On the Linearity of ESO CCD # 9 at CAT + CES

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1. Introduction

The Coudé Echelle Spectrograph (CES) is the main facility at ESO for doing high resolution, high signal-to-noise spectroscopy. The amount and quality of the work done with it clearly show its great interest. Reaching such high resolution ($\lambda/\Delta\lambda \sim$ 50,000–100,000) with a conveniently high signal-to-noise ratio would have been nearly unfeasible without the availability of efficient silicon detectors such as the CCDs. An RCA SID 006 EX High Resolution CCD (ESO number 9) is equipping the short camera (SC) since 1987, and has equipped the long one (in alternance with the Reticon) from 1987 to 1992. The CCDs have, compared to older detectors (e.g. the photographic plates), several advantages such as their high quantum efficiency and their linearity. The linearity is normally better than 1 per cent, sometimes reaching 0.1 per cent, in particular for an RCA CCD (McLean, 1989). This latter property greatly facilitates the reduction of the data while making it more precise. The idea that CCDs are linear is so common and the manuals are so much dwelling on that, that it became an every day unquestionable evidence.

In the course of the reduction of their data, both authors of the present article had sometimes the feeling that something went wrong. A few facts, noticed by several users, hinted towards a problem with that instrument:

- the equivalent widths measured at CAT + CES + SC + CCD # 9 are dependent on the exposure level in the continuum;
- the equivalent widths measured with the Reticon are smaller than those measured with the CCD (5 to 15% discrepancy);
- the result of the division of two consecutive columns of the CCD has a complicated, spectrum dependent shape;
- flat fields at levels differing too much from the science exposure are not adequate for flat fielding;
- flat fields corresponding to different exposure times are not always strictly proportional.

The above-mentioned statements are not necessarily independent and could furthermore represent different aspects of the same effect. Most of the time, they were attributed, without further analysis, to complicated, pernicious effects related to vignetting or, alternatively, to diffuse light in the spectrograph.

Recently, Magain et al. (1992) reported problems in the reduction of their data, including a clear non linearity of CCD#5. Shortly after, J. Surdej, J.P. Swings and A. Smette took the opportunity of an observing run to perform extensive tests on the CCD#8 mounted at the 2.2-m telescope, which led to the discovery of strong problems. At the same time, one of us (E.G.) was observing with the CAT. Following a telephone conversation with J. Surdej and A. Smette, E.G. decided to conduct similar tests on CCD#9 in order to further investigate the question. After all, although the idea of the existence of non-linearities in ESO CCDs could appear as heresy, a mere lack of linearity would naturally explain, at least qualitatively, all the above-mentioned problems. Indeed, quite recently (however not independently), Schwarz and Abbott (1993) reported the actual existence of such problems.

2. Test of the Linearity of CCD # 9

At the end of the night 01-02/03/92, we acquired a sequence of triplets and pairs of internal flat fields with the CES in the configuration SC + CCD#9. This corresponds to sequence number 5 in Table 1. The sequence was designed to study the linearity of the CCD. In particular, we waited for the lamp to stabilize and the shortest exposure time was chosen to be 5 s in order to avoid possible problems linked to the precision of the shutter at too short exposures. In addition, the sequence of exposure times is first decreasing and then increasing in order to check the stability of the flat-field lamp. We adopted the following sequence: 3×140 s, 3×120 s, 3×100 s, 3×80 s, 3×60 s, 3×40 s, 3×20 s, 3×5 s, 3×10 s, 2×30 s, 2×50 s, 2×70 s, 2×90 s, 2×110 s, 1×130 s (the sequence had been abruptly interrupted by a switch-off of the remote control line from La Silla). These exposures allow to explore the response curve up to 10,000 ADU.

The first method (M1) we used to analyse the data is based on the hypothesis that the flux rate is constant. If F is the received flux integrated over the exposure time Δt, then the flux rate $F/\Delta t$ is independent of the exposure time. If, in addition, the CCD is linear, the observed flux f should share the same property $f/\Delta t$ = constant.

First, a mean bias was subtracted from each flat field exposure. Then, 3 areas were defined on the CCD (they are given in Table 1) so that the spatial variation of the flux inside them was minimal. The observed flux rate $f/\Delta t$ is plotted in Figure 1 as a function of f. For the sake of clarity, the points coming from the three zones have been normalized to the same incident flux. Fig-

Table 1: *Additional information on the different sequences selected for our study (LS: La Silla; RC: Remote Control from Garching).*

Sequence	Date	Central wavelength	Number of flat fields	Place	Selected zone
1	02-03/05/1987	7790 Å	30	LS	X346-X355 Y939-Y995
2	12-13/06/1990	4057 Å	18	RC	X300-X306 Y200-Y350
3	12-13/06/1990	3835 Å	21	RC	X300-X306 Y650-Y800
4	25-26/05/1991	4057 Å	33	RC	X418-X423 Y170-Y350
5	01-02/03/1992	4542 Å	38	RC	X365-X380 Y270-Y330
					X365-X380 Y470-Y530
					X365-X380 Y670-Y730
6	09-10/03/1992	4057 Å	33	RC	X367-X377 Y040-Y140
					X367-X377 Y300-Y400
					X367-X377 Y850-Y950
7	21/07/1992	4130 Å	28	RC	X417-X429 Y409-Y754

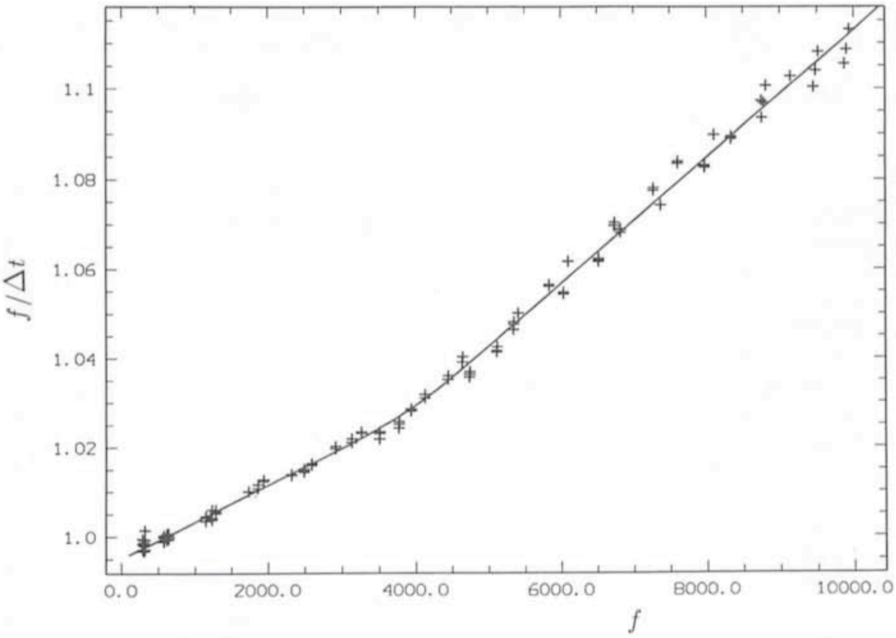

Figure 1: *Plot of the normalized observed flux rate* f/Δt *versus the observed flux* f. *The units are ADU. The continuous line is the fitted function* P(f).

ure 1 shows that $f/\Delta t$ is not constant. A linear increase (i.e. a second order response curve) is visible up to 3000 ADU; then, an elbow is present and a second linear increase, with a different slope, stands up to ~ 10,000 ADU. This is highly suggestive of non-linearities with a rather complex behaviour.

A function $P(f)$ (fourth order polynomial up to 4500 ADU and a straight line beyond, the continuity being imposed up to the first derivative) has been fitted and is also shown in Figure 1. Unfortunately, this method (M1) suffers from several weaknesses in the form of implicit hypotheses not necessarily satisfied. For example, it assumes the constancy of the flat field lamp emission. A slow drift is effectively present (one can see small oscillations in Figure 1 due to exposures of the increasing branch alternating with exposures of the decreasing branch) but the sequence has been designed to minimize the corresponding consequences. Faster variations could also be present and would be more cumbersome. In particular, uncertainties (particularly systematic ones) in the functioning of the shutter could annihilate any confidence in the results.

To further ascertain our approach, we used a second method based on the properties of the variance of a Poisson process.

The variance σ_F^2 of the flux is given by

$$\sigma_F^2 = (RON)^2 + \frac{F}{g} \qquad (1)$$

where RON is the read-out noise (possibly corrected for the effect of the bias subtraction) and g is the gain. If the CCD is linear, the law is also valid for the observed flux f. Usually, CCD#9 is operated at ~ 7 e^-/ADU.

We estimated σ_f^2 by dividing two flat fields of the same exposure time ($f_1 \sim f_2$) and by computing σ_{f_1/f_2}^2. We approximate σ_f^2 by 0.5 f^2 σ_{f_1/f_2}^2. In Figure 2, we plotted $\sigma_f^2 - (RON)^2$ as a function of f. Although the first part of the curve is compatible with linearity, an elbow is again present at about 3000 ADU and, beyond, the slope is markedly different. The data have been fitted with a function $Q(f)$ of the same form as $P(f)$ but constrained to go through the origin.

The lack of linearity of the variance could be due either to a lack of linearity of the response curve or to the presence of an additional, non poissonnian, flux dependent noise. The discrimination between the two causes is possible by comparing the functions $P(f)$ and $Q(f)$.

If R is the response curve, we have

$$f = R(F). \qquad (2)$$

We are interested in the reciprocal response function which is also the linearizing function

$$F = R^{-1}(f). \qquad (3)$$

We fitted the function

$$P(f) \propto \frac{f}{\Delta t}. \qquad (4)$$

F is proportional to Δt, so we obtain the following proportionality

$$R^{-1}(f) \propto \frac{f}{P(f)}. \qquad (5)$$

On the other hand, the variance of the observed flux as a function of the latter is given, in the case of no additional noise, by

$$\sigma_f^2 = (RON)^2 + \frac{R^{-1}(f)}{g}\left\{ \dot{R}\left[R^{-1}(f)\right]\right\}^2. \qquad (6)$$

To check the equivalence of the two approaches, we derived the expected σ_f^2 from the fitted function $P(f)$ through Eqs. 5 and 6. We found that the expected $\sigma_f^2 - (RON)^2$ function found in this way corresponds quite well to the function $Q(f)$. Therefore, we conclude that we have to deal with a clear non-linearity present in the response curve and not with the apparition of an additional strange noise.

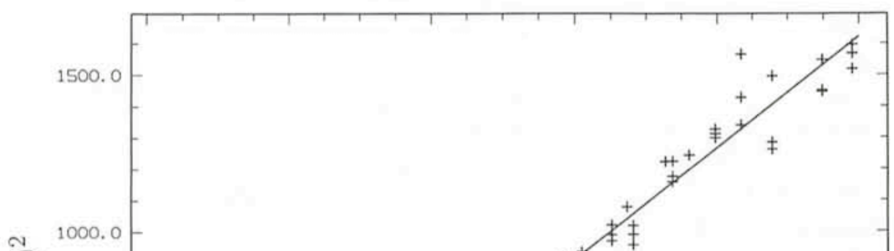

Figure 2: *Plot of the variance* σ_f^2 – (RON)^2 *as a function of the observed flux* f. *The units are ADU. The continuous line is the fitted function* Q(f).

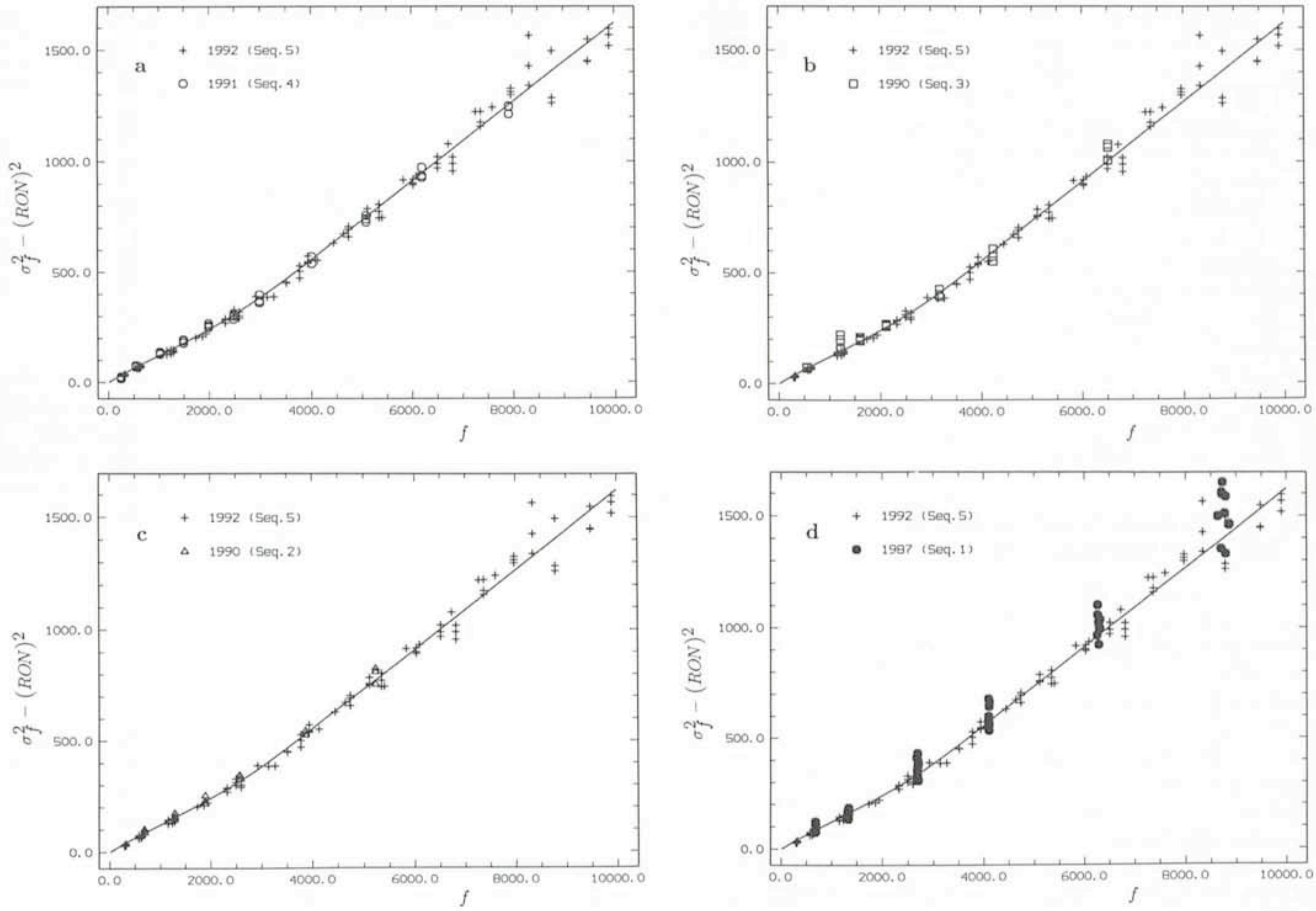

Figure 3: *Comparison of the variance plots corresponding to different epochs. The crosses correspond to the 1992 reference data. Panel (a) corresponds to the 1991 data (sequence 4); panel (b) to the 1990 data (sequence 3) and panel (c) to the same year (sequence 2); finally panel (d) corresponds to the 1987 data (sequence 1).*

It is rather surprising that we have to deal with the inverse phenomenon of a saturation: the higher the received flux is, the more strongly is the observed flux overestimated.

3. Persistence of the Phenomenon

After the existence of a non-linearity had been ascertained, we studied its evolution with time. Within our own archive, we found a few sequences of flat fields useful for such an investigation; they were however not designed for that purpose. We found an interesting sequence on the night 25–26/05/91, and two on the night 12–13/06/90. We can also add an older sequence on 02–03/05/87. Additional information is given in Table 1. The variance diagram ($\sigma_f^2 - (RON)^2$ as a function of f) is plotted in Figure 3 for all the selected sequences along with the 1992 one as a reference. It is seen that sequences 2 and 3 (1990) are in excellent agreement with the reference. Concerning the 1991 sequence (4), we had to increase $1/g$ by 15 % to get the agreement. Most probably, the gain was different at that time although

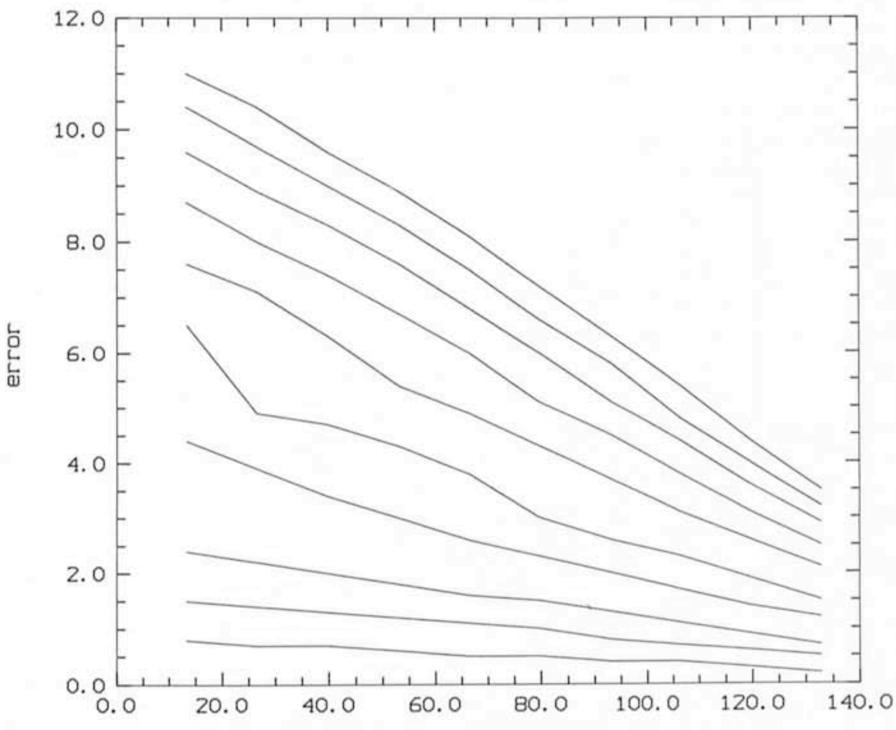

Figure 4: *Relative error on the measured equivalent width, as a function of the equivalent width (expressed in mÅ), for different levels of the continuum. The continuum varies from 1000 ADU (lower curve) to 10,000 ADU (upper curve) by steps of 1000 ADU. The line width remains fixed; the line depth varies from 10 % (left) to 100 % (right) of the continuum level.*

this was not mentioned in the descriptors (15 % is approximately one e^- at 7 e^-/ADU). The only slight discrepancy concerns the 1987 data. Clearly, the non-linearity is already present but the elbow could be at somewhat lower counts. In any case, the similarity between the curves is so strong that it indicates that the non-linearity was probably there from the beginning.

After our run (March 2, 1992), we complained about the problem described here and the electronic settings have been modified on several occasions, therefore changing the response curve. The situation after March 2, 1992 is described in section 6.

4. Correction of the Non-Linearity as Before March 2, 1992

Strong evidence of the stability of the inadequate response curve, at least since 1990, has been given in section 3. Therefore, we used the reference, sequence 5, as analysed in section 2, to derive a response curve and thus a linearizing function, adequate for correcting data obtained during that period.

From the function $P(f)$ fitted on the flux rate (Eq. 4), which is perfectly compatible (through Eqs. 5 and 6) with the fit $Q(f)$ made on the $\sigma_f^2 - (RON)^2$ corresponding either to sequence 5 alone or to sequences 2, 3, 4, 5 altogether, we can deduce the reciprocal response curve function $R^{-1}(f)$ (Eq. 5) within a multiplicative factor. Therefore, the linearized flux f_{LIN} which is directly proportional to F

Table 2: *Power expansion of the reciprocal response function R^{-1} (f) (see equation 9).*

Parameter	Value f ≤ 4500	Value f ≥ 4500
α_1	1.00475	1.02824
α_2	$-\ 0.7456.10^{-5}$	$-\ 1.4840.10^{-5}$
α_3	$-\ 1.0272.10^{-9}$	$+\ 2.142.10^{-10}$
α_4	$+\ 5.0929.10^{-13}$	$-\ 3.09.10^{-15}$
α_5	$-\ 8.0300.10^{-17}$	$+\ 4.5.10^{-20}$
α_7	$+\ 1.9823.10^{-25}$	—

$$f_{LIN} \propto F \quad (7)$$

can be expressed by

$$f_{LIN} \propto R^{-1}(f) \quad (8)$$

$$= a_1 f + a_2 f^2 + a_3 f^3 + a_4 f^4 + a_5 f^5 + a_7 f^7 . \quad (9)$$

The coefficients are given in Table 2. The high order of the polynomial is basically due to the elbow. The correction should be applied to the debiased exposures (science and flat field ones) prior to flat fielding.

5. The Scientific Impact of the Problem

On Figures 1 and 2, deviations from linearity of 5 to 10 % are clearly visible. The observed spectrum changes with exposure level and is different from the correct one. The line profiles are modified, the equivalent widths overestimated.

The effect on equivalent widths depends on the continuum level, on the shape of the spectrum perpendicular to the dispersion and on the line profiles. Simulations have been carried out for a typical case, and show the equivalent widths to be overestimated typically by 5%, but by more than 10% for weak lines on a well-exposed continuum (the best case for abundance analyses ...). Figure 4 exhibits the results of such a simulation.

6. The Response Curve After March 2, 1992

We had another run from 06/03/92 to 10/03/92. We took this opportunity to acquire another sequence of flat fields in order to further study the above-mentioned problems, particularly, as we knew that the electronic settings were changed. The variance diagram corresponding to this sequence (numbered 6 in Table 1) is given in Figure 5 along with the curve $Q(f)$ (introduced in section 2) for comparison. The response curve clearly changed: the non-linearity is anyway still present but to a lesser extent and the elbow is less obvious than in Figure 2. The variance however behaves more like a second-degree polynomial which underlines the persistence of the non-linearity.

Finally, we could make a last check in July 1992. Sequence 7 was acquired on 21/07/92; the corresponding variance diagram is also given in the same Figure 5. The curve is again different from all the others shown above. A non-linearity is still present but its nature seems more complex.

The conclusion is that, during the course of 1992, the non-linearity problem was not solved at all and that, in addition, variability of the response curve prevents to apply a general correction to the data similar to the one proposed in section 4.

As a last illustration, we decided to use a third method (M3) to investigate the linearity of CCD # 9. The principle is that the shape of a spectral feature should remain the same, independently of the exposure level. So, the profile of a strong line observed with different exposure times could be used to derive the non-linearity curve.

Here, we simulated such a broad emission line by narrowing the exit slit of

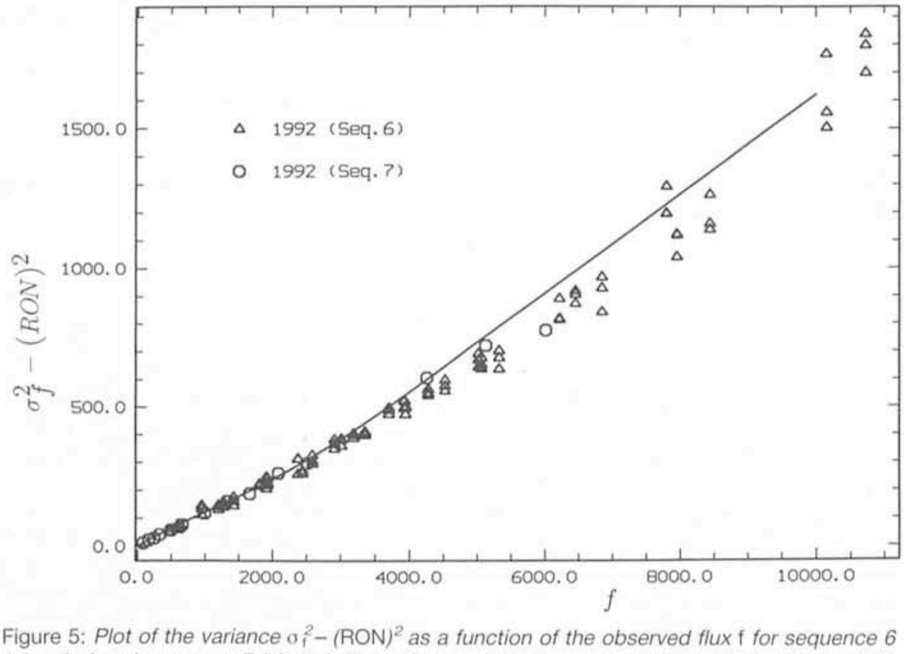

Figure 5: *Plot of the variance $\sigma_f^2 - (RON)^2$ as a function of the observed flux* f *for sequence 6 (triangles) and sequence 7 (circles). The units are ADU. The continuous line is the function* Q(f) *as introduced in section 2; it is given for comparison.*

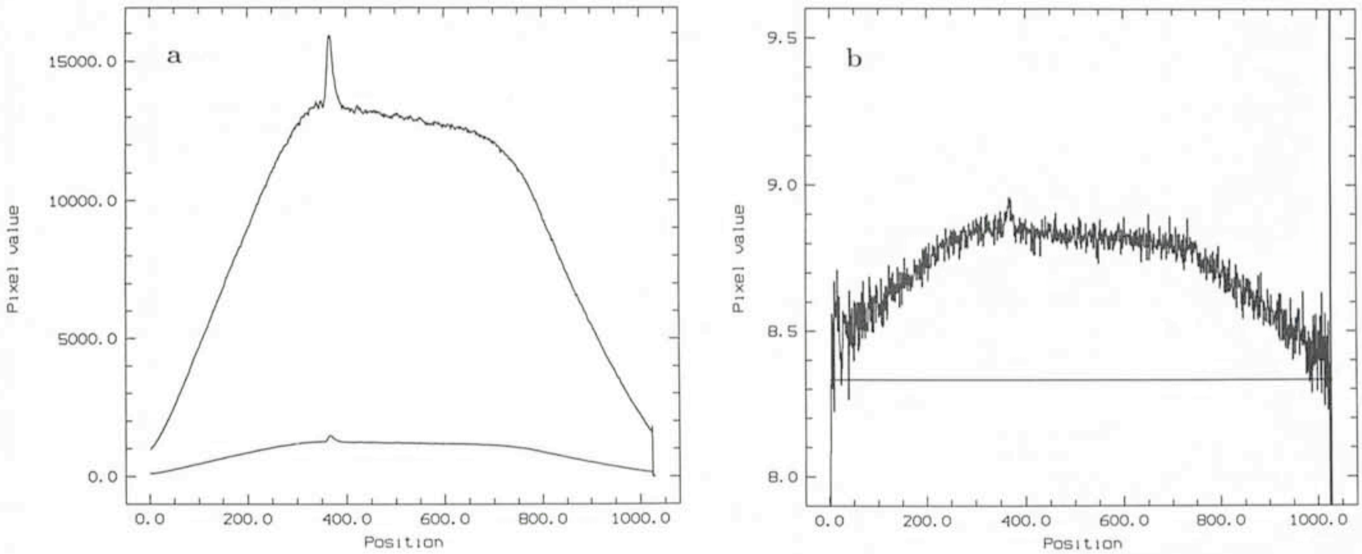

Figure 6: *Ratio of two vignetted flat fields of different exposures. Panel (a) shows the two flat fields (1000 and 120 seconds of exposure) averaged over the slit height. Panel (b) gives the ratio of the two flat fields compared to the ratio of the exposure times (the straight horizontal line).*

the pre-disperser in order to get strong vignetting of the flat fields. As an illustration, two flat fields of different exposure levels are shown in Figure 6. The ratio of the two is clearly flux dependent, showing that the response curve of CCD#9 was still clearly non linear in July 1992.

7. Conclusion

We gave evidence that ESO CCD#9 used at CAT + CES has never been linear from 1987, shortly after its installation at the CES, to 1992. The response curve seems to have been rather stable from the beginning up to March 2, 1992; this is certainly true during the years 1990 and 1991.

We briefly analysed the impact of the problem on abundance analysis works as those customarily done at CAT. We proposed a first order correction to be applied on the debiased frames. This correction is to be considered a first order one because we do not know the exact origin of the problem; the dependency of the response curve on the bias level, for example, is completely unknown.

RCA CCDs are usually thought to be pretty linear (McLean, 1989). This suggests that the problem of CCD#9 originates in fact in the electronics behind the CCD itself. This is supported by the strong dependency of the response curve on the electronic settings as evidenced after March 2, 1992.

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CCD Linearity at La Silla – a Status Report

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We believe that the non-linearities reported above by Gosset and Magain arise from a combination of two effects. First are the non-linearities reported in Schwarz and Abbott (1993), resulting from a failure in some new A/D converter chains in the Generation III CCD controllers. Secondly, in the process of replacing these converters, we discovered that many of our RCA CCDs exhibited some intrinsic non-linearities which may be related to the age of these devices. Unfortunately, we do not have adequate test data to demonstrate that our RCA CCDs were ever linear to better than 1 %, but they were certainly non-linear to as much as 8 % over their full dynamic range before March of 1993. At this time, we determined that we could reduce these non-linearities to acceptable levels by careful adjustment of the bias level of the output FET's drain voltage. It was found that a fraction of a volt may have a significant effect on the linearity. All RCA CCDs required adjustment, except RCA#13.

Below is a list of our CCDs and the most recently measured or most representative degree of non-linearity. For the RCA CCDs, data prior to adjustment of the output drain bias voltage is included. Non-linearities are expressed as the fractional amplitude of any trends in