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Plate Scales, Anamorphic Magnification & Dispersion: CCD Modes

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ABSTRACT

This report presents values of the plate scales and anamorphic magnification in the STIS CCD spectroscopic modes. The results of the in-flight geometric distortion test are adapted as the most reliable measure of the CCD camera mode magnification, yielding an imaging mode plate scale of 0.05071 0.0007 arcseconds per pixel. Differences with ray trace results amount to an as-built increased magnification of 1.00335. The measured grating dispersions are compared with the calculated values and show very consistent agreement provided the as-built magnification past the mode select mechanism (MSM) is 1.0027 that of the design. The combination of this result and the geometric distortion plate scale imply that the as-built OTA-MSM magnification is 1.00065 that of the design. The measured dispersions at four grating settings are unusually discrepant; the calculated dispersions are probably more reliable and will be incorporated for use in the calstis pipeline. A simple model incorporating only grating anamorphic magnification gives good agreement with direct ray tracing. The values of dispersion direction plate scales, incorporating the plate scale determination from the geometric distortion test, are derived and presented using this model. An example of the use of the model to determine the plate scale for specific wavelengths is presented.

1. Background and Introduction:

Direct measurements of the plate scales ["/pixel] have not been made in the CCD spectroscopic modes. Plate scales can be determined by ray tracing or other modeling of the optical paths using the nominal design values of all components. For the greatest accuracy however, such traces or models need to incorporate the actual, as-built component parameters.

During the Servicing Mission Orbital Verification (SMOV) of STIS, proposal 7131 was executed to determine the geometric distortion of the CCD imaging mode. This provided a very accurate plate scale determination for the camera configuration. Since all CCD imaging and spectroscopic modes follow the same path, differing essentially only in the element selected with the mode select mechanism (MSM), the camera mode results can be used to calibrate ray traces of the spectroscopic modes.

Because of the numerous spectroscopic modes, settings and field positions it is not possible to ray trace all possible combinations. However the CCD modes have a relatively straightforward geometry which does allow a simple spectroscopic model of each mode to be produced. This allows the calculation of accurate plate scales for any combination of mode, setting and field position as needed to reduce a particular observation.

Spectroscopic dispersions have been determined for each nominal setting of each mode from internal observations taken using the Pt-Ne/Ar line lamps (i.e. “wavecals”). Comparing these measured dispersions with predictions from ray traces or the mode models has several useful results.   The basic geometry and parameters used in the models can be confirmed. The difference between the design and as-built magnification can be divided into two parts - prior to and following the MSM. Since the UV modes follow the same optical path up to the MSM, knowledge of any magnification difference up to this point can be applied to the plate scale analysis of those modes as well. Finally, comparison between expected and measured dispersion may reveal errors in the measured values.

2. The CCD imaging mode plate scales

1. From analysis of the CCD mode geometric distortion test (Malumuth et al., ISR in preparation) a plate scale for the CCD camera modes was determined of:

0.05071 (+- 0.00007) ["/pixel]

valid at field center with negligible differences in the X,Y directions. This agrees with, but is more accurate than, the initial prelaunch estimate of 0.050"/pixel (Landsman, private communication).

The equality of the plate scale in both directions provides a limit to any tilt error between the focal plane and CCD detector surface as well. A difference of 0.00007"/pixel is equivalent to a tilt of 0.030 degrees.

2. A ray trace of the camera modes using all design values of optics and the OTA gives a plate scale in both X and Y directions of:

0.05088"/pixel

This is 1.00335x the plate scale determined by the SMOV test and differs by about 2.4 times the quoted accuracy of that determination. This result suggests that the overall magnification of the as-built OTA+instrument is 1.00335x the design. Another possibility is that some (or all) of this difference is due to an as-built CCD pixel size deviation from the nominal design value of 21.0 microns.

3. Grating dispersion results:

Pre-launch grating dispersions at the measured central wavelength of each setting in all CCD spectroscopic modes were determined by Don Lindler and have been confirmed subsequently on orbit (Lanning & Hulbert ISR in preparation). The grating groove densities are known accurately as well and the angular dispersion can be calculated. The measured linear dispersion for the CCD modes [Å/pixel] depends on (a) the ray separation between the detector and the point on the camera mirror (K3) at which rays from the grating strike, (b) the CCD pixel size (c) any off-nominal tilt of the detector.

Figure 1 shows a comparison between the ray traced dispersions at field center for the primary settings of mode G430M and the measured dispersions based on slit spectroscopy with one of the on-board arc lamps. The solid diamonds show the ratio of measured to ray traced linear dispersion using the nominal optical design values. The open diamonds show the result of dividing the traced spectral plate scale (Å/pixel) by 1.0026; this scale factor produces a single parameter least squares fit between the results of the ray trace and the measured dispersions.

The linear dispersion of each CCD spectroscopic mode at each nominal setting has been computed using the dispersion relation derived from the grating equation and the grating parameters. Figure 2 shows the overall comparison of the calculated and measured dispersions of all CCD spectroscopic modes. The distance between the camera mirror and the detector center was adjusted to produce the best fit between the calculations and the measurements, producing a value of s=629.53 mm. The best fit value of this single parameter will include any non-nominal camera mirror to detector separation as well as differences of CCD pixel dimensions, small detector tilts, CCD window index or thickness variations, etc. A few discrepant points were not included in this fit; they lie at the ends of the wavelength range where few Pt lamp lines are available to provide the measured dispersion solution. In these cases, the calculated values are probably more accurate than those determined from the spectra and will be adopted in the calstis pipeline. With this selection of s, all calculated dispersions at the central nominal central wavelengths agree with the measurements to within about 0.1%. The internal consistency between the calculated and measured dispersions for all the different modes shows that the basic grating geometry is accurately known. Figure 1 also shows the comparison between these calculated dispersions in mode G430M with s=629.53 mm and the ray traced dispersion rescaled by 1.0026. The results using either method are essentially identical.

From these two results, the imaging mode plate scale comparison and the dispersion comparisons, we conclude: (1) the overall as-built magnification of the OTA+STIS CCD path is 1.00335x the design, and (2) the magnification from the STIS MSM to detector in the CCD path is 1.0027x the design. We note that any out-of-nominal pixel size or detector tilts are included in both of these results. Combining these we conclude that the OTA+STIS magnification up to the MSM is 1.00335/1.0027 = 1.00065 compared to the ray trace (nominal design). This value represents the combined magnification difference of the OTA+STIS corrector + STIS collimator and can be applied as a correction to the UV modes in similar plate scale analysis of those modes; it's very small value, however verifies that up to the MSM, there is essentially no magnification difference between the as-built instrument and the current optical ray trace.

4. Plate Scale Determination

With this correction to overall magnification of the CCD modes, we can determine accurate values of the plate scales. In the cross dispersion direction of each spectroscopic mode, the spatial plate scale should match the value obtained in the camera mode determination, namely,

Plate Scale, Cross Dispersion Direction, All CCD Modes:

0.05071 (+- 0.00007) ["/pixel]

There should be a slight variation of cross dispersion plate scale along the length of the slit as shown by the camera mode geometric distorition test. From the results of that test, we derive an expression for the cross dispersion plate scale along the slit length of

$$d\phi / dY = 0.05071 - 1.59122 \times 10^{-8} (Y - 512) - 4.78704 \times 10^{-10} (Y - 512)^2 \text{ ["/pixel]}$$

where Y is the pixel position along the slit. At the ends of the slit (Y = 1,1024 pixels) the plate scale is about 0.05058 "/pixel, about 0.26% different than at the slit center.

The plate scale in the dispersion direction differs from this value primarily due to (1) anamorphic magnification in each mode due to the diffraction gratings, (2) differences in the point where the principal ray at each wavelength hits the camera mirror and the detector for each different wavelength and field position.

Anamorphic magnification of diffraction gratings is due to the typical inequality between the incident and exit directions of rays of a particular wavelength. If the grating incident angle (α_G) and exit angle (β_G) in the dispersion plane are known, the anamorphic magnification for a particular wavelength can be expressed as the differential quantity -

Grating anamorphic magnification:

(1) $$M_{ANA} = d\beta_G / d\alpha_G = \cos(\alpha_G)/\cos(\beta_G)$$

For all STIS grating modes, $\alpha_G > \beta_G$ so, for example, a feature 1 arcsecond in angular extent on the sky is compressed at the detector. The plate scale [in arcseconds per pixel] in the dispersion direction will thus increase in all spectroscopic modes compared to the camera mode. Accounting only for anamorphic magnification, the conversion between imaging mode plate scale and the plate scale in the dispersion direction is given by -

Plate Scale, Dispersion Direction, All CCD Modes:

(2) $$0.05071/M_{ANA} \text{ ["/pixel]}$$

The values of the dispersion plane grating incident and exit angles have been determined for each setting allowing the anamorphic magnification and plate scale to be determined in this manner. The necessary parameters of each CCD mode grating are listed in Table 1. The grating incident angles were determined from the modified grating equation -

(3) $$m\lambda/(\sigma\cos(\phi)) = 2\cos(\Psi)\sin(\alpha_G-\Psi)$$

$2\,\Psi$ = the dispersion angle = 20.678˚ for all CCD modes

σ = grating groove spacing

λ = central wavelength at each setting

ϕ = field angle (at the grating); =0 for nominal field center

m = grating order (=1 for all CCD gratings)

The values of the grating dispersion plane exit angle, β, may then be obtained from the normal grating equation -

(4) $$\sin(\alpha) + \sin(\beta) = m\lambda/(\sigma\cos(\phi))$$

The results of these calculations are presented in Tables 2-4 for all CCD modes, giving the values of calculated anamorphic magnification, M_{ANA} at field center for each nominal grating setting from equation (1) and the dispersion direction plate scales using equation (2). Each table also gives the anamorphic magnification and plate scales at the ends of the wavelength range for each setting. The shortest wavelength in a setting is indicated by λ_L, the longest by λ_H. The values of dispersion, plotted in Figure 2 were also calculated using these grating parameters for each setting, and showed very good consistency.

The results of these calculations may be summarized as follows. Each of the low resolution modes has an anamorphic magnification of less than about 2% and consequent similar difference of plate scale in the dispersion direction compared to the imaging case. The medium resolution modes have higher grating incident angles and so higher anamorphic magnification and more substantial differences in plate scale with respect to the imaging modes. The variation in plate scale in all medium resolution modes is about 7-12% for the run of grating settings compared to the imaging value. Within a particular setting the variation is typically only a few tenths percent over the wavelength range.

The variations of plate scale with field angle in the dispersion direction result in negligible differences from the values quoted in Tables 2-4, even at the edges of the field. As viewed from the grating, the field angle f is slightly less than 1° at the edge of the CCD field. For a particular wavelength, this effect enters as a slight change in exit angle, β, through the grating equation (4) compared to field center (ϕ = 0). Exit angle variation from field center to edge are typically < 0.005°. Since the plate scale depends on β through $\cos(\beta)$, such a small change in exit angle produces a negligible change in plate scale.

To determine the accuracy of the models and the magnitude of any other geometrical factors, these results may be compared to the results of ray tracing. Table 5 shows such a comparison for mode G430M. The ray traced results have been rescaled by 1.0027 to produce correction for the as-built parameters. The agreement between the ray trace and model results is <0.6% in all cases; one micron differences in the ray trace results, give 0.24% errors typically. The conclusion is that the magnitude of any other known geometric factors produces differences with the simple model of no greater than 0.6%.

Finally, these models can be used to predict the plate scales for specific lines. As an example, we determine the dispersion direction plate scales in mode G430M at 5007Å λ_{cen}=4961 and G750M at 6563Å for λ_{cen}=6748. These values would be needed to compare spatial extent of features in [OIII] and Hα for example. The procedure is as follows:

<u>5007</u>

(a) Determine the grating exit angle for this wavelength.

From Table 1, the grating entrance angle α for G430M, λ_{cen}=6768 is 27.952°, groove density σ is 0.83333 microns. Use the normal grating equation, Equation 4, to determine the exit angle β to be 7.592°.

(b) Determine the anamorphic magnification from Equation 2 to be 0.8912.

(c) The plate scale is then 0.05071/0.8912 = 0.05690 arcseconds/pixel.

<u>6563</u>

(a) Determine the grating exit angle for this wavelength.

From Table 1, the grating entrance angle α for G750M, λ_{cen}=6768 is 22.250°, groove density σ is 1.6667 microns. Use the normal grating equation, Equation 4, to determine the exit angle β to be 0.8666°.

(b) Determine the anamorphic magnification from Equation 2 to be 0.9256.

(c) The plate scale is then 0.05071/0.9256 = 0.05478 π/pixel

These plate scales differ by about 4%. For an extended object like the ~2" wide inner rings of SN1987a, the 5007 Å image would be 35.1 pixels wide while the 6563 Å image would be 36.5 pixels wide. The plate scale in the cross dispersion direction is just the nominal value of 0.05071"/pixel. A 2" object would cover 39.4 pixels in the cross dispersion direction.

5. Slitless Modes:

All of the calculations thus far have implicitly been assumed to operate in a slit mode. That is the input angle to the gratings, α, has a fixed value for any observation. This value is that subtended by the slit center and the particular grating normal. The list of incident angles in Table 1 are just such angles at slit center. As an object becomes more extended in the dispersion direction, this incident angle begins to change from nominal. The anamorphic magnification, depending on the cosine of incident and exit angles, changes slowly for all modes since all nominal angles are small. At the maximum, open slit configuration, α can be about 1° greater than the nominal values shown in Table 1. At the high wavelength settings, with incident angles of about 28 ° the anamorphic magnification and plate scale could change by about 1% from the values presented.

Table 1. Grating Model Parameters

	G430L	G430M	G750L	G750M	G230LB	G230MB
m =	1	1	1	1	1	1
σ[μm] =	8.33333	0.83333	14.80166	1.66667	4.16667	0.45455
2Ψ=	20.678	20.678	20.678	20.678	20.678	20.678

	G750L		**G430M**		**G750L**		**G750M**		**G23LB**		**G230MB**	
Internal Setting	λ_{cen}	α_G	λ_{cen}	α_G	λ_{cen}	α_G	λ_{cen}	α_G	λ_{cen}	α_G	λ_{cen}	α_G
P1	4300	11.844	3165	21.466	7751	11.867	5734	20.412	2375	11.999	1713	21.380
P2			3423	22.387	8975	12.105	6252	21.329			1854	22.305
P3			3680	23.307			6768	22.250			1995	23.233
P4			3936	24.230			7283	23.165			2135	24.155
P5			4194	25.162			7795	24.085			2276	25.080
P6			4451	26.092			8311	25.026			2416	26.017
P7			4706	26.998			8825	25.947			2557	26.954
P8			4961	27.952			9336	26.877			2697	27.893
P9			5216	28.893			9851	27.813			2836	28.830
P10			5471	29.828							2976	29.772
P11											3115	30.681
I1			3305	21.967			6094	21.056			2794	28.547
I2			3843	23.897			6581	21.917				
I3			4781	27.293			8561	25.469				
I4			5093	28.448			9286	26.789				
I5							9806	27.737				
L1							10363	28.761				

Notes to Table 1: λ_{cen} is the officially used wavelength use to designate the tilt of the grating at this setting (see the STIS Instrument Handbook, Chapter 13). Internal Setting gives the internally used (for commanding purposes) position name designated for that positioning of the grating, and is relevant for internal STScI use only.

Table 2. G430L and G430M Plate Scales and Anamorphic Magnification

Mode G430L - Plate Scales & Anamorphic Magnification

Internal Setting	λ_{cen} (desig)	λ_C (msd)	M_{ANA}	Sdisp ["/pix]	λ_L (msd)	MANA	Sdisp ["/pix]	λ_H (msd)	MANA	Sdisp ["/pix]
P1	4300	4307.54	0.99046	0.05120	2903.10	0.99324	0.05106	5712.00	0.98798	0.05133

Mode G430M - Plate Scales & Anamorphic Magnification

Internal Setting	λ_{cen} (desig)	λ_C (msd)	M_{ANA}	Sdisp ["/pix]	λ_L (msd)	M_{ANA}	Sdisp ["/pix]	λ_H (msd)	M_{ANA}	Sdisp ["/pix]
P1	3165	3164.12	0.93072	0.05448	3021.90	0.93064	0.05449	3306.10	0.93108	0.05446
P2	3423	3422.27	0.92505	0.05482	3280.00	0.92471	0.05484	3564.20	0.92565	0.05478
P3	3680	3679.37	0.91937	0.05516	3537.20	0.91878	0.05519	3821.10	0.92022	0.05511
P4	3936	3936.36	0.91366	0.05550	3794.30	0.91282	0.05555	4078.20	0.91476	0.05544
P5	4194	4194.57	0.90789	0.05585	4052.20	0.90681	0.05592	4335.90	0.90924	0.05577
P6	4451	4451.35	0.90211	0.05621	4309.40	0.90079	0.05630	4592.60	0.90370	0.05611
P7	4706	4700.35	0.89647	0.05657	4558.70	0.89491	0.05667	4841.30	0.89829	0.05645
P8	4961	4961.28	0.89051	0.05695	4819.80	0.88870	0.05706	5102.00	0.89258	0.05681
P9	5216	5217.04	0.88460	0.05733	5075.80	0.88255	0.05746	5357.4	0.88691	0.05718
P10	5471	5470.07	0.87870	0.05771	5329.30	0.87642	0.05786	5610.10	0.88125	0.05754
I1	3305	3304.72	0.92763	0.05467	3162.40	0.92741	0.05468	3446.60	0.92812	0.05464
I2	3843	3843.80	0.91572	0.05538	3701.60	0.91497	0.05542	3985.50	0.91673	0.05532
I3	4781	4781.20	0.89463	0.05668	4639.70	0.89299	0.05679	4922.10	0.89653	0.05656
I4	5093	5096.27	0.88740	0.05714	4954.80	0.88546	0.05727	5236.8	0.88960	0.05700

Notes to Table 2: This table lists the plate scale in the dispersion direction and anamorphic magnification of each nominal setting for modes G430L and G430M based on results using the geometric model of this mode. λ_{cen} is the officially used wavelength use to designate the tilt of the grating (see the STIS Instrument Handbook, Chapter 13).. The columns are: (1) Internal Setting, which gives the internally used (for commanding purposes) position name designated for that setting of the grating tilt, and is relevant for internal STScI use only, (2) the officially designated central wavelength ($\lambda_{cen\text{ - }desig}$) used to specify the setting (see Chapter 13 of the STIS Instrument Handbook), (3) the actual wavelength at the central pixel ($\lambda_{C\text{-}msd}$) measured as determined from the on-board Pt lamp spectrum, (4) the anamorphic magnification at the central wavelength, (5) the plate scale in the dispersion direction at the central wavelength, (6) the determined lowest wavelength (λ_L) at this setting (see Chapter 13 of the STIS Instrument Handbook), (7) the anamorphic magnification at the lowest wavelength, (8) the plate scale in the dispersion direction at the lowest wavelength, (9) the determined highest wavelength (λ_H) at the setting, (10) the anamorphic magnification at the highest wavelength, (λ_L) the plate scale in the dispersion direction at the highest wavelength. All wavelengths are in Angstroms, all plate scales are in arcseconds per pixel.

Table 3. G230LB G230MB Plate Scales and Anamorphic Magnification

Mode G230LB - Plate Scales & Anamorphic Magnification

Internal Setting	λ_{cen} (desig.)	λ_C (msd)	M_{ANA}	Sdisp ["/pix]	λ_L (msd)	M_{ANA}	Sdisp ["/pix]	λ_H (msd)	M_{ANA}	Sdisp ["/pix]
P1	2375	2374.83	0.98948	0.05125	1672.10	0.99221	0.05111	3077.2	0.98706	0.05137

Mode G230MB - Plate Scales & Anamorphic Magnification

Internal Setting	λ_{cen} (desig.)	λ_C (msd)	M_{ANA}	Sdisp ["/pix]	λ_L (msd)	M_{ANA}	Sdisp ["/pix]	λ_H (msd)	M_{ANA}	Sdisp ["/pix]
P1	1713	1712.76	0.93125	0.05445	1635.30	0.93119	0.05446	1790.20	0.93158	0.05443
P2	1854	1854.32	0.92555	0.05479	1776.70	0.92523	0.05481	1931.70	0.92613	0.05475
P3	1995	1995.72	0.91982	0.05513	1918.10	0.91926	0.05516	2073.00	0.92065	0.05508
P4	2135	2135.69	0.91413	0.05547	2058.20	0.91331	0.05552	2213.00	0.91521	0.05541
P5	2276	2275.60	0.90840	0.05582	2198.20	0.90734	0.05589	2352.80	0.90972	0.05574
P6	2416	2416.77	0.90258	0.05618	2339.40	0.90127	0.05626	2493.80	0.90415	0.05609
P7	2557	2557.33	0.89674	0.05655	2480.10	0.89519	0.05665	2634.20	0.89856	0.05644
P8	2697	2697.42	0.89087	0.05692	2620.30	0.88908	0.05704	2774.10	0.89293	0.05679
P9	2836	2836.43	0.88500	0.05730	2759.50	0.88297	0.05743	2913.0	0.88729	0.05715
P10	2976	2975.54	0.87906	0.05769	2898.70	0.87678	0.05784	3051.90	0.88159	0.05752
P11	3115	3108.89	0.87330	0.05807	3032.30	0.87080	0.05823	3185.10	0.87606	0.05788
I1	2794	2794.52	0.88678	0.05718	2717.50	0.88482	0.05731	2871.30	0.88900	0.05704

Notes to Table 3: This table lists the plate scale in the dispersion direction and anamorphic magnification of each nominal setting for modes G230LB and G230MB based on results using the geometric model of this mode. The columns are the same as for Table 2.

Table 4. G750LB G750M Plate Scales and Anamorphic Magnification

Mode G750L- Plate Scales & Anamorphic Magnification

Internal Setting	**λ_{en} (desig.)**	**λ_C (msd)**	**M_{ANA}**	**Sdisp ["/pix]**	**λ_L (msd)**	**M_{ANA}**	**Sdisp ["/pix]**	**λ_H (msd)**	**M_{ANA}**	**Sdisp ["/pix]**
P1	7751	7765.73	0.99031	0.05121	5269.30	0.99309	0.05106	10262.6	0.98785	0.05133
P2	8975	8977.25	0.98881	0.05128	6479.40	0.99151	0.05114	11475.1	0.98642	0.05141

Mode G750M - Plate Scales & Anamorphic Magnification

Internal Setting	**λ_{cen} (desig.)**	**λ_C (msd)**	**M_{ANA}**	**Sdisp [“/pix]**	**λ_L (msd)**	**M_{ANA}**	**Sdisp ["/pix]**	**λ_H (msd)**	**M_{ANA}**	**Sdisp ["/pix]**
P1	5734	5735.24	0.93722	0.05411	5450.60	0.93743	0.05409	6019.20	0.93728	0.05410
P2	6252	6251.62	0.93157	0.05444	5967.00	0.93152	0.05444	6535.70	0.93188	0.05442
P3	6768	6768.24	0.92589	0.05477	6483.70	0.92559	0.05479	7052.20	0.92645	0.05474
P4	7283	7279.82	0.92024	0.05511	6995.20	0.91969	0.05514	7563.40	0.92106	0.05506
P5	7795	7792.22	0.91456	0.05545	7507.80	0.91376	0.05550	8075.70	0.91562	0.05538
P6	8311	8314.28	0.90873	0.05580	8030.00	0.90768	0.05587	8597.20	0.91004	0.05572
P7	8825	8822.85	0.90302	0.05616	8539.00	0.90173	0.05624	9105.60	0.90457	0.05606
P8	9336	9334.41	0.89722	0.05652	9050.70	0.89569	0.05662	9616.40	0.89902	0.05641
P9	9851	9846.38	0.89138	0.05689	9563.40	0.88961	0.05700	10129.4	0.89343	0.05676
I1	6094	6097.85	0.93325	0.05434	5813.00	0.93328	0.05434	6381.80	0.93349	0.05432
I2	6581	6581.44	0.92794	0.05465	6296.90	0.92774	0.05466	6865.80	0.92842	0.05462
I3	8561	8558.81	0.90599	0.05597	8274.70	0.90482	0.05604	8841.60	0.90741	0.05588
I4	9286	9285.94	0.89778	0.05648	9002.60	0.89627	0.05658	9568.10	0.89955	0.05637
I5	9806	9805.13	0.89185	0.05686	9522.10	0.89010	0.05697	10088.0	0.89388	0.05673
L1	10363	10362.7	0.88543	0.05727	10082.1	0.88343	0.05740	10643.3	0.88771	0.05712

Notes to Table 4: This table lists the plate scale in the dispersion direction and anamorphic magnification of each nominal setting for modes G750L and G750M based on results using the geometric model of this mode. The columns are the same as in Table 2.

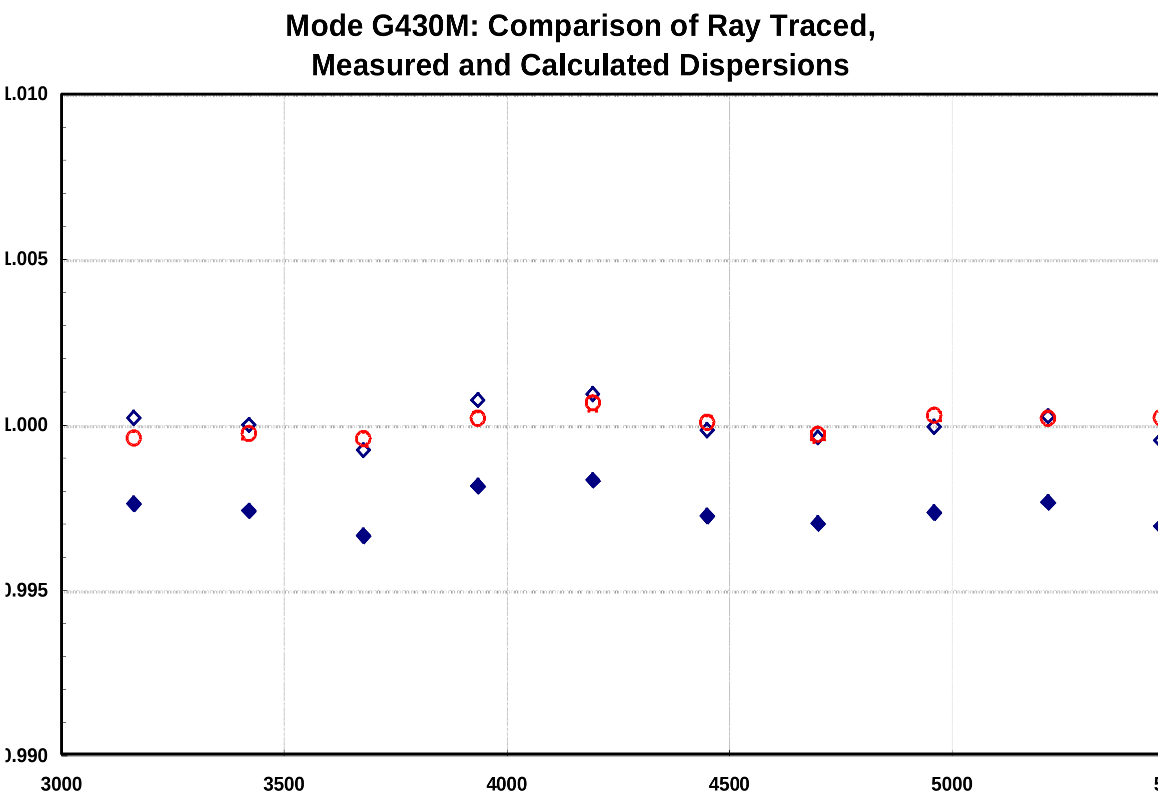
Table 5. Comparison Between Ray Traced and Model Results - G430M

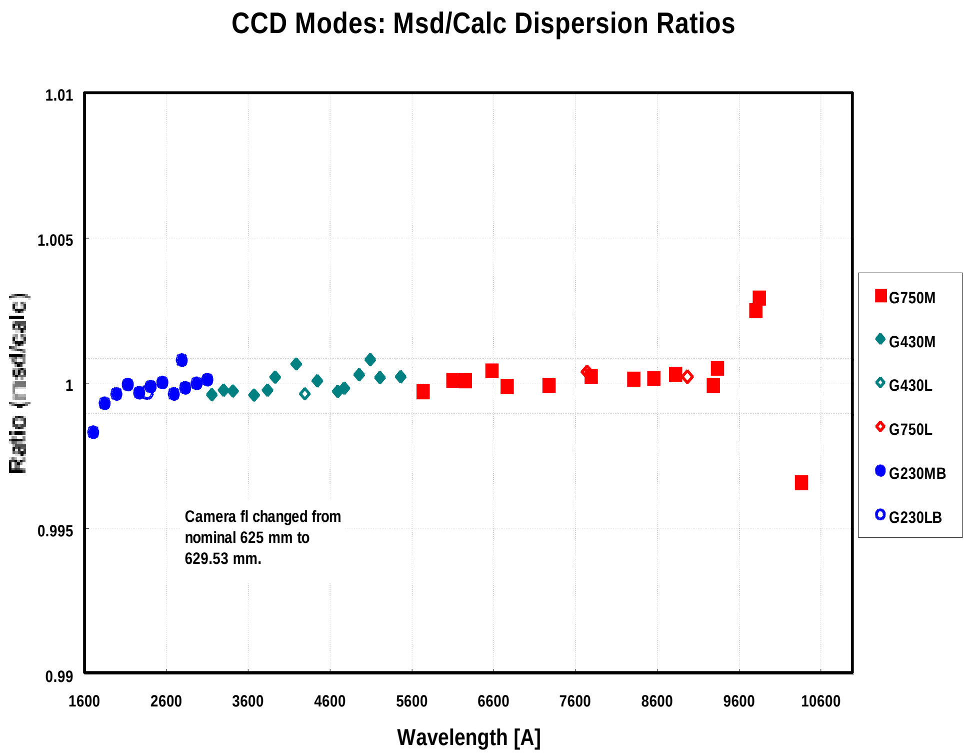
				Ray Trace Results rescale		**Model Results**		**Model Results divided by Ray Trace Results**	
Internal Setting	$\lambda_{cen.}$ (design.)	λ_c mes	**Field**	$\mathbf{S_{disp}}$	$\mathbf{S_{X\text{-}disp}}$	$\mathbf{S_{disp}}$	$\mathbf{S_{X\text{-}disp}}$	$\mathbf{S_{disp}}$	$\mathbf{S_{X\text{-}disp}}$
P1	3165	3164.12	ctr	0.05455	0.05075	0.05448	0.05071	0.99872	0.99921
			edge	0.05441	0.05062	0.05448	0.05071	1.00129	1.00178
		3021.90	ctr	0.05455	0.05063	0.05449	0.05071	0.99890	1.00158
			edge	0.05441	0.05050	0.05449	0.05071	1.00147	1.00416
P10	5471	5470.07	ctr	0.05768	0.05075	0.05771	0.05071	1.00052	0.99921
			edge	0.05768	0.05074	0.05771	0.05071	1.00052	0.99941
		5610.10	ctr	0.05721	0.05075	0.05754	0.05071	1.00577	0.99921
			edge	0.05721	0.05074	0.05754	0.05071	1.00577	0.99941

Notes to Table 5: This table compares plate scales determined by ray tracing with those obtained using the model of grating anamorphic magnification only. Values are given for two settings of mode G430M λ_c=3165, 5471 at central and extreme wavelengths in the settings, and for field positions at the slit center and end. All differences between ray traced and modeled results are <0.6%. First three columns as are in Table 2.

Figure 1: A comparison of the ratio of the measured to ray traced dispersions of mode G430M. The dispersion at the central wavelength of each setting is shown. The ratio using the nominal optical design is shown by solid diamonds. A single scaling parameter of 1.0028 produces the results indicated by the open diamonds. The open circles show the similar ratio comparison using the grating model for this mode and the best fit distance between the camera mirror and the detector center.

Figure 2: A comparison of the measured and calculated dispersions for all CCD modes at all nominal positions. The slit-detector magnification was varied to produce the best fit by altering the camera mirror (K3) focal length. The dashed lines indicate a difference in the measured/calculated ratio of 0.1%. The three longest wavelength points of mode G750M and the shortest point of G230MB appear significantly discrepant with the rest of the data and are probably in error due to the lack of Pt lines from the calibration lamp at these settings.


Mode G430M: Comparison of Ray Traced, Measured and Calculated Dispersions
1.010
1.005
1.000
0.995
0.990
3000
3500
4000
4500
5000



CCD Modes: Msd/Calc Dispersion Ratios
1.01
1.005
1
0.995
0.99
Ratio (msd/calc)
1600
2600
3600
4600
5600
6600
7600
8600
9600
10600
Wavelength [A]
Camera fl changed from
nominal 625 mm to
629.53 mm.
G750M
G430M
G430L
G750L
G230MB
G230LB