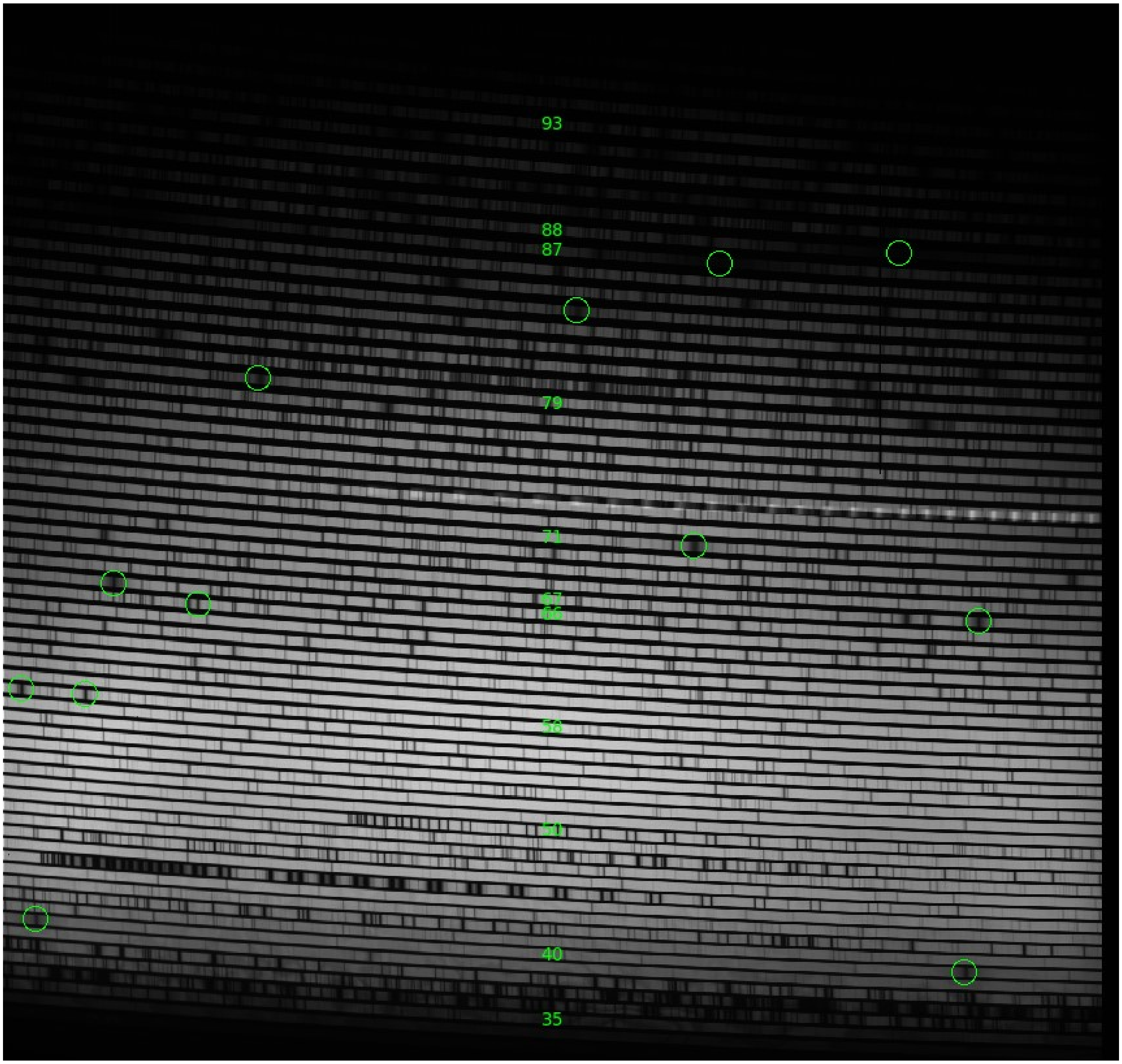
An Orientation to working with TS23-E2 and its images



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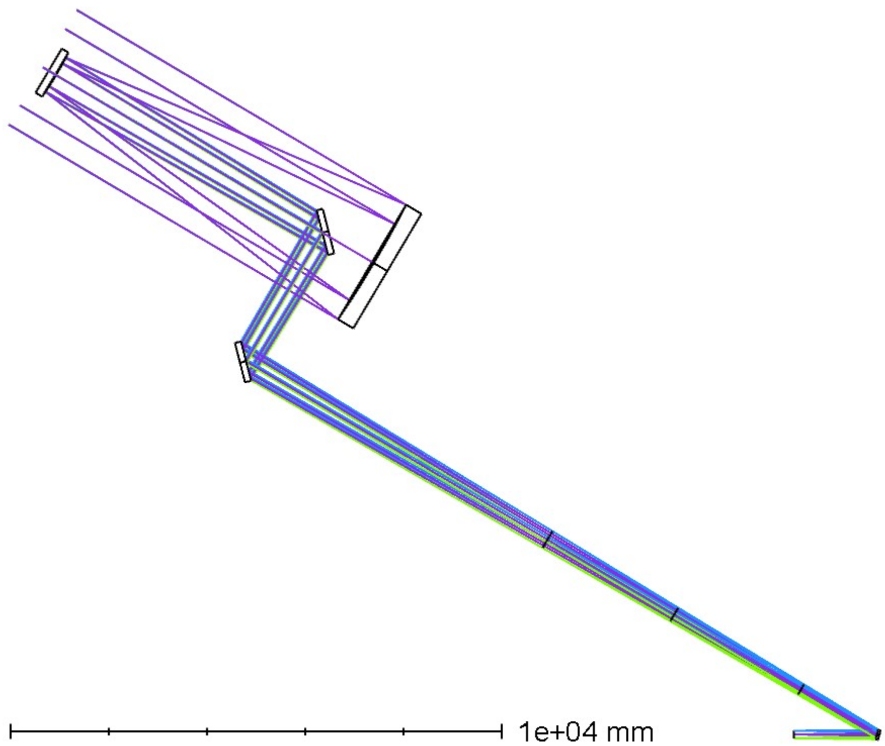
1 Background on the Spectrograph

1.1 The telescope

The spectrograph is fed by the McDonald Observatory telescope known by names including the 107 inch, the 2.7 meter, the HJST, and the Harlan J Smith Telescope. Harlan Smith was the first Texas-based director of McDonald Observatory, who had the telescope funded and built. The following figure shows the 5-mirror coude focus of the HJST that feeds the spectrograph located in the *coude spectrograph room* beneath the dome floor.



1.2 Spectrograph name

The spectrograph is known by the names TS2, Tull Spectrograph 2, and 2dcoude (pronounced 2-d-coude). The spectrograph is named for Bob Tull who was the McDonald Observatory lead instrument scientist for 40 years, and the PI (Principal Investigator) for the 2dcoude project. The project started in 1987.

1.3 Spectrograph type

TS2 is a cross-dispersed echelle spectrograph implemented as a white-pupil design. An echelle diffraction grating disperses the light into many diffraction orders, each order covering a different range of wavelengths, with all orders optically stacked on top of each other. Prisms separate the orders by dispersing the light perpendicular to the echelle dispersion (hence *cross dispersion*). The order numbers are designated algebraically by the symbol 'm'.

1.4 Papers

These are the references for the primary instrument paper, and the initial instrument paper

1) Tull, R.G., MacQueen, P.J., Sneden, C., & Lambert, D.L., 1995,"The high-resolution cross-dispersed echelle white-pupil spectrometer of the McDonald Observatory 2.7 m telescope", 1995, PASP, 107, 251.
2) MacQueen, P.J., & Tull, R.G.: "A New High-Resolution Spectrometer for the McDonald Observatory 2.7 m Telescope", in Instrumentation for Ground-based Optical Astronomy, ed. L.B. Robinson, (New York: Springer-Verlag),1987, p. 52.

1.5 Echelle grating names

There is a choice of two gratings, E1 and E2. Grating E2 is used >96% of the time.

1.6 Spectral orders used with E2

TS2-E2 uses 66 diffraction orders from m=98 at 3500 Å, to m=33 at 10400 Å. Figure 1 shows the *blaze profiles* of 5 adjacent orders. The *blaze wavelength*, λ_B, of each order is the wavelength of peak efficiency in the order. Each order also has a *Free Spectral Range* (FSR) which is the range of wavelengths where the order is more efficient than adjacent orders. The FSR of an order is FSR = λ_B / m

Figure 2 shows the FSR of every 5th order on the CCD. It also shows that for orders redder than about 5800 Å the FSR does not fit on the CCD. See Section 1.12 about spectrograph configurations.

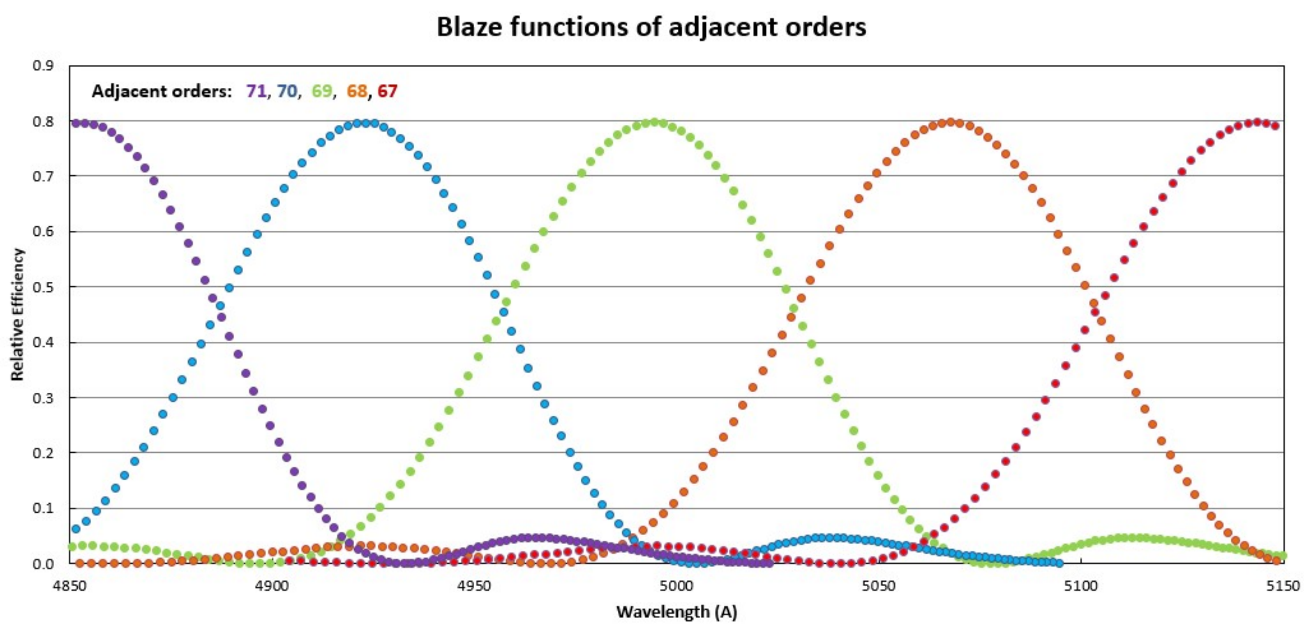


Figure 1: the blaze profiles for 5 adjacent orders of TS2-E2. The blaze wavelength λ_B is at the center of each order, and the Free Spectral Range of order m lies between the blue cross over between orders m+1 and m, and the red cross over between orders m and m-1. At any wavelength, the sum of the light in all orders adds up to unity.

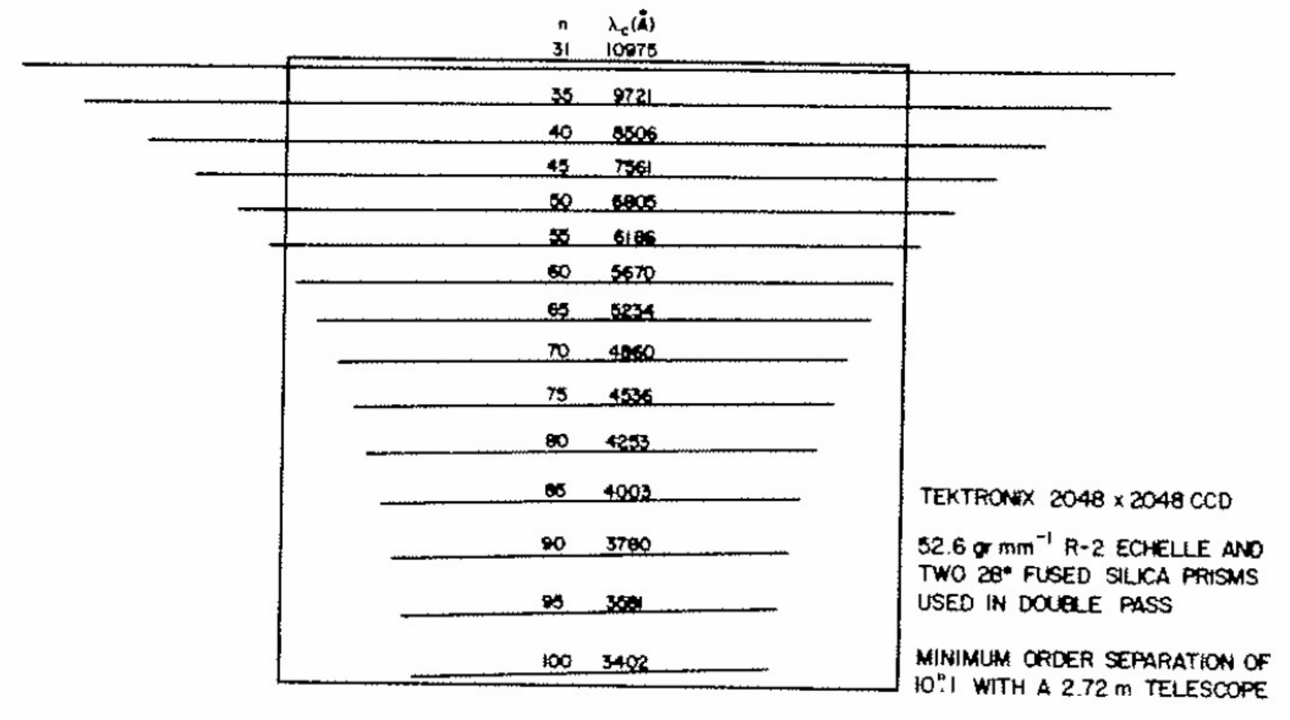


Figure 2: The spectral format of TS23-E2-TK3 (see sections 1.7 & 1.8 for additional nomenclature). The Free Spectral Range of every 5^{th} order (horizontal lines) is shown relative to the TK3 CCD (box). This is a figure made in 1987 during the instrument design phase. The actual prisms are 30°, and as seen on a ds9 image display, this figure would be flipped vertically.

1.7 Spectrograph foci

TS2 has two foci, that is, two locations at which the image detector can be mounted. The foci are known as TS21 and TS23. TS23 means Tull Spectrograph 2 focus number 3, and the TS23 configuration of the spectrograph is used >95% of the TS2 time. Relative to TS23, configuration TS21 offers 4.28x higher resolving power at the cost of 4.28^2 = 18.3x less spectral coverage. TS22 was a name reserved for a focus that has not been built (and won't be).

1.8 Spectrograph detector

The spectrograph detector is currently the CCD system called TK3 (Tektronix CCD #3). TK3 is a 2048 x 2048 CCD with 24 μm square pixels. A CCD system called EV2 is being built to replace TK3. EV2 is 4096x4096 with 15 micron square pixels.

The CCD array of pixels has a column and row architecture (c,r), that maps to (x,y) in a displayed image. A given echelle order is approximately parallel to a row, as can be seen in the image on the title page.

1.9 Spectrograph entrance slit

The entrance slit sets the spectrograph resolving power (see below), and the amount of light entering the spectrograph. TS2 offers a choice of slits. The slit used most of the time with TS23 is *Slit #4*.

1) The *Slit #4* dimensions are *Slit width* x *Slit height* = 1.18 x 8.0 arcseconds
2) TS23 images the *Slit #4* width to 2 TK3 pixels. It follows that Slit #4 is the narrowest slit width for TS23 with TK3 that meets the sampling theorem (is Nyquist sampled, or, has at least two pixels per resolution element).

1.10 Resolving power R

Echelle spectrographs are characterized by their resolving power, $R = \lambda / \Delta\lambda$. The quantity $\Delta\lambda$ is the wavelength resolution, not to be confused with resolving power (astronomers use these two terms interchangeably).

Slit #4 with echelle E2 yields R = 60,000.
Example 1: at λ = 6000 Å the wavelength resolution is 6000/60,000 = 0.100 Å
Example 2: at λ = 4000 Å the wavelength resolution is 4000/60,000 = 0.067 Å

R is constant from order to order down a column on the CCD
R varies slightly along an order, but for most purposes, can be treated as constant everywhere in the image.

1.11 Velocity resolution Δv

This is the ability to resolve the same spectral line at two redshifts.
$\Delta v = c / R$ and for TS23-E2-slit4 Δv = 5 km/s = 300,000 km/s divided by 60,000.
Given the spectral resolution is 2 pixels, it follows that 1 pixel = 2.5 km/s.
Note that because R is constant with wavelength, Δv is also constant.

1.12 Disperser configuration

The user can move the image around on the detector easily. Rotation of the echelle grating moves the image left-right on the detector parallel to the orders, and rotating the prisms moves the image up down on the detector perpendicular to the orders.

A particular combination of echelle and prisms positions is called a disperser configuration. Only several configurations are used by almost all observers. One is called *On-blaze* and the other is called *H-alpha*. The *On-blaze* configuration positions the order blaze peaks down the central column of the detector, and is the configuration used in this document’s examples. Data reduction pipelines benefit from the use of a repeatable configuration, as do precision radial velocity observations.

1.13 Fundamentals of observing with TS2

This is an overview of observing with TS2. Detailed documents are available elsewhere on the McDonald Observatory TS2 website.

1) The detector focus (section 1.7) and echelle grating (section 1.5) will have been chosen prior to observing, and these aspects of the spectrograph configuration will have been done by Observing Support
2) The ICE (Instrument Control Environment) package will be used within the IRAF (Image Reduction and Analysis Facility) software to take data (started from a *Launcher* on the task bar)
3) Program *tsgui* starts a GUI for control of much of TS2 (started from a *Launcher* on the task bar)
4) The disperser configuration (section 1.12) will be chosen, and if it is an established configuration, script *ts2cfg* will be run in ICE to configure the TS2 dispersers
5) Script *ts2foc* will be run in ICE to focus the spectrograph on the detector
6) Script *ts2cals* can be run in ICE to take a user defined set of calibrations
7) Program tcsgui (Telescope Control System GUI) is used to control the telescope and dome
8) Program *tsguider* will be used to acquire and guide a target star on the spectrograph slit (started from a *Launcher*)
9) Program *ts2wfs* will be used to focus the telescope on the spectrograph slit (started from a *Launcher*)
10) Program *emeter* (Exposure meter) can optionally be used to efficiently control observations, or to monitor the amount of light entering the spectrograph through the slit (started from a *Launcher*)
11) Program *dr* (Daily Report = Night Report) is filled in during the night to record observing conditions and report issues (started from a *Launcher*)

2 Working with images

2.1 Observer computer at the HJST

atlas.as.utexas.edu

The observer either sits at the console of atlas in the HJST control room, or uses Atlas via VNC when observing remotely. Atlas can also be reached with methods including ssh and scp.

2.2 Some example files

File location: on atlas in directory /home/hjst/example_files/TS23-E2-TK3
Image files:

```
  rv141635.fits          ; Solar Port (spectrum of daytime blue sky at the zenith)
  rv141680.fits          ; FF + CBF (Flat Field through the Color Balance Filter)
  TS23-E2-On_blaze.reg   ; ds9 region file marking some orders and spectral lines
  TS23-E2-On_blaze.pdf   ; a table of order number versus λB, FSR, and dispersion
```

2.3 Image FITS file characteristics

The image files from the detector are saved in the FITS format. When the TS2 exposure meter is used, all the non-calibration images are multi-extension FITS images. Extension [0] holds the image, and extension [1] holds the exposure meter data.

To display a multi-extension image in IRAF, specify the image extension as shown in the following IRAF command (note the [0]):

```
  display rv141635[0] 1
```

2.4 General image characteristics

See the image on the cover page. The general image characteristics shown are:
Blue orders (UV) are at the top of the image (higher image row numbers)
Red orders (NIR) are at the bottom of the image (lower image row numbers)
Within each order:

1) Blue wavelengths are on the left (lower image column numbers)
2) Red wavelengths are on the right (higher image column numbers)

2.5 Finding spectral features

Once a spectral feature has been identified in an image, other features can be found relative to that feature with simple equations and/or by using the table in the appendix.

Finding strong spectral lines

When TS2 is configured TS23-E2-On_blaze, images can be loaded into ds9 and a ds9 region file can be overlayed marking various strong spectral features and orders. The cover page shows the ds9 display if the previously specified example solar port image and region file are used. This display can be generated as follows:

1) Load the solar port spectrum into ds9
2) Load the regions file onto the solar port image in ds9.
   N.B. in ds9, in the *Edit* menu, make sure *Regions* is selected
   N.B. when loading regions, ds9 pops up a dialog box in some random place on the screen. Find and use that dialog box
3) The regions file displays order numbers on some orders, and the strong spectral features in the following table are circled. N.B. the circles are at the rest wavelengths of the spectral lines

Line	Lambda	Order	Location (column,row)	Å per pixel
Ca K	3933.7	88	(1673,1524)	0.03106
Ca H	3968.5	87	(1336,1508)	0.03142
H delta	4101.7	84	(2073,1417)	0.03254
H gamma	4340.5	79	(481,1290)	0.03460
H beta	4861.3	71	(1289, 978)	0.03850
Mg I (b2)	5172.7	67	(1819, 837)	0.04080
Mg I (b1)	5183.6	66	(206, 912)	0.04142
Fe (E2)	5270.4	65	(364, 871)	0.04205
Na (D2)	5889.9	58	(34, 712)	0.04713
Na (D1)	5895.9	58	(154, 703)	0.04713
Ca II	8542	40	(62, 282)	0.06834
H P12	8665	40	(1794, 183)	0.06834

Determining the order number for a wavelength
The order in which a wavelength is located can be found from the table at the end of this document, which is the file TS23-E2-On_blaze.pdf in the example files. The position of the wavelength within the order can also be estimated as the blue and red limits of each order are listed as λ_B – FSR/2 and λ_B + FSR/2

Example: the location of the Ca K line at 3933.6 Å is wanted. The table can be used to determine m=88, and that the line is near the red end of the order

Image calculation equations
A useful equation is: $m\lambda$ = constant

This equation is precise going down a CCD column from order to order. The equation says that order numbers increase when moving to bluer orders.

Example (using lines in the table above): The location of Mg B 5172 is known to be in order 67, and the location of Ca K is wanted. The order for Ca K is calculated from the equation as m = 5172.7 * 67 / 3933.6 = 88

Dispersion Table for an Echelle with Prism Cross-dispersion

Echelle parameters		Units	Type	Optical Parameters		Value	Units	Type	Variables
σ	52.6746	gr/mm	input	**Telescope:**	Aperture	2.718	m	input	grv length=
θ_B	65.293	deg	Measured		Focal ratio	32.315		input	173.3
$\tan(\theta_B)$	2.17		computed		EFL	87.83	m	computed	mm
θ	3.00	deg	input	**Collimator:**	Pupil diameter	190.0	mm	input	
γ	0.00	deg	input		Focal length	6140	mm	computed	Cam FoV=
d_E	18.98	μm	computed	**Camera:**	Focal length	775.0	mm	input	3.63x3.63
α_E	68.29	deg	computed		Focal ratio	4.079		computed	degrees
β_E	62.29	deg	computed	**Detector:**	Pixel size	0.024	mm	input	
Prism parameters				**Spectrometer:**	R * slit width	70,734	arcsec	computed	CCD =
Glass type	SiO2		input		2-pix R	63,008		computed	2k x 2k
Apex Angle	30.00	deg	input		H. slit demag.	9.959		computed	
Number	4		input		V. slit demag.	7.922		computed	interorder=
Incident angle	22.267	deg	computed		H. img scale	0.043	mm/arcsec	computed	10.324
λ_0, n_0	**4718.6**	**1.4640**	computed		V. img scale	0.054	mm/arcsec	computed	arcsec

Resolving power	30,000	40,000	45,000	50,000	60,000	80,000	95,000	120,000
Unbinned pixels per resel	4.20	3.15	2.80	2.52	2.10	1.58	1.33	1.05
Binning	2	1	1	1	1	1	1	1
Binned pixels per resel	2.10	3.15	2.80	2.52	2.10	1.58	1.33	1.05
Slit width (arcsec)	2.36	1.77	1.57	1.41	1.18	0.88	0.74	0.59

Dispersion constants	a_0	a_1	a_2	a_3	a_4	a_5	Glass No.	Glass name
(from sheet "Glass.dat")	2.104	-9.3311E-03	8.8009E-03	7.3331E-05	3.1905E-06	-6.7044E-08	2	SiO2

Order m_E	λ_B -FSR/2 (Å)	λ_B (Å)	λ_B +FSR/2 (Å)	dλ/dx (blue) (Å/px)	dλ/dx (blaze) (Å/px)	dλ/dx (red) (Å/px)	FSR dX (pixels)	Y (pixels)	dY (arcsec)
100	3427.37	3444.59	3461.81	0.02833	0.02733	0.02629	1261	1000	19.60
99	3461.81	3479.38	3496.96	0.02862	0.02761	0.02655	1274	956	19.47
98	3496.96	3514.89	3532.82	0.02893	0.02789	0.02681	1287	913	19.22
97	3532.82	3551.12	3569.43	0.02923	0.02818	0.02707	1300	870	18.96
96	3569.43	3588.12	3606.80	0.02955	0.02847	0.02734	1314	828	18.71
95	3606.80	3625.88	3644.97	0.02987	0.02877	0.02762	1328	786	18.46
94	3644.97	3664.46	3683.95	0.03020	0.02908	0.02790	1342	745	18.21
93	3683.95	3703.86	3723.77	0.03054	0.02939	0.02819	1356	705	17.97
92	3723.77	3744.12	3764.47	0.03088	0.02971	0.02848	1371	665	17.73
91	3764.47	3785.26	3806.06	0.03123	0.03004	0.02878	1386	625	17.49
90	3806.06	3827.32	3848.59	0.03159	0.03037	0.02908	1401	586	17.26
89	3848.58	3870.33	3892.07	0.03196	0.03071	0.02940	1417	548	17.03
88	3892.07	3914.31	3936.55	0.03234	0.03106	0.02971	1433	510	16.80
87	3936.54	3959.30	3982.05	0.03273	0.03142	0.03004	1450	473	16.57
86	3982.05	4005.34	4028.62	0.03312	0.03178	0.03037	1467	436	16.34
85	4028.62	4052.46	4076.30	0.03353	0.03216	0.03071	1484	400	16.12
84	4076.29	4100.70	4125.11	0.03394	0.03254	0.03106	1502	364	15.90
83	4125.11	4150.11	4175.11	0.03437	0.03293	0.03142	1520	328	15.69
82	4175.11	4200.72	4226.33	0.03480	0.03334	0.03178	1538	293	15.47
81	4226.33	4252.58	4278.83	0.03525	0.03375	0.03215	1558	259	15.26
80	4278.83	4305.74	4332.65	0.03571	0.03417	0.03253	1577	225	15.06
79	4332.64	4360.24	4387.84	0.03618	0.03460	0.03292	1597	192	14.85
78	4387.83	4416.14	4444.45	0.03667	0.03504	0.03332	1618	159	14.65
77	4444.45	4473.49	4502.54	0.03716	0.03550	0.03373	1639	126	14.45
76	4502.54	4532.36	4562.17	0.03767	0.03597	0.03415	1660	94	14.25
75	4562.17	4592.79	4623.41	0.03820	0.03645	0.03458	1682	62	14.06
74	4623.40	4654.85	4686.30	0.03874	0.03694	0.03502	1705	31	13.87
73	4686.30	4718.62	4750.94	0.03929	0.03744	0.03547	1729	0	13.68
72	4750.93	4784.15	4817.38	0.03986	0.03796	0.03594	1753	-30	13.50
71	4817.37	4851.54	4885.70	0.04045	0.03850	0.03641	1778	-60	13.31
70	4885.69	4920.84	4955.99	0.04106	0.03905	0.03690	1803	-90	13.14
69	4955.98	4992.16	5028.34	0.04168	0.03962	0.03740	1829	-119	12.96
68	5028.33	5065.57	5102.82	0.04232	0.04020	0.03792	1856	-148	12.79
67	5102.81	5141.18	5179.55	0.04298	0.04080	0.03845	1884	-177	12.62
66	5179.54	5219.08	5258.61	0.04367	0.04142	0.03900	1913	-205	12.46
65	5258.61	5299.37	5340.13	0.04437	0.04205	0.03956	1942	-232	12.30
64	5340.12	5382.17	5424.22	0.04510	0.04271	0.04013	1973	-260	12.14
63	5424.21	5467.60	5511.00	0.04586	0.04339	0.04073	2004	-287	11.99
62	5510.99	5555.79	5600.60	0.04663	0.04409	0.04134	2037	-313	11.84
61	5600.58	5646.87	5693.16	0.04744	0.04481	0.04197	2070	-340	11.69
60	5693.14	5740.98	5788.83	0.04827	0.04556	0.04262	2105	-366	11.55
59	5788.81	5838.29	5887.77	0.04914	0.04633	0.04329	2141	-392	11.42
58	5887.75	5938.95	5990.15	0.05003	0.04713	0.04398	2178	-417	11.29
57	5990.13	6043.14	6096.15	0.05096	0.04796	0.04469	2216	-442	11.17
56	6096.13	6151.05	6205.97	0.05192	0.04881	0.04543	2256	-467	11.05
55	6205.96	6262.89	6319.83	0.05292	0.04970	0.04619	2297	-492	10.94
54	6319.81	6378.87	6437.93	0.05396	0.05062	0.04697	2340	-516	10.83
53	6437.91	6499.23	6560.54	0.05504	0.05157	0.04779	2384	-540	10.74
52	6560.52	6624.21	6687.91	0.05616	0.05257	0.04863	2430	-564	10.65
51	6687.88	6754.10	6820.32	0.05733	0.05360	0.04950	2478	-588	10.57
50	6820.29	6889.18	6958.07	0.05855	0.05467	0.05040	2528	-611	10.50
49	6958.04	7029.78	7101.51	0.05982	0.05579	0.05133	2580	-635	10.44

48	7101.48	7176.23	7250.98	0.06115	0.05695	0.05230	2634	-658	10.39
47	7250.95	7328.92	7406.88	0.06254	0.05816	0.05331	2690	-681	10.35
46	7406.85	7488.24	7569.63	0.06399	0.05942	0.05435	2749	-705	10.33
45	7569.59	7654.65	7739.70	0.06551	0.06074	0.05544	2811	-728	10.32
44	7739.65	7828.61	7917.58	0.06711	0.06212	0.05657	2875	-751	10.33
43	7917.53	8010.68	8103.82	0.06878	0.06357	0.05774	2943	-774	10.36
42	8103.77	8201.41	8299.04	0.07054	0.06508	0.05897	3013	-797	10.41
41	8298.98	8401.44	8503.90	0.07239	0.06667	0.06024	3088	-821	10.48
40	8503.83	8611.48	8719.12	0.07434	0.06834	0.06157	3165	-844	10.58
39	8719.05	8832.28	8945.52	0.07639	0.07009	0.06296	3247	-868	10.71
38	8945.44	9064.71	9183.98	0.07857	0.07193	0.06441	3334	-892	10.88
37	9183.90	9309.70	9435.51	0.08086	0.07388	0.06593	3425	-917	11.08
36	9435.41	9568.31	9701.20	0.08330	0.07593	0.06752	3521	-942	11.32
35	9701.09	9841.69	9982.28	0.08588	0.07810	0.06918	3623	-967	11.61
34	9982.16	10131.15	10280.14	0.08863	0.08040	0.07092	3731	-994	11.97
33	10280.00	10438.15	10596.31	0.09155	0.08283	0.07275	3846	-1021	12.38
32	10596.15	10764.35	10932.54	0.09468	0.08542	0.07467	3968	-1049	12.88
31	10932.36	11111.58	11290.80	0.09802	0.08818	0.07668	4098	-1079	