Center for Astrophysics

Harvard College Observatory
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Synopis

The Tillinghast Reflection Echelle Spectrograph (*TRES*), will be a high-throughput, fiber fed echelle for the Mt. Hopkins 1.5 Meter Telescope. *TRES* will be cross-dispersed for a usable passband of $\sim$ 370 - 900 nm. *TRES* will accommodate three optical fiber pairs (science & sky) offering three different resolutions (41K, 30K & 20K). It will be a full double pass design (camera/collimator & cross disperser) and operate a 52.6 lpm R2 grating in quasi-Littrow mode. A high stability mode utilizing an iodine cell will be available to observers.

Introduction

The Tillinghast Reflection Echelle Spectrograph (*TRES*) is intended to be a general-purpose, high throughput echelle spectrograph for the Mt. Hopkins 1.5M telescope. *TRES* will be cross dispersed and is designed to have fairly uniform spectral coverage over the available passband as defined by the transmission of the optical fiber that will feed the spectrograph, (*i.e.* 370 - 900 nm). The choice of a fiber fed design over a Cass mounted instrument was made on grounds of high stability performance for radial velocity investigations, cost and the significant weight constraints on a Cass instrument.

After a review of modern echelle designs, I believe a "standard" configuration with the camera/collimator & cross disperser operated in double pass delivers the biggest "bang for the buck". White pupil echelle designs are very much in vogue,[1] as they offer some flexibility to the designer, but they are large and require numerous extra optical interfaces, which compromises efficiency and drives cost upward. *TRES* will

[1] See, for instance: Tull 1994 SPIE 2198, p.674, Dekker *et al.* 2000 SPIE 4008, p.534, Kaufer & Pasquini 1995 SPIE 3355, p.844, Pfeiffer *et al.* 1998 A& A 130, p.381, Gratton *et al.* 1994 SPIE 2198, p.309.

be a standard double-pass design is in the spirit of the Saniford Echelle[2]. *TRES* will be fed with three (*i.e. tres*) science fibers, offering resolutions from 20,000 - 40,000 (see Table 1). Each science fiber will have a matched sky fiber, and the two echellograms will be interleaved. Cross dispersion is be accomplished with a prism, which will give us a considerable efficiency boost over grating cross dispersed designs, as well as vastly more uniform efficiency across entire passband of *TRES*. An iodine absorption cell for high stability operation will be included in the design.

Fiber Dia.	Dia. on Sky	Resolution
75μ	$1\overset{''}{.}72$	41,000
100μ	$2\overset{''}{.}30$	30,000
150μ	$3\overset{''}{.}45$	20,000

Table 1: *TRES* resolution modes

The Design

The first design issue is the F/10 focal ratio of the 1.5M itself. The optimal input focal ratio to feed an optical fiber with is in the range of F/3-F/6. Below F/3, the cone angle of the beam is too wide for efficient total internal reflection in the fiber. At the other extreme, focal ratio degradation tends to reduce throughput for beams much slower than F/6. Testing for the Hectospec/chelle instruments indicates that for fibers similar to those we would use in *TRES*, a F/6 feed will yield a 85% absolute transmission through the fiber, compared with 70% for a fiber fed at F/10. Assuming a doublet system to convert from F/10 to F/6, we will introduce 4 air-glass interfaces in the process of conversion which will cost ∼4-7% total loss compared with a 19% loss at F/10.

While there are incremental gains to be made at faster focal ratios, the limits on usable fiber diameter sets a lower bound to the plate scale. The plate scales at F/10, 6 & 5 are 72, 44 & 36 μ/arcsec, respectively. While 100μ fiber can be used effectively in astronomical spectrographs[3], there is some erosion of performance below this threshold; I have taken a 75μ fiber as the lowest usable bound. Given the typical seeing on the Ridge (∼1.5"), the $1\overset{''}{.}72$ slit that would be achieved with a 75μ fiber and F/6 feed seemed a good match. I rejected F/5, since a 75μ fiber corresponds to a $2\overset{''}{.}1$ slit, and the larger fibers would result in really enormous slits.

The front end of the fiber will require a tip-tilt system similar to that in use by AFOE. The AFOE experience is that tip-tilt correction add 20% efficiency over

[2]McCarthy *et al.* 1993 PASP 105, p. 881

[3]see Kannappan, Fabricant & Hughes 2002 PASP 114, 577.

uncorrected operation, where losses are split between guiding errors and atmospheric effects. The control loop should operate at 5hz, and will require an intensified camera. Given that the field of the 1.5M is small, the only way to to guide is off the science object itself through a pellicle with a 95%/5% split. The net loss, pellicle & turning mirror operated at 45° is likely to cost 10% throughput, but this is considerably better than the 20%+ to be expected with the tip-tilt system.

A mechanism to select fibers at the focal plane will probably consist of a rotating mask with apertures that occult all but the selected fiber sky & science pair.

The fiber run from the focal to the spectrograph will use a modified version of the Hectospec/chelle fiber management system. The fiber run will be 10 meters long, assuming we can locate the optical bench near the AFOE. The mechanics of this run will be considerably simpler than that at the MMT, since no derotation will be required at the Cass location of the 1.5M.

The layout of *TRES* appears in Figure 1. The input and diffracted beams are fanned out by 6° in the cross dispersion direction to leave enough room to accommodate an iodine cell and shutter at the input side and the cold head of the camera on the diffracted side. I have chosen a 128mm beam size, set primarily by Richardson Grating Lab catalogue grating sizes. A 128mm × 256mm grating costs $15K. The next increment (154mm×308mm), is double the cost. This choice and the focal ratio of the system (F/6) then determines the focal length of the camera, chosen to be 762mm, slightly less than the nominal 768mm to slightly underfill the grating. This will compensate potential vignetting caused by the cross disperser fanning the beam onto the grating. As the design evolves, the focal length may be adjusted slightly to mitigate this vignetting further.

Since the system is in double pass, the magnification is 1. We will operate in Littrow ($\theta_{inc} = \theta_{diffr}$) so there is no anamorphic magnification. The camera collimator optics are not yet designed, but designs for similar spectrographs suggest a triplet lens system will do the job. I estimate the distance for the slit and focal plane to the triplet mid-plane to be 800mm. I further estimate the distance from the triplet mid-plane to the grating center line to be $\sim$ 400mm; the spectrograph is quite compact. The camera/collimator - grating distance must be made as small as possible to minimize the post-cross dispersion beam spreading, since a bigger beam requires larger diameter optics, which grows the cost of the spectrograph precipitously.

The baseline model for *TRES* is Model 1113. The echellogram and extensive data on this model are shown in Figure 2. I have considered a large number of possible grating/prism combinations and some details of the trade study I performed appear in Appendix A. The size and geometry of the grating (R2, Littrow) are set by pragmatic considerations. The grating dimensions and angle of incidence are set by cost. Bigger grating cost more and larger angles of incidence result in bigger beams which also drive up cost; Littrow is the most efficient operating mode for a grating. The adjustable parameters are then the apex angle of the cross disperser, the cross disperser glass and the pitch of the grating. The values I have chosen appear in Table 2

The fiber size, focal length, pixel size and angle of incidence set the resolution of the spectrograph. The residual issue is to fit the echellogram on an obtainable (finite cost) CCD format with adequate order separation at the red end of the echellogram where disperson is weakest so that the neighboring orders can be extracted cleanly. This later issue is complicated somewhat in *TRES*, since we want to interleave the science and sky echellogram. The maximum fiber size is 150μ and the magnification is 1, so the null between the reddest orders must be large enough to fit another order between them; the orders must be separated by somewhat more than 300μ to achieve this accommodation. This drives the choice of grating pitch, prism glass and prism apex angle. Lower pitch values produce shorter orders so the $\delta\lambda$ between orders is small, hence order separation is small. Lower dispersion glass and smaller apex angles also reduce order separation. We need a system that will produce 350-400μ interorder separation, or 1.85-3.7 pixels between interleaved orders. The red order separation cannot be widened arbitrarily since the echellogram rapidly becomes too large for the CCD format. A secondary issue is that as the prism apex angle increases, so does the angle of incidence at the air-glass interface of the prism. Although anti-reflection (AR) coatings mitigate interfacial losses, the problem becomes more vexing as the angle of incidence goes up (via the Fresnel equation).

Another matter that drives the choice of glass is internal absorption of blue wavelengths in the glass itself. The path through the glass is not negligible and the prism is used in double pass[4] While this instrument will not plumb the near ultraviolet, it should be extremely efficient at Ca H & K and have some usable response at [O II] 3727[5]. For this reason I have restricted myself to the Ohara I-line catalogue of glass that are all optimized for blue transmission. I find the best choice is BSL 7Y, a blue transmissive version of BK7. Operated with a 52.6 lpm grating at an apex angle of 37°, I calculate that we should obtain the echellogram shown in Figure 2. This choice of ruling pitch is a catalogue value, but my attempts to optimize the

[4]It turn out that using 1/2 the length of the base of the triangular cross-section as the absorption path length is an excellent approximation to the exact integral absorption averaged from the apex to base.

[5]While it does not appear that 3727 falls on the CCD format in Fig 2, I think we can tweak the design as it matures to get it in

Parameter	**Value**
Beam diameter	128 mm
Cross disperser glass	BSL 7Y
Prism apex angle	35°
Grating size	128mm × 256mm
Grating pitch	52.6 lpm
Grating blaze angle	63.5° (R2)
Operating mode	Littrow
CCD Format	2048 × 4608 pixels
Pixel size	13.5μ
Focal length	762mm
Passband	388.8-861.3nm

Table 2: *TRES* spectrograph parameters, Model 1113

design with (expensive) custom rulings did not improve matters significantly (see Appendix A.). I have checked with Ohara, and boules of glass large enough to fabricate this prism can be obtained for ~$4K.

I have chosen the format of the Megacam/Hectospec/chelle CCD for the focal plane, a 2048 × 4608 pixel CCD with 13.5μ pixels. These small pixels offer a resolution advantage over more common 15μ pixel devices. I expect we will accrue considerable advantage using devices we have considerable experience with and we will clone readout electronics developed for the MMT instruments; an extremely economical approach.

Model 1113 has several prominent virtues. The order separation at the red limit is 421μ which will cleanly separate the interleaved red orders. The echellogram fits on the CCD format quite neatly. Longward of ~660nm the orders are larger than the CCD format. We can address this by decentering the echellogram so important lines are on the format. I will also explore a including a tilt mechanism in the grating support to permit observer adjustment of the location the echellogram on the focal plane. I will also explore the possibility of reducing the apex angle of the prism to include slightly more blue orders (see Model 1112, Fig 10 in Appendix A., which has a larger passband and a slightly smaller red order separation).

For the purposes of calibration, we will include several fibers in the fiber feed which are fed by thorium lamps, and which may be operated at any time during observations.

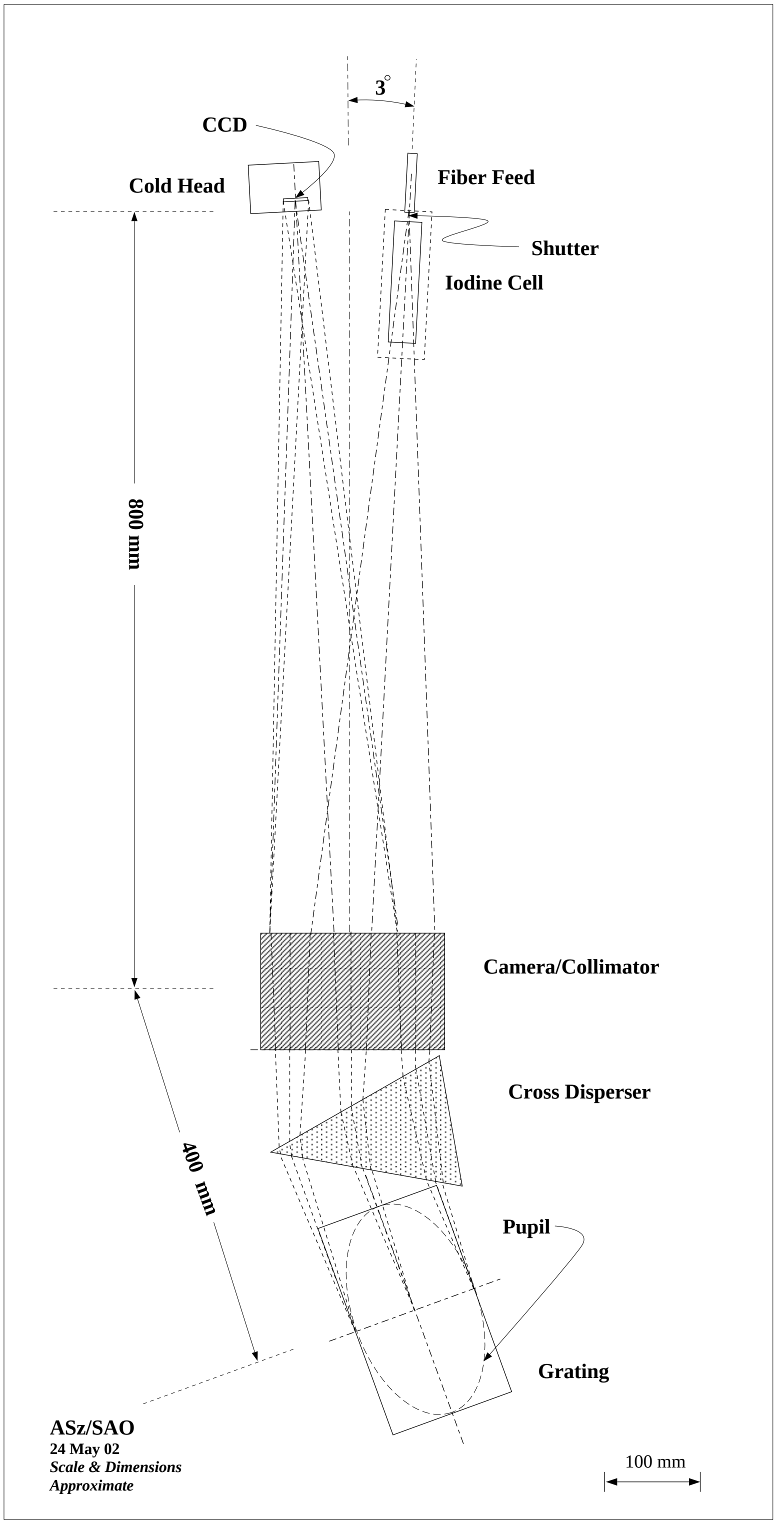
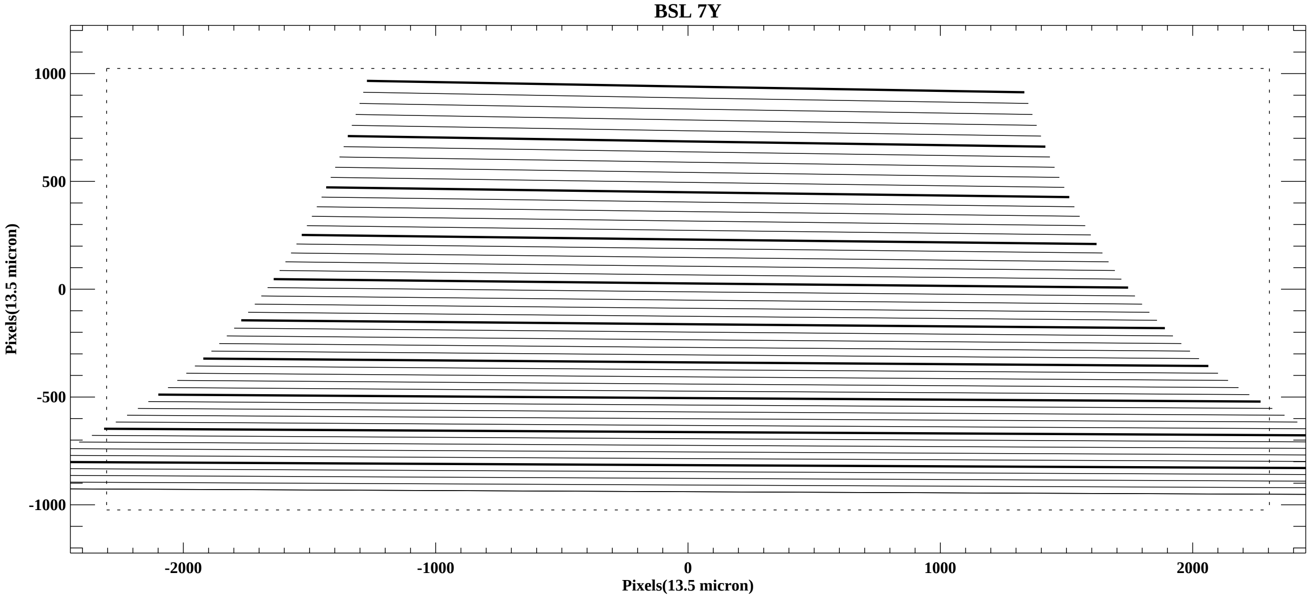


Figure 1: Layout of the *TRES* spectrograph. The diffractive dispersion direction is out of the page at the CCD, and cross dispersion is in the plane of the page.

BSL7Y_1113

Glass:	**BSL 7Y**	**CCD Format:**	**4608 x 2048 pix**
Model #:	**1113**	**Pitch:**	**52.600000 lpm**
Cam. Focal Len.:	**762.00000 mm**	**Pixel size:**	**13.500000 microns**
Central wavel.:	**0.57186500**	**Number of passes:**	**2**
Index - A1:	**1.1332938**	**Number of prisms:**	**1**
Index - A2:	**0.13689720**	**Min Wavl.:**	**0.38900000 Order: 87**
Index - A3:	**0.70345600**	**Max Wavl.:**	**0.88949900 Order: 38**
Index - B1:	**0.0066940787**	**# Orders:**	**50**
Index - B2:	**0.023739176**	**Min/Max Order Sep:**	**421.57674 / 706.44307 microns**
Index - B3:	**70.703032**	**Min/Max Order Sep:**	**31.227907 / 52.329116 pixels**
Index:	**1.5318647 @ 0.38900000 microns**	**Total Order Sep:**	**25370.953 microns**
Index:	**1.5200272 @ 0.51425000 microns**	**Total Order Sep:**	**1879.3299 pixels**
Index:	**1.5143955 @ 0.63950000 microns**	**Min FSR:**	**44.9571 Angstr.**
Index:	**1.5110385 @ 0.76475000 microns**	**Max FSR:**	**235.650 Angstr.**
Index:	**1.5086863 @ 0.88949900 microns**	**Min FSR:**	**35.174997 mm**
Alpha:	**63.500000**	**Max FSR:**	**80.937919 mm**
Beta:	**63.500000**	**Min FSR:**	**2605.5553 pixels**
Apex angle:	**37.000000**	**Max FSR:**	**5995.4014 pixels**



BSL 7Y

Order	Bl. Wavel. (Angstr.)	C.Wavel. (angstr.)	R.Wavel. (angstr.)	Refr.Ang. (degrees)	D(Refr.Ang.) (microns)	D(Refr.Ang.) (pixels)	FSR (angstr.)	FSR (pixels)
39	8613.25	8725.11	8836.97	-0.922	421.57674	31.227907	223.721	5839.8069
46	7316.97	7397.37	7477.78	-0.704	414.62767	30.713161	160.812	4942.8709
53	6359.79	6420.36	6480.93	-0.479	437.79123	32.428980	121.139	4285.5575
60	5624.06	5671.32	5718.58	-0.238	476.89676	35.325686	94.5222	3782.9369
67	5040.89	5078.79	5116.70	0.0272	526.03984	38.965914	75.8028	3386.0444
74	4567.30	4598.37	4629.44	0.3209	582.90410	43.178082	62.1399	3064.6547
81	4175.05	4200.98	4226.91	0.6465	646.49034	47.888173	51.8641	2799.0593
87	3888.78	3911.26	3933.73	0.9538	706.44307	52.329116	44.9571	2605.5553

Figure 2: Echellogram and associated data for Model 1113, the baseline model for

The *TRES* Performance

The key parameter of an echelle is its efficiency. I have plotted the efficiency of the *TRES* in Figure 3. I have considered two cases - with and without iodine cell, since the iodine cell will add four refractive interfaces. I am not sure how to account for light loss at the input end due to overfilling the fiber, seeing and guiding errors, so this has not been included. I have a reasonably good model of the fiber supported by actual test data for the Hectospec/chelle program. The CCD quantum efficiency is also well understood from this program. The grating absolute reflectivity is measured by Richardson Grating Lab for their 31.6 lpm grating, however it is not a terrible *ansatz*. I will include efficiency measurements for the 52.6 lpm grating when it becomes available.

The issue of transmission of the refractive elements is slipperier. I assume there are 16 air glass interfaces without the iodine cell and 20 with it. I further assume that all antireflection coating is Sol Gel on fused silica. This is certainly not the case for the dewar entrance window/field flattener and the first element of the focal ratio conversion optics; these optics will certainly not be quite as tranmissive as Sol Gel coated optics. I also am not sure what the camera/collimator lenses will look like; there is a good chance they will be oiled together and not all fused silica. For the purposes of this exercise I assume the camera/collimator can be modeled as three surfaces in double pass, i.e. a total of six air-glass interfaces. I further assume the focal ratio converter is an air-gapped doublet. A final effect I have neglected is the loss of efficiency at the red end in the 75 micron fiber, which will probably not be negligible.

Appendix A.: Grating/Prism Trade Study

The choice of Model 1113 was made after an extensive study of possible grating/prism glass combinations. It is worth comparing the results in Figure 2 with some other possibilities. One might first ask if perhaps a better choice of grating pitch might be better. Figs 4 and 5 show echellograms where the grating pitch has been changed to 79 lpm and 31.6 lpm, respectively. These are chosen since they are Richardson Grating Lab catalogue ruling available at R2. It is clear that the 79 lpm case suffers from orders that are far too long for the CCD format. In the 31.6 lpm case, the order separation at the red end of the spectrum is insufficient since interleaved science and sky fiber echellograms would be inseparable.

A custom ruling, not in the Richardson catalogue, is probably too costly for the *TRES* program, it is worth checking. I have run cases where Model 1113 is modified to grating pitches intermediate between 52.6 lpm and 31.6 lpm. The case of a 45 lpm appears in Figure 6. While this is probably an acceptable fit to our requirements,

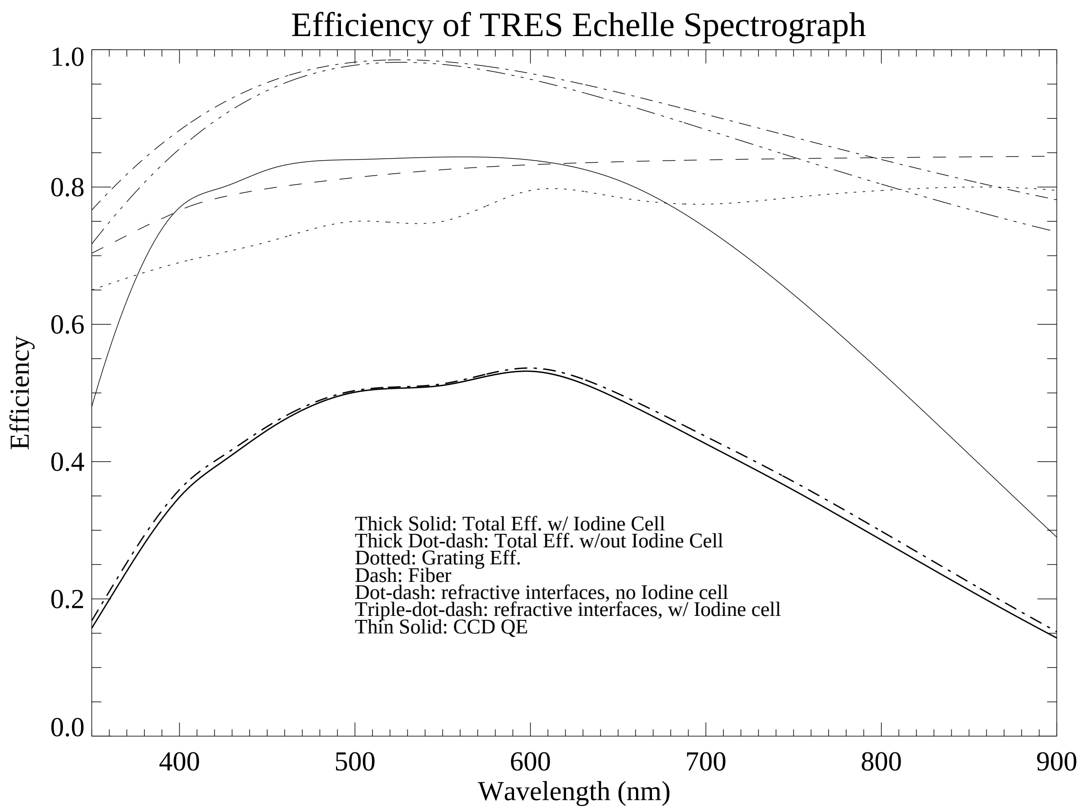


Figure 3: Efficiency of the *TRES* spectrograph

it is probably a little less robust than Model 1113. Given the cost increment, this does not seem a fruitful parameter to explore.

I have also explore other glass possibilities, confining myself to Ohara I-line glasses with good near-UV transmission since the path through the prism is not small and we want to guarantee good transmission an Ca H & K and possibly some response at [O III] 3727. Two alternate choices were PBM 8Y and PBL 25Y, which have lower Abbe numbers than BSL 7Y and might deliver more dispersion with a smaller prism apex angle (hence smaller angle of incidence and correspondingly smaller interfacial losses as per the Fresnel equation.) Both these glasses were vastly overdispersed at the apex angle of Model 1113, and overflowed the CCD format across dispersion. Model Model 1109, shown in Figure 7, is same as Model 1113 except the apex angle is 23° and the prism glass is now PBL 25Y. Model 1118 is the analogue of Model 1113 with a 21° apex angle and a PBM 8Y prism. In both cases, one find that when the prism apex angle is small enough to fit the an echellogram with the desired passband on the CCD format, the order separation at the red end of the passband is insufficient to separate interleaved fibers. The only way to achieve sufficient red order separation is to sacrifice some passband, which is undesirable and unnecessary considering the performance of the BSL 7Y.

The last available adjustable parameter is the apex angle of the prism. Figs 9, 10 & 11 show variations on Model 1113, where the apex angle varies from 30° to 39°. Model 1112 is also an acceptable design, but Model 1111, with a 30° apex angle lack sufficient red order separation. Model 1125, with an 39° apex angle overfills the CCD format. The optimal apex angle for the cross dispersing prism then lies in a fairly narrow interval between 35° & 37°.

Appendix B.: A Name?

I have struggled to come up with a good name/acronym for our project. Barbara Carter came up with a potential winner, the Fiber Fed Echelle Spectrograph for the Tillinghast Reflector (FFESTR), but on reflection this seems like a hard sell to our Director. I like JEFE, but can't think of a good association for the J & extra E. *TRES* will have to do until something better comes along.

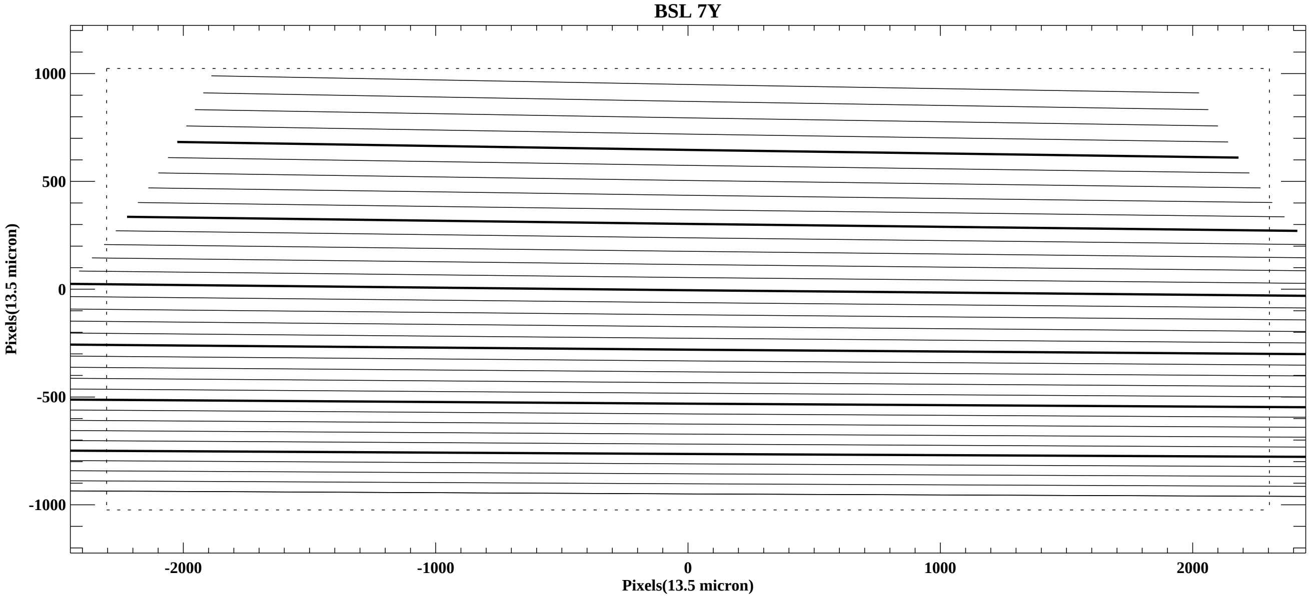
I have out of hand rejected: Nutchelle, Chelleshock, Chellac, Chellf, Hot Echelle, Mortar Chelle, Pi Chelle, Chellefish, SoftChelle, HardChelle, GaFFE, BouFFE, BuFFE, SheriFFE, Trifle & TartuFFE. Seachelle has been used. I think Argus is overwrought. LusTRE might be made to work with some effort. Same is true of GiraFFE. Atomic Chelle seems weak. Halfchelle? Kchelle? Lchelle? CaFFE? MassIFFE?

I am open to suggestion.

BSL7Y_1114

Glass:	BSL 7Y	CCD Format:	4608 x 2048 pix
Model #:	1114	Pitch:	79.000000 lpm
Cam. Focal Len.:	762.00000 mm	Pixel size:	13.500000 microns
Central wavel.:	0.57186500	Number of passes:	2
Index - A1:	1.1332938	Number of prisms:	1
Index - A2:	0.13689720	Min Wavl.:	0.38900000 Order: 58
Index - A3:	0.70345600	Max Wavl.:	0.88949900 Order: 25
Index - B1:	0.0066940787	# Orders:	34
Index - B2:	0.023739176	Min/Max Order Sep:	634.72688 / 1058.8017 microns
Index - B3:	70.703032	Min/Max Order Sep:	47.016806 / 78.429752 pixels
Index:	1.5318647 @ 0.38900000 microns	Total Order Sep:	25641.831 microns
Index:	1.5200272 @ 0.51425000 microns	Total Order Sep:	1899.3949 pixels
Index:	1.5143955 @ 0.63950000 microns	Min FSR:	67.3503 Angstr.
Index:	1.5110385 @ 0.76475000 microns	Max FSR:	362.505 Angstr.
Index:	1.5086863 @ 0.88949900 microns	Min FSR:	52.839798 mm
Alpha:	63.500000	Max FSR:	124.07482 mm
Beta:	63.500000	Min FSR:	3914.0591 pixels
Apex angle:	37.000000	Max FSR:	9190.7275 pixels

BSL 7Y



BSL 7Y

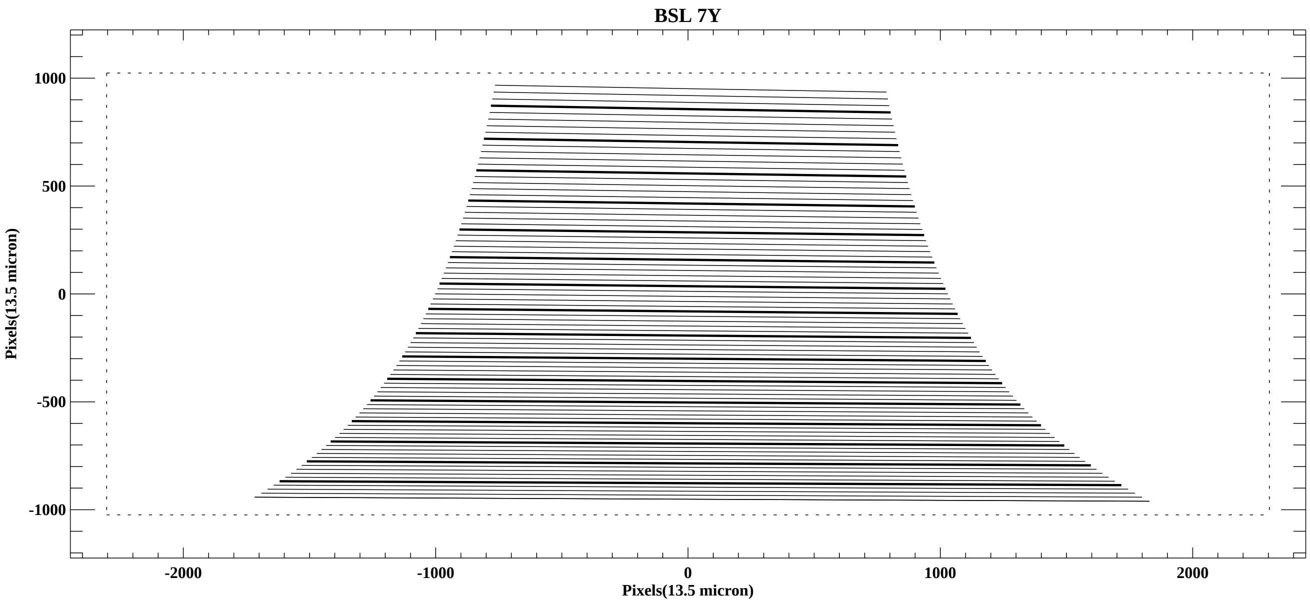
Order	Bl. Wavel. (Angstr.)	C.Wavel. (angstr.)	R.Wavel. (angstr.)	Refr.Ang. (degrees)	D(Refr.Ang.) (microns)	D(Refr.Ang.) (pixels)	FSR (angstr.)	FSR (pixels)
26	8546.49	8714.06	8881.64	-0.916	634.72688	47.016806	335.156	8827.0277
34	6565.70	6663.70	6761.69	-0.538	643.44728	47.662761	195.991	6711.3353
42	5330.20	5394.42	5458.64	-0.120	744.50397	55.148443	128.438	5418.2336
50	4486.00	4531.31	4576.63	0.3739	886.48295	65.665404	90.6262	4544.4779
58	3872.63	3906.30	3939.98	0.9640	1058.8017	78.429752	67.3503	3914.0591

Figure 4: Model 1114 changing Model 1113 grating pitch to 79 lpm

BSL7Y_1115

Glass:	**BSL 7Y**		
Model #:	**1115**		
Cam. Focal Len.:	**762.00000 mm**		
Central wavel.:	**0.57186500**		
Index - A1:	**1.1332938**		
Index - A2:	**0.13689720**		
Index - A3:	**0.70345600**		
Index - B1:	**0.0066940787**		
Index - B2:	**0.023739176**		
Index - B3:	**70.703032**		
Index:	**1.5318647**	**@ 0.38900000 microns**	
Index:	**1.5200272**	**@ 0.51425000 microns**	
Index:	**1.5143955**	**@ 0.63950000 microns**	
Index:	**1.5110385**	**@ 0.76475000 microns**	
Index:	**1.5086863**	**@ 0.88949900 microns**	
Alpha:	**63.500000**		
Beta:	**63.500000**		
Apex angle:	**37.000000**		

CCD Format:	**4608 x 2048 pix**		
Pitch:	**31.600000 lpm**		
Pixel size:	**13.500000 microns**		
Number of passes:	**2**		
Number of prisms:	**1**		
Min Wavl.:	**0.38900000**	**Order:**	**146**
Max Wavl.:	**0.88949900**	**Order:**	**64**
# Orders:	**83**		
Min/Max Order Sep:	**252.61903 / 430.11546 microns**		
Min/Max Order Sep:	**18.712521 / 31.860405 pixels**		
Total Order Sep:	**25689.838 microns**		
Total Order Sep:	**1902.9510 pixels**		
Min FSR:	**26.5720 Angstr.**		
Max FSR:	**138.285 Angstr.**		
Min FSR:	**20.944761 mm**		
Max FSR:	**47.863448 mm**		
Min FSR:	**1551.4638 pixels**		
Max FSR:	**3545.4406 pixels**		



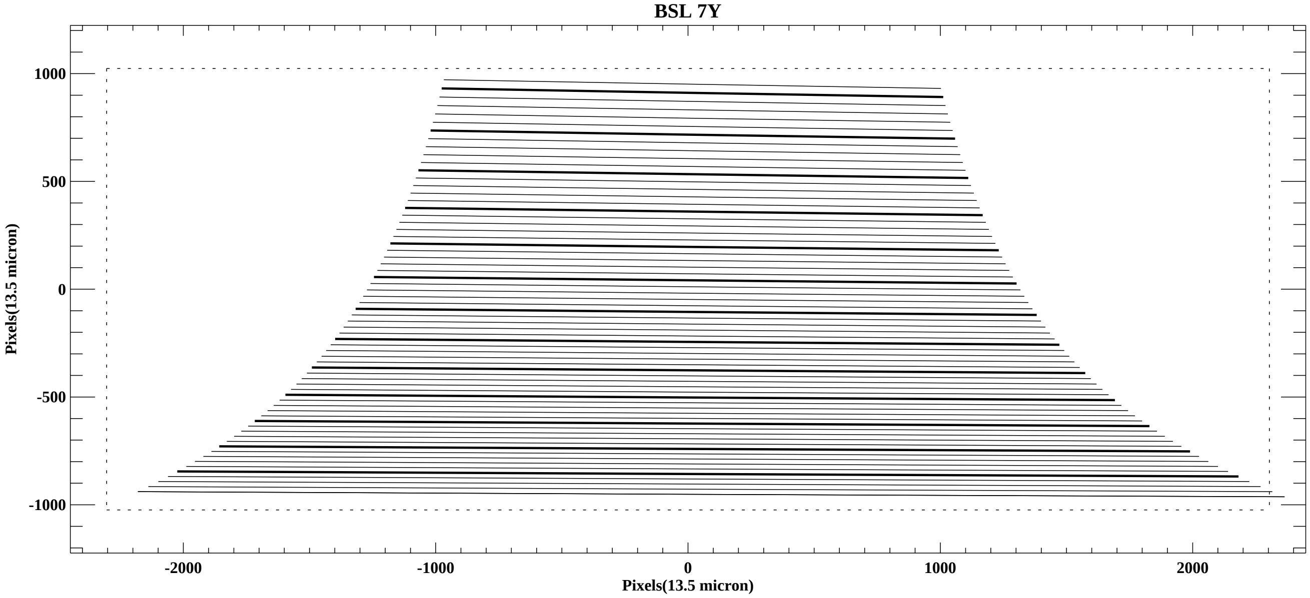
BSL 7Y

Order	Bl. Wavel. (Angstr.)	C.Wavel. (angstr.)	R.Wavel. (angstr.)	Refr.Ang. (degrees)	D(Refr.Ang.) (microns)	D(Refr.Ang.) (pixels)	FSR (angstr.)	FSR (pixels)
65	8647.03	8714.06	8781.09	-0.946	252.61903	18.712521	134.062	3490.6623
72	7812.23	7866.86	7921.49	-0.815	247.75922	18.352535	109.262	3150.0755
79	7124.42	7169.80	7215.18	-0.684	251.16563	18.604861	90.7570	2870.1212
86	6547.92	6586.21	6624.50	-0.549	259.97686	19.257545	76.5836	2635.9287
93	6057.73	6090.47	6123.22	-0.409	272.42160	20.179378	65.4888	2437.1023
100	5635.82	5664.14	5692.46	-0.261	287.50062	21.296342	56.6417	2266.1865
107	5268.85	5293.59	5318.33	-0.105	304.75974	22.574796	49.4730	2117.6975
114	4946.75	4968.54	4990.34	0.0608	323.83561	23.987823	43.5838	1987.4837
121	4661.77	4681.11	4700.45	0.2374	344.45572	25.515238	38.6867	1872.3690
128	4407.83	4425.11	4442.40	0.4253	366.62006	27.157042	34.5710	1769.8572
135	4180.12	4195.66	4211.20	0.6253	390.14697	28.899776	31.0791	1677.9903
142	3974.79	3988.83	4002.88	0.8381	415.12728	30.750169	28.0902	1595.2003

Figure 5: Model 1115 changing Model 1113 grating pitch to 31.6 lpm

BSL7Y_1122

Glass:	BSL 7Y	CCD Format:	4608 x 2048 pix
Model #:	1122	Pitch:	40.000000 lpm
Cam. Focal Len.:	762.00000 mm	Pixel size:	13.500000 microns
Central wavel.:	0.57186500	Number of passes:	2
Index - A1:	1.1332938	Number of prisms:	1
Index - A2:	0.13689720	Min Wavl.:	0.38900000 Order: 115
Index - A3:	0.70345600	Max Wavl.:	0.88949900 Order: 50
Index - B1:	0.0066940787	# Orders:	66
Index - B2:	0.023739176	Min/Max Order Sep:	320.97423 / 541.75472 microns
Index - B3:	70.703032	Min/Max Order Sep:	23.775869 / 40.129979 pixels
Index:	1.5318647 @ 0.38900000 microns	Total Order Sep:	25684.343 microns
Index:	1.5200272 @ 0.51425000 microns	Total Order Sep:	1902.5439 pixels
Index:	1.5143955 @ 0.63950000 microns	Min FSR:	33.8349 Angstr.
Index:	1.5110385 @ 0.76475000 microns	Max FSR:	178.987 Angstr.
Index:	1.5086863 @ 0.88949900 microns	Min FSR:	26.597395 mm
Alpha:	63.500000	Max FSR:	61.350452 mm
Beta:	63.500000	Min FSR:	1970.1774 pixels
Apex angle:	37.000000	Max FSR:	4544.4779 pixels



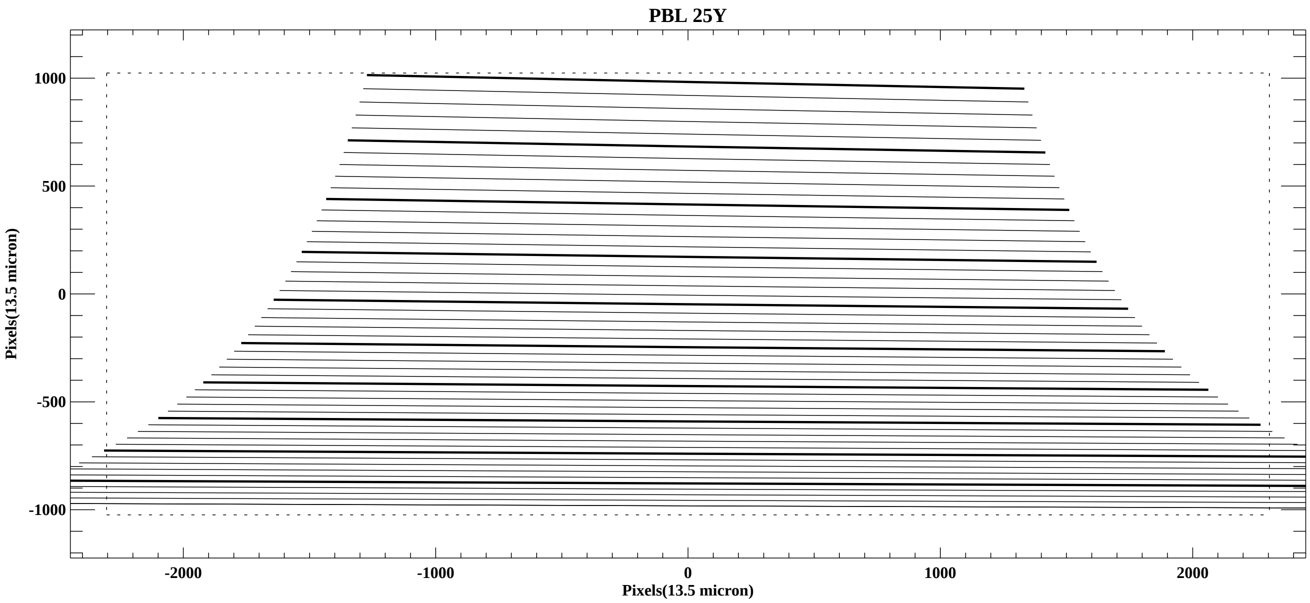
BSL 7Y

Order	Bl. Wavel. (Angstr.)	C.Wavel. (angstr.)	R.Wavel. (angstr.)	Refr.Ang. (degrees)	D(Refr.Ang.) (microns)	D(Refr.Ang.) (pixels)	FSR (angstr.)	FSR (pixels)
51	8687.85	8773.87	8859.88	-0.941	320.97423	23.775869	172.037	4454.7507
58	7648.44	7714.95	7781.46	-0.775	313.79807	23.244301	133.016	3914.0591
65	6831.16	6884.11	6937.06	-0.608	322.29137	23.873435	105.909	3490.6623
72	6171.66	6214.82	6257.98	-0.433	340.00468	25.185532	86.3171	3150.0755
79	5628.29	5664.14	5699.99	-0.247	363.53159	26.928266	71.6978	2870.1212
86	5172.86	5203.11	5233.36	-0.048	391.60037	29.007435	60.5011	2635.9287
93	4785.61	4811.48	4837.34	0.1671	423.12098	31.342294	51.7365	2437.1023
100	4452.30	4474.67	4497.05	0.4001	457.63922	33.899201	44.7467	2266.1865
107	4162.39	4181.94	4201.48	0.6521	495.24593	36.684884	39.0834	2117.6975
114	3907.94	3925.15	3942.37	0.9248	535.66861	39.679156	34.4309	1987.4837

Figure 6: Model 1122 changing Model 1113 grating pitch to 45 lpm, a custom ruling

PBL25Y_1109

Glass:	PBL 25Y		CCD Format:	4608 x 2048 pix
Model #:	1109		Pitch:	52.600000 lpm
Cam. Focal Len.:	762.00000 mm		Pixel size:	13.500000 microns
Central wavel.:	0.57186500		Number of passes:	2
Index - A1:	1.3196063		Number of prisms:	1
Index - A2:	0.12375263		Min Wavl.:	0.38900000 Order: 87
Index - A3:	0.21005535		Max Wavl.:	0.88949900 Order: 38
Index - B1:	0.010186341		# Orders:	50
Index - B2:	0.048359360		Min/Max Order Sep:	346.45414 / 842.24510 microns
Index - B3:	27.327203		Min/Max Order Sep:	25.663270 / 62.388526 pixels
Index:	1.6110729	@ 0.38900000 microns	Total Order Sep:	26524.998 microns
Index:	1.5880385	@ 0.51425000 microns	Total Order Sep:	1964.8147 pixels
Index:	1.5781229	@ 0.63950000 microns	Min FSR:	44.9571 Angstr.
Index:	1.5726766	@ 0.76475000 microns	Max FSR:	235.650 Angstr.
Index:	1.5691918	@ 0.88949900 microns	Min FSR:	35.174997 mm
Alpha:	63.500000		Max FSR:	80.937919 mm
Beta:	63.500000		Min FSR:	2605.5553 pixels
Apex angle:	23.000000		Max FSR:	5995.4014 pixels



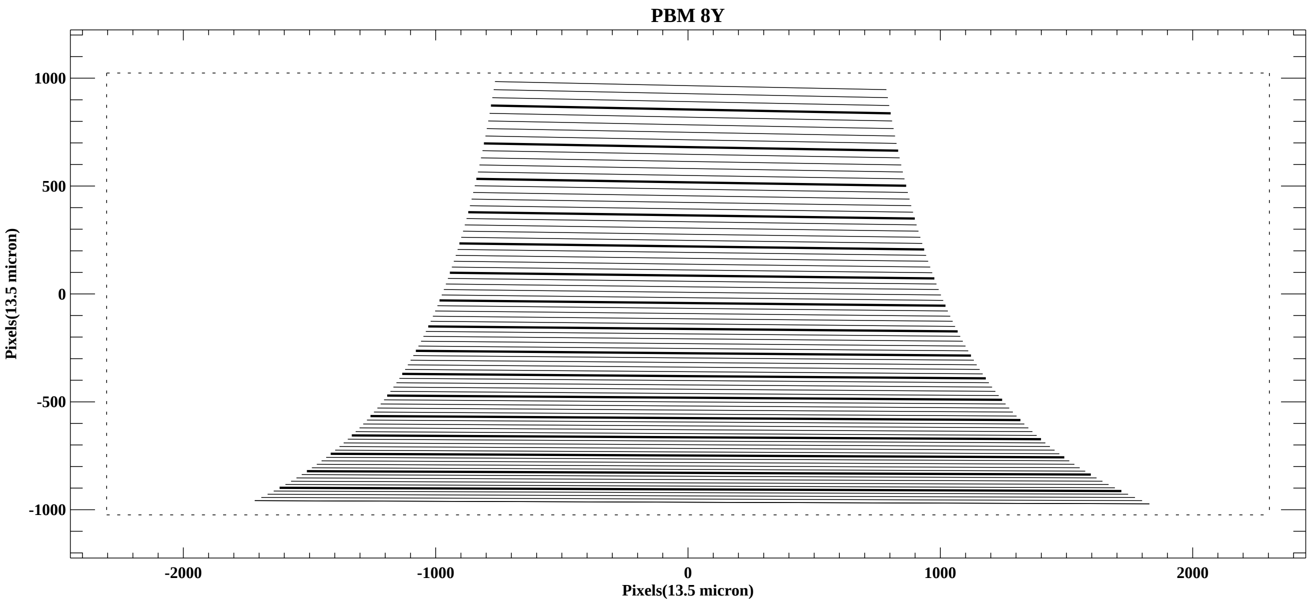
PBL 25Y

Order	Bl. Wavel. (Angstr.)	C.Wavel. (angstr.)	R.Wavel. (angstr.)	Refr.Ang. (degrees)	D(Refr.Ang.) (microns)	D(Refr.Ang.) (pixels)	FSR (angstr.)	FSR (pixels)
39	8613.25	8725.11	8836.97	-0.971	346.45414	25.663270	223.721	5839.8069
46	7316.97	7397.37	7477.78	-0.780	377.47514	27.961122	160.812	4942.8709
53	6359.79	6420.36	6480.93	-0.567	426.02777	31.557613	121.139	4285.5575
60	5624.06	5671.32	5718.58	-0.325	486.61637	36.045657	94.5222	3782.9369
67	5040.89	5078.79	5116.70	-0.048	558.24172	41.351239	75.8028	3386.0444
74	4567.30	4598.37	4629.44	0.2698	642.08472	47.561831	62.1399	3064.6547
81	4175.05	4200.98	4226.91	0.6368	741.23383	54.906209	51.8641	2799.0593
87	3888.78	3911.26	3933.73	0.9972	842.24510	62.388526	44.9571	2605.5553

Figure 7: Model 1109 changing Model 1113 prism glass to PBL 25Y and apex angle

PBM8Y_1118

Glass:	PBM 8Y		CCD Format:	4608 x 2048 pix	
Model #:	1118		Pitch:	31.600000 lpm	
Cam. Focal Len.:	762.00000 mm		Pixel size:	13.500000 microns	
Central wavel.:	0.57186500		Number of passes:	2	
Index - A1:	1.3535132		Number of prisms:	1	
Index - A2:	0.13021291		Min Wavl.:	0.38900000	Order: 146
Index - A3:	0.15833727		Max Wavl.:	0.88949900	Order: 64
Index - B1:	0.010562463		# Orders:	83	
Index - B2:	0.049660665		Min/Max Order Sep:	198.61615 / 503.19421 microns	
Index - B3:	20.796581		Min/Max Order Sep:	14.712307 / 37.273645 pixels	
Index:	1.6271881	@ 0.38900000 microns	Total Order Sep:	26064.679 microns	
Index:	1.6025298	@ 0.51425000 microns	Total Order Sep:	1930.7170 pixels	
Index:	1.5919900	@ 0.63950000 microns	Min FSR:	26.5720 Angstr.	
Index:	1.5862288	@ 0.76475000 microns	Max FSR:	138.285 Angstr.	
Index:	1.5825605	@ 0.88949900 microns	Min FSR:	20.944761 mm	
Alpha:	63.500000		Max FSR:	47.863448 mm	
Beta:	63.500000		Min FSR:	1551.4638 pixels	
Apex angle:	21.000000		Max FSR:	3545.4406 pixels	



PBM 8Y

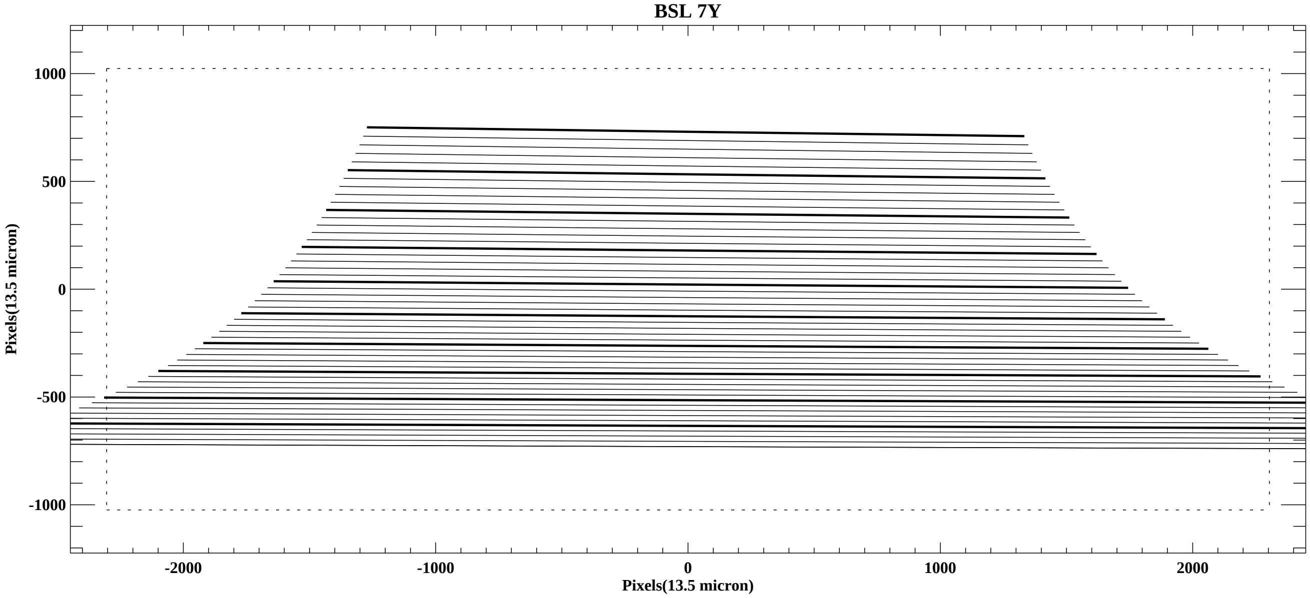
Order	Bl. Wavel. (Angstr.)	C.Wavel. (angstr.)	R.Wavel. (angstr.)	Refr.Ang. (degrees)	D(Refr.Ang.) (microns)	D(Refr.Ang.) (pixels)	FSR (angstr.)	FSR (pixels)
65	8647.03	8714.06	8781.09	-0.964	198.61615	14.712307	134.062	3490.6623
72	7812.23	7866.86	7921.49	-0.857	208.74453	15.462557	109.262	3150.0755
79	7124.42	7169.80	7215.18	-0.743	223.18769	16.532421	90.7570	2870.1212
86	6547.92	6586.21	6624.50	-0.620	240.71932	17.831061	76.5836	2635.9287
93	6057.73	6090.47	6123.22	-0.488	260.83982	19.321468	65.4888	2437.1023
100	5635.82	5664.14	5692.46	-0.344	283.23126	20.980093	56.6417	2266.1865
107	5268.85	5293.59	5318.33	-0.187	307.93905	22.810300	49.4730	2117.6975
114	4946.75	4968.54	4990.34	-0.017	335.19030	24.828911	43.5838	1987.4837
121	4661.77	4681.11	4700.45	0.1675	365.16666	27.049383	38.6867	1872.3690
128	4407.83	4425.11	4442.40	0.3695	398.36776	29.508723	34.5710	1769.8572
135	4180.12	4195.66	4211.20	0.5901	435.33862	32.247305	31.0791	1677.9903
142	3974.79	3988.83	4002.88	0.8315	476.94218	35.329050	28.0902	1595.2003

Figure 8: Model 1118 changing Model 1113 prism glass to PBM 8Y and apex angle

BSL7Y_1111

Glass:	**BSL 7Y**		
Model #:	**1111**		
Cam. Focal Len.:	**762.00000 mm**		
Central wavel.:	**0.57186500**		
Index - A1:	**1.1332938**		
Index - A2:	**0.13689720**		
Index - A3:	**0.70345600**		
Index - B1:	**0.0066940787**		
Index - B2:	**0.023739176**		
Index - B3:	**70.703032**		
Index:	**1.5318647**	**@ 0.38900000 microns**	
Index:	**1.5200272**	**@ 0.51425000 microns**	
Index:	**1.5143955**	**@ 0.63950000 microns**	
Index:	**1.5110385**	**@ 0.76475000 microns**	
Index:	**1.5086863**	**@ 0.88949900 microns**	
Alpha:	**63.500000**		
Beta:	**63.500000**		
Apex angle:	**30.000000**		

CCD Format:	**4608 x 2048 pix**		
Pitch:	**52.600000 lpm**		
Pixel size:	**13.500000 microns**		
Number of passes:	**2**		
Number of prisms:	**1**		
Min Wavl.:	**0.38900000**	**Order:**	**87**
Max Wavl.:	**0.88949900**	**Order:**	**38**
# Orders:	**50**		
Min/Max Order Sep:	**328.15039 / 548.11335 microns**		
Min/Max Order Sep:	**24.307436 / 40.600989 pixels**		
Total Order Sep:	**19715.003 microns**		
Total Order Sep:	**1460.3706 pixels**		
Min FSR:	**44.9571 Angstr.**		
Max FSR:	**235.650 Angstr.**		
Min FSR:	**35.174997 mm**		
Max FSR:	**80.937919 mm**		
Min FSR:	**2605.5553 pixels**		
Max FSR:	**5995.4014 pixels**		



BSL 7Y

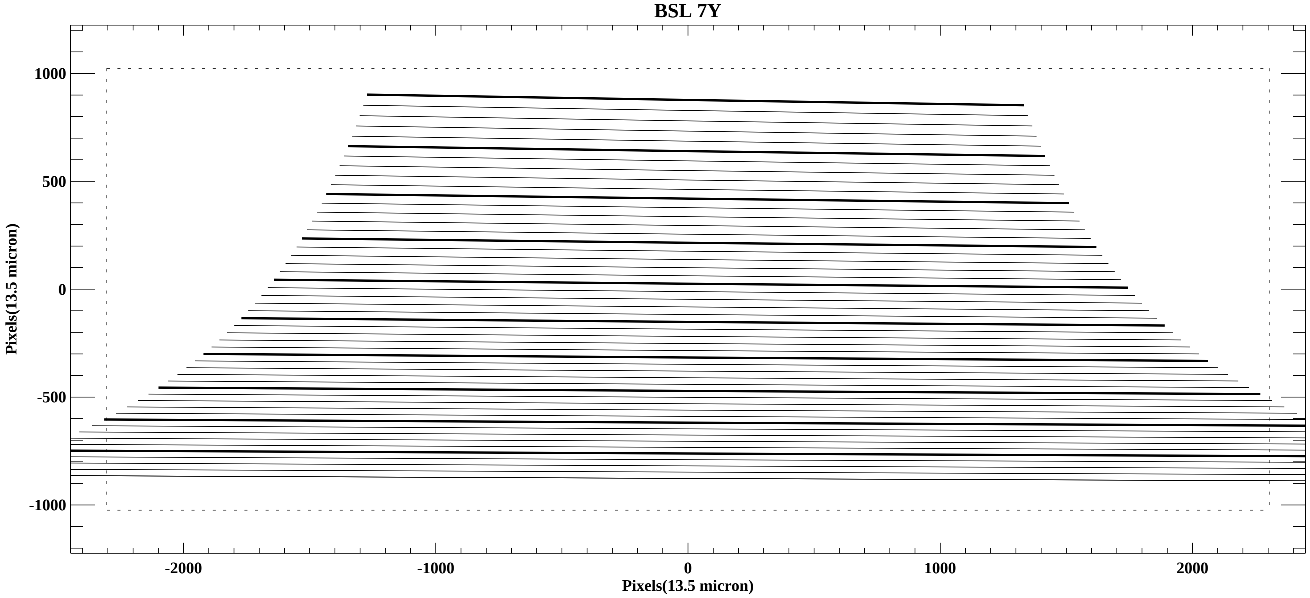
Order	Bl. Wavel. (Angstr.)	C.Wavel. (angstr.)	R.Wavel. (angstr.)	Refr.Ang. (degrees)	D(Refr.Ang.) (microns)	D(Refr.Ang.) (pixels)	FSR (angstr.)	FSR (pixels)
39	8613.25	8725.11	8836.97	-0.716	328.15039	24.307436	223.721	5839.8069
46	7316.97	7397.37	7477.78	-0.546	322.51847	23.890257	160.812	4942.8709
53	6359.79	6420.36	6480.93	-0.372	340.45887	25.219176	121.139	4285.5575
60	5624.06	5671.32	5718.58	-0.184	370.70775	27.459833	94.5222	3782.9369
67	5040.89	5078.79	5116.70	0.0217	408.76865	30.279160	75.8028	3386.0444
74	4567.30	4598.37	4629.44	0.2498	452.73399	33.535851	62.1399	3064.6547
81	4175.05	4200.98	4226.91	0.5027	501.87707	37.176079	51.8641	2799.0593
87	3888.78	3911.26	3933.73	0.7411	548.11335	40.600989	44.9571	2605.5553

Figure 9: Model 1111 changing Model 1113 prism apex angle to 30°

BSL7Y_1112

Glass:	BSL 7Y		
Model #:	1112		
Cam. Focal Len.:	762.00000 mm		
Central wavel.:	0.57186500		
Index - A1:	1.1332938		
Index - A2:	0.13689720		
Index - A3:	0.70345600		
Index - B1:	0.0066940787		
Index - B2:	0.023739176		
Index - B3:	70.703032		
Index:	1.5318647	@ 0.38900000 microns	
Index:	1.5200272	@ 0.51425000 microns	
Index:	1.5143955	@ 0.63950000 microns	
Index:	1.5110385	@ 0.76475000 microns	
Index:	1.5086863	@ 0.88949900 microns	
Alpha:	63.500000		
Beta:	63.500000		
Apex angle:	35.000000		

CCD Format:	4608 x 2048 pix		
Pitch:	52.600000 lpm		
Pixel size:	13.500000 microns		
Number of passes:	2		
Number of prisms:	1		
Min Wavl.:	0.38900000	Order:	87
Max Wavl.:	0.88949900	Order:	38
# Orders:	50		
Min/Max Order Sep:	393.68963 / 658.98049 microns		
Min/Max Order Sep:	29.162195 / 48.813370 pixels		
Total Order Sep:	23679.423 microns		
Total Order Sep:	1754.0313 pixels		
Min FSR:	44.9571 Angstr.		
Max FSR:	235.650 Angstr.		
Min FSR:	35.174997 mm		
Max FSR:	80.937919 mm		
Min FSR:	2605.5553 pixels		
Max FSR:	5995.4014 pixels		



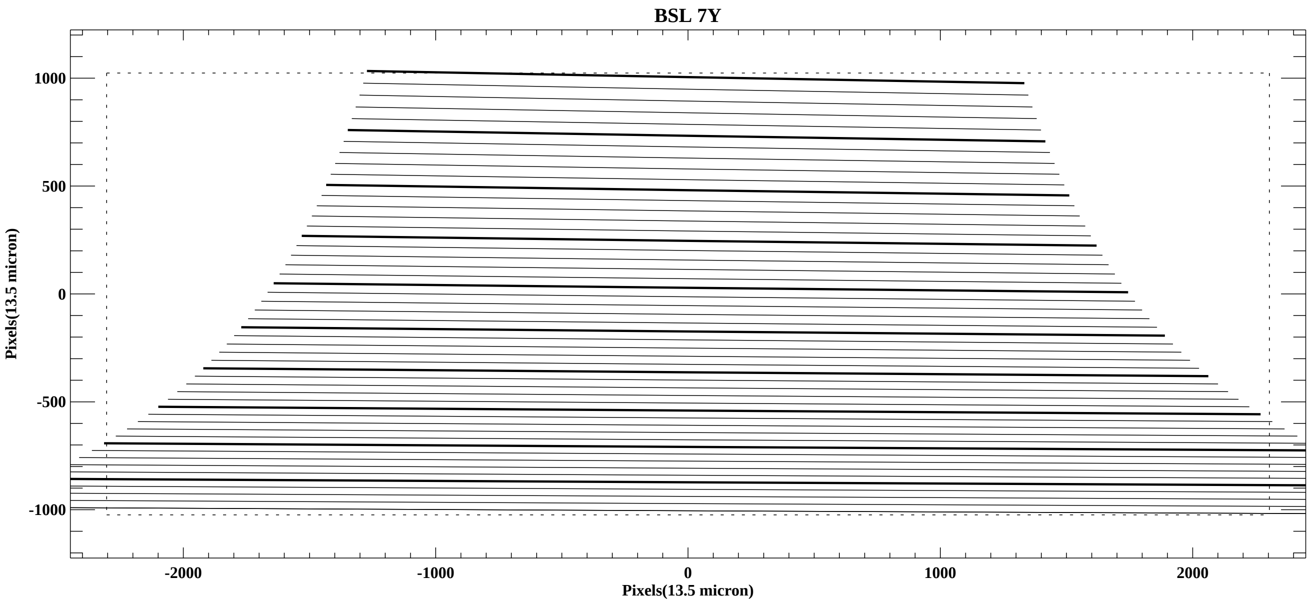
BSL 7Y

Order	Bl. Wavel. (Angstr.)	C.Wavel. (angstr.)	R.Wavel. (angstr.)	Refr.Ang. (degrees)	D(Refr.Ang.) (microns)	D(Refr.Ang.) (pixels)	FSR (angstr.)	FSR (pixels)
39	8613.25	8725.11	8836.97	-0.860	393.68963	29.162195	223.721	5839.8069
46	7316.97	7397.37	7477.78	-0.657	387.10392	28.674364	160.812	4942.8709
53	6359.79	6420.36	6480.93	-0.447	408.72324	30.275795	121.139	4285.5575
60	5624.06	5671.32	5718.58	-0.222	445.14906	32.974005	94.5222	3782.9369
67	5040.89	5078.79	5116.70	0.0256	491.02199	36.371999	75.8028	3386.0444
74	4567.30	4598.37	4629.44	0.2997	543.93482	40.291468	62.1399	3064.6547
81	4175.05	4200.98	4226.91	0.6035	603.20628	44.681946	51.8641	2799.0593
87	3888.78	3911.26	3933.73	0.8902	658.98049	48.813370	44.9571	2605.5553

Figure 10: Model 1112 changing Model 1113 prism apex angle to 35°

BSL7Y_1125

Glass:	BSL 7Y		CCD Format:	4608 x 2048 pix		
Model #:	1125		Pitch:	52.600000 lpm		
Cam. Focal Len.:	762.00000 mm		Pixel size:	13.500000 microns		
Central wavel.:	0.57186500		Number of passes:	2		
Index - A1:	1.1332938		Number of prisms:	1		
Index - A2:	0.13689720		Min Wavl.:	0.38900000	Order:	87
Index - A3:	0.70345600		Max Wavl.:	0.88949900	Order:	38
Index - B1:	0.0066940787		# Orders:	50		
Index - B2:	0.023739176		Min/Max Order Sep:	450.73557 / 755.94950 microns		
Index - B3:	70.703032		Min/Max Order Sep:	33.387820 / 55.996259 pixels		
Index:	1.5318647	@ 0.38900000 microns	Total Order Sep:	27134.790 microns		
Index:	1.5200272	@ 0.51425000 microns	Total Order Sep:	2009.9844 pixels		
Index:	1.5143955	@ 0.63950000 microns	Min FSR:	44.9571 Angstr.		
Index:	1.5110385	@ 0.76475000 microns	Max FSR:	235.650 Angstr.		
Index:	1.5086863	@ 0.88949900 microns	Min FSR:	35.174997 mm		
Alpha:	63.500000		Max FSR:	80.937919 mm		
Beta:	63.500000		Min FSR:	2605.5553 pixels		
Apex angle:	39.000000		Max FSR:	5995.4014 pixels		



BSL 7Y

Order	Bl. Wavel. (Angstr.)	C.Wavel. (angstr.)	R.Wavel. (angstr.)	Refr.Ang. (degrees)	D(Refr.Ang.) (microns)	D(Refr.Ang.) (pixels)	FSR (angstr.)	FSR (pixels)
39	8613.25	8725.11	8836.97	-0.986	450.73557	33.387820	223.721	5839.8069
46	7316.97	7397.37	7477.78	-0.753	443.28690	32.836066	160.812	4942.8709
53	6359.79	6420.36	6480.93	-0.513	468.08553	34.673002	121.139	4285.5575
60	5624.06	5671.32	5718.58	-0.255	510.05244	37.781662	94.5222	3782.9369
67	5040.89	5078.79	5116.70	0.0288	562.64734	41.677581	75.8028	3386.0444
74	4567.30	4598.37	4629.44	0.3429	623.50845	46.185811	62.1399	3064.6547
81	4175.05	4200.98	4226.91	0.6913	691.72740	51.239067	51.8641	2799.0593
87	3888.78	3911.26	3933.73	1.0201	755.94950	55.996259	44.9571	2605.5553

Figure 11: Model 1125 changing Model 1113 prism apex angle to 39°