CanHiS User Manual

Version 2.1

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Contents

Chapter 1

Introduction

The Cananea High-Resolution Spectrograph —CanHiS, is a $f/13.5$, “R3.2” very high spectral resolution echelle spectrograph ($\mathcal{R} \approx 85\,000 - 185\,000$), with adjustable quasi-Littrow mounting. It uses medium-band interference filters to isolate individual dispersion orders. Not having a cross disperser, CanHiS is therefore a very high efficiency instrument (≈ 36% according to Hunten et al., 1991).

Table 1.1 summarizes the principal opto-mechanical characteristics of CanHiS, attached to the 2.1-m Telescope of the OAGH.

Table 1.1: CanHiS Performance Specifications

Entrance aperture (at 2.1 m – $f/12$ Cananea Telescope)	
Maximum (slit width ≈ 50 μm)	0″.410
Minimum (slit width ≈ 25 μm)	0″.205
Spatial resolution (at 2.1 m – $f/12$ Cananea Telescope)	
Maximum (slit length ≈ 4.62 mm)	37″.8
Minimum (slit length ≈ 2.81mm)	23″.0
Resolution $\delta\lambda$	
Maximum (at minimum slit width)	≈ 0.03 Å
Minimum (at maximum slit width)	≈ 0.08 Å
Power resolution $\mathcal{R} = \lambda_c/\delta\lambda$	
Maximum	≈ 185 000
Minimum	≈ 85 000
Typical wavelength range $\Delta\lambda$	≈ 50 Å (near to 4 500 Å) ≈ 90 Å (near to 6 300 Å) ≈ 140 Å (near to 7 800 Å)
Limiting magnitude m_v (at $\delta\lambda \approx 0.200$ Å, and $\lambda_c \approx 6\,707$ Å)	≈ 10.2 mag

Chapter 2

The instrument

Figure 2.1 shows a general opto-mechanical layout of CanHiS, located into a x, y, z coordinate system. The main rectangular box of the spectrograph is divided into two chambers: a small upper compartment, containing a box with guiding optics and comparison sources, and a lower and principal compartment, containing the spectrograph optics, separated between them by a shelf. The total size of the spectrograph box is $8.50 \times 47.9 \times 25.0$ inches, in the x, y, z axes, respectively. Figure 2.2 shows an isometric opto-mechanical modelling of the instrument.

2.1 The optics

2.1.1 Comparison and flat field lamps

CanHiS uses an internal Uranium-Neon hollow-cathode discharge lamp (Fig. 2.3a) for high-resolution wavelength calibration, and an “external” halogen lamp (Fig. 2.3b), placed at the spectrograph rear side, for flat fields response detector correction. Both lamps are situated in the upper compartment containing the guiding optics. A pair of motors, attached to the righ side of the spectrograph (the x-z side, Fig. 2.4a), control both the selection of the pencil-beam light from the telescope or the light from lamps, as well as the type of lamp to use: either the internal UNe lamp or the external halogen lamp. The two motors are remotely controlled through the general software control (Fig. 2.4b).

2.1.2 The guiding optics

For the time being CanHiS only has one single method to help guiding and verify the placement of the target object at the entrance slit. An external camera (Fig. 2.5b) used as an ocular microscope situated at the entrance slit observation point (Fig. 2.5a), on the front of the instrument (the y - z side), allows to check, on a monitor at the control room, if the target is centered at the entrance slit, at the same time that it provides a

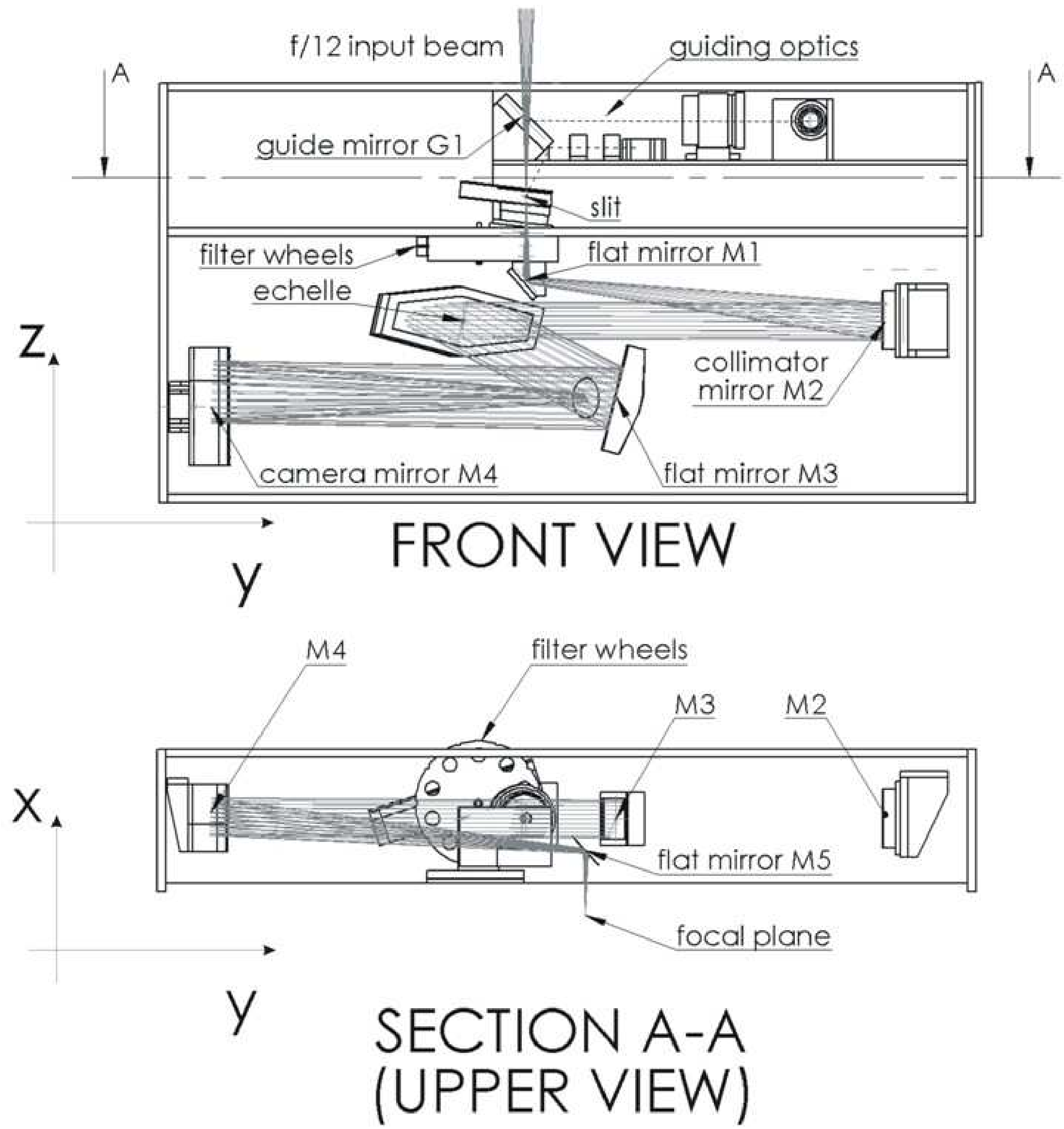


Figure 2.1: CanHiS optical sketch and mechanical layout

way to help the guiding.

2.1.3 The spectrograph

The spectrograph optics consists of the following relevant elements: (a) the configurable entrance slit; (b) a set of interchangeable interference filters for isolating individual dispersion orders (instead of a cross disperser system); (c) the adjustable quasi-Littrow mounting echelle grating attached to the M_3 mirror; and (d) the detector, by the time a 2k×2k EE2V 42-40 CCD, with 15 μm pixels.

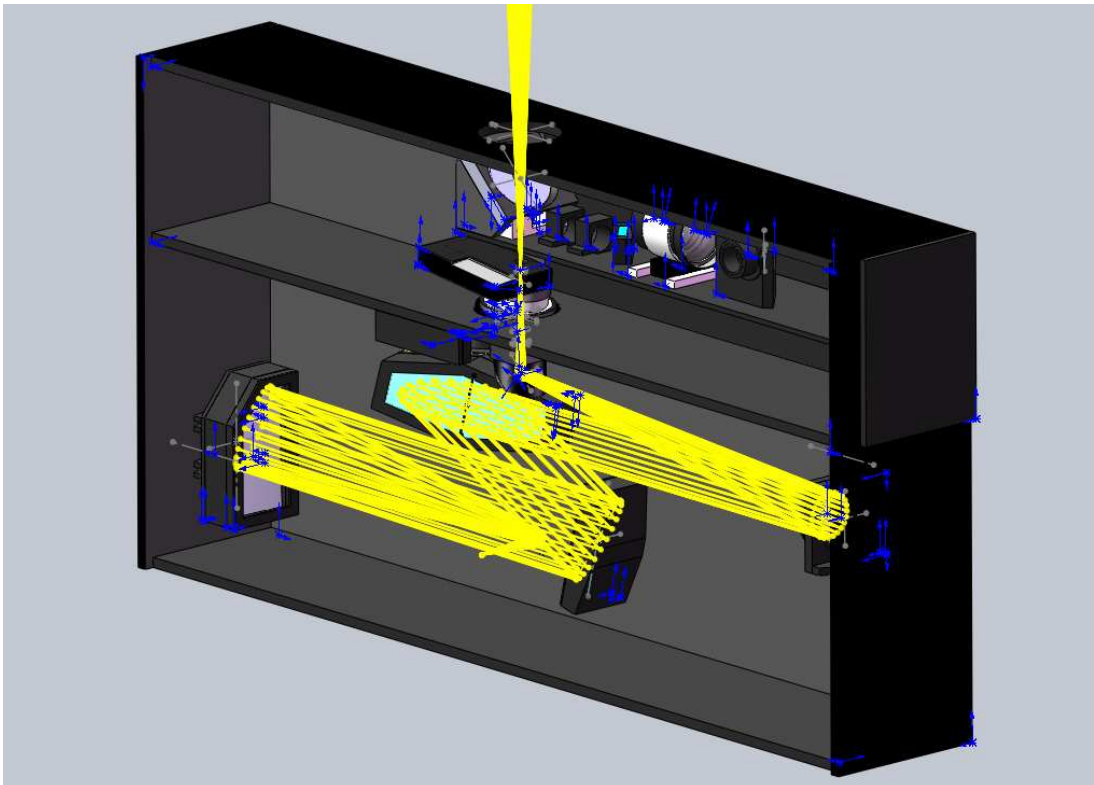
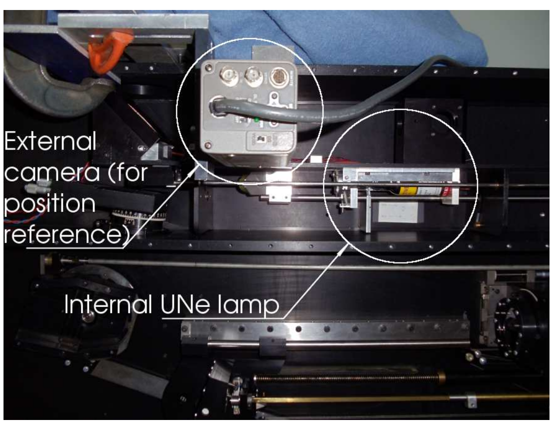


Figure 2.2: Opto-mechanical simulation of CanHiS.



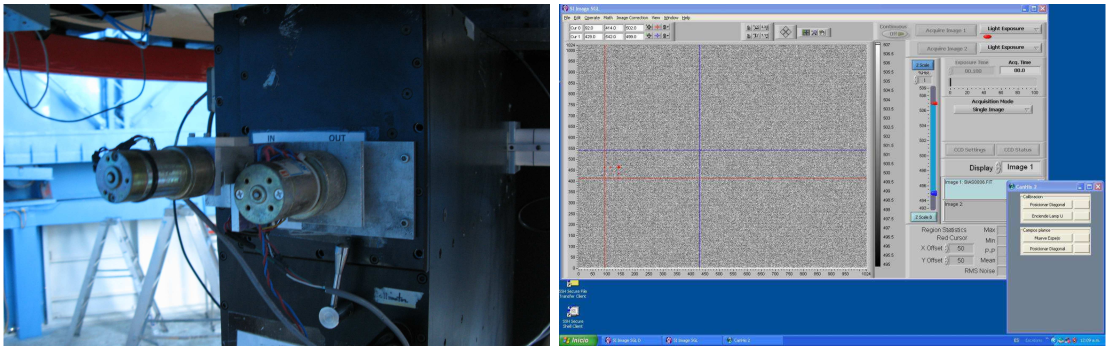
(a)

(b)

Figure 2.3: a) Internal Uranium-Neon hollow-cathode discharge lamp, inside the upper compartment; and b) “External” halogen lamp, at the spectrograph rear side.

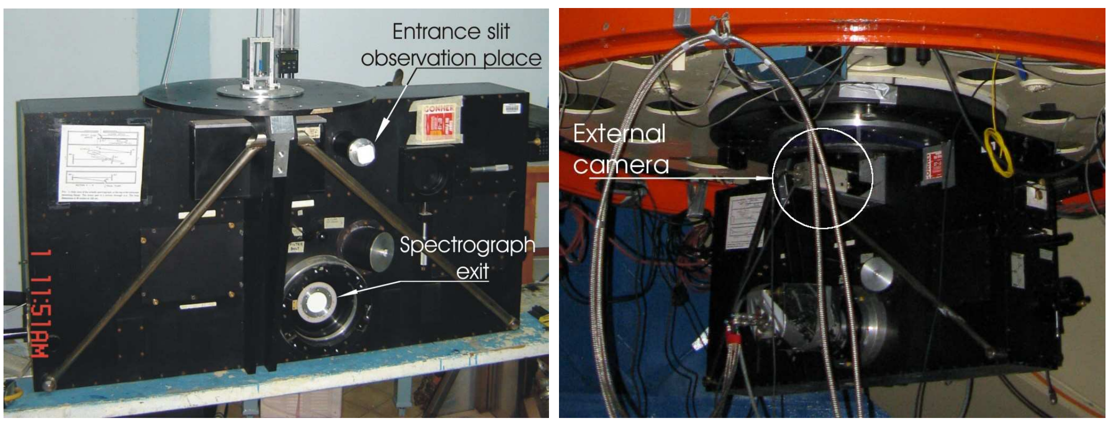
2.1.3.1 The configurable entrance slit

The entrance slit is placed into a special box which provides four independent degrees of freedom to set: a) the slit width (from less than 25 to ≈ 50 μm); b) the slit length (from ≈ 2.81 to 4.62 mm); c) the slit position over the observation plane, into a square spatial



(a) (b)

Figure 2.4: a) Engines for selecting either the light from the telescope or the light from calibration lamps, as well as the type of lamp to use; b) Screenshot of the current E2V CCD control and imaging software and the control software for the calibration lamps.



(a) (b)

Figure 2.5: a) External spectrograph entrance slit observation point; b) Current external camera, at the external spectrograph entrance slit observation point, used to check from the control room the target object positioning.

range of ≈ 1.81 mm by side; and d) the slit rotation with respect to the grooves of the echelle grating. The slit width, length, and position are handled by three independent micrometers, while the slit rotation is set through a screw and a calibrate dial at the box base. Figure 2.6 shows each one of the aforementioned elements.

Table 2.1 gives the slit length and the slit position as a function of the corresponding micrometer scale, and a approximate value for the slit width. For this last value, fine tuning needs to be experimentally determined because the corresponding micrometer is affected by mechanical worn-out.

Figure 2.6: Micrometers used to set the slit length, position and width. The screw allows to set the rotation angle.

Table 2.1: Numerical matching between micrometers scales and slit width, slit lenght and slit position. For the slit position, micrometer value of 0.″300 is established as the zero-point value (0.00 mm) over the observation plane (the center of the CCD at the spatial direction), keeping the dispersion axis of the spectrum parallel to one side of the CCD and the spatial axis perpendicular. If dispersion axis is inverted and horizontal in the CCD, the minus sign represents slit upwards displacements respect the dispersion axis; if vertical, it represents displacements to the left.

micrometer	slit width		slit length		slit position	
scale [inches]	[μm]	[arc-seconds]	[mm]	[arc-seconds]	[mm]	[arc-seconds]
0.075	—	—	4.62	37.79	—	—
0.100	—	—	4.20	34.37	−1.20	−9.83
0.125	—	—	3.78	30.94	—	—
0.150	—	—	3.38	27.62	—	—
0.175	—	—	2.94	24.09	—	—
0.200	—	—	2.54	20.77	−0.59	−4.86
0.225	—	—	2.11	17.24	—	—
0.250	—	—	1.63	13.37	—	—
0.275	—	—	1.22	09.94	—	—
0.300	—	—	1.05	08.62	0.00	0.00
0.325	—	—	—	—	—	—
0.350	—	—	0.73	05.97	—	—
0.375	—	—	—	—	—	—
0.380	50.76	0.42	—	—	—	—
0.385	—	—	—	—	—	—
0.390	—	—	—	—	—	—
>0.395	21.70	0.18	—	—	—	—
0.400	—	—	—		+ 0.61	+ 4.97

2.1.3.2 The transmission filters set

The filters set is formed by a pair of hand-movable concentric filter wheels containing fifteen medium-band interference transmission filters for isolating individual dispersion orders, two transparent windows (one in each filter-wheel), and three dimmers. The desired filter is selected by chosing the corresponding label attached to the edge of each wheel, through a small section of the wheels that protrudes on the spectrograph rear side (parallel to y-z plane, Fig. 2.7). Table 2.2 lists the central wavelengths for each filter, and shows the order in which they are placed in the wheels.

Figure 2.7: Filter wheels window at the rear side of the spectrograph used for selecting the desired interference filter.

Table 2.2: List of filters mounted on the wheels, and its corresponding central wavelength and measured FWHM.

Upper Wheel	Central lambda	FWHM	Lower Wheel	Central lambda	FWHM
A	CLEAR	—	**0**	CLEAR	—
B	4086 Å	Å	**1**	ND 1	—
C	6723 Å	Å	**2**	ND 2	—
D	5890 Å	Å	**3**	ND 3	—
E	6306 Å	Å	**4**	4227 Å	Å
F	5007 Å	Å	**5**	4589 Å	Å
G	3725 Å	Å	**6**	7325 Å	Å
H	7682 Å	Å	**7**	6563 Å	Å
J	8151 Å	Å	**8**	8047 Å	Å
K	8273 Å	Å	**9**	10970 Å	—

Appendix A depicts the normalized response for 14 filters, from 3 725 to 8 273 Å. Only the 10 970 Å filter at the near-infrared region is not characterized. The response of the transparent windows, made in BK7 glass to give clearance to the light at the filter wheel which is not in use (named as CLEAR and labeled as **A** and **0** in Table 2.2), are also shown, as well as the response of the dimmers named ND1, ND2 and ND3 (labeled **1, 2, 3**), which attenuate the light to 10.0 %, 1.0 % and 0.1 %, respectively.

Table 2.3 displays the normalized transmission and the FWHM for the filters, obtained through a simple Gaussian fit.

Table 2.3: List of filters mounted on the wheels

Central lambda	Normalized transmission	Central lambda fit	FWHM
3 725 Å	1.0 %	3 755.1 Å	52.4 Å
4 086 Å	35.3 %	4 071.0 Å	38.6 Å
4 227 Å	37.9 %	4 217.1 Å	41.5 Å
4 589 Å	63.8 %	4 582.0 Å	50.5 Å
5 007 Å	69.9 %	4 989.6 Å	59.9 Å
5 890 Å	> 90 %	5 881.0 Å	73.5 Å
6 306 Å	> 90 %	6 297.7 Å	83.8 Å
6 563 Å	> 90 %	6 548.4 Å	90.2 Å
6 723 Å	> 90 %	6 706.9 Å	110.1 Å
7 325 Å	> 90 %	7 303.0 Å	123.7 Å
7 682 Å	> 90 %	7 669.5 Å	122.7 Å
8 047 Å	> 90 %	8 033.4 Å	149.4 Å
8 151 Å	> 90 %	8 158.3 Å	151.5 Å
8 273 Å	> 90 %	8 254.9 Å	158.0 Å

2.1.3.3 The quasi-Littrow mounting Echelle grating

The CanHiS configuration is based on the *quasi-Littrow mounting* (QLM), one of the three possible Echelle spectrograph designs referred to the orientation of the incident light beam with respect the grating echelle normal, in which the so-called off-axis angle γ is not equal to zero, and has a direct effect on the blaze function, the efficiency of the grating and the inclination of the projected slit on the detector (Schroeder & Hilliard, 1980).

Echelle grating is ruled at 79.01 l mm^{-1} with a blaze angle δ of 72°.5 ("R3.2"; tan $\delta = 3.2$). The suitable opto-mechanical arrangement allows to adjust with high-precision the off-axis angle γ between 8° and 18°, while at the same time the mirror M_3 rotates and moves to follow the central diffracted wavelength, ensuring that this wavelength will be diffracted at the peak of the blaze function and then sent to the camera mirror M_4 and the detector. A high-precision external crank, placed at the right side of the spectrograph box, controls γ (from 8° to 18°) correlating its angular value with a numerical code between 0000 and 7298 (Fig. 2.8).

Figure 2.8: Crank that correlates the angular value of γ with a numerical code.

At the centre of the slit, $\gamma = \gamma_0$ and central wavelength diffracted is (Hunten et al., 1991, Eq. 2.1):

$$\lambda_0 = \frac{2\sigma \ \sin \ \beta}{m} \cos \ \gamma_0 \ , \tag{2.1}$$

where $\sigma = 79.01^{-1}$ mm, β is equal to the echelle blaze angle δ of $72\overset{\circ}{.}5$, and m is the best-suited dispersion order for the central wavelength selected. Appendix B presents a table correlating the numerical code provided by the crank, the central wavelength displayed and the best-suited order. As is evident from the Table **??**, γ values between 8° to 18° had been chosen in order to cover the whole spectral range.

Diffracted spectral lines suffer an undesirable tilt angle χ, due to the aforementioned inclination of the projected slit on the detector (Hunten et al., 1991, expressed as $\tan\chi = 2\tan\delta\sin\gamma$). This slant can be prevented by rotating the slit in a suitable position, using the relation between the central wavelength to observe and the graduation of the dial at the slit box base (Table 2.4).

Table 2.4: Numerical matching between dial value and the central wavelength of the filters.

central wavelength	dial scale
4086 Å	
4227 Å	
4589 Å	
5007 Å	
5890 Å	215.5
6306 Å	211.5
6563 Å	217.5
6723 Å	214.5
7325 Å	
7682 Å	

Chapter 3

Observation tutorial

The following procedure describes how to carry out an observational run with CanHiS. As an example, we will obtain a spectrum at the highest resolution ($\mathcal{R} \approx 140\,000$, with the slit as narrow as possible) attainable with a pixel size of 20 μm (square), which is the size of the pixel of the VersArray CCD (That was used for the instrument commissioning and first light), using the filter named **C**, nominally centered at 6 723 Å.

3.1 Comparison lamp image

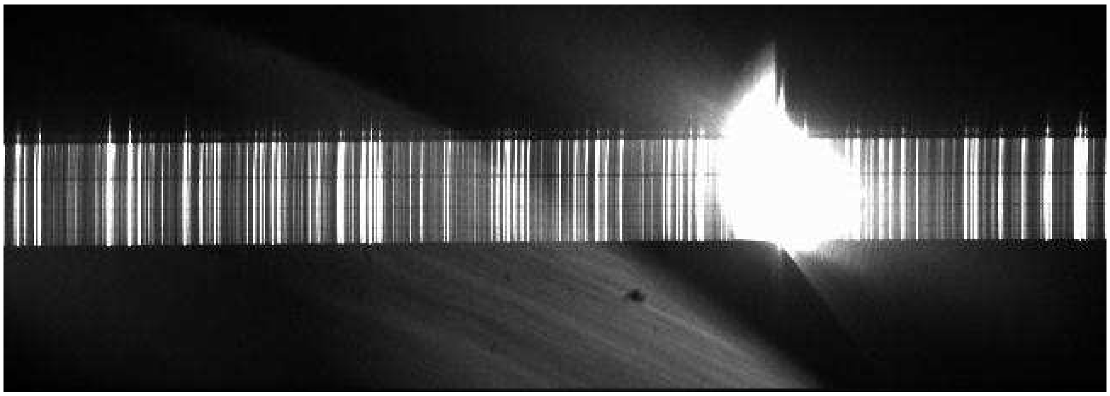
1. As a first step, set the slit length micrometer to $0\farcs200$, the position micrometer to $0\farcs200$, and the dial at the slit box to 214.5. With this configuration the slit has a physical length of $\approx$ 2.54 mm (or 20.8 arcsec), it is centered on the optical path of the spectrograph, and it has the suitable angle for setting the spectral dispersion direction perpendicular to the spatial one. For this observation, the slit width micrometer was positioned to $0\farcs395$, which corresponds to a slit width ≤ 25 μm. This uncertainty is caused by the mechanical worn-out of the micrometer associated with the control of the slit width.

2. Turn-on the UNe lamp through the lamp control software (Fig. 2.4b), by ponting and clicking at the "Enciende Lamp U" button. To illuminate the slit with the UNe lamp, click at the "Posicionar Diagonal" button.

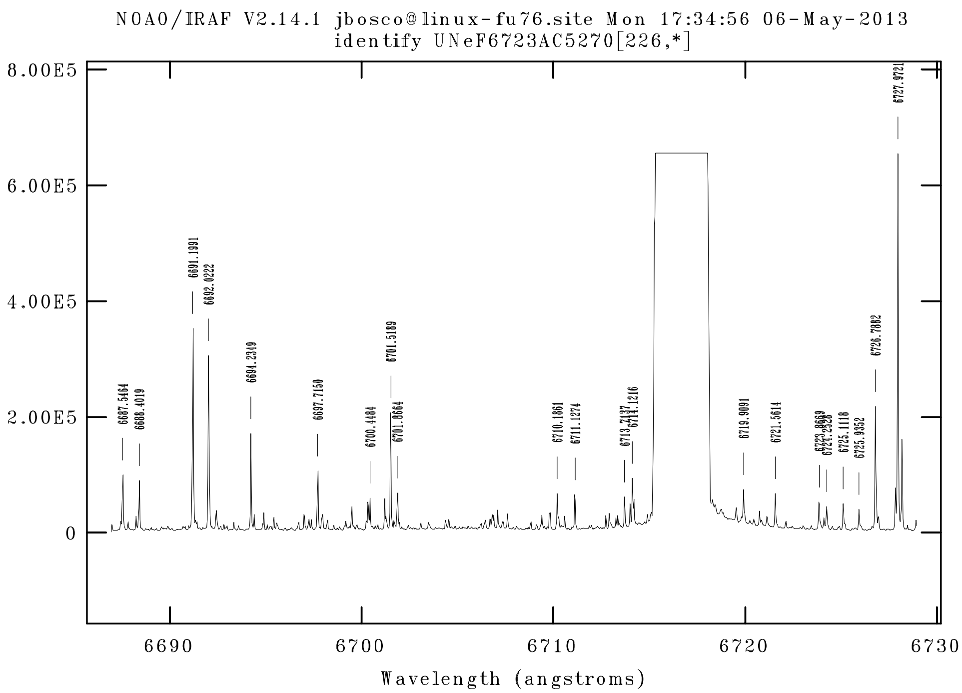
3. Set the upper filter wheel to the letter **C** (6 723 Å), and the lower filter wheel to the number **0** (transparent BK7 window).

4. From Table B, we choose a crank value of 5260 to center the wavelength range at $\lambda_c = 6\,707$ Å [it represents an intermediate value between 5270 (6 710 Å) and 5360 (6 705 Å) in the 35th order]. Note that the value of $\lambda_c = 6\,707$ Å is at the center of the 35th order, to avoid, as far as possible, wavelength overlap from adjacent orders.

5. A first image of the UNe lamp can now be taken. With the narrowest slit, an exposure time of a few seconds provides clear emission lines (Fig. 3.1).



(a)



(b)

Figure 3.1: Example of a 2-d and transversal cut of a spectrum from the UNe lamp. Note the saturated Neon line at about 6 717 Å.

6. Once the calibration lamp image have been taken, turn-off the UNe lamp by clicking again in the "Enciende Lamp U" button, from the lamp control software (Fig. 2.4b). Remove the mirror that illuminates the slit by clicking the "Posicionar Diagonal" button.

7. To take a flat image, turn on the halogen lamp and move accordingly the mirrors by

selecting “Mueve Espejo” and “Posicionar diagonal” in the lamp control software. The voltage of the halogen lamp is also controlled from the control room. An exposure time of a few seconds is sufficient to obtain high signal-to-noise ratio (S/N) flat field images, with the voltage of the lamp set at 10 V.

8. Turn off the halogen lamp and set the instrument ready for the target observation by clicking again on “Mueve Espejo” and “Posicionar diagonal” in the lamp control software.

3.2 Target observation

1. The instrument is ready to observe the target object. Fig. 3.2 shows a 1-d uncalibrated very high-resolution ($\mathcal{R} \approx 140\,000$) flux spectra of the bright G-type star ($m_{\rm v} = 3.45$) *eta Cas*, acquired with the same configuration set for the UNe lamp of Fig. 3.1, with a exposure time of 600 s. The depicted spectrum has a high S/N ≥ 150.

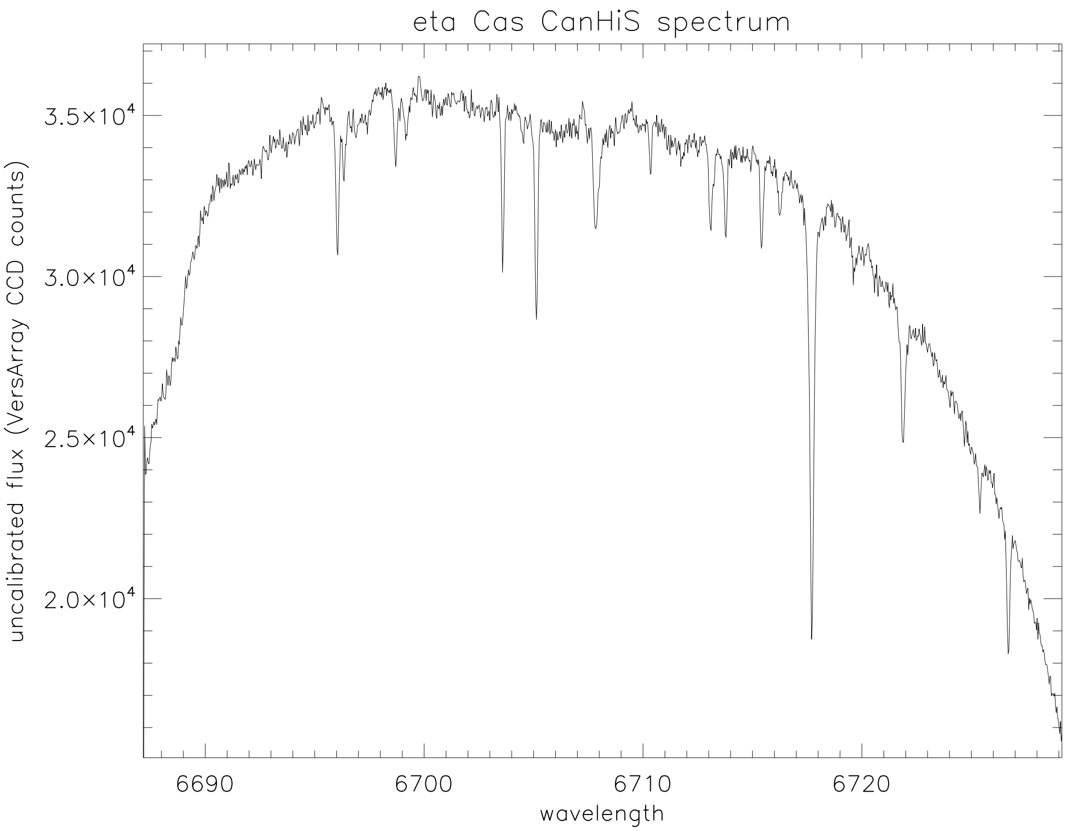
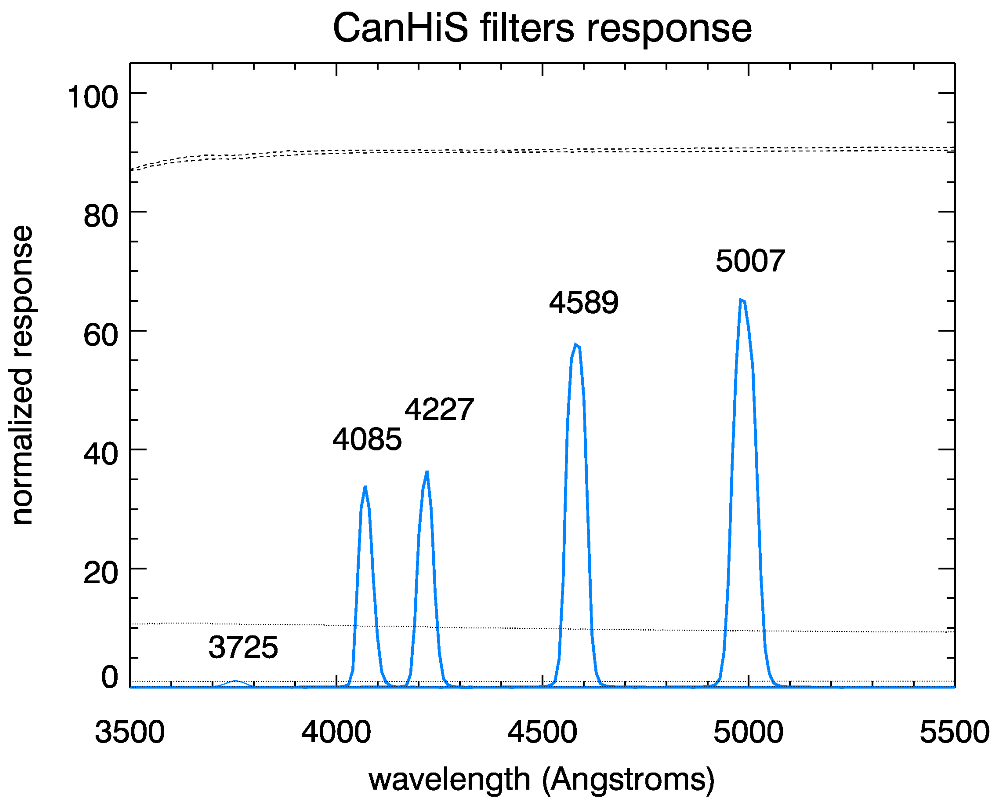


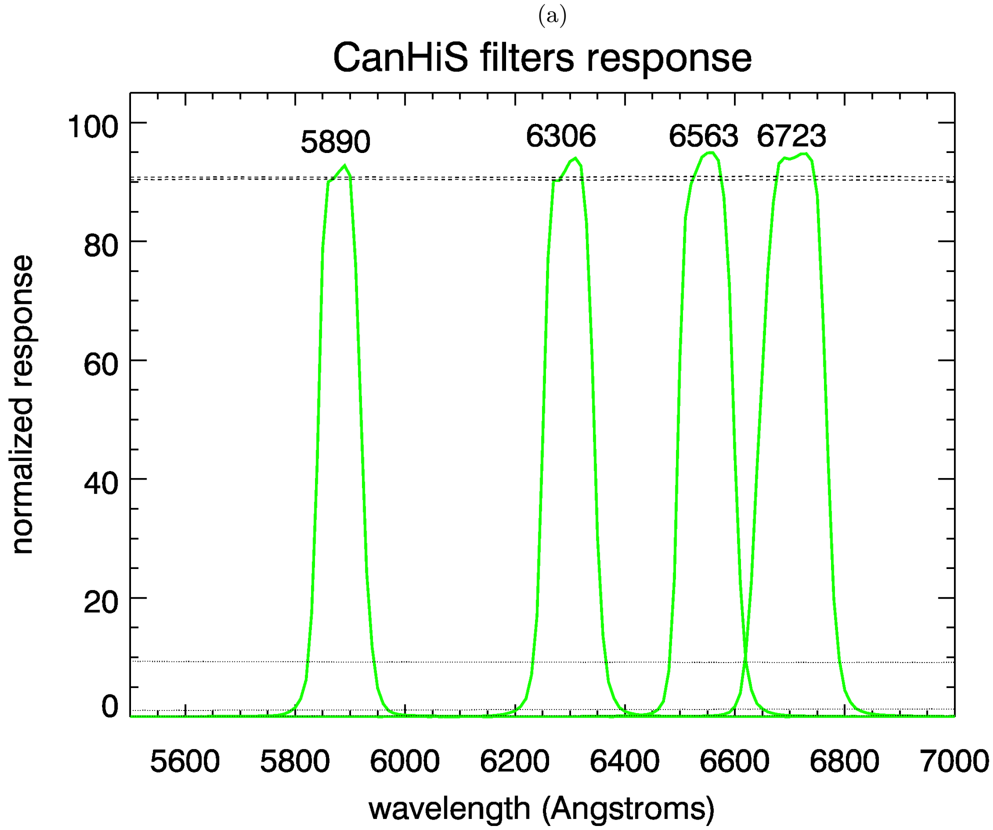
Figure 3.2: Uncalibrated spectrum of *eta Cas*, acquired with CanHiS at the 2.1-m OAGH Telescope and with the 1340 × 1300 CCD VersArray, 20 μ × 20 μ pixel size, during the CanHiS commissioning.

Appendix A

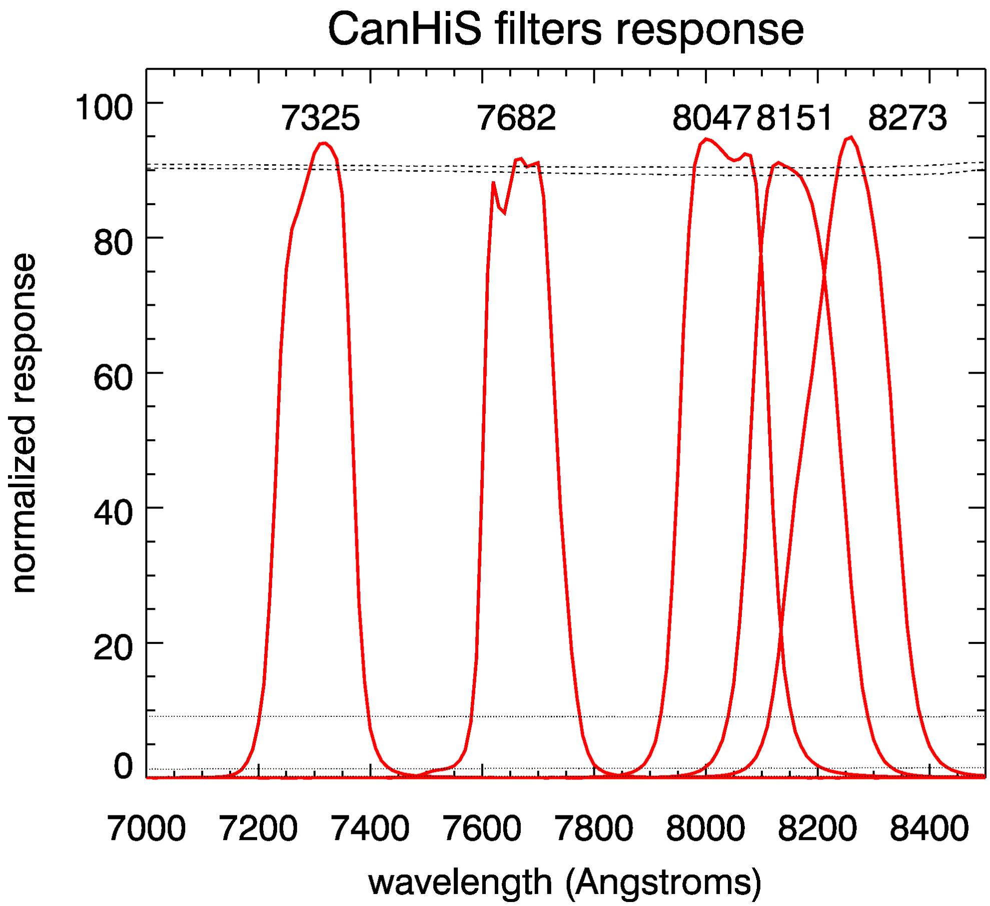
Normalized Filters Response


CanHiS filters response
normalized response
wavelength (Angstroms)
3725
4085
4227
4589
5007
0
20
40
60
80
100
3500
4000
4500
5000
5500

(a)


CanHiS filters response
normalized response
wavelength (Angstroms)
5890
6306
6563
6723
0
20
40
60
80
100
5600
5800
6000
6200
6400
6600
6800
7000

(b)



(c)

Figure A.1: Normalized response for 14 intermediate band filters used by CanHiS. Dashed lines depicts the response for the BK7 windows, whereas dotted lines shows the response for the dimmers. In a), filter **G** (3 725 Å) is practically useless because of the very low filter efficiency, and filters **B** and **4** (4 085 and 4 227 Å, respectively) have less than the 50% of efficiency, whereas filter **F** (5 007 Å) has approximately an efficiency of 65%. In b), all the filters have an efficiency up to 90%, but filters **7** and **C** (centered at 6 563 and 6 723 Å, respectively) suffer of a small overlapping between them, although this occurs at wavelengths where the blaze function makes it irrelevant. At c), the red region, filters **8**, **J** and **K**, show serious overlapping, particularly the filters centered at 8 151 and 8 273 Å.

Appendix B

Wavelength as Function of Crank Number and Order

Table B.1: Echelle spectrograph wavelengths as a function of crank number and dispersion order. The table shows the lowest orders dispersion (21—33) displaying their corresponding wavelengths (from 6 976 to 11 386 Å) and the crank value (1st column) needed to select a specific central wavelength λ_c. Crank values were selected in such a way that wavelengths rows are separated by 3 mm at the spectrograph camera focus (turning the crank to the following row, the wavelength image shifts 3 mm).

Cr. - Ord.	21	22	23	24	25	26	27	28	29	30	31	32	33
0	11386	10868	10396	9963	9564	9196	8856	8540	8245	7970	7713	7472	7246
470	11378	10861	10389	9956	9558	9190	8850	8534	8239	7965	7708	7467	7241
890	11370	10853	10381	9949	9551	9183	8843	8528	8233	7959	7702	7462	7235
1270	11362	10846	10374	9942	9544	9177	8837	8522	8228	7953	7697	7456	7230
1610	11354	10838	10367	9935	9537	9171	8831	8516	8222	7948	7691	7451	7225
1920	11346	10830	10359	9928	9531	9164	8825	8510	8216	7942	7686	7446	7220
2210	11338	10823	10352	9921	9524	9158	8818	8504	8210	7937	7681	7441	7215
2480	11329	10814	10344	9913	9516	9150	8811	8497	8204	7930	7674	7435	7209
2730	11321	10806	10337	9906	9510	9144	8805	8491	8198	7925	7669	7429	7204
2950	11313	10799	10329	9899	9503	9137	8799	8485	8192	7919	7664	7424	7199
3170	11305	10791	10322	9892	9496	9131	8793	8479	8186	7914	7658	7419	7194
3370	11297	10784	10315	9885	9489	9125	8787	8473	8181	7908	7653	7414	7189
3550	11289	10776	10307	9878	9483	9118	8780	8467	8175	7902	7647	7408	7184
3730	11281	10768	10300	9871	9476	9112	8774	8461	8169	7897	7642	7403	7179
3900	11272	10760	10292	9863	9468	9104	8767	8454	8162	7890	7636	7397	7173
4050	11264	10752	10285	9856	9462	9098	8761	8448	8157	7885	7630	7392	7168
4200	11256	10744	10277	9849	9455	9091	8755	8442	8151	7879	7625	7387	7163
4340	11248	10737	10270	9842	9448	9085	8748	8436	8145	7874	7620	7382	7158
4480	11240	10729	10263	9835	9442	9078	8742	8430	8139	7868	7614	7376	7153
4610	11232	10721	10255	9828	9435	9072	8736	8424	8134	7862	7609	7371	7148
4730	11224	10714	10248	9821	9428	9066	8730	8418	8128	7857	7603	7366	7143
4850	11215	10705	10240	9813	9421	9058	8723	8411	8121	7851	7597	7360	7137
4960	11207	10698	10232	9806	9414	9052	8717	8405	8115	7845	7592	7355	7132
5070	11199	10690	10225	9799	9407	9045	8710	8399	8110	7839	7586	7349	7127
5170	11191	10682	10218	9792	9400	9039	8704	8393	8104	7834	7581	7344	7122
5270	11183	10675	10211	9785	9394	9032	8698	8387	8098	7828	7576	7339	7116
5360	11175	10667	10203	9778	9387	9026	8692	8381	8092	7823	7570	7334	7111
5450	11167	10659	10196	9771	9380	9020	8685	8375	8086	7817	7565	7328	7106
5540	11158	10651	10188	9763	9373	9012	8678	8369	8080	7811	7559	7322	7101
5625	11150	10643	10180	9756	9366	9006	8672	8363	8074	7805	7553	7317	7095
5705	11142	10636	10173	9749	9359	8999	8666	8357	8068	7799	7548	7312	7090
5785	11134	10628	10166	9742	9353	8993	8660	8351	8063	7794	7542	7307	7085
5860	11126	10620	10159	9735	9346	8986	8654	8345	8057	7788	7537	7301	7080
5935	11118	10613	10151	9728	9339	8980	8647	8338	8051	7783	7532	7296	7075
6005	11110	10605	10144	9721	9332	8973	8641	8332	8045	7777	7526	7291	7070
6075	11101	10596	10136	9713	9325	8966	8634	8326	8039	7771	7520	7285	7064
6145	11093	10589	10128	9706	9318	8960	8628	8320	8033	7765	7515	7280	7059
6210	11085	10581	10121	9699	9311	8953	8622	8314	8027	7760	7509	7275	7054
6270	11077	10573	10114	9692	9305	8947	8615	8308	8021	7754	7504	7269	7049
6330	11069	10566	10106	9685	9298	8940	8609	8302	8015	7748	7498	7264	7044
6390	11061	10558	10099	9678	9291	8934	8603	8296	8010	7743	7493	7259	7039
6450	11053	10551	10092	9671	9285	8927	8597	8290	8004	7737	7488	7254	7034
6510	11044	10542	10084	9664	9277	8920	8590	8283	7997	7731	7481	7248	7028
6565	11036	10534	10076	9657	9270	8914	8584	8277	7992	7725	7476	7242	7023
6620	11028	10527	10069	9650	9264	8907	8577	8271	7986	7720	7471	7237	7018
6670	11020	10519	10062	9643	9257	8901	8571	8265	7980	7714	7465	7232	7013
6720	11012	10511	10054	9636	9250	8894	8565	8259	7974	7708	7460	7227	7008
6770	11004	10504	10047	9629	9243	8888	8559	8253	7968	7703	7454	7221	7003
6820	10996	10496	10040	9622	9237	8881	8552	8247	7963	7697	7449	7216	6997
6865	10987	10488	10032	9614	9229	8874	8545	8240	7956	7691	7443	7210	6992
6910	10979	10480	10024	9607	9222	8868	8539	8234	7950	7685	7437	7205	6987
6955	10971	10472	10017	9600	9216	8861	8533	8228	7945	7680	7432	7200	6982
7000	10963	10465	10010	9593	9209	8855	8527	8222	7939	7674	7427	7194	6976

Table B.2: Echelle spectrograph wavelength as function of crank number and dispersion order. Table shows central orders dispersion (34—42) reporting their corresponding wavelengths (from 7 033 to 5 482 Å) and the crank value needed to select a specific central wavelength λ_c.

Cr. - Ord.	34	35	36	37	38	39	40	41	42
0	7033	6832	6642	6462	6292	6131	5978	5832	5693
470	7028	6827	6637	6458	6288	6127	5973	5828	5689
890	7023	6822	6633	6453	6283	6122	5969	5824	5685
1270	7018	6817	6628	6449	6279	6118	5965	5820	5681
1610	7013	6812	6623	6444	6275	6114	5961	5815	5677
1920	7008	6808	6619	6440	6270	6109	5957	5811	5673
2210	7003	6803	6614	6435	6266	6105	5952	5807	5669
2480	6997	6797	6609	6430	6261	6100	5948	5803	5665
2730	6992	6793	6604	6425	6256	6096	5944	5799	5661
2950	6987	6788	6599	6421	6252	6092	5939	5794	5657
3170	6983	6783	6595	6416	6248	6087	5935	5790	5653
3370	6978	6778	6590	6412	6243	6083	5931	5786	5649
3550	6973	6773	6585	6407	6239	6079	5927	5782	5645
3730	6968	6769	6581	6403	6234	6074	5923	5778	5641
3900	6962	6763	6575	6398	6229	6070	5918	5773	5636
4050	6957	6758	6571	6393	6225	6065	5914	5769	5632
4200	6952	6754	6566	6389	6220	6061	5909	5765	5628
4340	6947	6749	6561	6384	6216	6057	5905	5761	5624
4480	6942	6744	6557	6379	6212	6052	5901	5757	5620
4610	6937	6739	6552	6375	6207	6048	5897	5753	5616
4730	6932	6734	6547	6370	6203	6044	5893	5749	5612
4850	6927	6729	6542	6365	6198	6039	5888	5744	5608
4960	6922	6724	6537	6361	6193	6035	5884	5740	5604
5070	6917	6719	6533	6356	6189	6030	5879	5736	5600
5170	6912	6715	6528	6352	6185	6026	5875	5732	5596
5270	6907	6710	6523	6347	6180	6022	5871	5728	5592
5360	6902	6705	6519	6343	6176	6017	5867	5724	5588
5450	6897	6700	6514	6338	6171	6013	5863	5720	5584
5540	6892	6695	6509	6333	6166	6008	5858	5715	5579
5625	6887	6690	6504	6328	6162	6004	5854	5711	5575
5705	6882	6685	6500	6324	6157	6000	5850	5707	5571
5785	6877	6680	6495	6319	6153	5995	5845	5703	5567
5860	6872	6676	6490	6315	6149	5991	5841	5699	5563
5935	6867	6671	6486	6310	6144	5987	5837	5695	5559
6005	6862	6666	6481	6306	6140	5982	5833	5690	5555
6075	6857	6661	6476	6301	6135	5977	5828	5686	5551
6145	6852	6656	6471	6296	6130	5973	5824	5682	5547
6210	6847	6651	6466	6291	6126	5969	5820	5678	5543
6270	6842	6646	6462	6287	6121	5965	5815	5674	5539
6330	6837	6641	6457	6282	6117	5960	5811	5669	5535
6390	6832	6637	6452	6278	6113	5956	5807	5665	5531
6450	6827	6632	6448	6273	6108	5952	5803	5661	5527
6510	6821	6626	6442	6268	6103	5947	5798	5657	5522
6565	6816	6622	6438	6264	6099	5942	5794	5653	5518
6620	6811	6617	6433	6259	6094	5938	5790	5648	5514
6670	6806	6612	6428	6255	6090	5934	5786	5644	5510
6720	6802	6607	6424	6250	6086	5930	5781	5640	5506
6770	6797	6602	6419	6246	6081	5925	5777	5636	5502
6820	6792	6598	6414	6241	6077	5921	5773	5632	5498
6865	6786	6592	6409	6236	6072	5916	5768	5627	5494
6910	6781	6587	6404	6231	6067	5912	5764	5623	5490
6955	6776	6583	6400	6227	6063	5907	5760	5619	5486
7000	6771	6578	6395	6222	6059	5903	5756	5615	5482

Table B.3: Echelle spectrograph wavelength as function of crank number and dispersion order. The highest orders dispersion (43—60) reporting their corresponding wavelengths (from 5 561 to 3 837 Å) and the crank value needed to select a specific central wavelength λ_c.

Cr. - Ord.	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60
0	5561	5434	5313	5198	5087	4981	4880	4782	4688	4598	4511	4428	4347	4270	4195	4123	4053	3985
470	5557	5430	5310	5194	5084	4978	4876	4779	4685	4595	4508	4425	4344	4267	4192	4120	4050	3982
890	5553	5427	5306	5191	5080	4974	4873	4775	4682	4592	4505	4422	4341	4264	4189	4117	4047	3980
1270	5549	5423	5302	5187	5077	4971	4869	4772	4678	4589	4502	4419	4338	4261	4186	4114	4044	3977
1610	5545	5419	5299	5183	5073	4967	4866	4769	4675	4585	4499	4415	4335	4258	4183	4111	4041	3974
1920	5541	5415	5295	5180	5069	4964	4863	4765	4672	4582	4496	4412	4332	4255	4180	4108	4038	3971
2210	5537	5411	5291	5176	5066	4960	4859	4762	4669	4579	4492	4409	4329	4252	4177	4105	4036	3968
2480	5533	5407	5287	5172	5062	4956	4855	4758	4665	4575	4489	4406	4326	4248	4174	4102	4032	3965
2730	5529	5403	5283	5168	5058	4953	4852	4755	4662	4572	4486	4403	4323	4245	4171	4099	4030	3962
2950	5525	5399	5279	5165	5055	4949	4848	4751	4658	4569	4483	4400	4320	4242	4168	4096	4027	3960
3170	5521	5396	5276	5161	5051	4946	4845	4748	4655	4565	4479	4396	4316	4239	4165	4093	4024	3957
3370	5517	5392	5272	5157	5048	4942	4842	4745	4652	4562	4476	4393	4313	4236	4162	4090	4021	3954
3550	5513	5388	5268	5154	5044	4939	4838	4741	4648	4559	4473	4390	4310	4233	4159	4087	4018	3951
3730	5509	5384	5264	5150	5040	4935	4835	4738	4645	4556	4470	4387	4307	4230	4156	4085	4015	3948
3900	5505	5380	5260	5146	5036	4932	4831	4734	4641	4552	4466	4384	4304	4227	4153	4081	4012	3945
4050	5501	5376	5257	5142	5033	4928	4827	4731	4638	4549	4463	4380	4301	4224	4150	4078	4009	3942
4200	5497	5372	5253	5139	5029	4925	4824	4728	4635	4546	4460	4377	4298	4221	4147	4075	4006	3940
4340	5493	5368	5249	5135	5026	4921	4821	4724	4632	4542	4457	4374	4295	4218	4144	4073	4004	3937
4480	5489	5365	5245	5131	5022	4918	4817	4721	4628	4539	4454	4371	4292	4215	4141	4070	4001	3934
4610	5485	5361	5242	5128	5019	4914	4814	4717	4625	4536	4450	4368	4289	4212	4138	4067	3998	3931
4730	5481	5357	5238	5124	5015	4911	4810	4714	4622	4533	4447	4365	4286	4209	4135	4064	3995	3928
4850	5477	5353	5234	5120	5011	4907	4806	4710	4618	4529	4444	4361	4282	4206	4132	4061	3992	3925
4960	5473	5349	5230	5116	5007	4903	4803	4707	4615	4526	4441	4358	4279	4203	4129	4058	3989	3922
5070	5469	5345	5226	5113	5004	4900	4800	4704	4611	4523	4437	4355	4276	4200	4126	4055	3986	3920
5170	5465	5341	5222	5109	5000	4896	4796	4700	4608	4519	4434	4352	4273	4197	4123	4052	3983	3917
5270	5461	5337	5219	5105	4997	4893	4793	4697	4605	4516	4431	4349	4270	4194	4120	4049	3980	3914
5360	5458	5334	5215	5102	4993	4889	4789	4694	4601	4513	4428	4346	4267	4191	4117	4046	3978	3911
5450	5454	5330	5211	5098	4990	4886	4786	4690	4598	4510	4425	4343	4264	4188	4114	4043	3975	3908
5540	5449	5325	5207	5094	4985	4882	4782	4686	4594	4506	4421	4339	4260	4184	4111	4040	3971	3905
5625	5445	5322	5203	5090	4982	4878	4779	4683	4591	4503	4418	4336	4257	4181	4108	4037	3969	3903
5705	5441	5318	5200	5087	4978	4875	4775	4680	4588	4500	4415	4333	4254	4178	4105	4034	3966	3900
5785	5438	5314	5196	5083	4975	4871	4772	4676	4585	4496	4412	4330	4251	4175	4102	4031	3963	3897
5860	5434	5310	5192	5079	4971	4868	4768	4673	4581	4493	4408	4327	4248	4172	4099	4028	3960	3894
5935	5430	5306	5188	5076	4968	4864	4765	4670	4578	4490	4405	4324	4245	4169	4096	4025	3957	3891
6005	5426	5302	5185	5072	4964	4861	4761	4666	4575	4487	4402	4321	4242	4166	4093	4023	3954	3888
6075	5421	5298	5180	5068	4960	4857	4758	4662	4571	4483	4399	4317	4239	4163	4090	4019	3951	3885
6145	5418	5294	5177	5064	4956	4853	4754	4659	4568	4480	4395	4314	4236	4160	4087	4016	3948	3883
6210	5414	5291	5173	5061	4953	4850	4751	4656	4564	4477	4392	4311	4232	4157	4084	4014	3946	3880
6270	5410	5287	5169	5057	4949	4846	4747	4652	4561	4473	4389	4308	4229	4154	4081	4011	3943	3877
6330	5406	5283	5166	5053	4946	4843	4744	4649	4558	4470	4386	4305	4226	4151	4078	4008	3940	3874
6390	5402	5279	5162	5050	4942	4839	4740	4646	4555	4467	4383	4302	4223	4148	4075	4005	3937	3871
6450	5398	5275	5158	5046	4939	4836	4737	4642	4551	4464	4379	4298	4220	4145	4072	4002	3934	3869
6510	5394	5271	5154	5042	4935	4832	4733	4638	4548	4460	4376	4295	4217	4142	4069	3999	3931	3865
6565	5390	5267	5150	5038	4931	4828	4730	4635	4544	4457	4373	4292	4214	4138	4066	3996	3928	3863
6620	5386	5263	5146	5035	4927	4825	4726	4632	4541	4454	4370	4289	4211	4136	4063	3993	3925	3860
6670	5382	5260	5143	5031	4924	4821	4723	4628	4538	4450	4366	4286	4208	4133	4060	3990	3922	3857
6720	5378	5256	5139	5027	4920	4818	4719	4625	4534	4447	4363	4282	4205	4130	4057	3987	3920	3854
6770	5374	5252	5135	5024	4917	4814	4716	4622	4531	4444	4360	4279	4202	4127	4054	3984	3917	3851
6820	5370	5248	5131	5020	4913	4811	4713	4618	4528	4441	4357	4276	4198	4124	4051	3981	3914	3849
6865	5366	5244	5127	5016	4909	4807	4709	4615	4524	4437	4353	4273	4195	4120	4048	3978	3911	3845
6910	5362	5240	5124	5012	4906	4803	4705	4611	4521	4434	4350	4270	4192	4117	4045	3975	3908	3843
6955	5358	5236	5120	5009	4902	4800	4702	4608	4517	4431	4347	4267	4189	4114	4042	3972	3905	3840
7000	5354	5232	5116	5005	4898	4796	4698	4604	4514	4427	4344	4263	4186	4111	4039	3969	3902	3837

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