Calibrating the position of images and spectra in the NIRSpec instrument for the James Webb Space Telescope

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ABSTRACT

The Near Infrared Spectrograph (NIRSpec) is one of four science instruments on board the James Webb Space Telescope (JWST). NIRSpec offers multi-object, fixed slit, and integral field spectroscopy. There are eight optical elements mounted on the grating wheel assembly (GWA), six gratings, a double-pass prism, and a mirror. The precise knowledge of the position and tilt of these elements is critical for target acquisition and an accurate extraction and calibration of science data. We present the concept of calibrating the position/tilt sensors during the NIRSpec flight model ground calibration campaign, the performance of the sensors and first results concerning the GWA repeatability.

Keywords: James Webb Space Telescope, Multi-object spectrograph, Infrared, spectral calibration, NIRSpec, tilt sensor

1. INTRODUCTION TO NIRSPEC

On board the James Webb Space Telescope (JWST)[1,2] there are four scientific instruments, one of which is the Near InfraRed Spectrograph (NIRSpec)[3,4]. It is designed to measure the spectra of at least 100 objects simultaneously in the wavelength range from 0.6 µm to 5.0 µm. A schematic overview of the telescope and instrument optical train is shown in Figure 1. NIRSpec will be operated in three different modes with spectral resolutions of R~100, R~1000 and R~2700. The first mode covers the full spectral range with a prism as the dispersing element, while in the other modes the wavelength range is split into three different bands, with a grating available for each of them. There is also an Integral Field Spectrograph (IFU), typically used for high resolution 3D spectroscopy between 1.0 µm and 5.0 µm.

The Optical Telescope Element (OTE) provides a focal surface with a focal ratio of f/20 and a curvature radius of ~3040 mm to the science instruments. The NIRSpec optics starts with the pick-up and FORE-optics, guiding the light from the OTE into the instrument itself. At the next pupil plane, there is a Filter Wheel Assembly (FWA) with eight positions. Four of them are equipped with long pass filters, two with broad band filters used in an imaging mode for target acquisition, one with a clear filter to provide an equal path length difference as the other filters, and one is a closed element, which serves as an instrument shutter, as a pupil alignment reference and, on the rear (instrument) side, as a mirror for the on-board calibration optical train.

The beam is then directed into a Refocusing Mirror Assembly (RMA) that permits to compensate for possible focal shifts in the OTE focus. The design is such that, when the mechanism is run, the optical axis does not move

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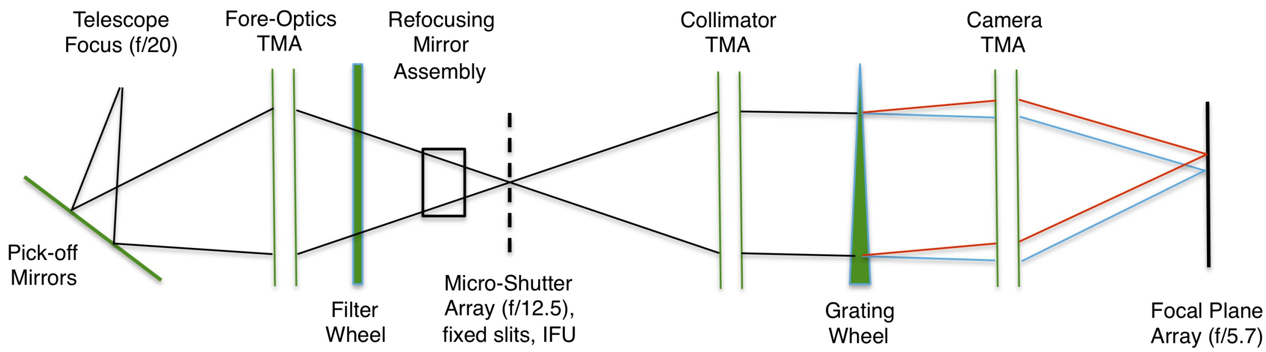

Figure 1. Schematic overview of the NIRSpec optics.

laterally and, with a subsequent telecentric focal plane, the image scale stays the same. At this focal plane, with a ratio of f/12.5, the Micro Shutter Array (MSA) is located. The MSA houses four quadrants of microshutter arrays, which allow the selection of targets in the field of view (FOV), the five high-contrast fixed slits, and the entrance to the IFU.

The light passing through the MSA is then imaged onto the Grating Wheel Assembly (GWA) by the collimator optics (COL). The dispersive elements are situated in a pupil plane. In total, the GWA contains eight selectable optical elements, providing dispersion into spectra or imaging of the FOV for target acquisition. Passing through the camera (CAM) module, the light finally reaches the Focal Plane Assembly (FPA), where the two 2K x 2K HgCdTe detectors are located. At this point, the focal ratio is f/5.6.

For the in-orbit calibration during commissioning and operations phase, NIRSpec is equipped with a Calibration Assembly (CAA). The CAA is coupled into the instrument optical path by setting the filter wheel to the closed position. At this particular position of the filter wheel, a small spherical mirror is located at the backside of the shutter element, allowing the on-board calibration light beam to be injected into the instrument optical path.

As mentioned previously, NIRSpec's GWA has 7 dispersers and one imaging mirror. Due, amongst others, to severe envelope constraints, the NIRSpec GWA had to be arranged such that its rotational axis is oriented horizontally, i.e. parallel to the NIRSpec optical bench. The direction of dispersion is orthogonal to the NIRSpec optical bench plane. A more realistic picture of NIRSpec is shown in Figure 2. Except for the filters and prism, it is an all reflective instrument.

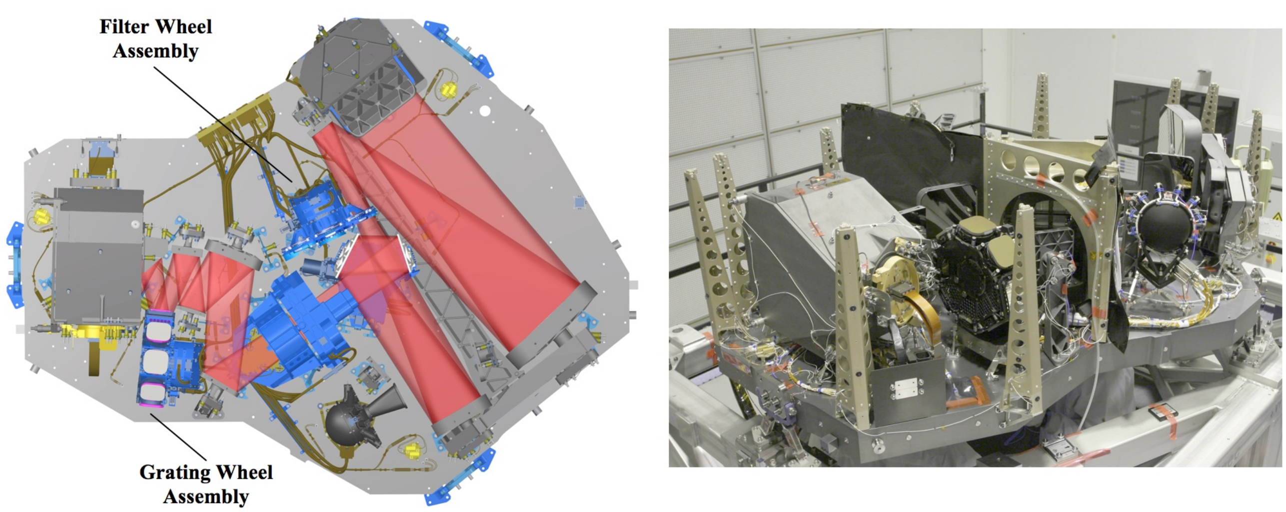

Figure 2. More realistic representation of the NIRSpec structure and layout. The actual flight hardware is shown on the right.

Any rotational non-repeatability of the GWA will result in a small shift of the image or spectrum at the detector plane. It is obvious that for good science performance these shifts have to be minimised, accurately known and corrected for if too large. In order to have high mechanical angular reproducibility of the GWA, a ratchet is used to achieve accurate positioning of the optical element that is selected. This ratchet comprises two flexural pivots, which point in the same direction as the wheel axis. The ratchet subassembly is mounted on the mechanical support structure of the GWA. A spring draws the top part of the ratchet onto the index bearings, which reside on the wheel structure. The wheel can reside in eight different equilibrium positions. The GWA with its most important components is shown in Figure 3.

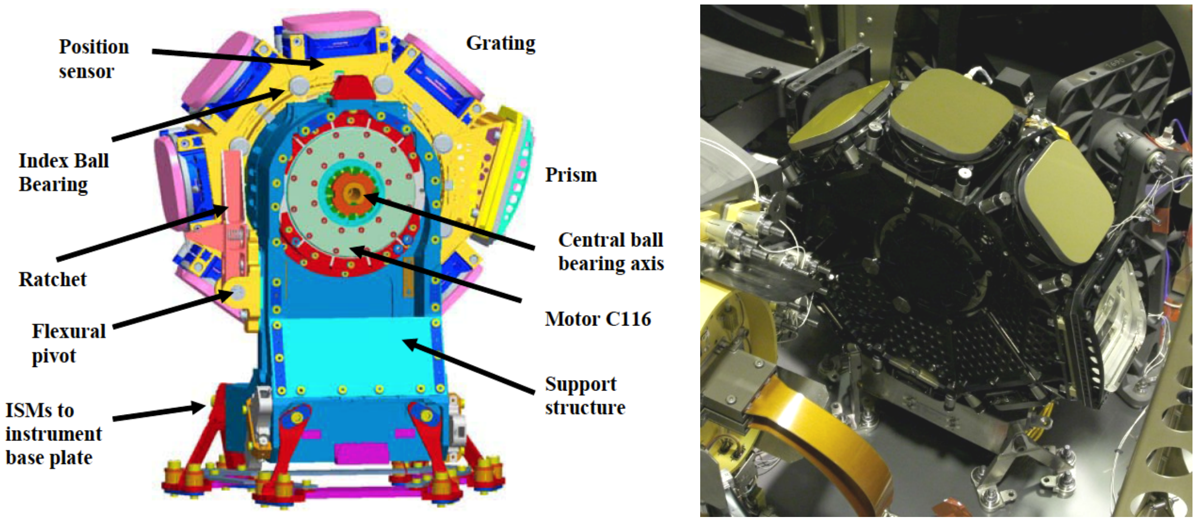

Figure 3. NIRSpec grating wheel assembly with ratchet and index bearings. The actual flight hardware is shown on the right.

The mechanical angular reproducibility of the GWA mechanism is very good due to the very high quality bearings and ratchet assembly[5,6]. Typically the reproducibility is ~2.5 arcsec (1 σ). However, for optimal scientific performance this is not sufficient, as this small angular variation already changes the position of the image on the detector plane by ~0.4 pixel. This mechanical angular reproducibility is too large to accept for two main reasons, as explained in the following.

1. Target acquisition. In order to acquire the scientific targets whose spectra have to be analysed, NIRSpec first has to position these potential science targets with respect to the MSA shutter grid. As NIRSpec does not have a detector in the MSA plane, one has to rely on the MSA image formed at the FPA plane by the COL and CAM three-mirror anastigmat (TMA) optical systems. The angularly not perfectly reproducing GWA is positioned between these two TMA optical systems. It is therefore obvious that the relationship between a position in the MSA plane and the corresponding position in the FPA plane is significantly influenced by this repositioning uncertainty, which needs to be corrected. In the target acquisition error budget, a maximum allowable contribution of ~1/20 of a pixel (equal to 5 mas on the sky) has been allocated for uncertainties in the MSA to FPA transfer. This translates into a required angular knowledge of the actual GWA optical element orientation of ~ 0.3 arcsec, or about 10 times better than the typical mechanical angular reproducibility of the GWA. In the current science operations scenario, this knowledge is obtained by taking a short exposure with the internal continuum lamp to illuminate the fixed slits on the MSA. The exact tilt of the imaging mirror in the grating wheel is derived from the location of the slit images on the detector.

2. Spectral calibration. The NIRSpec spectra will be shifted along the dispersion direction due to the non-perfect GWA reproducibility. The required accuracy for wavelength calibration is 1/8 of a spectral resolution element, corresponding to 1/4 of a pixel. This implies that the grating wheel must place a spectral feature of known wavelength always at the same detector position along the dispersion direction, to within 1/4 of a pixel.

2. THE GRATING WHEEL TILT SENSOR

For the reasons mentioned in the previous section, a grating wheel tilt sensor system was developed that would provide a much better knowledge of the actual orientation of the selected GWA optical element. Two of these tilt sensors have been installed on the GWA. The first system measures the actual orientation of the GWA optical elements along the dispersion direction and the second system measures the orientation along the cross-dispersion direction. The latter is mainly determined by the quality of the GWA wheel bearings. The focus in this paper will be on the tilt sensor that measures the orientation along the dispersion direction, as this is most critical for NIRSpec's performances.

For each of the eight wheel positions, a magnet pair is mounted onto the grating wheel structure. The paired magnets provide a slit for transit of the sensor field-plates, which are fixed to the support structure. The magnetic field is strong and well defined (collimated) in the slit between the magnets. The change of the field strength during transition through the magnets is detected by the field-plates. Magnetic field plates type Infineon FP 420L90B are used that are fully functional over the complete temperature range between 4 and 300 K.

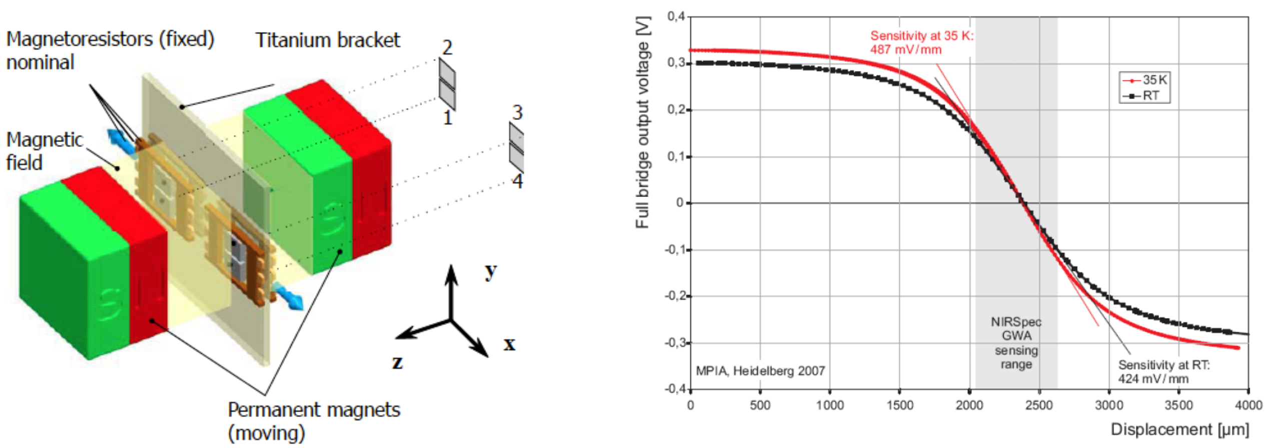

Figure 4. *Left:* Schematic view of the 1-D magneto-resistive position sensor. Four field plates (1–4) on the same side of the holder are located in the strong magnetic field region between a sensor magnet pair providing the nominal signal. *Right:* Test results for the sensitivity of the GWA position sensor based on 4 magnetic field plates in full bridge configuration for a supply voltage of 0.5 V. The two types of curve refer to the sensitivity at 35 K and at room temperature (RT).

The left panel of Figure 4 indicates the four field plates of the nominal sensor unit (marked 1 through 4) at a single location. The angular deviations are derived from lateral displacements along the direction indicated by the arrows. The position sensitivity, as indicated in the right panel, depends on the steepness of the spatial gradient of the magnetic field strength along the indicated direction in Figure 4. A sensitivity of 400 µV/µm in the most sensitive range of the sensor bridge relates to 0.2 arcsec angular resolution of the wheel based on a sensitivity of 20 µV of the readout electronics.

3. FIRST RESULTS

In order to assess and calibrate the accuracy and reliability of the position sensors, we analysed all exposures collected during the first NIRSpec calibration campaign (held in February – March 2011, as described in Ref. 7) that contain clearly resolved spectral features. These include spectra obtained with the external Argon emission line source, with the external rare earth absorption line source (Erbium) and with the external unresolved line source (a laser source).

An example of one such exposure is shown in Figure 5. It presents the Argon spectral line source observed with NIRSpec in IFU mode, through the G140H high-resolution grating (R~2700), centered at 1.4 µm. Only one of the two

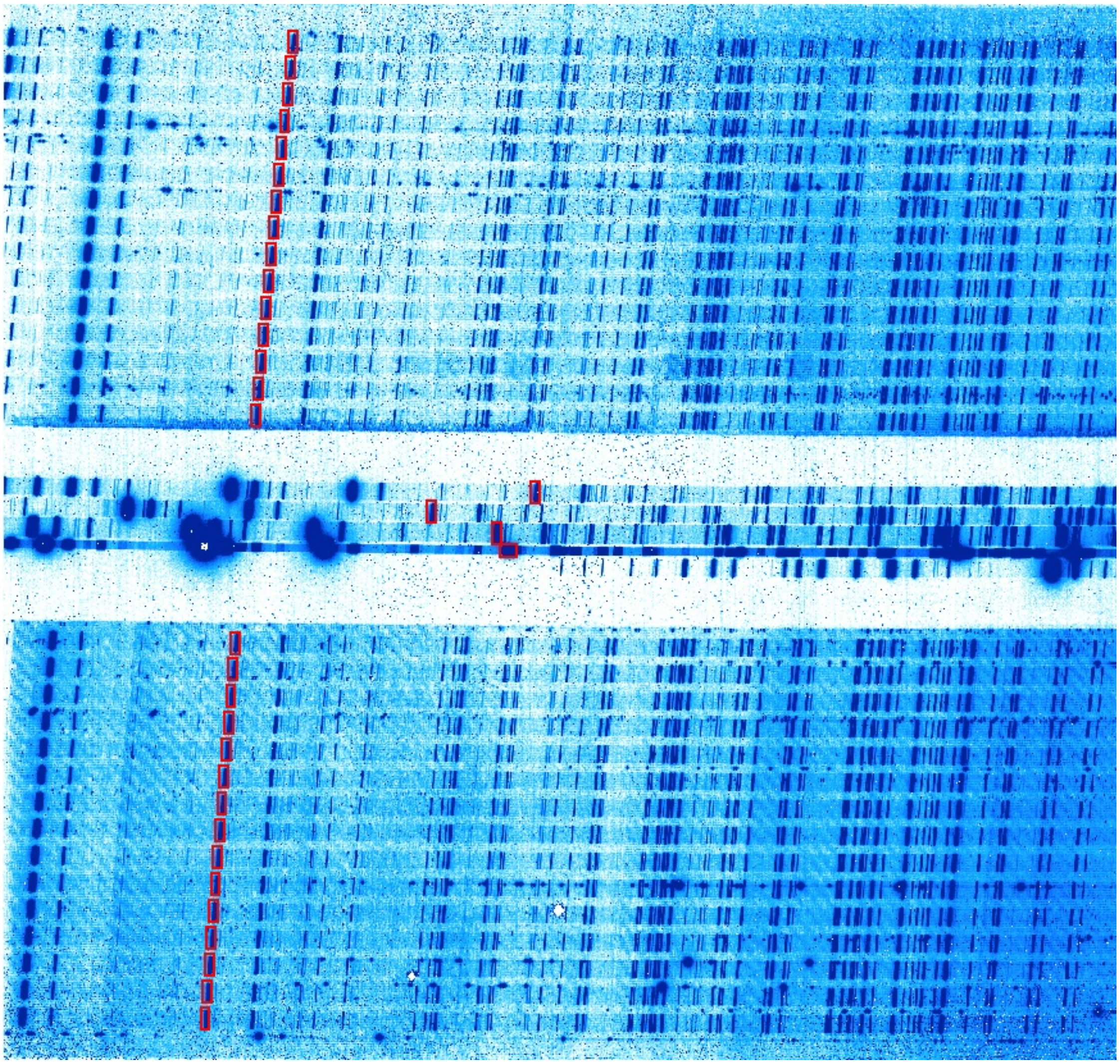

Figure 5. Count-rate image showing the Argon spectral source as observed with NIRSpec in IFU mode, through the G140H high-resolution grating (R~2700). The rectangular boxes correspond to regions including unresolved spectral features that were used to determine the absolute positions of the spectra. The same regions are used in all exposures with the same GWA configuration, and the observed spectral shifts in detector pixels are correlated with the readings of the tilt sensor.

NIRSpec detectors is shown in this figure, showing approximately the wavelength range between 1.0 and 1.4 μm.

The analysis consists in determining the pixel position of a number of well defined, preferably unresolved spectral features, such as those marked by the boxes shown in Figure 5, in all exposures taken at different times but through the same spectral configuration. Since the grating wheel moves between these reconfigurations, the observations allow us to look for and characterise any correlation between the reading of the grating wheel tilt sensors and the actual position of well defined spectral features on the frames.

To this aim, an IDL procedure has been written that extracts from each pre-processed image of the same type a predefined number of regions where the spectral features are expected to be located. The extracted regions have the same exact pixel coordinates in all exposures. A simple cross-correlation routine is used to determine and measure the displacement of the spectral features between exposures and since many regions are considered in each exposure also a reliable uncertainty can be derived. Finally, the IDL procedure looks for a correlation between the displacement of the

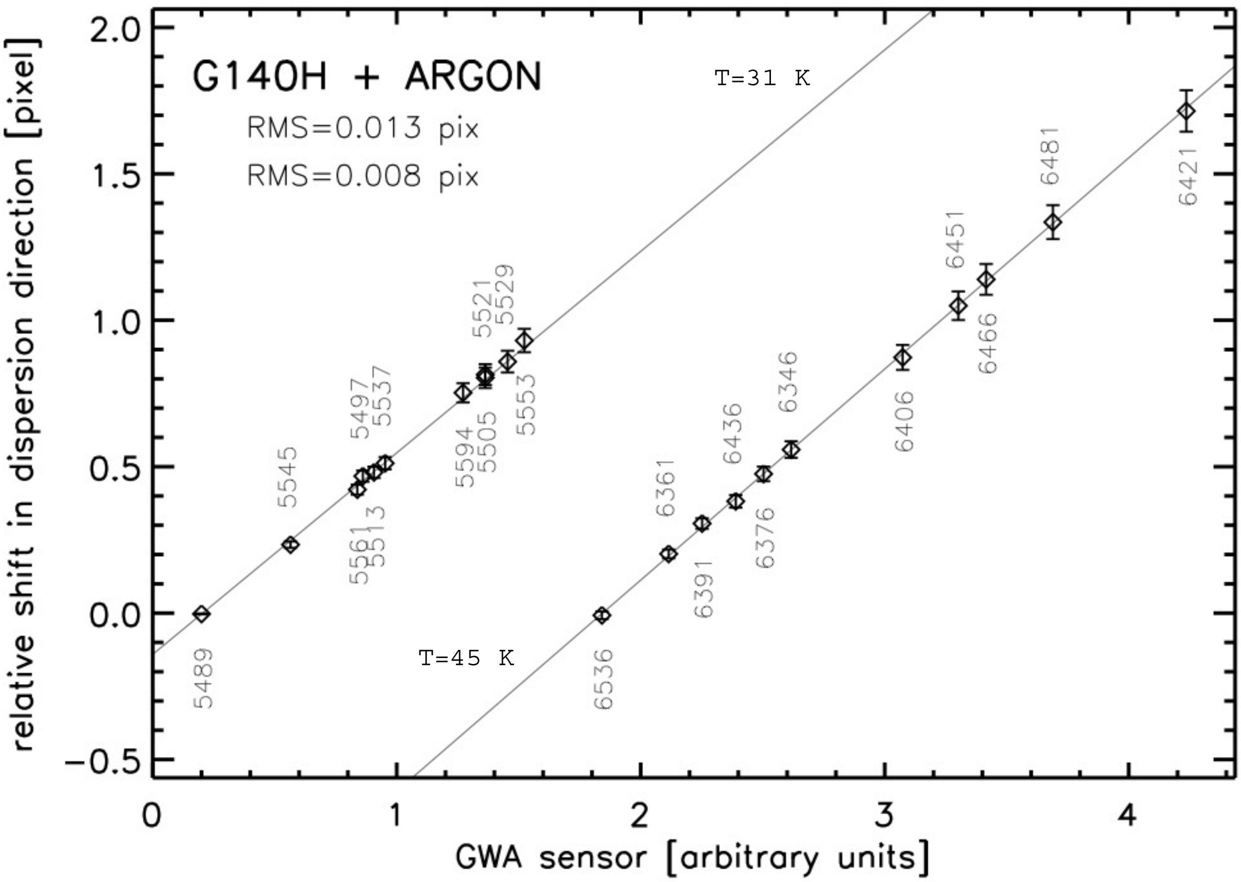

Figure 6. Relative pixel shift measured along the dispersion direction as a function of the reading of the grating wheel sensor. NIRSpec is in high-resolution mode (Band I, from 1.0 to 1.8 μm), using the external Argon lamp as a source. The two sets of data points refer to two different bench temperatures (31 K and 45 K, as indicated). Each exposure is identified by its reference number.

spectral features and the reading of the GWA sensor, which is generated by NIRSpec when the data are acquired and is stored in the header of each exposure.

An example of the results obtained in this way is offered by the graphs shown in Figures 6 and 7. They provide the relative pixel shift measured along the dispersion direction as a function of the reading of the grating wheel sensor. Note that although the latter are shown here in arbitrary units, for simplicity, these values are immediately related to the voltage readings provided by the NIRSpec electronics.

Figure 6 illustrates the excellent correlation existing between the sensor reading and the measured pixel offset in the case of the G140H grating (the same configuration as shown in Figure 5). Each point in this graph corresponds to a separate exposure (indicated by its reference number) and the error bars reflect the scatter in the displacement of different features in the same exposure (i.e. different boxes in Figure 5). In most cases, the error bars are smaller than the size of the symbols and are thus difficult to see.

Note that there are two series of measurements, since in the course of the campaign NIRSpec underwent a planned reset of the temperature of the optical bench (from 31 K to 45 K), meant to test the performances at the extremes of the planned range for operations. As Figure 4 implies, a temperature change affects the readings of the grating wheel sensor as well. Therefore, the two series of measurements were considered separately in the analysis, but as it will be clear hereafter, they gave very consistent results. The solid lines represent the best linear fits to the two distributions and they

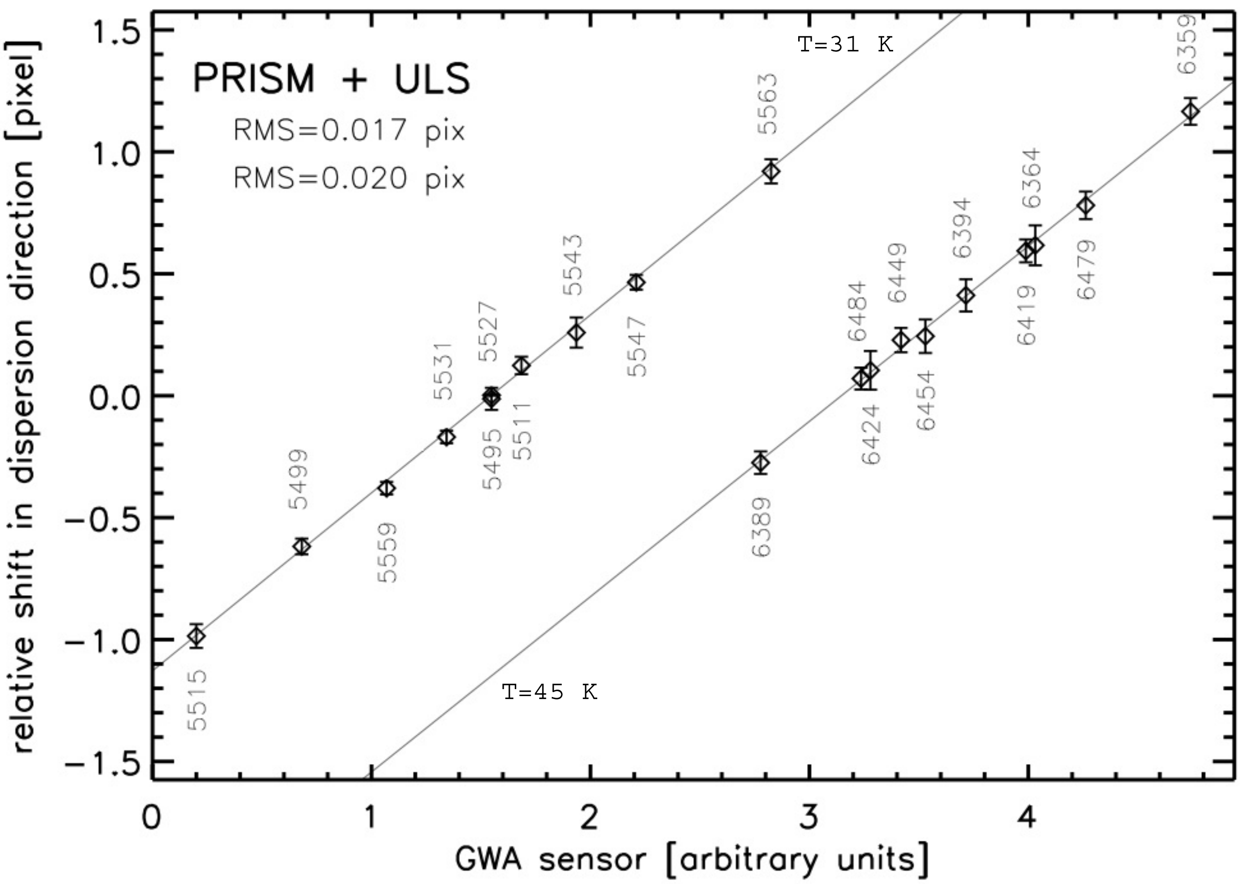

Figure 7. Relative pixel shift measured along the dispersion direction as a function of the reading of the grating wheel sensor. NIRSpec is in low resolution mode (R~100), using the prism and the external unresolved-line source (laser) as spectral input. The two sets of data points refer to two different bench temperatures (31 K and 45 K, as indicated). Each exposure is identified by its reference number.

are characterised by a slope of 0.720 ± 0.015 pixel/unit (for temperature 31 K) and 0.744 ± 0.017 pixel/unit (for temperature 45 K). Within the stated measurement uncertainties, the two slopes are therefore indistinguishable.

More importantly, the data points present a very small scatter around the linear fit, confirming that the sensor's reading correlates very well with the position of the spectral features on the detector. The root mean square (RMS) deviations are 0.013 pixel (for the series at 31 K) and 0.008 pixel (for the series at 45 K), which correspond, respectively, to about 1/150 and 1/285 of a resolution element, thus much smaller than the 1/4 of a pixel required to achieve the desired accuracy in the wavelength calibration. In general, the RMS never exceeds 0.025 pixel, or 1/80 of a resolution element and therefore the accuracy is at least ten times better than the one required for wavelength calibration[8] and at least twice as good as the requirements for target acquisition (see Section 1).

Similarly, Figure 7 shows the results of our analysis for a different configuration, i.e. an unresolved-line source (laser) observed with the NIRSpec low-resolution mode, namely the prism (R~100). As in Figure 6, the two series of data points refer to before and after the temperature change, but the slopes of the best fitting lines are in excellent agreement, respectively 0.730 ± 0.018 pixel/unit and 0.719 ± 0.030 pixel/unit. The RMS deviations around the best linear fits (shown by the solid lines) are respectively 0.017 pixel for the series at 31 K temperature and 0.020 pixel for the series at 45 K temperature, or better than 1/100 of a resolution element in both cases.

4. CONCLUSIONS

We have presented the concept and design of NIRSpec's grating wheel tilt sensors. These sensors were designed and successfully implemented to improve the knowledge on the actual angular orientations of the GWA's optical elements in use.

In conclusion, this analysis demonstrates that, using the sensors installed on NIRSpec's grating wheel, it is possible to predict the position on the detector of any spectral feature of known wavelength with an accuracy at least 10 times better than that required for wavelength calibration, regardless of the target's location across the FOV. This level of accuracy implies an uncertainty in the MSA to FPA transfer of less than 1/40 of a pixel, or half of the maximum allowable contribution allocated in the error budget for target acquisition.

These findings can have important implications for the efficiency of NIRSpec's science operations. It is presently envisaged that, at least in the initial phase of operations, internal spectral calibration data will be automatically obtained after each pointed observations, before the grating wheel is moved, in such a way that the zero point of the wavelength calibration can be directly derived. However, if the ability of the grating wheel's sensor to accurately predict the position of any spectral feature on the detector is confirmed during the second phase of the NIRSpec ground calibration campaign and during on-orbit commissioning and early operations (using the internal Erbium spectral source), it will be possible to abandon this scenario and rely exclusively on the position/tilt sensors for the zero point of the wavelength calibration. In principle, even the target acquisition process might not need to make use of the planned short exposures with the internal continuum lamp, which are meant to infer the exact tilt of the imaging mirror in the grating wheel from the location of the slit images on the detector. Measurements collected during the commissioning and early operations phase will be crucial to understand whether the accuracy delivered by the GWA tilt sensors consistently reaches the levels required for target acquisition. Although at the moment the baseline approach for NIRSpec's science operations remains unchanged, the performances and reliability of the GWA position sensors measured so far suggest that, in the longer term, it should be possible to reduce the need for internal calibration exposures, thus saving both time and usage of the internal mechanisms.

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