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NIRSpec Performance Report
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Optical Throughput of the NIRSpec Instrument

Abstract:

This report aims to demonstrate that the NIRSpec instrument meets all its requirements related to optical throughput. Using a series of exposures obtained during the first cryogenic calibration campaign in February 2011, and illuminated by different calibrated optical stimuli, we measure the end-to-end throughput of the NIRSpec optical train. Our results indicate that NIRSpec meets or exceeds all throughput requirements.

1 INTRODUCTION

The NIRSpec instrument underwent two cryogenic test campaigns in February 2011 and January 2013 (hereafter Cycle 1 and Cycle 2, respectively). The content and timeline of the test campaigns are detailed in Ferruit et al. 2011 (NTN-2011-001), while the design and capabilities of the Optical Ground Support Equipment (OGSE) used during the campaigns are described in Birkmann et al. 2011 (NTN-2011-002).

The data acquired during the two test campaigns allow an early assessment of some key aspects of the NIRSpec performance, and will provide the basis for evaluating whether NIRSpec meets its performance requirements detailed in the Functional Requirements Document (JWST-RQMT-002060). This note specifically addresses the requirements related to instrument throughput, in particular NFSR-42, NFSR-43, and NFSR-44. For convenience, these requirements are reproduced in Appendix A.

The analysis presented in this note compares the measured electron rates (computed after standard pre-processing of NIRSpec raw exposures) to the photon signal provided by the OGSE calibration lamps. The results provide confidence that NIRSpec meets all throughput requirements with margin.

2 CALIBRATED REFERENCE LAMPS

2.1 CLS

The reference lamp acting as the flux standard throughout the NIRSpec on-ground calibration campaign was the Calibration Light Source (CLS). For the throughput measurements discussed in this note, we exclusively used the CLS configurations FF1, FF2, FF3, and FFB, which provide continuum spectra for the various NIRSpec dispersers. Their output spectra were measured by the National Physics Laboratory (NPL) and supplied, together with the hardware, by the CLS vendor (Mullard Space Science Laboratory, MSSL), and. The NIRSpec Instrument Performance Simulator (IPS) software is used to smooth the measured output spectra, and to correct them for the reflectivity of the OGSE folding mirror that steers the CLS beam onto the NIRSpec coupling optics. The resulting spectra[1] of the CLS beam entering NIRSpec are reproduced in Figure 1.

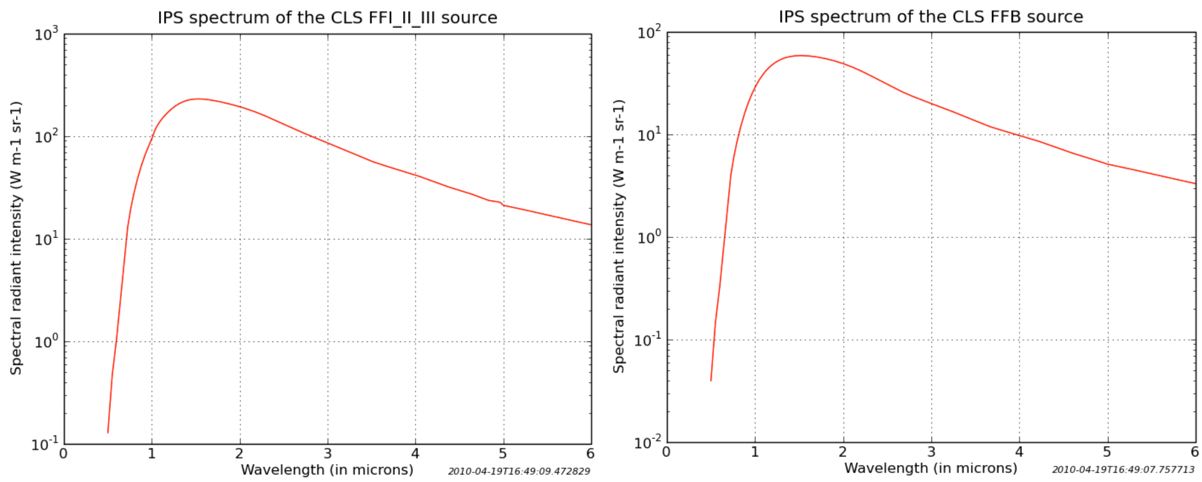

Figure 1: Output spectra for CLS lamps FF1-3 (left) and FFB (right), as measured by MSSL.

These spectra specify the spectral intensity I_{CLS} (in units of [W m^{-1} sr^{-1}]) emanating from the CLS. The expected number of photons per wavelength interval can be calculated as

$$n_{ph} = (I_{CLS} * A_{eff} * \Omega) / h\nu \quad [ph/s/m]$$

Here, the solid angle Ω covered by the NIRSpec entrance aperture is $1/d^2$ [sr] where d=3.198m is the distance between the CLS exit aperture and the NIRSpec entrance aperture. The factor A_{eff} is the effective area of a NIRSpec resolution element in the NIRSpec entrance plane (i.e. the OTE focal plane), taking into account the magnification of the NIRSpec optics as defined by the focal ratios at the respective image planes (OTE, MSA, and FPA), the physical width of the slit aperture in the MSA plane (W_{slit}), and the physical size of a detector pixel (W_{pix}):

$$A_{eff} = W_{slit} * W_{pix} * f\#_{OTE}/f\#_{FPA} * f\#_{OTE}/f\#_{MSA}$$

[1] as specified in files *OGSE05_CLS_FFI_II_III.src* and *OGSE05_CLS_FFB.src*

With W_{pix} = 18μm, W_{slit} = 81μm (appropriate for the S200 slits), and the as-built focal ratios for the FORE, COLL and CAM optics, this becomes A_{eff} = 8.833E-09 m².

Finally, the CLS calibration at MSSL was performed with the default positions of the various attenuation wheels. For FF1-3, the NIRSpec-level calibration measurements were done with identical wheel settings. In the case of FFB, however, it was necessary to reduce the CLS output in order to avoid saturation. For this reason, the reference spectrum of the FFB lamp was scaled down by the appropriate attenuation spectrum as measured by the ratio of the two corresponding NIRSpec exposures (NID 4408 and 4414).

To allow direct comparison with the calibration data described in Section 3, the CLS spectra were re-binned to a regular wavelength grid with a sampling of 0.005 μm (0.02 μm in the case of the FFB lamp).

2.2 RCSS

In order to provide a consistency check of the CLS calibration accuracy, we also use exposures of the Radiometrically Calibrated Spectral Source (RCSS). This lamp, which is located in the NIRSpec entrance focal plane, provides a single point source with a JWST-like PSF.

The RCSS was calibrated – for wavelengths below 1.6 μm – in 2010 by the Physikalisch-Technische Bundesanstalt (PTB) in Berlin, Germany. The results of the calibration are summarized in the report NIRS-ASD-TR-0106. The correspondence between the source names used in that report and those used for the RCSS telemetry can be found in NTN-2012-008. We adopt the measurement uncertainties quoted by PTB in their report.

3 CALIBRATION DATA

The data set used to compute a first estimate of the instrument throughput was selected from the COMBO1 test sequence executed on February 23, 2011. The numerical identifiers (NIDs) of the exposures used for each NIRSpec disperser are summarized in Appendix B.

We rely primarily on data from Cycle 1 because it was discovered during Cycle 2 that the output of the CLS had degraded between the two test cycles, presumably caused by the ~2 years of storage.

The calibration data were run through the NIRSpec pre-processing pipeline (Birkmann et al. 2001, NTN-2011-004) to compute electron rate maps that are corrected for detector dark current, linearity, and gain. From these electron rate maps, rectified one-dimensional (i.e. averaged along the spatial direction) spectra for the S200_A1 slit were extracted via the Python routine *p_getSpectrumSlitdrr*. The output spectra are wavelength-calibrated based on a model of the instrument dispersion[2], and are re-sampled onto regular wavelength intervals.

To enable a direct comparison of the NIRSpec spectra to the CLS reference spectra, both are rebinned to a common wavelength sampling (0.005 μm for FF1-3, and 0.02 μm in the case of FFB).

For wavelengths shorter than ~1.4 μm, it is important to correct for the quantum yield of the NIRSpec detectors, i.e. the generation of multiple electrons per photon. This mechanism has been studied by Lindler et al. who provide a recipe to correct the derived electron rates. The following analysis uses this correction, which is shown in Figure 2 for the two NIRSpec SCAs as a function of wavelength.

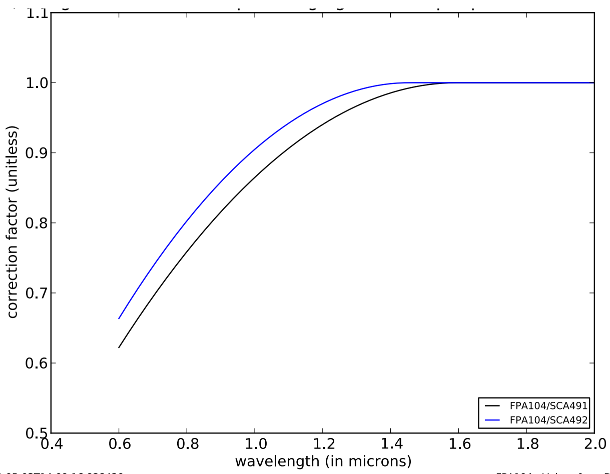

Figure 2: Correction factor to account for the generation of multiple electrons per photon at short wavelengths, a.k.a. quantum yield correction (D. Lindler, priv. communication).

A custom written IDL routine called *calc_throughput.pro* was used to perform the above steps and to compute, for each disperser, the instrument throughput as the ratio between the measured electron rates and the input photon rate. Note that at the moment, the routine does not accept any input parameters, and must be edited according to the combination of data set and lamp spectrum used for the computation.

[2] Specifically, the instrument model *NIRS_FM1_optimized_02* was used.

4 RESULTS

The resulting throughput curves for the CLS exposures of the six NIRSpec gratings and the PRISM, are presented in Figs. 3 and 4 (black curves). The top two panels in Fig. 2 compare the CLS measurements for the two band I gratings (G140m and G140H) to the corresponding results derived from the RCSS data.

The important conclusion from this comparison is that the derived NIRSpec throughput values agree rather well for the two OGSE sources, which have been calibrated completely independently using different flux standards at different laboratories. Although a similar comparison is not possible for bands II and III (because the RCSS calibration was limited to wavelengths below 1.6 μm), the calibrated CLS output spectrum in Fig. 1 is "anchored" well by the RCSS calibration data, and therefore provides confidence also in the results for bands II and III which must rely solely on CLS data.

For all seven NIRSpec configurations shown in Figs. 3 and 4, the derived throughput curves are also compared to the expected "worst case" throughput (red curves) derived from sub-system and component-level data as described in NIRS-CRAL-TN-017.

For convenience, Appendix A reproduces all throughput-related requirements listed in the two governing documents: the NIRSpec System Functional Requirements Document (SRD) and the NIRSpec Functional Requirements Document (FRD).

In Figs. 3 and 4, the SRD requirements for the minimum throughput in each NIRSpec mode are indicated by the horizontal black lines. The SRD also specifies requirements for the average throughput in each band, which are identically repeated in the FRD. Table 1 summarizes the comparison between these requirements and the measured and predicted "worst case" values.

As can be seen, the calculated NIRSpec throughput significantly exceeds the expectations in all modes. An important implication of this result is that it validates the approach of using of the "worst case" component-level throughput estimates for the verification of the SRD requirements by ASD, as described in NIRS-CRAL-RP-0002.

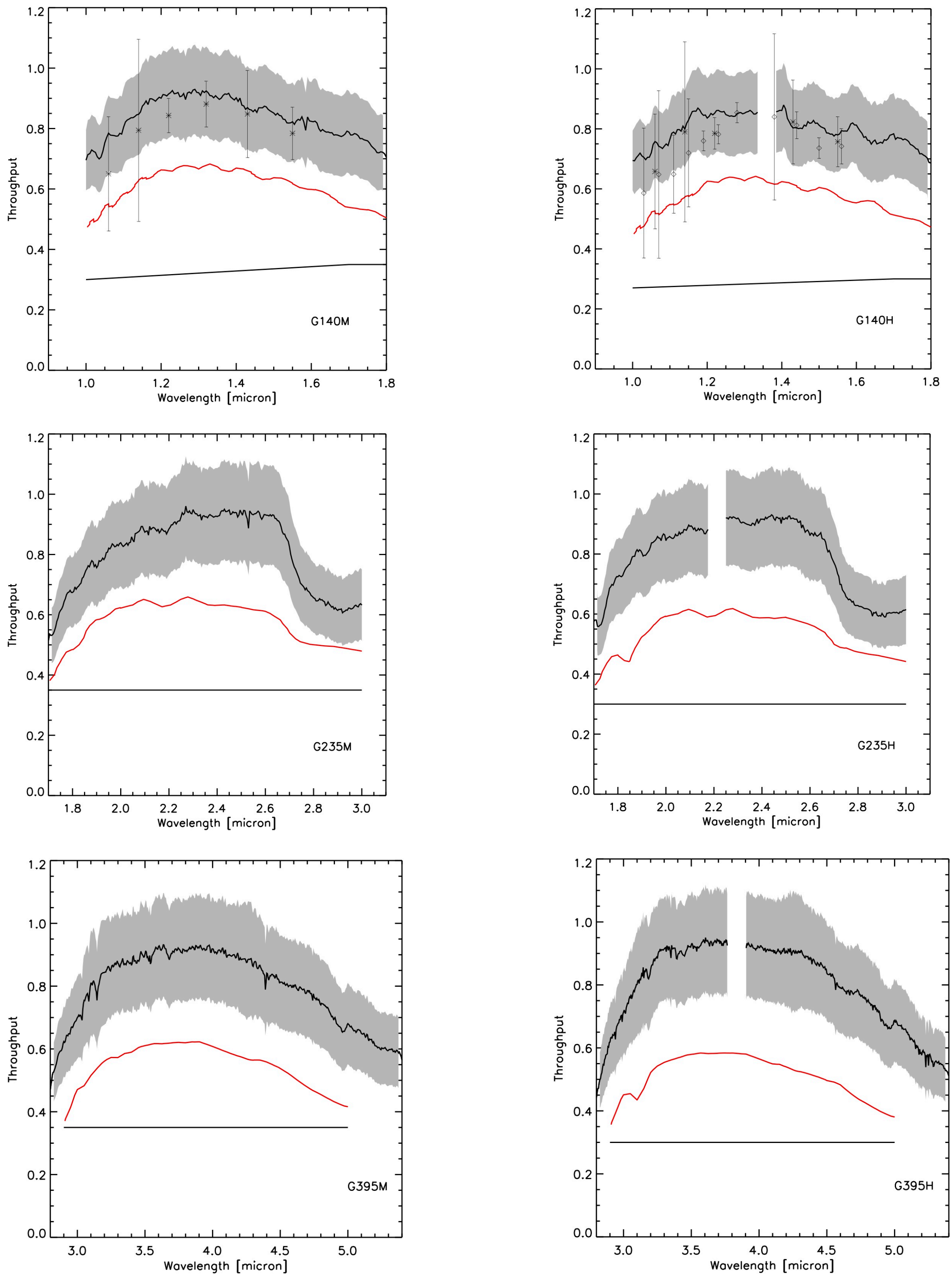

Figure 3: Optical throughput for the six NIRSpec gratings (black curves), estimated using the calibrated lamp spectra for CLS lamps FF1, FF2, and FF3 as reference. The shaded band denotes the total measurement uncertainty, which includes the CLS calibration error, the detector DQE uncertainty, as well as smaller contributions due to OGSE alignment errors and cryo-induced changes of mirror reflectivities. For comparison, the expected “worst case” throughput estimate based on component-level measurements is also shown (red curves). The black horizontal lines denote the SRD requirements for minimum throughput as listed in Appendix A.

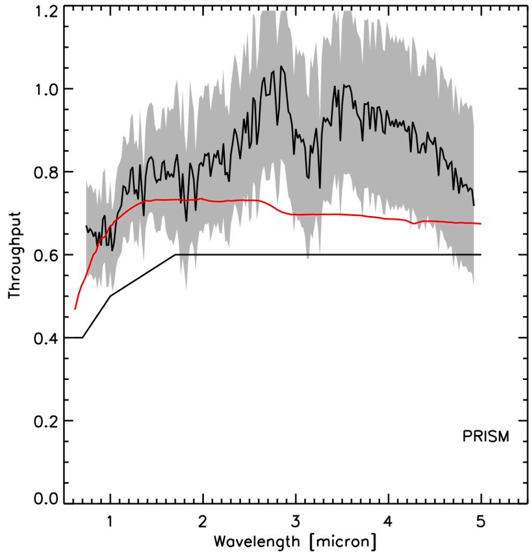

Figure 4: Optical throughput for the NIRSpec PRISM, estimated using the calibrated lamp spectra for the CLS lamp FFB as reference. The error band is as described for Figure 3. The lower red curve indicates the expected "worst case" throughput based on component-level measurements. The lower black line marks the SRD requirement for minimum throughput as listed in Appendix A.

Grating	Average Throughput (measured)	Average Throughput (worst case estimate)	FRD Requirement
G140M	0.846	0.608	0.44
G235M	0.805	0.575	0.45
G395M	0.791	0.548	0.45
G140H	0.771	0.571	0.39
G235H	0.754	0.536	0.40
G395H	0.753	0.512	0.40

Table 1: Comparison of measured and estimated ("worst case") average throughput values to the FRD requirements

5 SUMMARY

Given the good agreement between the CLS and RCSS measurements, the analysis presented here demonstrates that the NIRSpec throughput meets or exceeds all related requirements, and is significantly better than the conservative "worst case" expectation based on sub-system and component-level data. This validates the approach of using of the "worst case" component-level throughput estimates for the verification of the SRD requirements by ASD, as described in NIRS-CRAL-RP-0002.

APPENDIX A THROUGHPUT REQUIREMENTS

1) SRD - the relevant section of the NIRSpec System Requirements Document reads:

2.4.4 Throughput

Definition: Throughput is defined at BOL.
Definition: Throughput at wavelength λ is defined as the product of the reflectivity and/or transmission of the complete NIRSpec optical train (*) times the peak efficiency of the relevant grating and its blaze function at wavelength λ.
Definition: The average optical throughput is defined as the mean optical throughput over the specified spectral range.
(*) The optical train comprises all the mirrors, starting at the Pick-Off Mirror and ending at the last Camera Optics mirror just in front of the FPA. It also includes the dispersing element and the optical filter(s), but does not include light losses at the MSA or fixed slits or the quantum efficiency of the detector.

R 224: In R=100 mode, the optical throughput of the NIRSpec optics, including the R=100 dispersing element and the clear aperture filter shall exceed the following values for any position in the EFOV and the fixed slits. Linear interpolation shall apply for wavelengths between 0.7μm and 1.0 μm and for wavelengths between 1.0 and 1.7μm.

R=100	**0.6 – 0.7 μm**	**at 1.0 μm**	**≥ 1.7 μm**
Minimum throughput	40%	50%	60%

R 225: In R=1000 mode, the optical throughput of the NIRSpec optics, including the relevant R=1000 dispersive element and the relevant order blocking filter, shall exceed the listed values for any position in the EFOV and the fixed slits. Concerning minimum throughput, linear interpolation shall apply for wavelengths between 1.0 and 1.7μm. The average throughput requirements are applicable over the full band I, II, III wavelength regions.

R=1000	**Band I** **At 1.0 μm**	**Band I** **1.7 μm -1.8 μm**	**Band II** **1.7 μm – 3.0 μm**	**Band III** **2.9 μm – 5.0 μm**
Minimum throughput	30%	35%	35%	35%
Average throughput	44%		45%	45%

R 226: In R=3000 mode, the optical throughput of the NIRSpec optics, including the relevant R=3000 dispersive element and the relevant order blocking filter, shall exceed the listed values for any position in the EFOV and the fixed slits. Linear interpolation shall apply for wavelengths between 1.0 and 1.7μm. Average throughput requirement is applicable over the full band I, II, III wavelength regions.

R=3000	**Band I** **At 1.0 μm**	**Band I** **1.7 μm -1.8 μm**	**Band II** **1.7 μm – 3.0 μm**	**Band III** **2.9 μm – 5.0 μm**
Minimum throughput	27%	30%	30%	30%
Average throughput	39%		40%	40%

2) FRD - the relevant section of the NIRSpec Functional Requirements Document reads:

3.4.2 Throughput

Note: Throughput at wavelength λ is defined as the product of the reflectivity and/or transmission of all optical elements along the NIRSpec optical train, multiplied with the peak efficiency of the relevant grating and its blaze function at wavelength λ. The optical train comprises all NIRSpec mirrors, (starting at the pick-off mirror [POM] and ending at the last camera optics mirror just in front of the FPA) and the optical filter(s), but does not include diffraction light losses at the slit(s) or the quantum efficiency of the detector.

NSFR-42
In R=100 mode, the optical throughput at BOL of the NIRSpec optics, including the R=100 dispersing element and any required order blocking filter shall be, for any position in the FOV:

≥ 40 % for the spectral range between 0.6μm and 0.7μm
≥ 50 % at 1.0μm
≥ 60 % for the spectral range between 1.7μm and 5.0μm

Linear interpolation shall apply for wavelengths between 0.7μm and 1.0μm and for wavelengths between 1.0μm and 1.7μm.

NSFR-43
In R=1000 mode, the average optical throughput at BOL of the NIRSpec optics including the relevant R=1000 dispersive element and the relevant order blocking filters, shall be for any position in the FOV:

≥ 44 % for Band I (between 1.0μm and 1.8μm)
≥ 45 % for Band II (between 1.7μm and 3.0μm)
≥ 45 % for Band III (between 2.9μm and 5.0μm)

NSFR-44
In R=3000 mode, the average optical throughput at BOL of the NIRSpec optics including the relevant R=3000 dispersive element and the relevant order blocking filters, shall be for any position in the FOV:

≥ 39 % for Band I (between 1.0μm and 1.8 μm)
≥ 40 % for Band II (between 1.7μm and 3.0 μm)
≥ 40 % for Band III (between 2.9μm and 5.0 μm)

APPENDIX B CALIBRATION DATA

The following Table summarizes which exposures were used to analyze the NIRSpec throughput in the various dispersers:

NID	Disperser	Filter	CLS lamp	comment
"standard" calibration (COMBO1-01)				
5653	G140H	F100LP	FF1	
5662	G235H	F170LP	FF2	
5663	G395H	F290LP	FF3	
5664	G395H	F290LP	CLOSE	background exp.
5677	G140M	F100LP	FF1	
5678	G235M	F170LP	FF2	
5686	G395M	F290LP	FF3	
5687	G395M	F290LP	CLOSE	background exp.
5701	PRISM	CLEAR	FFB	
5702	PRISM	CLEAR	CLOSE	background exp.