MMTF testing at OCIW, January 2006

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1 Introduction/Background

The Maryland-Magellan Tunable Filter is a 150mm aperture Fabry-Perot etalon and accompanying CS-100 electronic controller, manufactured by IC Optical Systems (UK). The MMTF is designed to be used in the collimated beam of the IMACS spectrograph at the Magellan Baade 6.5m telescope.

At OCIW on January 25 – February 1, 2006, we carried out a number of tests to characterize the optical properties and behavior of the MMTF, before it is to be shipped to Las Campanas and commissioned at the telescope. Most of the tests were done with an optical bench set up to pass collimated light through the etalon and reimage it onto a CCD detector. This set up is a sort of junior version of placing the MMTF in the collimated beam of IMACS; limitations of the optics mean that it is not an exact analog. However, we were able to physically access the etalon and its cabling during the process, which will be much more awkward inside IMACS.

Among the goals of these tests were: to verify operation of the MMTF, to measure various optical quantities such as the range of bandpasses available, to test MMTF integration with the IMACS control software, and to test the viability of calibration procedures that will be needed during MMTF observing runs.

2 Procedure/optical setup

Initial tests were done with the most basic test setup: the etalon was cabled to the CS-100 controller and operated while placed on a light box with a mercury lamp. This allowed us to observe spectral line rings by eye and to parallelize the etalon plates.

For subsequent tests the etalon was mounted in the mounting plate that will be used in IMACS, and this was fixtured vertically on an optical table. A telescope of 2000mm focal length (f/10, 8 inch aperture) lent by Caltech was used to project a collimated beam of light through the etalon, with light sources mounted behind a diffusing disk at the eyepiece holder. Neon and hydrogen lamps were used. After passing through the etalon and the narrow band filter (6560 Å, 260 Åwidth) that will be used in IMACS, the beam was imaged by a 180mm focal length camera lens (f/2.8, 64mm aperture) onto an Apogee 1Kx1K cooled CCD camera (24 micron pixels) provided by the University of Maryland. Etalon, filter, and camera were mounted on the table with fixtures designed by Tyson Hare and fabricated at OCIW. Figure 1 shows the assembled testing apparatus.

Images were acquired as FITS data on a Linux computer. The data acquisition computer was also cabled to control the CS-100 through its RS-232 interface, using a C program. As a separate test, we cabled Christoph Birk's Linux laptop, running the IMACS control software, to the RS-232 interface of the CS-100 and verified that the software controls the CS-100 properly, and that the interface provides the information the observer will need during operation.

The primary optical setup described, with a 2000mm telescope/collimator and 180mm camera lens, has a demagnification of 11x. The illuminated area of the diffusing disk at the telescope eyepiece is ~ 20 mm, so only about a 2mm circle on the CCD is illuminated. This samples only a small part of the fringe pattern, so to construct spectra, we scanned the etalon by stepping in plate spacing, taking short exposures at each spacing.

For one test which imaged the circular fringe pattern of the etalon, we replaced the camera lens with a 135mm lens for a wider field, and bypassed the telescope, placing a neon lamp and diffusing screen directly behind the etalon to illuminate the full 150mm aperture at a range of beam angles.

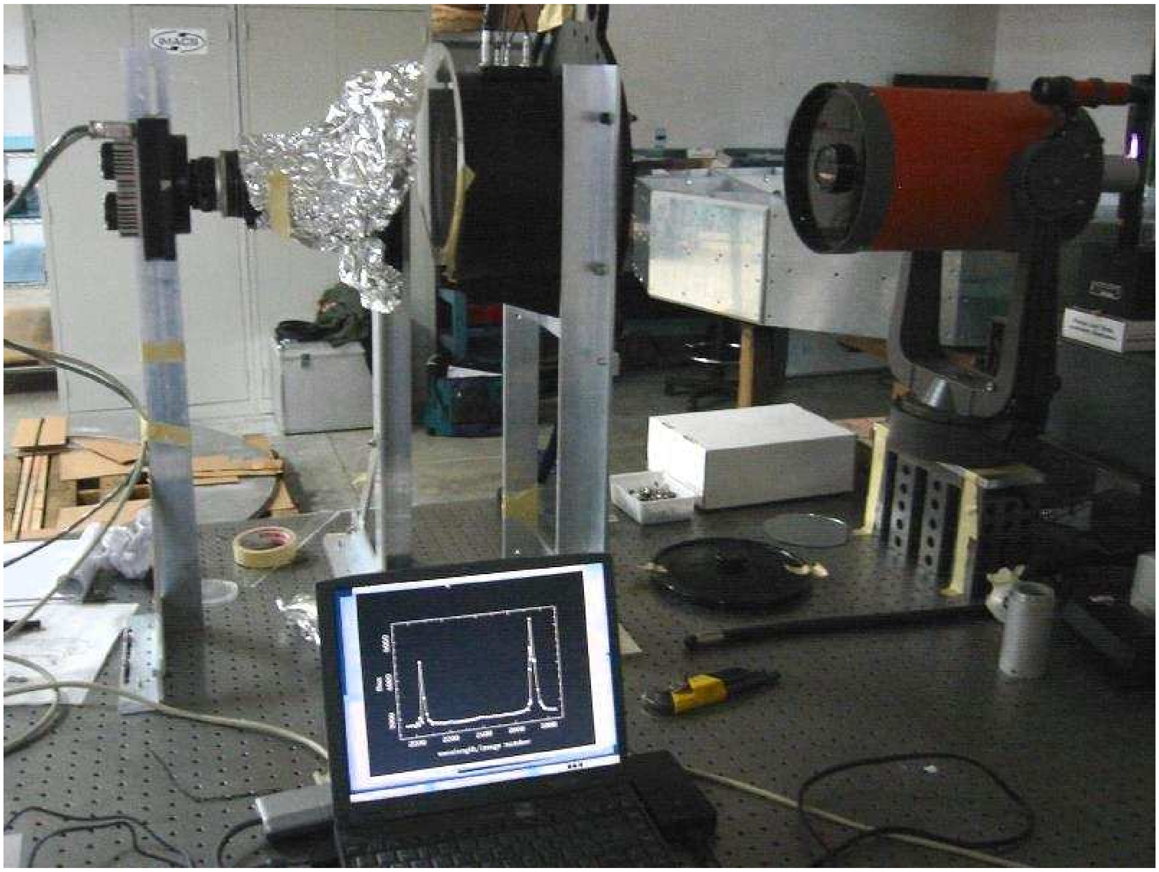

Figure 1: Optical bench in OCIW lab
From right to left, the hydrogen lamp, Celestron collimating telescope, etalon, narrowband filter (behind foil baffle), camera lens, and CCD camera. The data acquisition computer is in the foreground and the CS-100 is out of the picture.

3 Operating Range

We cabled the CS-100 and etalon with first a 3m cable, and then the full set of cables that will be used in IMACS: 15m, 3m and a short adapter cable with bulkhead connectors. We balanced the etalon control loops from the front panel by the standard procedures from the CS-100 manual.

The Z front panel settings on the CS-100 control the plate spacing; spacing is close to linear in Z. With the etalon on the mercury light box, before mounting it on the optical bench, we tested the range of Z over which the etalon can be balanced, parallelized and safely operated. Using the mercury light box, the etalon can be parallelized by eye, using the size of visible rings to equalize plate spacing in X and Y. The coating surfaces exhibit some curvature from center to edge, which was also seen in the Maryland ET-70 70mm etalon and is not unusual.

When changing the Z setting by a coarse step, the etalon frequently goes out of range. In practice, the quadrature error settings need to be changed when Z changes by a large amount to prevent this. For example to do a -1 coarse step in Z, it helps to: bring the Z fine dial down while in Operate mode; switch panel meters to "quadrature balance" and re-null the meters with the quad error dials; switch to Balance mode; bring the Z fine dial back up; switch Z coarse down. Then switch to Operate and re-null the quad errors if necessary.

Following this procedure, using the 15+3m cables, we were able to operate and parallelize the etalon over a range from Z (coarse, fine) of (–3, 1.30) to (+4, 9.99). The parallelized settings at the Z extremes were:

	coarse	fine	quad bal
X	–1	6.10	6.52
Y	0	6.78	6.82
Z	–3	1.30	8.14

	coarse	fine	quad bal
X	–1	6.10	7.00
Y	0	6.65	7.40
Z	+4	9.99	9.33

The lower limit in Z is set by the appearance of distortions in the ring pattern caused by pressure points, probably dust specks within the etalon; at this point, the coatings of the plates are nearly touching and closer spacings are not advisable, nor useful. We were not able to operate the etalon at Z spacings higher than +4, 9.99.

Because the computer control range of 0–4095 allows adding negative spacing to the front panel setting, users should not be allowed to add negative spacing (computer setting below 2048) when the etalon is close to the lowest front panel setting, or the front panel setting should be restricted to a value higher than –3, 1.30.

The X and Y values that achieve parallelism are essentially unchanged over a wide range of Z spacing. This is very helpful in operation because we should be able to scan in Z, or set to achieve different resolutions within a run, without having to touch the parallelism settings. In general, the etalon was parallelized a number of times during the testing week and the X and Y values were always similar, for a given cableset.

4 FSR/Resolution

After setting up the optical bench, we used the neon lamp plus telescope to illuminate the etalon. We built up spectra by taking scans in Z setting and measuring the signal in the small area of the CCD illuminated by the beam, e.g. measuring the average in a 50x50 pixel box in each image of the scan. This is often referred to as a ”sausage cube” in tunable filter use.

It proved to be easier to identify lines by using a hydrogen lamp since Hα 6563 Å is the only line in the narrow-band filter. Then switching to the neon lamp allowed us to identify several neon emission lines. Identification can be difficult initially because at many etalon settings, the order separation (free spectral range, FSR) is less than the 260 Å width of the filter. The line pattern repeats with a period equal to the FSR. Figures 2 and 3 show spectra of the hydrogen and neon lamps constructed from scans over slightly more than a full FSR, for a front panel setting of Z coarse = 0, Z fine = 0.20. Similar neon spectra for the full range of Z are shown at the end of this report.

In general the procedure when setting up an observing run is to identify and measure lines to determine the zeropoint and slope of the $\lambda(Z)$ relation. At a given gap spacing, $d\lambda/dZ$ is fairly constant from run to run, but the zeropoint can change. Knowing the expected $d\lambda/dZ$ ahead of time makes it much easier to identify lines. (However, working in an unfamiliar wavelength region for the first time can be confusing and extra calibration time should be allowed for. Good linelists and a choice of several lamps are very helpful.)

We constructed sausage cubes and measured the locations of lines to determine the FSR and the change in wavelength with Z. We fit Voigt profiles to lines to measure the FWHM of the bandpass. Because the camera lens is smaller than the etalon and only sees through part of it, the camera and collimator focus are not perfect, and because the coated etalon surfaces are not uniformly flat, the FWHM at IMACS will differ slightly from the FWHM on the optical bench.

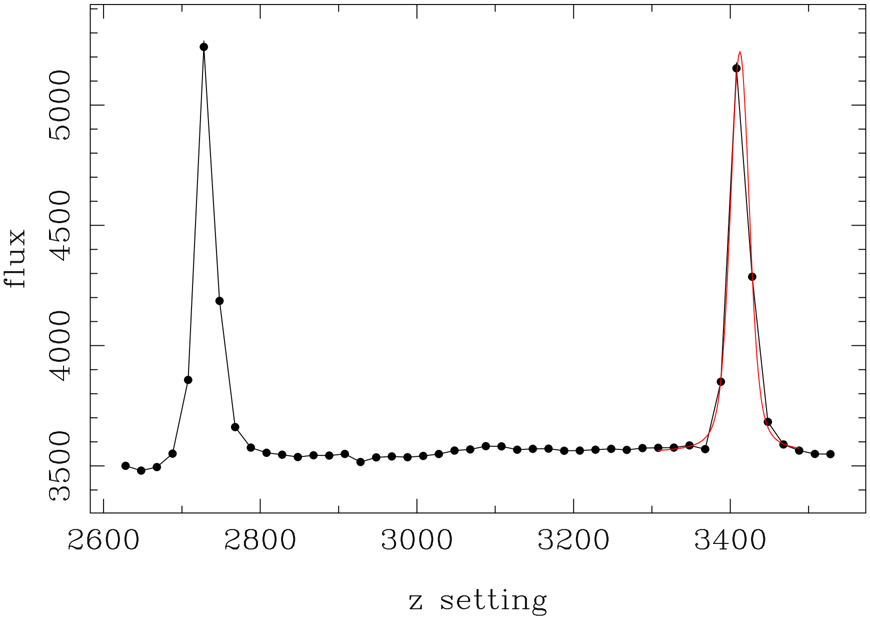

Figure 2: Spectral scan over > 1 FSR, Hα lamp

The x axis is CS-100 Z computer setting. Front panel Z was 0, 0.20. The line is 6563 repeated in 2 orders. The FSR is $\sim$ 690 in Z, the scan step is 20, and the FWHM is $\sim$ 27 in Z, so the steps are undersampled.

We took several scans at a range of coarse spacings to measure the free spectral range, resolution, order number, and $d\lambda/dZ$. The equations that govern the behavior of a Fabry-Perot etalon for a beam on the optical axis are:

$$d = N\lambda/2,$$

$$FSR = \lambda/N,$$

$$\text{finesse(total)} = FSR/FWHM,$$

$$\text{finesse(refl)} = \pi\sqrt{R}/(1-R),$$

where d is the effective plate spacing, N is the order, FSR and FWHM are the free spectral range and the FWHM of the bandpass, and R is the reflectivity of the plates. By measuring λ, FSR and FWHM, we compute N and finesse.

Figures 5 to 10 summarize the measured quantities over the range of operation in Z. All are measured at $\sim$ 6600 Å. These behave sensibly: etalon gap and order are linear with Z, while FSR, FWHM, and $d\lambda/dZ$ are $\sim 1/Z$. Finesse is not exactly constant with Z, which probably indicates that the FWHMs are a little off or affected by undersampling.

The range of resolutions attainable is roughly FWHM = 6 − 18 Å, at $\lambda \simeq$ 6600 Å. It was not possible to bring the etalon plates close together enough to reach FWHM > 18 Å, because the effective reflective surface of the coatings is below the physical surface of the coatings. The finesse of $\sim$ 25 is lowered somewhat by non-flatness of the coating and decollimation issues; taken literally it would imply reflectivity $R = 88\%$ but the true R is probably somewhat higher.

The field of an imaging Fabry-Perot is not monochromatic: there is a gradient in transmitted wavelength from center to edge because the off-axis beams pass through the etalon at an angle. The transmitted wavelength is given by

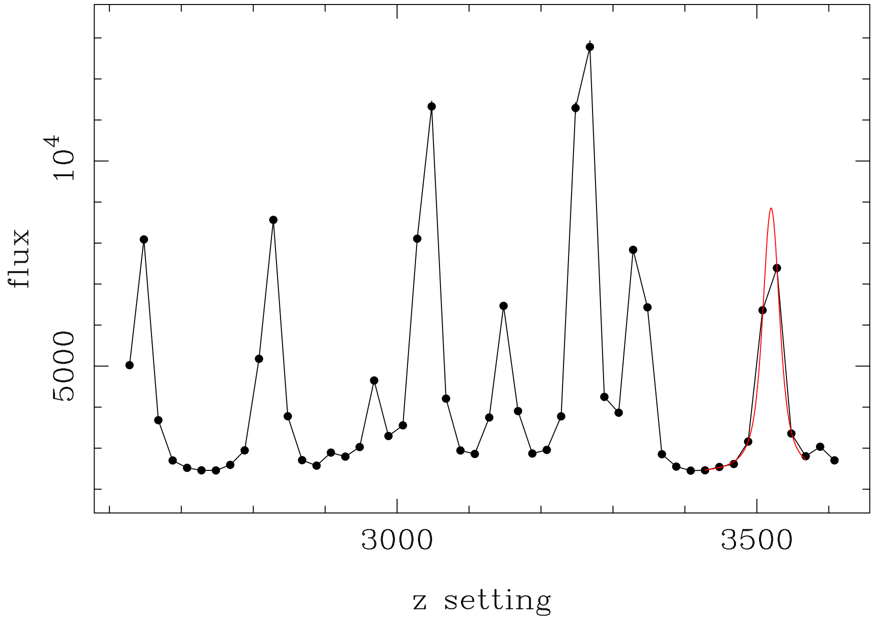

Figure 3: Spectral scan over > 1 FSR, Ne lamp
The x axis is CS-100 Z computer setting. Front panel Z was 0, 0.20. The lines are Ne 6533, 6599, 6402, 6678, 6717, 6507, 6534, 6599 in orders 26 and 27; $d\lambda/dZ = 0.36$ Å, FSR = 248 Å. The FSR is $\sim$ 690 in Z, the scan step is 20, and the FWHM is $\sim$ 27 in Z, so the steps are undersampled.

$$\lambda(r) = \lambda_0/\sqrt{1 + r^2/f^2},$$

where r is the radius and f is the camera focal length. Thus $\Delta\lambda(r) \simeq -0.5r^2/f^2$. For the IMACS f/2 camera, the fractional gradient $\Delta\lambda/\lambda$ is 0.0146 to the edge of the square CCD array and 0.0255 to the edge of the illuminated field. At $\lambda = 6600$ Å, the gradients are 96 and 168 Å.

These gradients are significantly larger than the broadest FWHM attainable, but smaller than the FSR. Because the gradient is quadratic, the center of the field is still relatively monochromatic; with FWHM of 18 Å, the radius of the monochromatic spot, where FWHM = $\Delta\lambda(r)$, is $\sim$ 1750 pixels or 350". Monochromatic imaging over a larger area will require scanning the etalon in Z. The ratio of gradient/FWHM, and the size of the gradient, mean that night sky lines will appear as rings in the images rather than diffuse background. These rings can be subtracted with software we have developed for previous Fabry-Perot instruments, and are useful to self-calibrate the wavelength of night-time images.

5 Imaging

We reconfigured the optical setup to take images that resemble Fabry-Perot imaging at the telescope with a range of beam angles. We replaced the 180mm camera lens with a 135mm f/2.8 lens to image a wider range of angles. Because the collimating telescope has a narrow field, it can only illuminate a small beam angle. We bypassed it by hanging a diffusing sheet behind the etalon and placing the neon lamp to illuminate it directly. Although the light from the diffuser is not collimated as it passes through the etalon, in principle if the camera lens is focused at infinity and well baffled, the rays striking any given pixel come from a collimated beam.

We were able to image rings and to scan the etalon through an FSR, building up a data cube. A sample image from the scan is shown in Figure 4, with two concentric rings produced by two neon

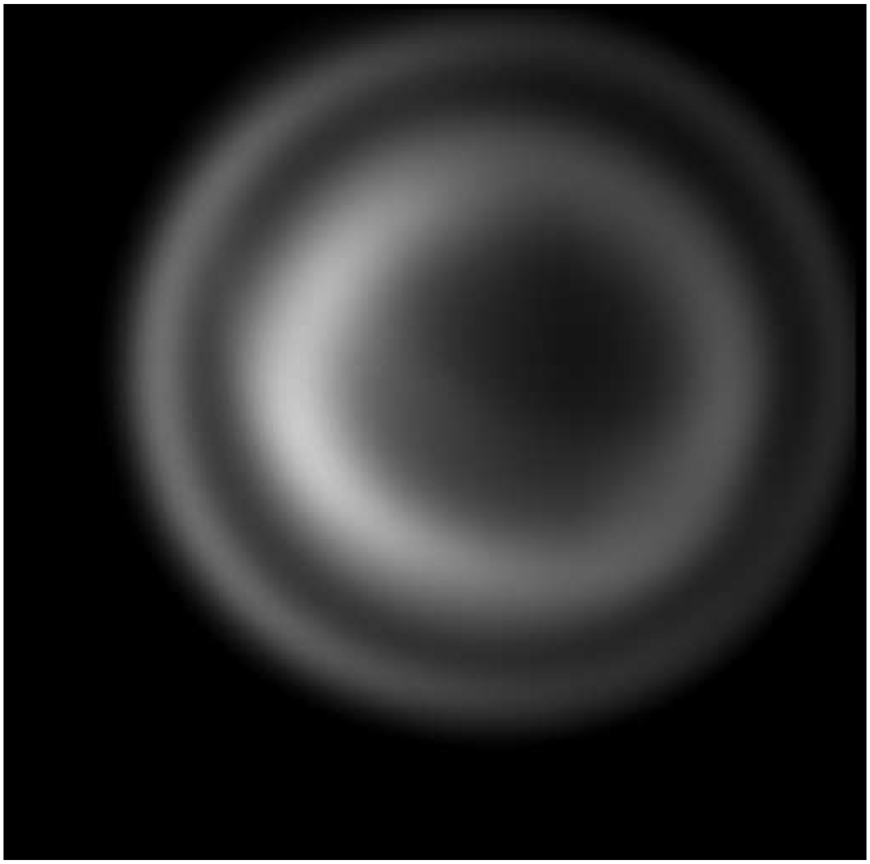

Figure 4: Neon rings in full CCD imaging mode
Rings from two neon lines, obtained by illuminating the etalon aperture diffusely so that the camera could image a wide range of beam angles. The field illumination is not even, causing the rings' asymmetric brightness.

lines. At some places in the scan, a higher order, off center ring pattern appears. This pattern is due to reflections between the narrowband filter and the etalon, which were both in the collimated beam. We verified the cause by tilting the filter and seeing the pattern move. In use in IMACS, the filter will be in the converging beam, so this type of ghost will not occur.

6 Stability

We tested the stability of the etalon and CS-100 system by measuring the position of a line, leaving the system static for some time, and re-measuring the line. The required static time usually meant the test had to be done overnight.

Results of this testing were inconclusive. The CS-100 was occasionally found out-of-range in the morning, possibly having suffered some electrical interference. (The condition is cured by switching to balance mode or by cycling the CS-100 power.) Some tests suggested that the etalon may drift by ~ 30 Z units or about one FWHM, while other tests found less drift. Experience with smaller etalons at the Las Campanas Dupont 100" has not usually found the drift to be as large as a FWHM. It is unclear if the temperature and electrical environment in the OCIW labs could affect the etalon more than at LCO.

We also observed that after stepping the etalon gap up through a full FSR and returning to the beginning of a scan, the etalon sometimes had drifted by ~ 10 Z units. This backlash-like phenomenon is not a behavior we have seen with smaller, unsealed, FP etalons that also have a smaller range of scannable gap spacing. It did not appear to always be the same amount of drift.

In principle etalon drift is a nuisance if it requires many calibrations during the night, and worse if backlash means that the calibration changes from one sausage cube to the next. In practice, the large wavelength gradient of the FP field when used in the fast IMACS beam (∼ 168 Å at 6600 Å) means that many night-time exposure should be self-calibrated in wavelength from night sky lines. This also means that the it will be easier to study and quantify drift when the etalon is in use at the telescope.

7 Interference

The long cable run required inside IMACS could lead to electrical interference which causes the etalon to be unstable or to oscillate. Ted Williams has observed severe RF interference with the etalons for SALT, apparently due to walkie-talkies (?), and had to shield the cables. We ran nearly all tests with the full 15m+3m cable length that will be used in IMACS (although the cable was mostly coiled rather than extended).

We did not have interference problems, even when a laptop with wireless card was operating on the optical bench. We did observe likely interference problems (1) with a laptop placed directly on the CS-100 controller box, and (2) with a Pen-Ray neon lamp hung directly next to the etalon. Both of these are more severe than should occur in real use, but potential interference should be minimized. Alan Bagish has put shielding on a set of cables, though installing the short (?) cable in IMACS requires significant disassembly of the instrument. Our present plan is to proceed with only the long cable shielded; the short cable may be replaced if IMACS is apart at a later date.

8 Parallelism through partial apertures

When the etalon is mounted in the IMACS disperser wheel, it will be difficult or impossible to parallelize it by eye as we did on the mercury lightbox. Because the cables are permanently mounted inside IMACS, we will not be able to test parallelism with the same set of cables outside the instrument, as we did for the Fabry-Perot at the Dupont 100".

The method at the AAT with the TTF is to use pupil masks to mask off all but one quadrant of the etalon in turn. When the etalon is out of parallel, one side will be at higher gap than the other at a given Z. The observer takes sausage cubes across a spectral line, notes the position in Z of the line, and adjusts the X or Y setting until the line is at the same position for opposing quadrants. Because IMACS does not have a pupil mask wheel, this procedure will have to be done at the beginning of the run with a manually installed rotating pupil mask, that is removed for actual observations.

We simulated pupil masking by shifting the camera and lens in X and Y to image through different parts of the etalon. In one set of tests, we set the etalon to by-eye parallelism values of X= -1, 6.09, Y= 0, 6.76, , with Z=+3, 0.20 (relatively high resolution). We then experimented with tuning the etalon off the nominal X value, and taking short scans across an spectral line, with the camera shifted to left and right sides of the etalon. We fit a Voigt profile to each scan to measure the location and width of the line. The results are summarized below. The values are Z computer units in displacement from Z=2168. The scan step between images was 10 Z units.

X fine	left		right	
	peak	sigma	peak	sigma
5.69	75.5	11.4	48.7	9.8
5.89	76.1	9.7	65.7	9.7
6.09	76.4	9.3	83.1	10.7
6.29	73.1	11.4	99.6	10.3

Requiring that the line center be at the same Z for left and right sides of the etalon is a sensitive test of fairly fine adjustments of X. Attempting to minimize the line width as seen through one side or the other is more ambiguous. Adjusting X appears to move the line in the right side more than the left. Possibly the latter two effects are related to the non-flatness of the coating (the gap is smaller at the edge of the aperture). A similar test in Y yielded these results:

Y fine	down		up	
	center	sigma	center	sigma
6.56	11.27	1.10	8.77	1.02
6.76	8.24	0.99	7.75	0.92
6.96	5.36	1.00	6.64	0.94

Like the X behavior, adjusting Y moves one side more than the other. These tests were carried out with the etalon mounted vertically, cables entering from above, and the "top" side of the etalon facing the CCD camera (mounting plate away from CCD camera). The Y-axis is along the direction of cable entry.

9 Effect of different cable sets

After dismantling the optical bench we tested the effect of using different length cables between CS-100 and etalon, balancing the etalon and using the mercury lightbox to parallelize it. For each cable in turn, we balanced the etalon, iterating nulling balance and quadrature error as prescribed in the manual. We then switched to operate mode and parallelized the etalon by adjusting X and Y, and re-nulled the quadrature balances wile in operate mode.

We first used the 15m plus 3m cables and passthrough connector, the set that will be used at the telescope, and recorded the following values:

15m + 3m + passthrough cables

	balance			parallelized			renulled QB
X	-1	4.13	6.39	-1	5.55	6.39	6.35
Y	0	1.16	7.53	0	6.59	7.53	7.45
Z	0	5.90	8.60	0	1.52	8.60	8.64

Note that the X and Y values for parallelism are those necessary to parallelize the plates, but the Z value is arbitrary - it is whatever Z value allowed us to see the ring we used to judge parallelism. Quadrature balance does not change from the first step to the second. In the third step of re-nulling quadrature balances, only the QB dial changes, XYZ coarse and fine are unchanged.

With just the 15m cable we recorded the following values:

15m cable

	balance			parallelized			renulled QB
X	-1	4.79	5.56	-1	6.19	5.56	5.53
Y	0	2.08	6.26	0	6.99	6.26	6.17
Z	0	5.93	6.76	0	4.09	6.76	6.83

With just the 3m cable we recorded the following values:

3m cable

	balance			parallelized			renulled QB
X	-1	5.73	4.03	-1	7.13	4.03	3.99
Y	0	2.32	4.06	0	7.24	4.06	3.92
Z	0	5.43	4.03	0	3.61	4.03	4.07

Comparing the values across different cable lengths shows that the XYZ values in the balance state and the XY values in the parallelized state vary systematically with cable length, but the amount of variation is not very large. The quadrature balance increases systematically with cable length, and the amount of increase is relatively large, compared to the total range of adjustment. This is somewhat understandable because the X and Y coarse/fine are controlling the drive high voltage, while the quadratures are adjusting the sensing circuit, which could be affected by the capacitance/inductance of the cable.

An interesting effect is that the X and Y values for balance and parallelism appear to change together. The offset of parallelism from the balance position is relatively constant. Extracting the relevant numbers from the tables above, for the XY fine dials:

		15m+3m	15m	3m
balance	X	4.13	4.79	5.73
	Y	1.16	2.08	2.32
paralellism	X	5.55	6.19	7.13
	Y	6.59	6.99	7.24
par-bal	X	1.42	1.40	1.60
	Y	5.43	4.91	4.92

Apart from one oddball (Y with the 15m+3m cables), the offset of parallelism from the balance position is roughly constant. This may reflect (speculatively) that the etalon is balanced in its "resting" state, taking out cable effects, and then the offset from resting state to parallel is always about the same.

This regularity may prove useful in operation with the etalon inside IMACS. The etalon is balanced just by looking at the CS-100 front panel, but parallelizing involves taking sausage cubes and iterating adjustments to the X and Y settings. Applying the parallelism-balance offset should get the etalon close to parallel and speed up the iterating procedure.

10 Miscellaneous

The CS-100 can be knocked out of range by static discharges. We should buy several grounding straps to be used when adjusting the CS-100 and etalon during the balancing and parallelizing process at the beginning of a run.

The hydrogen lamp was essential for initial line identification. Now that we know the approximate FSR and $d\lambda/dZ$ over the operating range of Z, this is less of a problem, but it may recur when we move to new wavelength ranges. It is a good idea to have multiple lamps available at the telescope. Even if not actually mounted on the telescope they can be used by pointing toward the flat screen, since uniformity of illumination is not critical.

For commissioning and beginning of the run calibrations, a slit mask with off center pinholes for finding the optical center, and a manual rotating pupil mask are needed. A scratch design for the pupil mask was suggested and Tyson Hare is in charge of further work on it.

11 Summary: findings, open issues

The MMTF etalon and CS-100 controller have been verified to work with the cable setup that will be used at the telescope. Computer control of the CS-100 works well, from the simple control program and from Christoph Birk's IMACS software.

The range of gaps accessible is measured; and the behavior of the FSR and FWHM at 6600 Å over gap spacing is measured and behaves as expected. Measurements at other wavelengths than 6600 A will have to be done separately; we could do predictions from some of the ICOS measurements of the coating and effective gap spacing (which varies with wavelength due to coating depth effects).

It is necessary to keep in mind re-nulling the quadrature balances while operating. This is mostly necessary to make large changes in the Z setting and to insure stability. We should only have to do this at the beginning of a run, unless there are big changes in Z, like using different resolutions. Observers should probably be discouraged from trying to change the resolution in the middle of the night (unlikely to be a pressing scientific need for this anyway).

The zeropoint drift and hysteresis after scanning over large ranges in Z are unresolved, and should be separable and better testable at the telescope. Observations can be self calibrated if there are night sky lines in the region of interest (which should be true redward of 6500 A at least).

The parallelism values are steady over a wide range of spacings and stable in time.

Parallelizing with pupil masking should work well. It is probable that we can predict the parallelism position well enough to start off close, by applying an offset to the balance position read off the front panel. In prior experience with ICOS etalons, the parallelism position does not vary much from run to run as long as the same etalon, controller and cable are used.

12 activities for commissioning

A detailed list and schedule for commissioning activities is shown separately in the MMTF pre-ship review presentation.

Acknowledgments

Many people contributed to assembling the necessary materials for MMTF testing and dealing with problems that arose during testing. We are especially thankful for the help of Alan Uomoto, Tyson Hare, Patrick Shopbell, Christoph Birk, Robert Storts, Alan Bagish, and the rest of the OCIW staff. We are grateful to Caltech for lending the Celestron 8" telescope and to the Palomar staff and Patrick Shopbell for locating and lending a hydrogen lamp on short notice.

Appendixes

Linelists (in air):
Ne I: 6402?, 6506.529, 6532.882, 6598.953, 6652.093 (very weak), 6678.276, 6717.043
Hydrogen: 6562.799
A very useful site for wavelengths is `http://www.pa.uky.edu/~peter/atomic/`

Table of fsr, dw/dz etc as measured at various Z settings, at 6600 Å:

Zcoarse	Zfine	$d\lambda/dZ$, Å	FSR, Å	FWHM, Å	order
–3	3.00	0.536	375	18.0	17.6
–2	0.20	0.469	325	15.0	20.3
–1	0.20	0.413	285	13.0	23.2
0	0.20	0.361	248	9.7	26.6
1	0.20	0.330	226	8.9	28.9
2	0.20	0.294	202	9.0	32.7
3	0.20	0.268	185	7.9	35.7
4	0.20	0.251	173	6.7	38.2
4	9.99	0.236	163	5.9	40.5

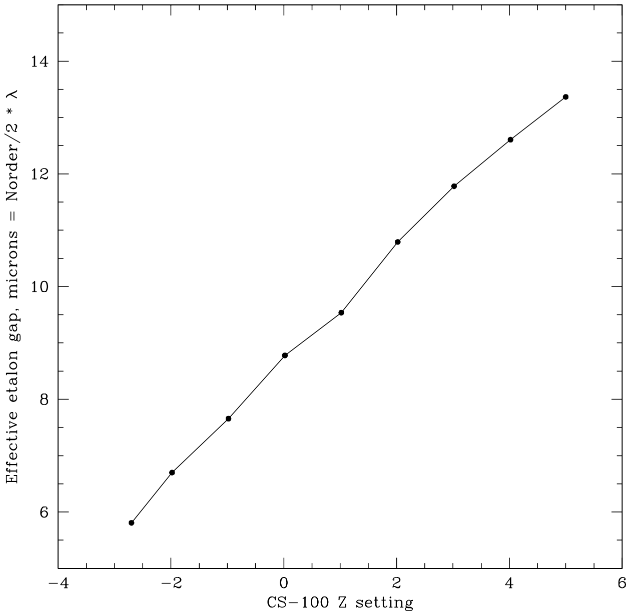

Figure 5: Effective etalon gap d as a function of CS-100 setting Z, at 6600 A

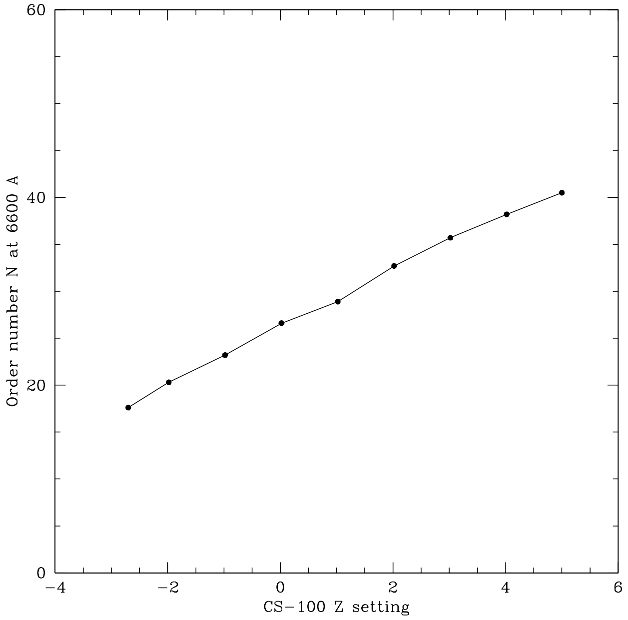

Figure 6: Order N as a function of CS-100 setting Z, at 6600 A

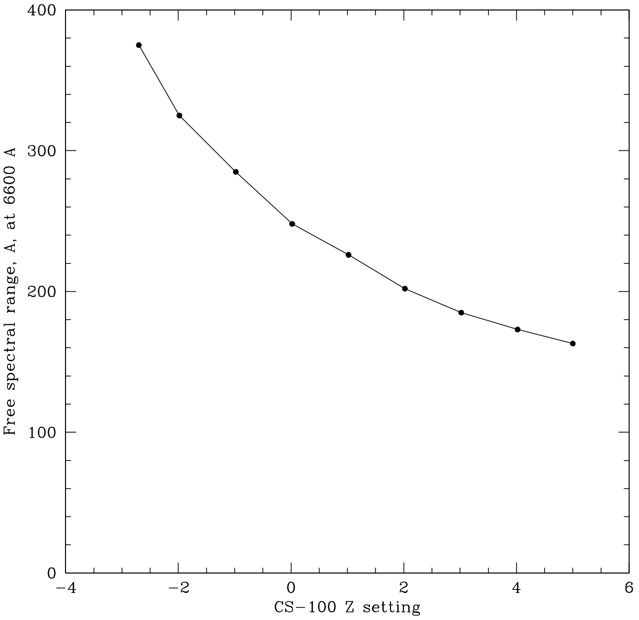

Figure 7: Free spectral range (FSR) as a function of CS-100 setting Z, at 6600 A

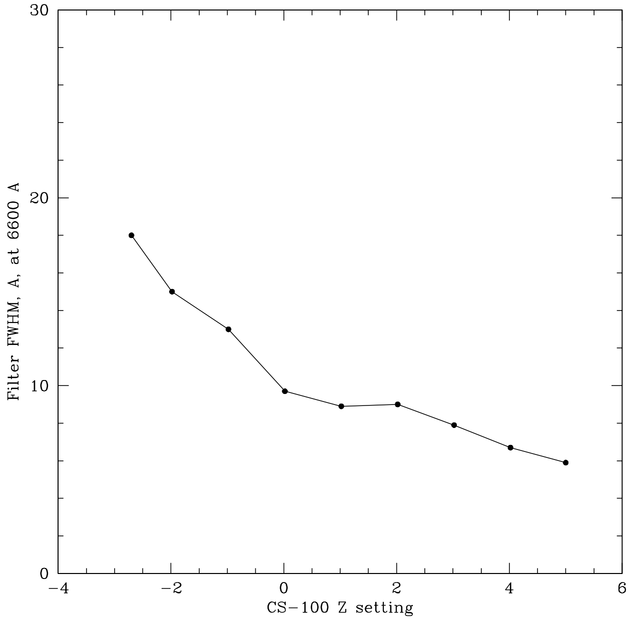

Figure 8: Bandpass width (FWHM) as a function of CS-100 setting Z, at 6600 A

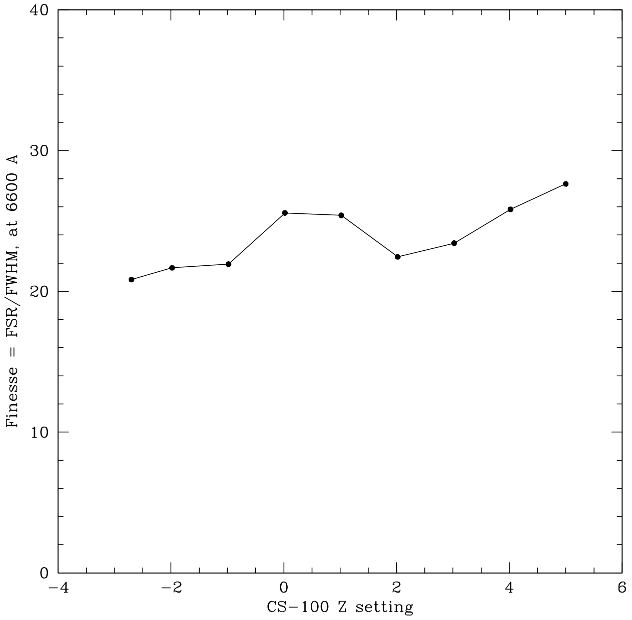

Figure 9: Finesse (FSR/FWHM) as a function of CS-100 setting Z, at 6600 A

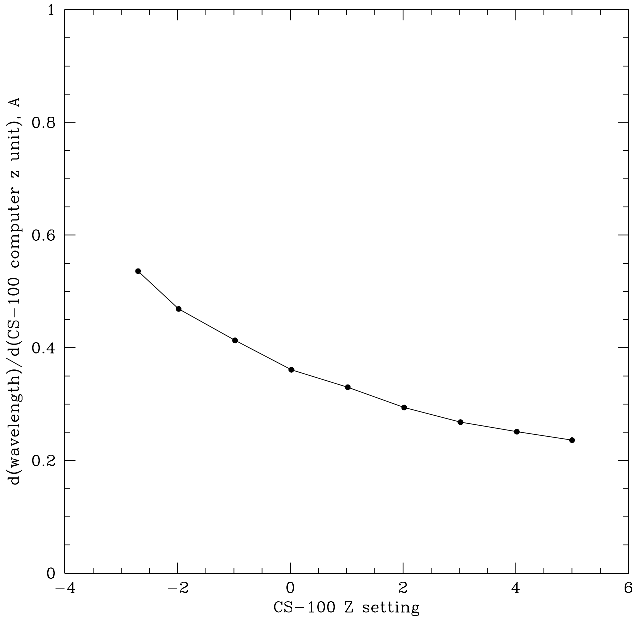

Figure 10: $d\lambda/dZ$ as a function of CS-100 setting Z, at 6600 A

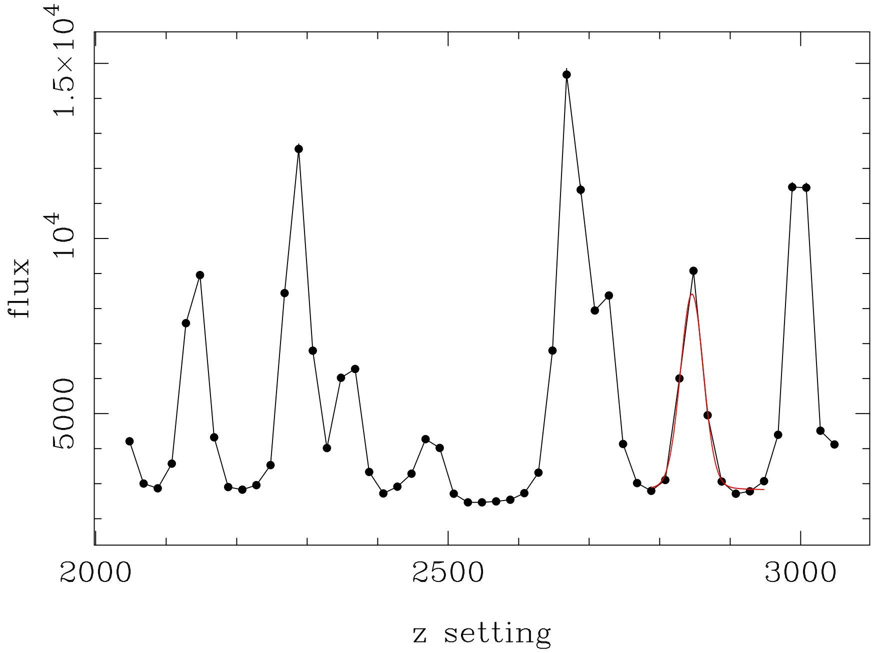

Figure 11: Spectral scan over > 1 FSR, Ne lamp

The x axis is CS-100 Z computer setting. Front panel Z was –3, 3.00. The lines are Ne 6599, 6678, 6717, 6402, 6507, 6533, 6599, 6678.

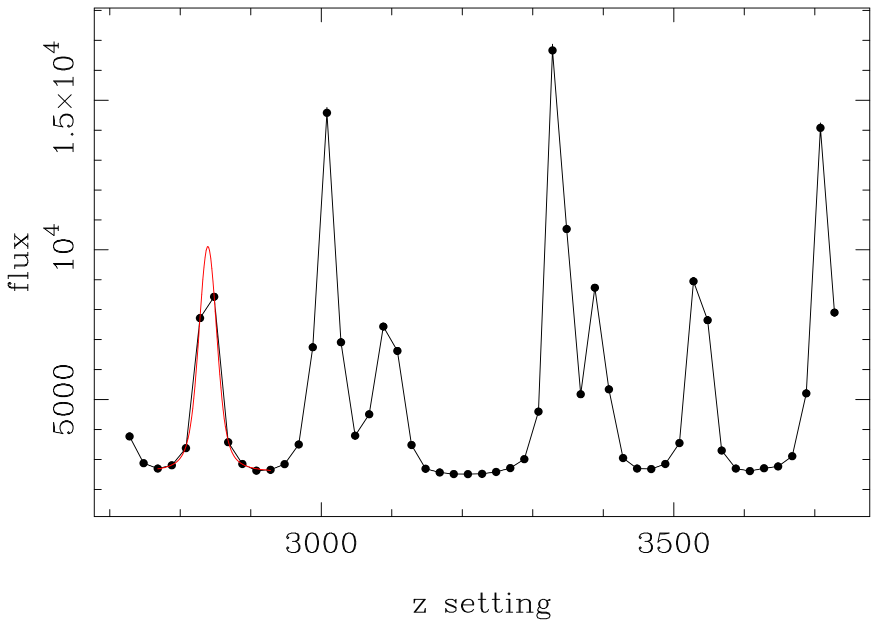

Figure 12: Spectral scan over > 1 FSR, Ne lamp
The x axis is CS-100 Z computer setting. Front panel Z was –2, 0.20. The lines are Ne 6599, 6678, 6717, 6507, 6533, 6599, 6678.

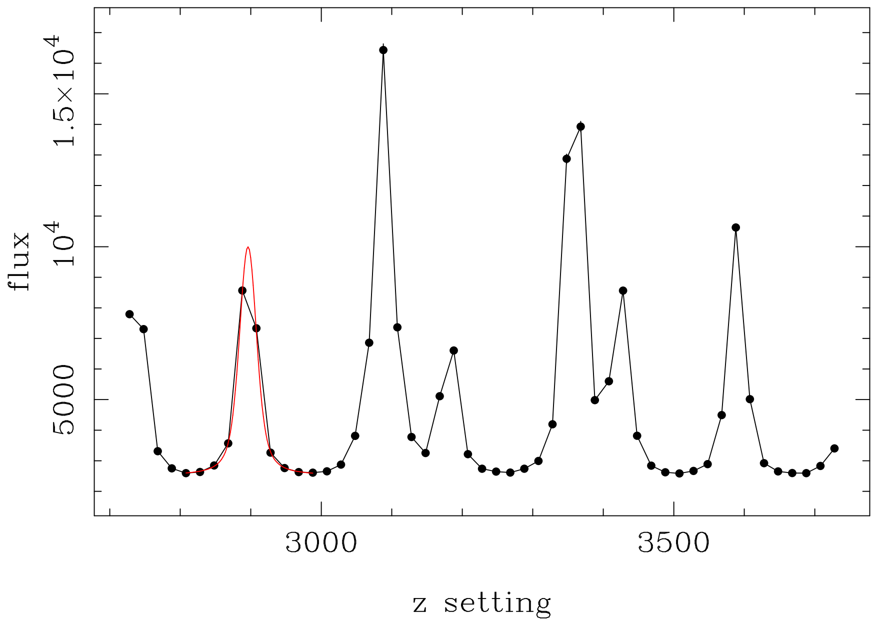

Figure 13: Spectral scan over > 1 FSR, Ne lamp
The x axis is CS-100 Z computer setting. Front panel Z was –1, 0.20. The lines are Ne 6599, 6678, 6717, 6507, 6533, 6599.

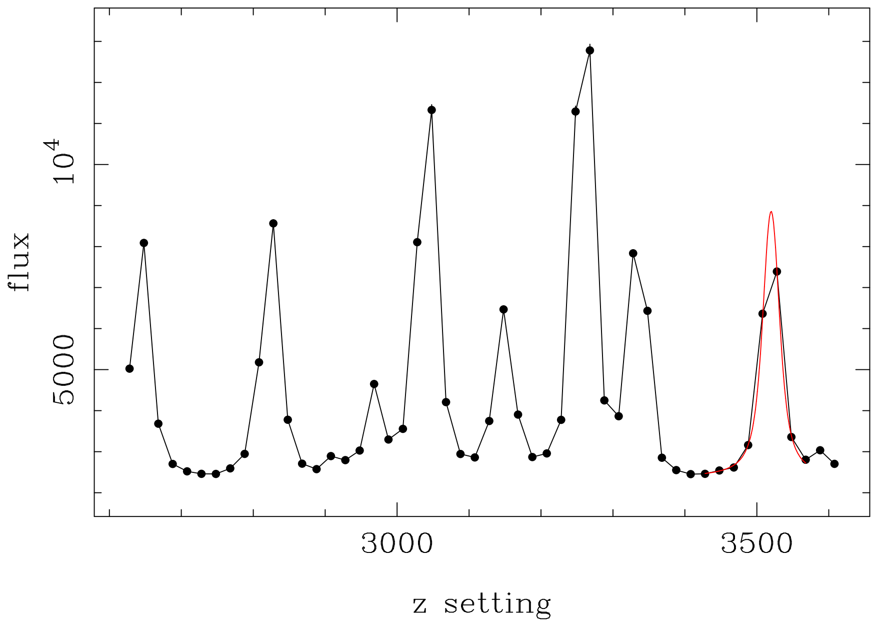

Figure 14: Spectral scan over > 1 FSR, Ne lamp
The x axis is CS-100 Z computer setting. Front panel Z was +0, 0.20. The lines are Ne 6533, 6599, 6402, 6678, 6717, 6507, 6533, 6599.

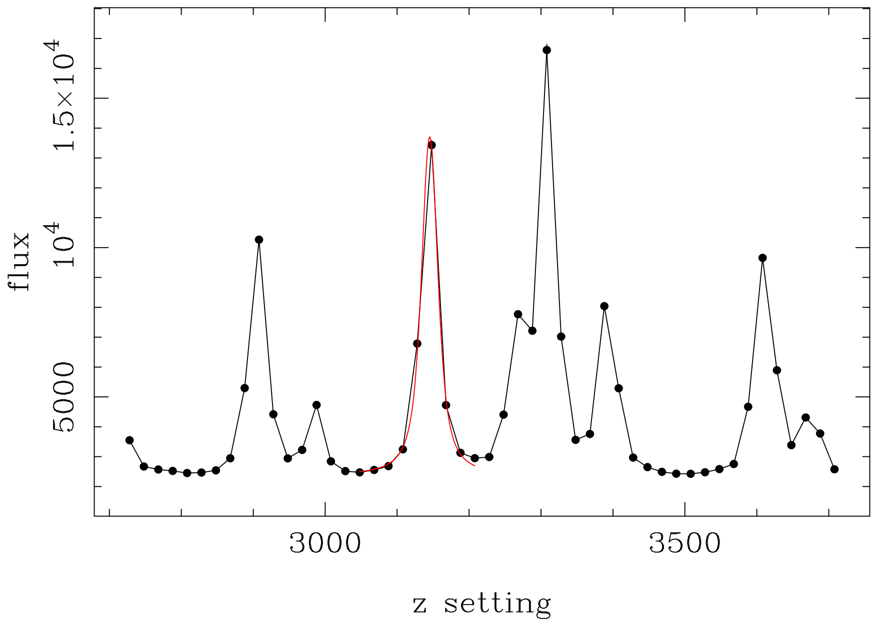

Figure 15: Spectral scan over > 1 FSR, Ne lamp
The x axis is CS-100 Z computer setting. Front panel Z was +1, 0.20. The lines are Ne 6599, 6402, 6678, 6717, 6507, 6533, 6599, 6402.

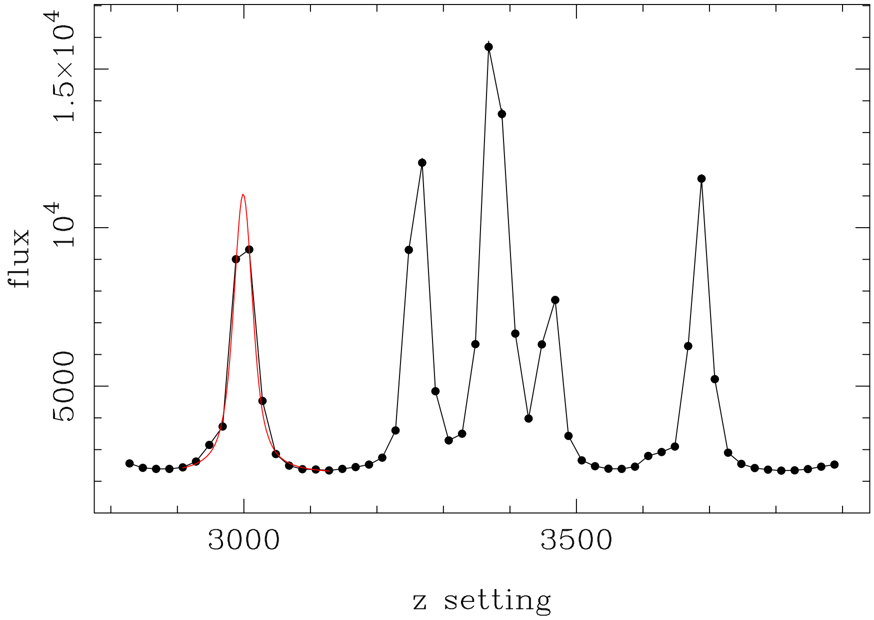

Figure 16: Spectral scan over > 1 FSR, Ne lamp
The x axis is CS-100 Z computer setting. Front panel Z was +2, 0.20. The lines are Ne 6599, 6678, 6717+6507, 6533, 6599.

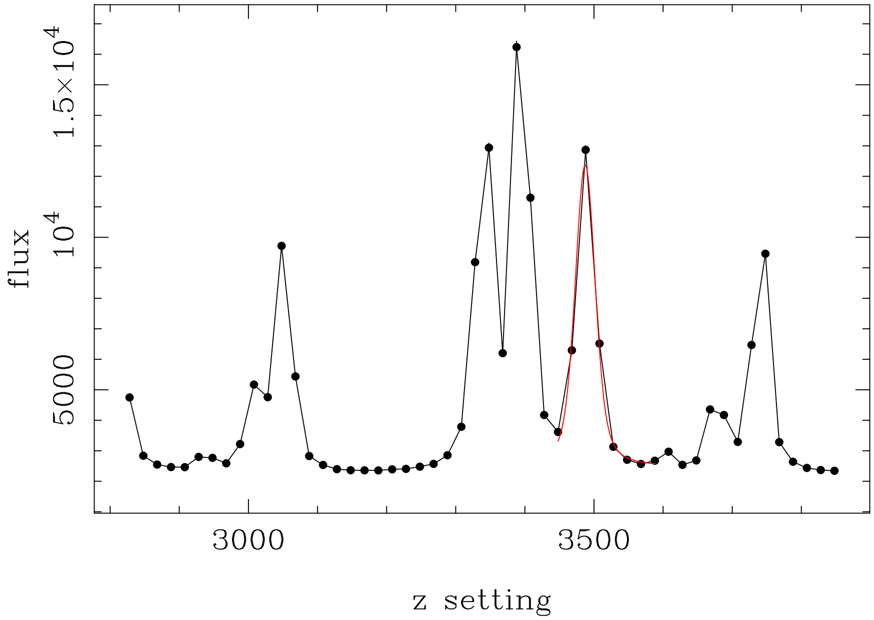

Figure 17: Spectral scan over > 1 FSR, Ne lamp
The x axis is CS-100 Z computer setting. Front panel Z was +3, 0.20. The lines are Ne 6402, 6599, 6678, 6507, 6533+6717, 6402, 6599.

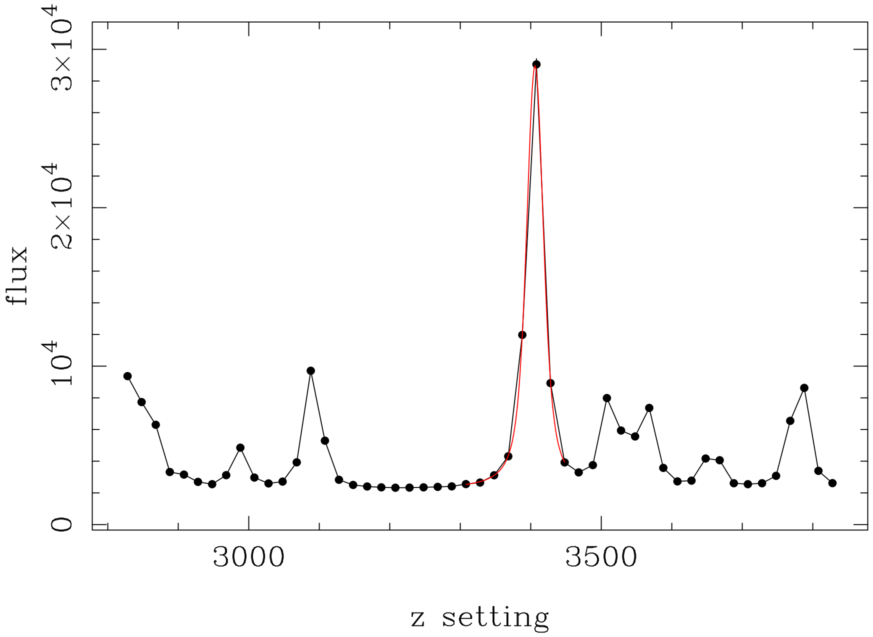

Figure 18: Spectral scan over > 1 FSR, Ne lamp

The x axis is CS-100 Z computer setting. Front panel Z was +3, 9.99. The lines are Ne 6402, 6599, 6678+6507, 6533, 6717, 6402, 6599.