On the Accuracy of the Wavelength Calibration and of the Flat-Fielding of the CCD CASPEC Spectra

S. D'Odorico and D. Ponz, ESO

Great care has to be used in the calibration of echelle spectra, both in wavelength and in intensity because most observational programmes which are carried out with CASPEC call for the highest accuracy in the velocity determinations or for the detection and measurements of faint features in the spectra.

The well-known difficulties in the reduction of the spectroscopic data in the echelle format are coupled in CASPEC with the problems of flat-fielding the CCD images.

In this short note we report on the results obtained on spectra from the commissioning phase of the instrument, using the software developed within the ESO MIDAS data reduction on the VAX computer in Garching. They represent a good reference point: the users should consider them as the minimal goal to achieve in reducing their data, but they could certainly do better by refining the calibration procedure and the reduction software.

The Wavelength Calibration

The dispersion coefficients are determined from the spectra of the Thorium-Argon hollow cathode lamp, obtained with the same instrumental configuration and at the same telescope position as the science frame.

In the reduction procedure, the orders are automatically defined via the flat-field exposure, and extracted using a sampling step of 1 pixel.

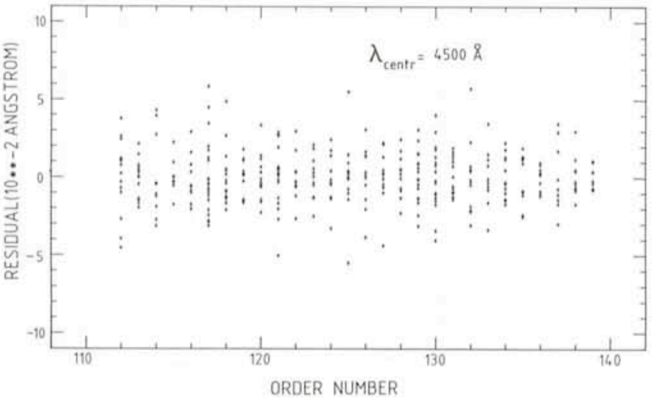
The calibration lines are then identified with a detection criterion which is based on the width of lines and their intensity above the background.

The actual position of the lines is defined as the centre of gravity of the two brightest pixels relative to the third brightest. Initial guesses for the wavelength calibration are obtained by entering manually the identification of a few lines in the frame, and then improved by comparison with the reference catalogue of thorium lines (1). The dispersion coefficients are computed by means of a regression analysis, where the equation conditions are similar to the one used in the calibration of the IUE high resolution spectra. In our case it is reduced to

$$x = a_o + a_1 m\lambda + a_2 (m\lambda)^2 + a_3 m + a_4\lambda + a_5 m\lambda^2 + a_6 m^2\lambda$$

where m is the order number.

In a typical reduction, between 100 and 300 lines are used in the regression analysis. Fig. 1 shows the behaviour of the residuals for two calibration images centred at 4500 Å and 6200 Å respectively.



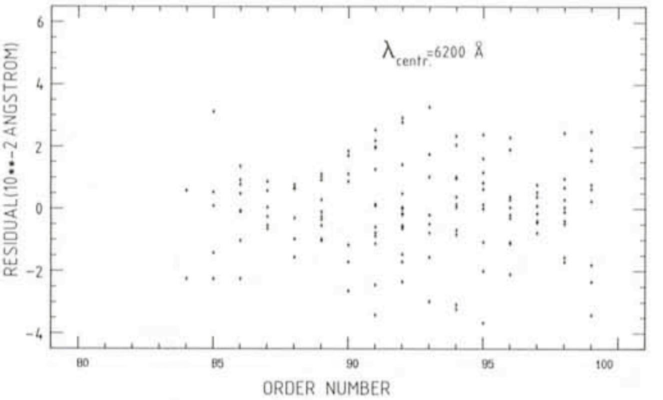


Fig. 1: *Plots of the residuals ($\Delta\lambda = \lambda_{lab} - \lambda_{comp}$) of two wavelength calibrations for the velocity standard stars as a function of order number. 350 and 142 lines were used for the blue and red frame respectively with corresponding standard deviations of 0.02 and 0.01 Å.*

In the commissioning phase, we have obtained nine spectra of 4 velocity standard stars (2) and reduced them with the standard procedure in MIDAS (3). Table 1 summarizes the results, Table 2 gives the list of lines which have been used in the radial velocity measurements. Typical exposure times were five minutes. When more than one spectrum per star is given, they were taken at intervals of about 15 minutes and calibrated with the same thorium exposure.

TABLE 1: OBSERVATIONS OF VELOCITY STANDARD STARS

Name HD	Spectral type	Velocity (km/sec)	Date	λ_{Cent} (Å)	Measured velocity (km/sec)	σ (km/sec)	No. lines
51250	K2 III	19.6 ± 0.5	18/1/84	6200	19.8	1.5	20
66141	K2 III	70.9 ± 0.3	14/1/84	6200	68.3	2.7	19
107328	K1 III	35.7 ± 0.3	20/6/83	6500	35.0	0.9	17
"			21/6/83	4500	35.0	3.4	18
"			"	"	34.9	3.3	18
"			"	"	35.0	3.5	18
136202	F8 IV-V	53.5 ± 0.2	20/6/83	6500	53.7	1.8	18
"			"	"	53.5	1.8	18
"			"	"	52.3	1.9	18

TABLE 2: LIST OF WAVELENGTHS USED IN THE DETERMINATION OF THE RADIAL VELOCITY

Blue spectra		Red spectra	
Ion	Wavelength (Å)	Ion	Wavelength (Å)
FeI	4152.170	NiI	6108.123
FeI	4174.917	CaI	6122.218
FeI	4191.436	FeI	6141.759
FeI	4202.031	FeI	6151.632
FeI	4219.364	CaI	6162.172
FeI	4383.547	FeI	6230.728
FeI	4404.752	FeI	6252.561
FeI	4415.125	FeI	6393.605
FeI	4427.312	FeI	6430.851
CoI	4549.656	CaI	6439.073
FeI	4611.289	CaI	6462.566
FeI	4602.944	FeI	6546.245
FeI	4654.624	Hα	6562.808
Hβ	4861.33	FeI	6592.919
FeI	4920.505	NiI	6643.641
FeI	4934.023	FeI	6677.993
FeI	4957.609	NiI	6767.778
FeI	4973.108	NiI	6772.36
FeI	4991.277	FeI	6663.446
		FeI	6717.556
		TiI	5866.462
		NaI	5889.953
		NaI	5895.923
			5922.123

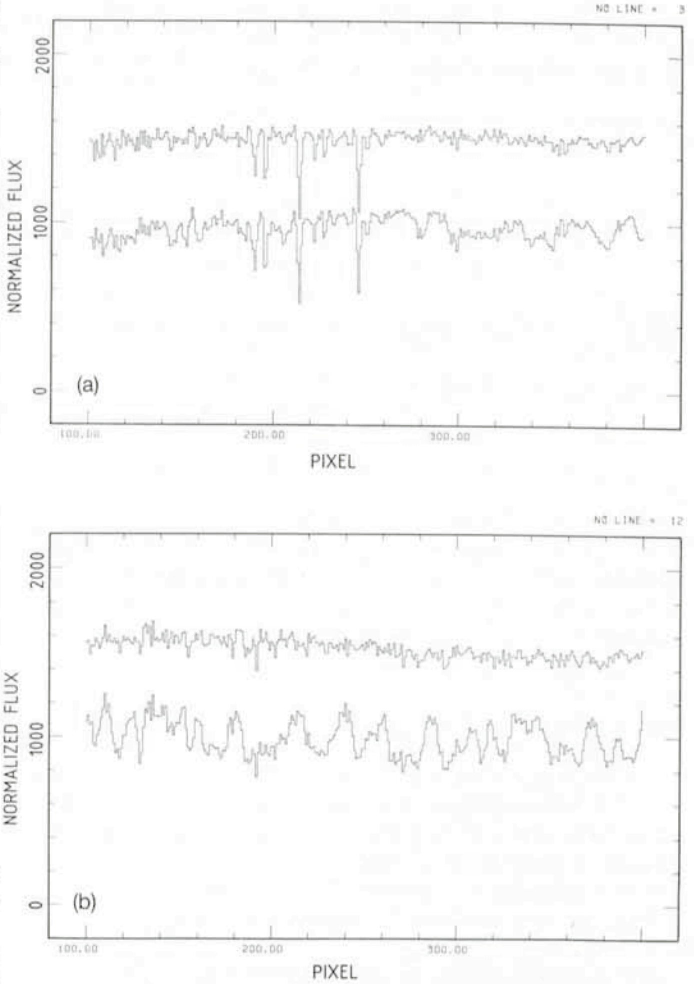


Fig. 2: Two extracted orders of a CASPEC exposure of the 12.1 m_v star LTT 3864, centred at λ 5900 Å (a) and 6700 Å (b). The extraction step is the CCD pixel. Lower tracings show the spectra extracted from the original CCD frame, the upper ones from the flat-fielded image. The spectra have been normalized and shifted one with respect to the other to make the comparison easier.

The velocities were derived from gaussian fitting of the lines in the flat-fielded, λ-calibrated and merged spectra using an IHAP command. The line FWHM is typically 2–3 pixels.

Most of the 9 spectra give velocities within 1 km/sec from the standard value, with the largest discrepancy being 2.5 km/sec and with no trace of systematic deviations.

The pixel size being about 9 km/sec, these results indicate that radial velocity measurements with an accuracy of a fraction of the pixel size can easily be achieved.

This accuracy is also confirmed by the measurements on the telluric emission lines, e.g. OI 5577 and 6300 Å, which are detected in long exposures. The radial velocities of these lines are within 2 km/sec of the zero redshift.

The Flat-Fielding of the CCD CASPEC Frames

As the use of CCD has become more and more common in astronomy, the procedure to flat-field a CCD image, that is to correct for offset values in the pixel intensity read-outs, for deviations from linearity and for chip defects, has become an art in itself. An additional feature which is particularly bothering in echelle spectra taken with the thinned, back illuminated RCA CCD is the fringing effect, due to reflections in the thinned silicon layer of the CCD. They produce an interference pattern whose variations depend on the wavelength of the incident light and the CCD thickness. The effect is as high as 30 % in the red part of the spectra with the chip we used in the commissioning phase, but is less conspicuous in a new RCA chip which has recently come into operation.

We do not venture here into a discussion of the advantages of the various flat-fielding methods, but simply describe the procedures we have followed and the results we have obtained to provide, as pointed out above, a reference point to the other users.

In the standard reduction procedure implemented in MIDAS, an average dark exposure, which might incorporate the preflash exposure applied to improve poor charge transfer efficiency, is subtracted from the science exposure and from the corresponding flat-field exposure with a continuous lamp. The residual background in the images, which is due to scattered light in the spectrograph and to the dark current of the chip, is then automatically fitted by a surface which interpolates values at interorder positions and again subtracted from the frames. The resulting background free science and flat-field exposures are then divided one by the other. Finally, the spectral orders are extracted and eventually normalized.

The flat-field exposure ist taken with an internal lamp through a projection system to the slit which reproduces the focal ratio and the central obstruction of the telescope. The intensity of the flat-field spectra is sufficiently high to have a negligible shot noise but still far from saturation.

As a representative example, we show in Figure 2 a, b two orders from a 25 min. exposure on the 12.1 visual magnitude star LTT 3864, a white dwarf used as a flux standard star. The orders were extracted from the original and flat-fielded frames respectively, with a step of 1 CCD pixel, and are centred on the interstellar sodium lines at 5900 Å and to the red of Hα. At these wavelengths, the fringing effect in the original data is shown to be as high as 30 %, but the noise is successfully reduced to better than 3 % in the flat-fielded spectrum. The equivalent widths of the faintest interstellar lines recorded in the spectrum are about 40 mÅ.

References

(1) S. D'Odorico, C. la Dous, D. Ponz and J. F. Tanné, "An Atlas of the Thorium-Argon Spectrum for the ESO Echelle Spectrograph", ESO Scientific Report No. 2.

(2) The Astronomical Almanac, 1984, Naval Observatory and Royal Greenwich Observatory.

(3) MIDAS, Munich Image Data Analysis System, 1984, ESO Operating Manual No. 1.

IRAS* Ground-based Follow-up at ESO

T. de Jong, Astronomical Institute Anton Pannekoek, University of Amsterdam

Introduction

The InfraRed Astronomical Satellite (IRAS) was successfully launched on 26 January 1983 from Western Test Range, Lompoc, California. The satellite died when the superfluid liquid helium which kept the telescope and the infrared instrumentation at its operating temperature of a few degrees Kelvin ran out on 22 November 1983. The very good performance of the satellite, the telescope and the infrared instrumentation has surpassed most preflight expectations. Due to the excellent attitude control system IRAS source positions are generally accurate to about 20 arcseconds. The extraordinary dark current stability of the infrared detectors has made it possible to attain an overall photometric accuracy of about 10 % and has in addition enabled us to also study extended emission features in the infrared sky.

The daily avalanche of infrared data accumulated over the 300 day IRAS mission has resulted in infrared parameters of about 300,000 astronomical sources. These sources are inhomogeneously distributed over the sky, with source densities varying from about 50 sources per square degree in the galactic plane (the source confusion limit) to about one source per square degree at the galactic poles. The reduction of the IRAS data and the preparation of the IRAS point source catalogue is carried out under the responsibility of the Joint IRAS Science Working Group consisting of astronomers from the three participating countries. The IRAS catalogue is presently scheduled to come out in November 1984.

The focal plane of the 60 cm Ritchey-Chretien telescope accommodated three separate instruments:

(i) The survey array, built in the US, and consisting of eight rows of altogether 62 detectors, two rows for each wavelength band (for detector sensitivities, fields of view and wavelength ranges see Table 1), and two additional Dutch instruments:

(ii) the Low Resolution Spectrometer (LRS), a slitless spectrograph, that registered 8–23 μm spectra with a spectral resolution of about 20 of all sufficiently strong (SNR $>\sim 50$) point sources observed in the survey, and

(iii) the Chopped Photometric Channel (CPC) designed to map sources at 50 and 100 μm with higher spatial resolution (1.2 arc minutes) but lower sensitivity than the survey array.

The main purpose of the IRAS mission was to systematically survey the whole sky at infrared wavelengths. About 60 % of the total available observing time was spent on carrying out this survey which was successfully completed apart from a five degree wide gap roughly centred at ecliptic longitudes 160 and 340 degrees that was missed because of operational problems. The remaining 40 % observing time was spent on mapping about 3,000 preselected sources and areas of sky at higher sensitivity (survey array) and better spatial resolution (CPC).

Due to the survey character of the IRAS mission the scientific results cover a wide spectrum of astronomical scenery and astrophysical processes, ranging from comets to quasars and providing new insights in the evolution of the solar system, stars and galaxies. Since cosmic infrared radiation is predominantly emitted by small dust particles heated by starlight, regions of high density close to stars generally stand out most clearly in the infrared. This makes the infrared the wavelength range "par excellence" to study stars in the process of formation when they are still immersed in the gas and dust clouds from which they have formed as well as stars at the end of their lives when they have evolved to red giants and are blowing off their envelopes on a relatively short time scale ($\sim 10^5$ years) before turning into white dwarfs or exploding as supernovae.

Ground-based IRAS Follow-up

To illustrate the capabilities of IRAS compared to ground-based telescopes in the infrared, it is instructive to compare the performances at 10 and 20 μm where observing from the ground is possible but severely hampered by atmospheric emission. To reach the same limiting sensitivity as IRAS at 10 μ with the 3.6 m ESO telescope requires 200 times longer integration times (40 seconds) at 10 μm and about 30,000 times longer (2 hours) at 20 μm in spite of the fact that the collecting area of the 3.6 m is about 40 times larger than that of the IRAS mirror. For this estimate I have assumed that sources are pointlike (smaller than the 3 arcseconds diaphragm of the IR photometer). If, as for virtually all protostars and galaxies, the sources are extended, the integration times go up proportional to the area of the source. In fact, to reach the same surface brightness sensitivity as IRAS, one would have to integrate about 2,000 times longer than estimated above.

This little bit of trivial numerology shows that ground-based follow-up of IRAS sources in the infrared is only profitable at 10 μm and shorter infrared wavelengths and would greatly benefit from the availability of an array-photometer, now in use at several other major observatories in the world. The enhanced spatial resolution that one can reach from the ground makes it worthwile to have such an instrument for more detailed studies of fine-scale structure in the brightest sources detected by IRAS.

Two infrared observing runs that we had in 1983 were totally unsuccessful because of bad weather but in view of the considerations above it is doubtful in retrospect how much could have been achieved with the conventional infrared photometer presently available at the 3.6 m telescope.

* The InfraRed Astronomical Satellite was developed and is operated by the Netherlands Agency for Aerospace Programmes (NIVR), the US National Aeronautics and Space Administration (NASA), and the UK Science and Engineering Council (SERC).