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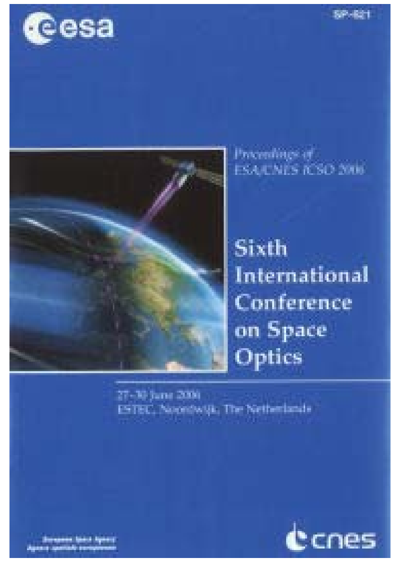

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DESIGN AND MANUFACTURING METHODS FOR THE INTEGRAL FIELD UNIT OF THE NIRSPEC INSTRUMENT ON JWST

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ABSTRACT

An integral field unit, to be used with the near-IR spectrometer instrument of the James Webb Space Telescope (JWST), is currently under development by SSTL and CfAI. Special problems in design and manufacture of the optical system are outlined, and manufacturing methods for critical optical elements are discussed. The optical system is complex, requiring a total of 95 mirrors to produce 30 output channels. Emphasis is placed on the advantages of free-form machining in aluminium. These include: resistance to launch stress, insensitivity to temperature variations from ambient to cryogenic, and the possibility of relatively complex mirror surface shapes.

1. IFU FUNCTION AND REQUIREMENTS

The Near-IR Spectrometer (NIRSpec), at the JWST focal plane, will operate over the wavelength range from 700nm to 5000nm, and will include an Integral Field Unit (IFU). The IFU is located at a sky image formed by the telescope and NIRSpec fore optics, before the spectrometer collimator, gratings and re-imaging optics.

The IFU will be used in spectral analysis of nebulae and other extended objects. Its function is to receive a small square section of the sky image, and to dissect and re-assemble this area as a long slit image, for analysis in the following spectrometer system. The IFU allows analysis of an extended object in a single NIRSpec frame, avoiding the necessity to scan the area across a fixed entrance slit in several frames. IFUs have been constructed mainly for use in ground-based telescope systems [1, 2, 3].

1.1 Input and output

The input field, formed at f/12.5 by the telescope and NIRSpec fore-optics, is nominally 1.2mm x 1.2mm. This corresponds to a sky area 3 arc seconds square. This field is split into 30 slices, each 1.2mm x 0.04mm at the input field.

The IFU outputs the slice images in a common line, forming a “virtual slit” with 30 sub-slits. The magnification of the IFU is x1 in the direction parallel with the virtual slit. In this paper, the slit direction is designated X, while the input and output light direction is Z. The magnification is x2 in the Y direction, orthogonal to the sub-slits, which is of course the dispersion direction in the following spectrometer system. Each sub-slit is nominally 1.2mm long and 0.08mm wide. The sub-slits are arranged in two groups of 15; the separation of sub-slit centres in each group is 2mm, and the central separation between groups is >14mm, so that the overall length of the virtual slit is 74mm.

The output image is formed at f/12.5 in the XZ section. In the YZ section, the geometrically-traced output is at f/25, but diffraction produced at the slicer elements spreads the beam significantly at the longer wavelengths in the NIRSpec range, so that the aim is to output a beam up to f/12 in both sections.

The spectrometer optics following the IFU are designed for telecentic input (i.e. output beams from the IFU are required to be parallel within specified telecentricity errors).

1.2 Environment and envelope

The IFU will be integrated and launched at normal terrestrial temperatures, but it will operate, and be tested, at around 30K. The system must therefore survive temperature cycling between ambient and cryogenic temperatures, and will preferable provide good optical performance at both extremes. It must also of course survive launch vibration loads without significant loss of optical performance due to distortion of optics or the whole unit.

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Some significant problems in design are presented by limitations in space that can be allocated to the IFU, within NIRSpec. In fact the IFU will be mounted on the NIRSpec Micro-Shutter Assembly (MSA), which is located at the input focal plane of the spectrometer sub-system. The MSA has four sub-arrays provides micro-windows for a total input field area approximately 80mm square: the IFU will receive light through a 2mm diameter window in a space between two lower sub-arrays.

The rough dimensions of the allowable envelope (ignoring some cut-aways and allowed bulges) are:

X: 150mm, Y: 70mm, Z:200mm.

The limitation in Y is required, since the IFU must be located in space between the beams from the MSA and the bracket on which the MSA is mounted. The limitation in Z (in and out light direction) is due to a fold mirror that follows the MSA. The IFU structure cannot be placed less than 36mm from the focal plane.

1.3 Optical performance

The basic specification for the IFU includes:

Throughput:	>50% at all wavelengths
Wavefront error:	<100nm rms
Telecentricity errors:	<0.2°
Stray light:	<5% sub-slit cross-talk
Sub-slit tilts:	<70 arc minutes

The wavefront error (WFE) is required to include defocus caused by inaccuracies in initial location of the IFU, and subsequent perturbations, including shifts due to cool-down.

1.4 Brief introduction to IFU principles

A conventional IFU optical design, indicated schematically in Fig. 1, includes:

Pick-off (input fold) mirror. A pick-off mirror must be used to receive light from the telescope focal plane, and reflect the light into the following IFU optics. The NIRSpec IFU will differ from most existing IFU designs in that the pick-off mirror cannot be placed at the focal plane; this tends to increase problems in achievement of optical performance, in a confined optics envelope.

Re-imaging mirrors. Re-imaging mirrors will form a magnified image of the input field onto a slicer (at which the input image is dissected). To produce the required magnification in a limited space, a telephoto arrangement can be used, with a concave first re-imaging mirror and a convex second re-imaging mirror. For the NIRSpec IFU, greater magnification is required overall in the X (spectral) direction, than in the Y direction, by a factor 2; it is most convenient to introduce anamorphic magnification using the two re-imaging mirrors. For the NIRSpec IFU, magnification factors x10 and x20 will be used in Y and X sections respectively: providing nominal facet areas 12mm x 0.8mm, which are convenient for manufacture of the slicer.

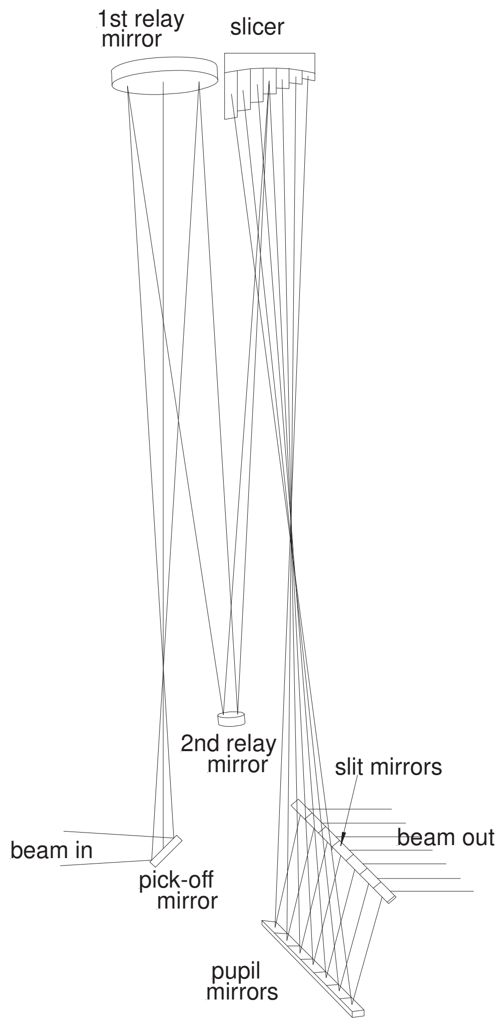

Figure 1 IFU schematic

Slicer. The slicer is located at the magnified image produced by the re-imaging mirrors; it will split this image at 30 mirror facets. The next set of mirrors – the pupil mirrors – are typically in a common line. Each slicer facet is curved and tilted on X and Y axes to direct the slice-image beam onto a unique associated pupil mirror.

Pupil mirrors and slit mirrors. The pupil mirrors are curved and tilted to form sub-slit images in a common line – effectively the entrance slit of the following spectrometer. The sub-slit images are normally formed on the surfaces of a line of slit mirrors. The slit mirrors are curved and tilted such the output beams, from all image points in all sub-slit images, are directed towards a common spectrometer entrance pupil. The NIRSpec IFU differs from some existing systems in that the slit mirrors cannot be located at the focal plane: for NIRSpec the slit mirrors will be followed by a **final fold mirror**, which will reflect a virtual image of the slits at the spectrometer input focal plane.

2. OPTICAL DESIGN OF THE IFU

The baseline optical design is shown in Fig. 2 and Fig.3. Fig. 2 is a view in the X direction, with rays drawn for only 5 points in the field (reflected from 5 slices of the slicer). An all-mirror system is naturally preferred, to deal with the wide spectral range of NIRSpec.

Two flat mirrors – pick-off and a second fold mirror – direct the beam from the input field onto the first re-imaging mirror. The first relay mirror – the largest continuous optical surface – is a concave toroid with small cubic perturbations. It reflects the beam onto the second relay mirror: this is a small mirror located between two groups of pupil mirrors; it is a convex toriod, also with small cubic perturbations. The two relay mirrors form a good image of the input field on the slicer, at magnification factors x20 in the YZ section and x10 in XZ.

A detail of the slicer is shown in Fig. 4, with principle rays to extremes of each sub-slit field included. The slicer has 30 facets, with facet dimensions averaging 0.8mm (Y) by 12mm (X). The slicer facets are shaped to image the pupil (which is at infinity in FRF-space) onto individual pupil mirrors. The slicer facets are made slightly toric, to correct for astigmatism in pupil-imaging by the two relay mirrors. They are tilted on X and Y axes to direct beams at the pupil mirrors.

The pupil mirrors – see Fig. 5 – are arranged in a common (curved) line, in two groups of 15. The common spacing is 2mm and the centre spacing is 15mm. (I.e. centres of inner pupil mirrors are at Y = 8.5mm and -8.5mm; centres of outer pupil mirrors are at Y = 36.5mm and -36.5mm.) Note that the second relay mirror is located between the two groups of pupil mirrors.

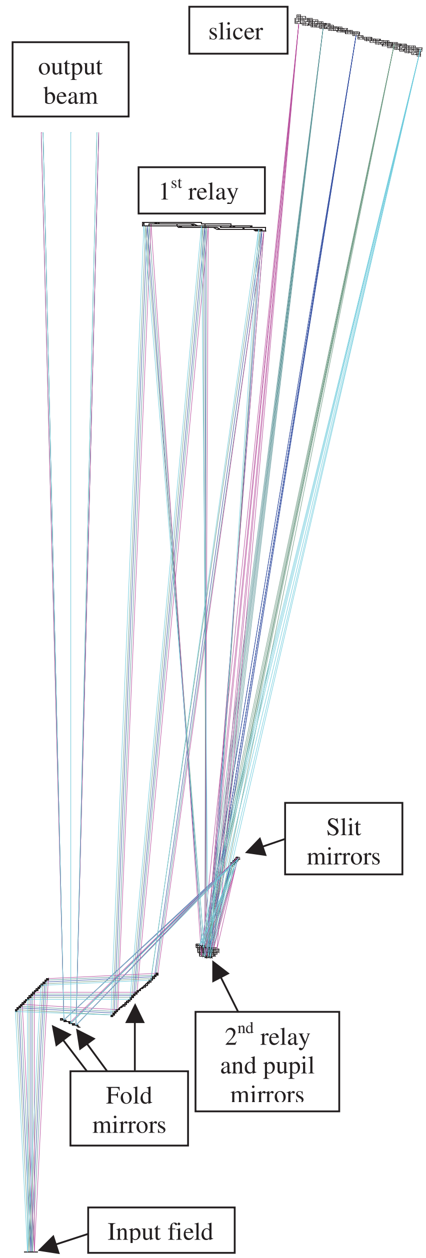

Fig. 2 Baseline optical design – view on YZ plane

The pupil mirrors are tilted on X and Y axes such that the reflected beams are directed at the slit mirrors, also shown in Fig. 5, which includes centre-field principle rays for each sub-slit field. The pupil mirrors are concave toroids with added cubic perturbations.

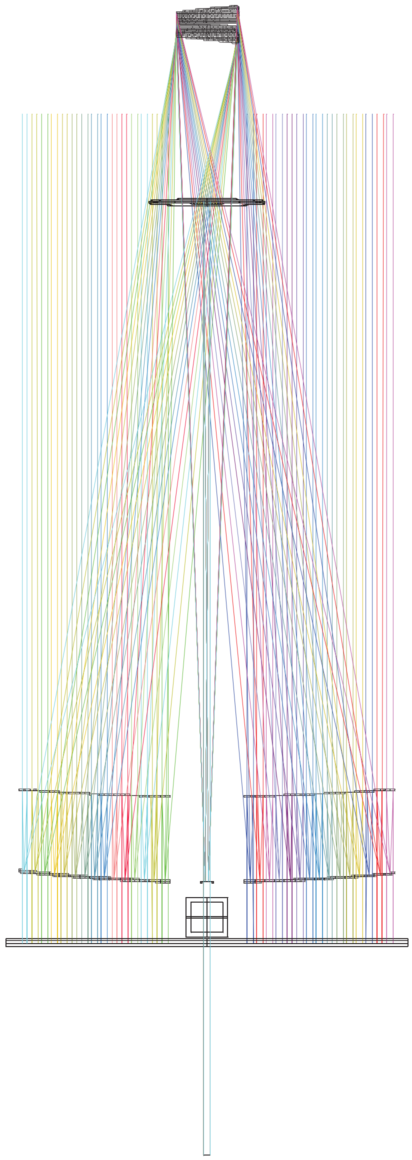

Fig.3 Baseline optical design – view on XZ plane

The pupil mirrors form slit images close to a line of slit mirrors (also curved): the Y-separations of the slit mirrors are the same as the Y-separation of the pupil mirrors. The slit mirrors are concave and spherical; they deflect the beams onto a single flat fold mirror, which will reflect the output beams towards the NIRSpec spectrometer.

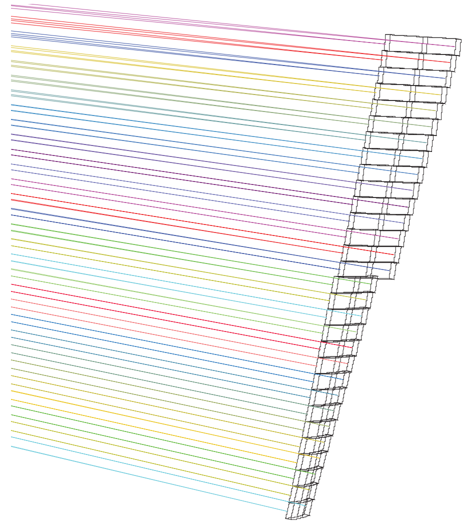

Fig. 4 Slicer

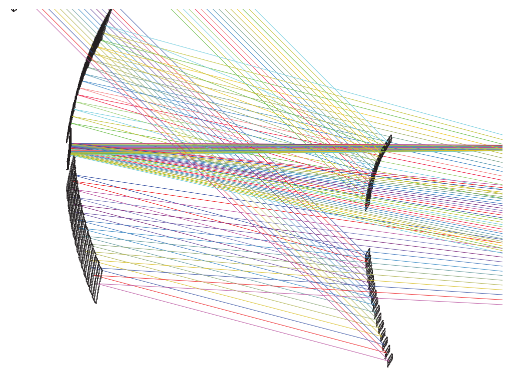

Fig. 5 Pupil and slit mirrors

The locations and Y-axis tilts of the slit mirrors and final fold mirror are controlled such that the output image – the virtual slit – is located in the same plane as the input field (with a required Y-separation with respect to the centre of the input field).

3. MANUFACTURING METHODS

3.1. Materials

An all-aluminium design is preferred for optics and structure, using diamond machining to produce all optical surfaces and critical mounting interfaces. The same billet of aluminium alloy is used for all optical components and for the main frame to which the optical components are attached. The material is selected primarily for strength, but also allows adequate surface quality in diamond-machined mirror surfaces. Each of the 3 mirror arrays (slicer, pupil mirrors and slit mirrors) will be machined as a monolithic optical component in a single complex machining operation, without remounting the aluminium work-piece. The second relay mirror, which is located in the centre of the pupil-mirror array as indicated in Fig. 5, will be formed on the pupil-mirror monolith.

The essential advantages of this approach are:

- Perfectly athermal design: with no change of focus or other aberrations for co-planar input and output image fields: this is highly desirable for construction, testing and operation over a very wide overall temperature range,
- Elimination of significant risks in the integrity of joints between optics and structure,
- Very precise control of the relative alignment of mirror facets within each of the 3 mirror-arrays,
- Great simplification of the optics alignment process: 91 of a total of 95 mirror surfaces will be pre-aligned on only 3 components.

3.2. Machining methods

For different reasons, all or most of the IFU mirror surfaces will be machined by "raster fly-cutting". In this process, the cutting tool is rotated at relatively high speed on a machine Z axis, the tip of the tool tracing a toric surface, with radii determined respectively by the tool-tip distance from the Z axis and the radius of the tool tip itself. Both these radii must be less than the local radii to be produced on the work-piece (unless the required surface is convex). The work-piece is mounted on a table, and moved very precisely on 3 axes, so that the required mirror surface shape is generated in a series of "pecks".

Raster fly-cutting is slower than a turning operation (in which the work-piece rotates fast on the Z axis, while the tool moves radially and in Z). However, although turning is a possible option for flat fold mirrors, it is unrealistic for the array elements and for the small second relay mirror. It also proves to be impractical for the first relay mirror; an approximation to the ideal shape could in principle be turned for the 1^{st} relay, but the turning radii required in this case are too large.

3.3 Design impact of diamond machining

Use of diamond machining has two types of impact on detailed optical design. The first is a significant advantage, particularly in the case of the NIRSpec IFU. Freeform machining by raster fly-cutting allows literally any surface shape to be produced, without significant impact on surface-form accuracy (provided only that local concave radii are smaller than the radii produced by the cutter). Because of its relatively small envelope, the powers of optical surfaces tend to be large, and the extreme angles of incidence on optical surfaces also tend to be fairly large.

- The relay mirrors must in any case be toric, to generate anamorphic magnification at the slicer, but, using simple toric curves, they also produce significant coma and tilt of the best-focus plane. The quality of image formed at the slicer is improved by including shape terms $\rho^3\sin(\theta)$ (coma, where ρ is pupil radius and θ is azimuth) and $\rho^3\sin(3\theta)$ (which partially corrects image tilt), as well as the toric term in $\rho^2\cos(2\theta)$.
- Significant astigmatism and coma can also be corrected at the pupil mirrors, using shape terms $\rho^2\cos(2\theta)$, $\rho^2\sin(2\theta)$, $\rho^3\cos(\theta)$ and $\rho^3\sin(\theta)$. The weighting of sine and cosine coefficients varies to correct for aberrations produced by a range of azimuths in the planes of incidence.

Other impacts on design relate to specific problems in formation of array elements using diamond machining. In the case of the slicer, the most significant problem is in cutting right-angle steps between facets. This is classically done using a "half radius" tool as indicated in Fig. 6. The process is facilitated by making the steps monotonic, so that all facets can be cut without a major re-orientation of the work-piece with respect to the cutter. However, because there is a gradation between facet angles, and all mirrors must be cut using a rounded part of the tool tip, this demands that the work-piece shall be precisely rotated between the operations on successive facets. This has an impact on tilts of the slice images.

There is a similar problem in the case of the pupil mirrors. The pupil mirrors are at different angles on local Y axes, so that normally it would be necessary to produce steps between the mirrors. However, we can eliminate the spatial discontinuities between facets (and avoid the need to use a half-radius tool) by placing facet centres on an arc, as indicated in Fig.5: the arc approximates a parabola with focus at the slicer. The slit-mirror line is also curved, to provide equal magnifications of the sub-slits. (Steps between slit mirrors are not a serious problem, because the beam widths on these mirrors are substantially smaller than the centre separations.)

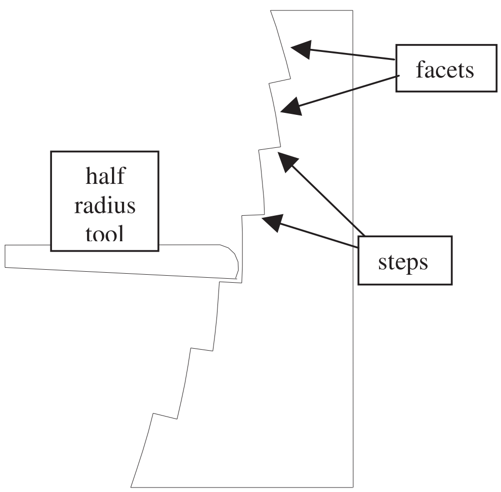

Fig. 6 Slicer schematic: cutting problem

4. MOUNTING AND ALIGNMENT

The main structure for the IFU will be a monolithic framework. Mounting faces on optical components and the structure will be diamond machined flats, allowing sufficiently precise location of most elements without adjustments. It will be possible to limit systemmatic adjustments to 3 components. The adjusted components will be:

- 1st relay mirror. X, Y and Z shifts and rotation on the Z axis: essentially to optimise the quality of the image formed on the slicer, correcting effects of errors in location of the input fold and second relay mirrors.

- Slicer. X, Y and Z shifts and rotation on the Z axis: essentially to centre pupil images on pupil mirrors, and for fine adjustment of telecentricity.

- Slit mirrors. X and Y shifts for coarse adjustment of telecentricity. Z shift and rotation on Y for optimisation of output image focus.

5. PERFORMANCE

The IFU design achieves its major performance requirements, as outlined in 1.3 above.

Preliminary breadboarding indicates that rms surface roughness <10nm will in general be achieved, giving scatter losses <3.2% per surface at 700nm; gold coatings will absorb approximately 4% at the same wavelength, giving worst-case throughput calculated at 57%. Much higher throughput will be achieved at longer wavelengths. Only part of the surface scatter will appear as stray light: worst case cross-talk is estimated at 4%, assuming a BRDF function of the form: $B.\theta^{-2}$.

Design wavefront aberration, for the worst-case channel is <25nm rms. The most significant contribution to total wavefront errors is likely to be due to alignment errors, for which a total contribution up to 50nm rms is estimated.

6. ACKNOWLEDGEMENTS

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