That ability will provide JWST with very powerful capability, not only for surveys of deep fields and star formation regions but also for extra-solar planet characterization. The detector is the same type as for the FGS-Guider. The capability of the passband tuning to the user specified wavelength is provided by a Fabry-Perot etalon. Table 2 summarizes current FGS-TFI parameters. The optical lay-out is shown in Fig.2. The FGS-TFI POM is adjacent to the FGS-Guider POM in the JWST OTE focal plane. The POM relays this field of view to a TMA assembly which collimates the light, placing an image of the JWST OTE primary at a pupil mask located at the outer wheel of the dual wheel assembly. The inner wheel of this assembly contains blocking filters, which allow the proper interference order of the next optical element, an etalon, to be selected.

Table 2

FOV (arcmin)	Pixel Scale (milli-arcsec)	Spectral range ( $\mu\text{m}$ )	Spectral Resolution	Wavefront Error (nm) -Guider only	Sensitivity (nJy at $3.5\mu\text{m}$ )	Optic mass (kg) Guider and TFI
2.23x2.23	65-65.5	1.6-2.5 and 3.2-4.9	72-118	79	85	82.4

After the etalon a second TMA assembly re-images the field of view onto a single detector. The focusing function is performed by the POM. Additional optical hardware located adjacent to the pupil wheel allows

calibration light to be injected into the optical path. This calibration is for monitoring the spatial flat field and for maintenance of the etalon spectral spacing calibration. The TFI incorporates also a set of four occulting masks at the edge of the POM and a set of pupil masks in the dual wheel assembly. These masks allow coronagraphic observations to be made [2]. The etalon assembly consist of a two highly polished flat silicon plates with a wideband reflective coatings and gold capacitive displacement sensors.

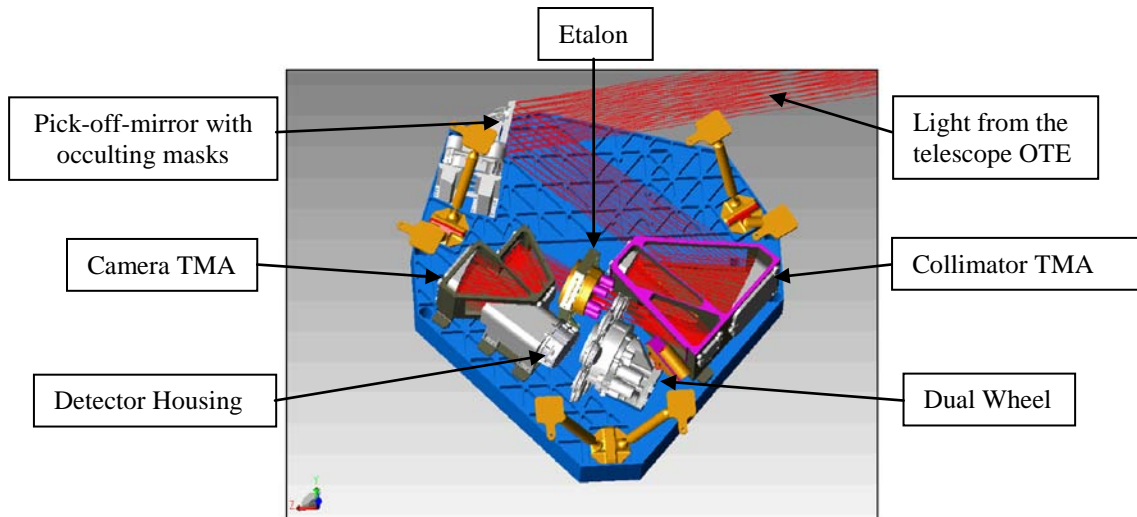


Fig.2. FGS-TFI Optical Assembly

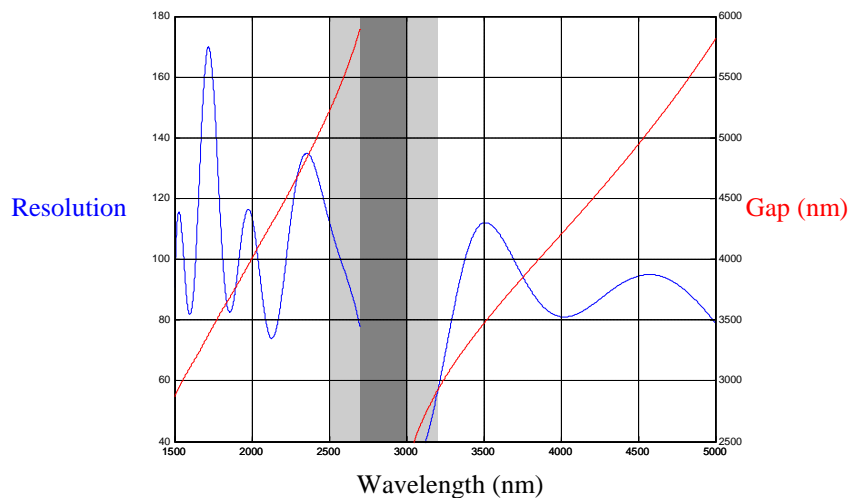


Fig.3. Etalon predicted resolution (left axis) and mirror spacing (right axis) versus wavelength

The final coating prescription includes a total of seventeen layers of a-Si and SiO<sub>2</sub>. The outer sides of the silicon plates are coated with 21 layer broadband anti-reflection coating. The motions of the etalon are controlled by six low voltage stack type hollow cylinder ceramics piezoelectric actuators (three per each silicon plate). The etalon coating optimization was driven by the small plates travel of only 3 μm resulting from the reduced travel range of the piezoelectric actuators at 35 K. Only the first and third orders of interference are utilized. Another design driver was the maintenance of a near-constant spectral resolution while maximizing the wavelength coverage [3]. Fig.3 shows final etalon predicted resolution and mirror spacing versus wavelength. Flight etalon assembly prototype is shown in Fig. 4.

#### IV. FGS-Guider STATUS

The Engineering Test Unit (ETU), see Fig.5, of a fully functional (one detector channel only) FGS-Guider went successfully through the whole AIT process. The ambient alignment was evaluated at cryogenic temperatures and verified by combination of physical and optical testing, analysis and measurement of alignment features. The initial optical designs are "cold" to match "cold" OTE design. The instrument level optical design files were then scaled to an ambient temperature lay-out to be integrated with the mechanical assembly lay-out. Detailed alignment error budgets, Structural, Thermal and Optical (STOP) analysis and characterization, extensive metrology plus high precision machining resulted in the FGS-Guider alignment meeting all its requirements without a need for readjustments. The sub-assemblies like TMAs and Detector Assembly were aligned and tested as separate units before being integrated to the optical bench. For focus, FOV and functional tests an Optical GSE (OGSE) in the form of 8 per each FOV f/20 telescopes was used to simulate the focal plane of the cold OTE.

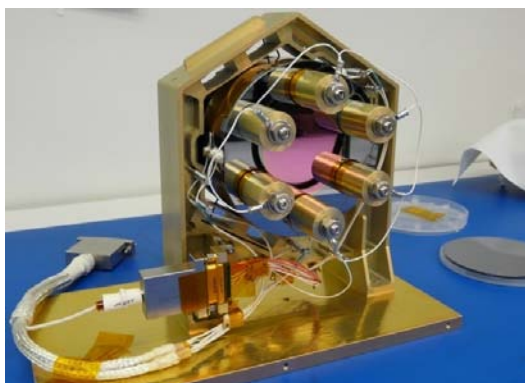


Fig.4. FGS-TFI flight etalon assembly

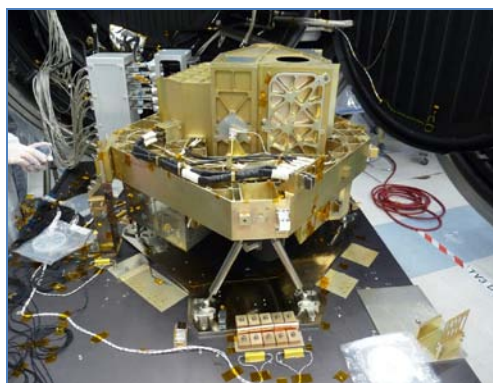


Fig.5. FGS-Guider Engineering Test Unit

The most challenging task was pupil alignment and pupil shear measurement, caused by the OTE pupil location at about 3m away from the FGS. It was however successfully completed in two stage process; first at ambient temperature and then at 35K with optical path between the FGS and pupil temporary folded with OGSE mirrors in order to fit into a TVAC chamber.

#### V. FGS-TFI STATUS

The AIT process of the FGS-TFI Protoflight Model (PFM) together with FGS-Guider PFM commenced recently, starting with pupils and detectors alignment. Currently, most of the effort is directed towards etalon, characterization. A 1.6  $\mu\text{m}$  laser source is used to establish parallelism of the etalon plates at a set of gaps corresponding to multiple orders of the 1.6  $\mu\text{m}$  resonance. The operational etalon gap range of 2.5 to 5.5  $\mu\text{m}$  was achieved by applying approximately  $\pm 90\text{V}$  to the piezoelectric actuators pairs. The measured and modeled transmission spectra of a broadband source showed excellent agreement across whole functional spectral range. The work is continuing on refining the closed-loop electronics in order to minimize capacitive sensor drift and cross-talk corresponding to the required level of less than 10 nm of the etalon gap over several hours.

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