Photometric Techniques II
Data analysis, errors, completeness

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.

Before starting…..

There are at least five things you should know before starting:

Basic data

- Read out noise;
- Conversion factor (electrons to ADU);
- Maximum linear signal (physical or electronic saturation level);
- Size of typical stellar images (seeing, FWHM in pixels)

- Map of bad pixels, rows, columns;

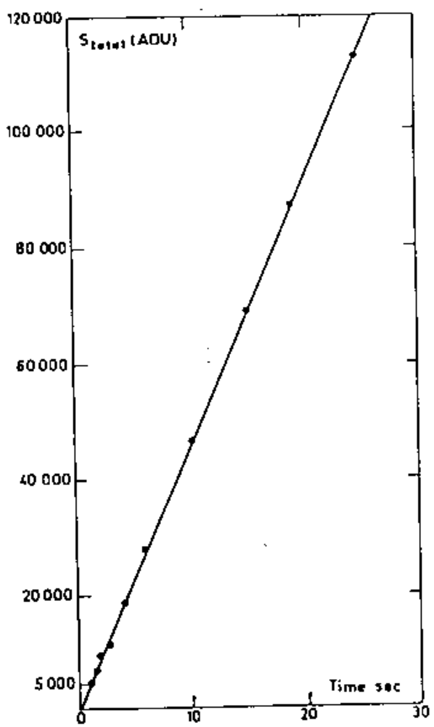


Fig. 3a. Linearity of the CCD. The straight line is the total output signal on the central pixel and those on the same column.

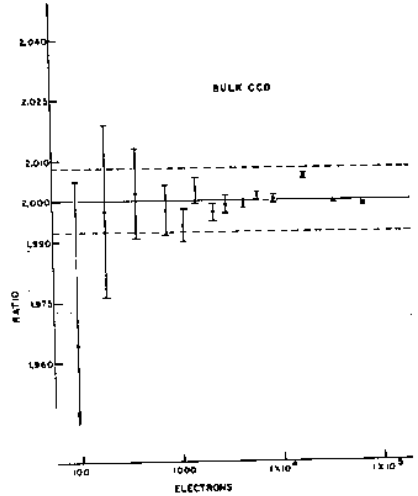


Figure 11. Linearity plot of an RCA bulk CCD.

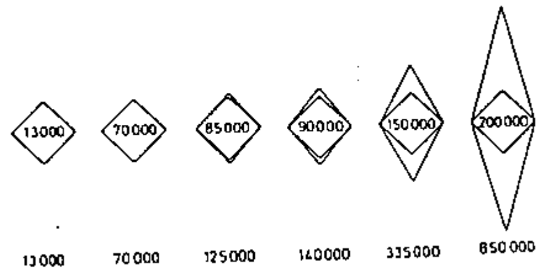


Fig. 3b. Evolution of the FWHM with input signal increase: the output signal on the illuminated pixel is represented on the central diamond. We mention below each of them the total charge read by the CCD. Note the diamond shape along the columns whereas no degradation is observed along the rows

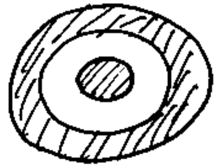
In conclusion the intensity level of the CCD is linear up to the saturation limit, but there is a spilling of charges well before the saturation if single pixels are exposed

A practical suggestion:

1) **Stars with a peak above 90% of the saturation value should be not used for calibration neither for the PSF.**

The best choice is a star with the peak at half of the dynamic range

CCD RELATIVE (INSTRUMENTAL) PHOTOMETRY



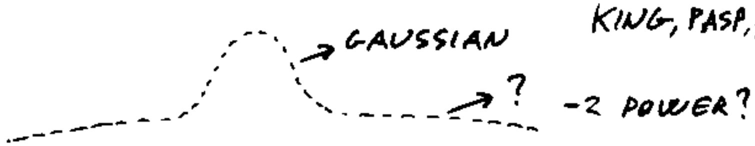
APERTURE PHOTOMETRY:

PROBLEMS: 1) CROWDING
2) SIZE OF THE APERTURE:
- S/N RATIO OR (BIG APERTUR
- CENTERING PROBLEMS (SMALL "

FITTING TECHNIQUES:

WHAT IS THE SHAPE OF STELLAR IMAGES?
THE PSF (POINT SPREAD FUNCTION) PROBLEM
- GAUSSIAN ONLY IN THE CENRAL PART
- EXTENDED WIDE WINGS IN THE OUTER PAR

KING, PASP, 83, 199



1) GAUSSIAN + EMPIRICAL (STETSON 1987)
2) MOFFAT (MOFFAT, A.A. 3, 455, 1969
3) LORENTZIAN (DIEGO, PASP, 97, 1209, 1985)
SEE ALSO BUONANNO (A.A., 126, 278, 1983)

FIND (2)

Basic idea: A star is brighter than its sorrounding;

Simple method: set a brightness threshold at some level above the sky brightness level;

Complications:

1. The sky brightness might vary across the frame

2. Blended objects, extended objects, artifacts, cosmic rays must be recognized. Some filtering should be applied.

Fundamental tasks for stellar photometry

FIND	crude estimate of star postion and brightness + + preliminary ap. photom.
PSF	determine stellar profile (point spread function)
FIT	fit the PSF to multiple, overlapping stellar images (and sky)

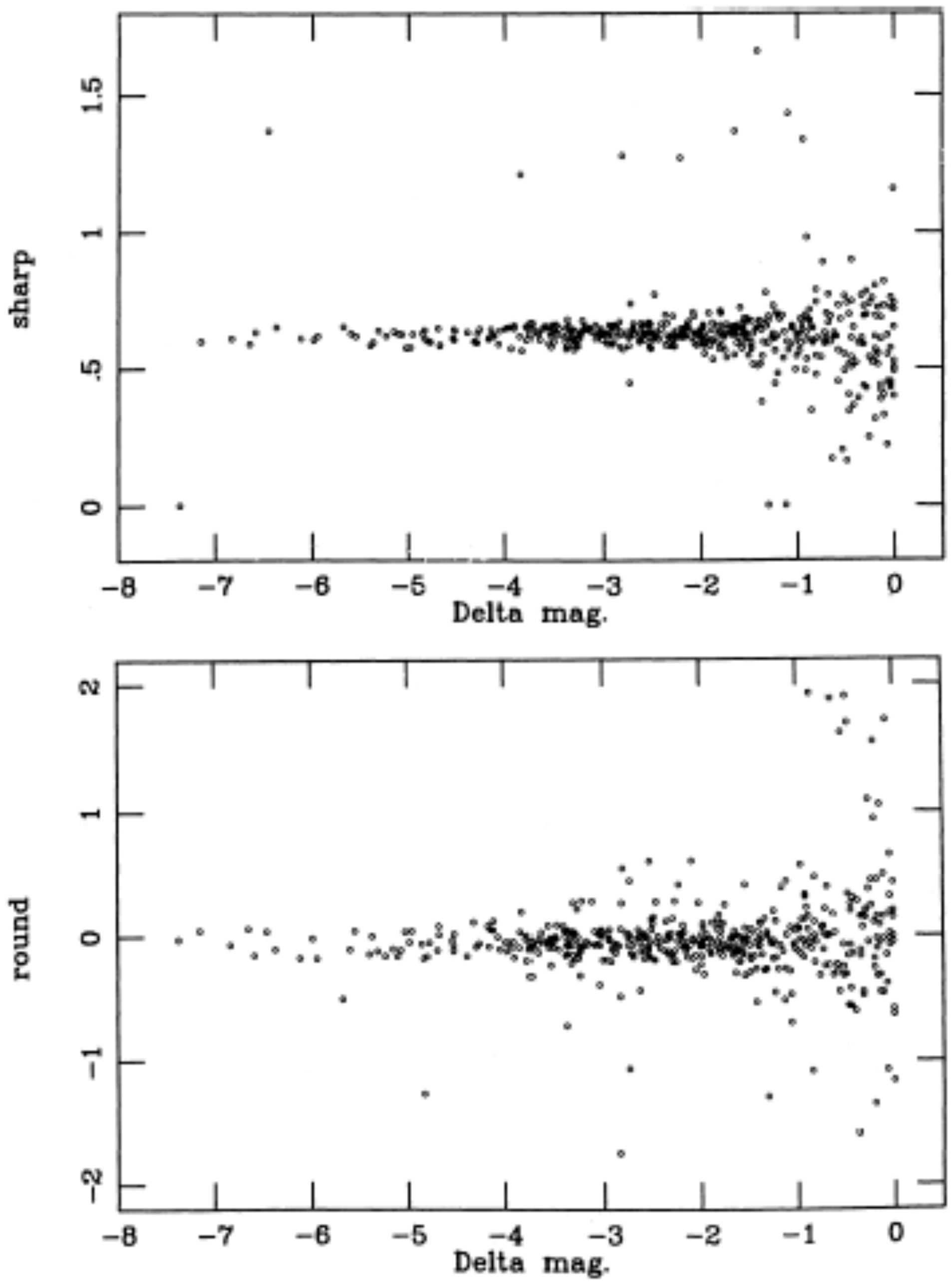
Further analysis of the data:

SUBTRACT	subtract stellar images from the frame
ADD	add artificial stellar images to the frame

ANALYSIS

	DAOPHOT	ROMAFOT	INVENTORY
SKY :			
ANAL. :	MULTIPLE FITTING ADD/DELETE COMP.	MULTIPLE FITTING NO ENTRY CHANGES	ITERAT. CLEA./SUBTR. ADD/DELETE COMP. GALAXY DETECTION
PSF :	ANAL. (CENTER) EMPIR. (WINGS)	ANAL. (MOFF. OR GAUSS.)	EMPIRICAL
	• MANUAL	MANUAL	• MANUAL OR AUTOM.
	- SLOW IN CROWDED FIELDS	VERY SLOW IN CROWDED FIELDS	VERY FAST IN CROWDED FIELDS
	- LIMITED INTERACTIONS	- MANY INTERACTIONS	- TWO COMMANDS ONLY
SENSITIV. TO INPUT PARAM. :	LOW	HIGH	VERY HIGH

Two parameters to help eliminating non-stellar objects:



SHARPNESS

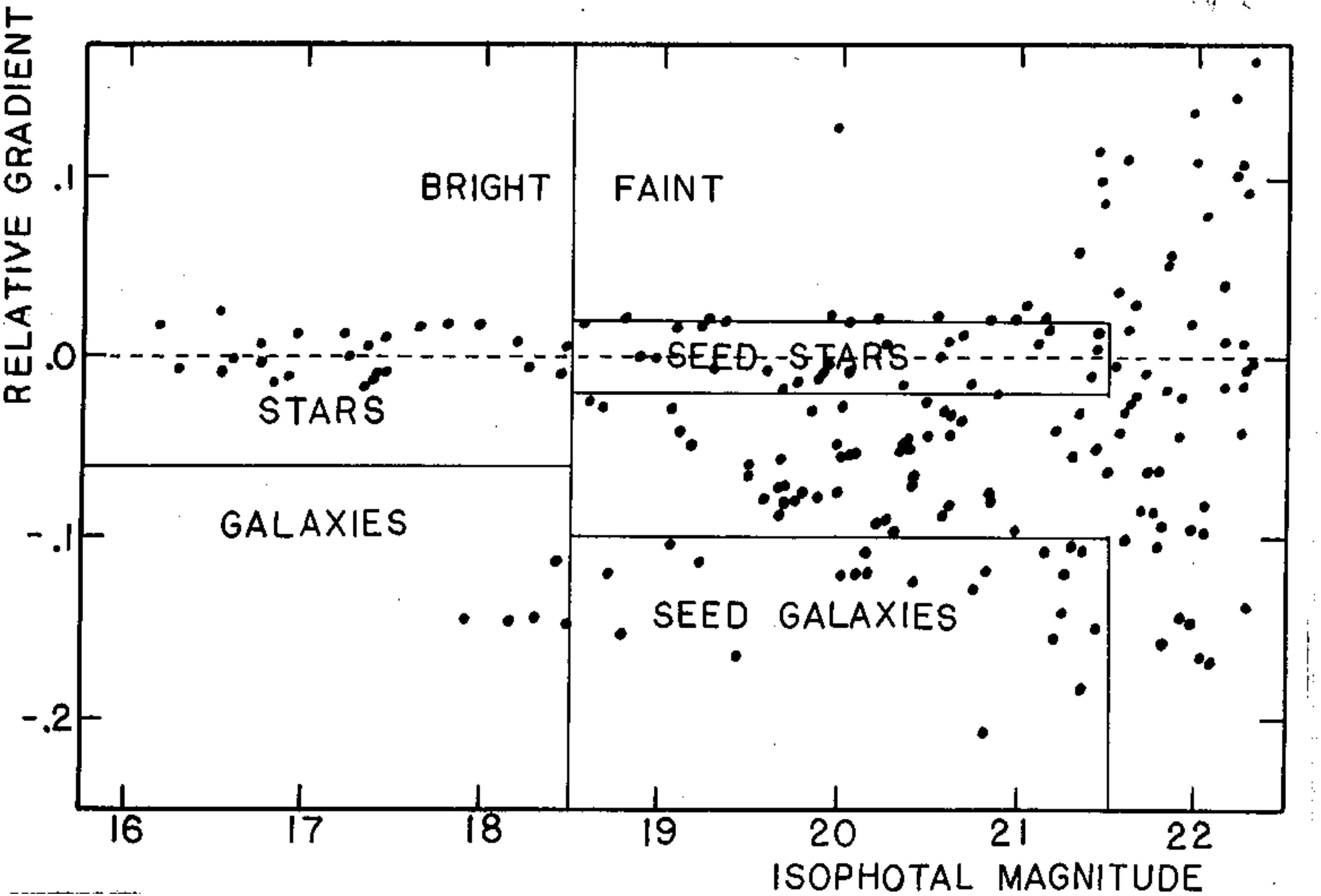
$d_{i0,j0} = D_{i0,j0} / \langle D_{i,j} \rangle$, with (i,j) near (i_0,j_0), but different from (i_0,j_0)

$SHARP = d_{i0,j0} / C_{i0,j0}$

ROUNDNESS

$ROUND = 2*(C_x - C_y)/(C_x + C_y)$

C_x from the monodimensional Gaussian fit along the x direction
C_y from the monodimensional Gaussian fit along the y direction



RELATIVE GRADIENT
.1
.0
-.1
-.2
BRIGHT
FAINT
STARS
SEED STARS
GALAXIES
SEED GALAXIES
16
17
18
19
20
21
22
ISOPHOTAL MAGNITUDE

WEST, KRUSZEWSKI

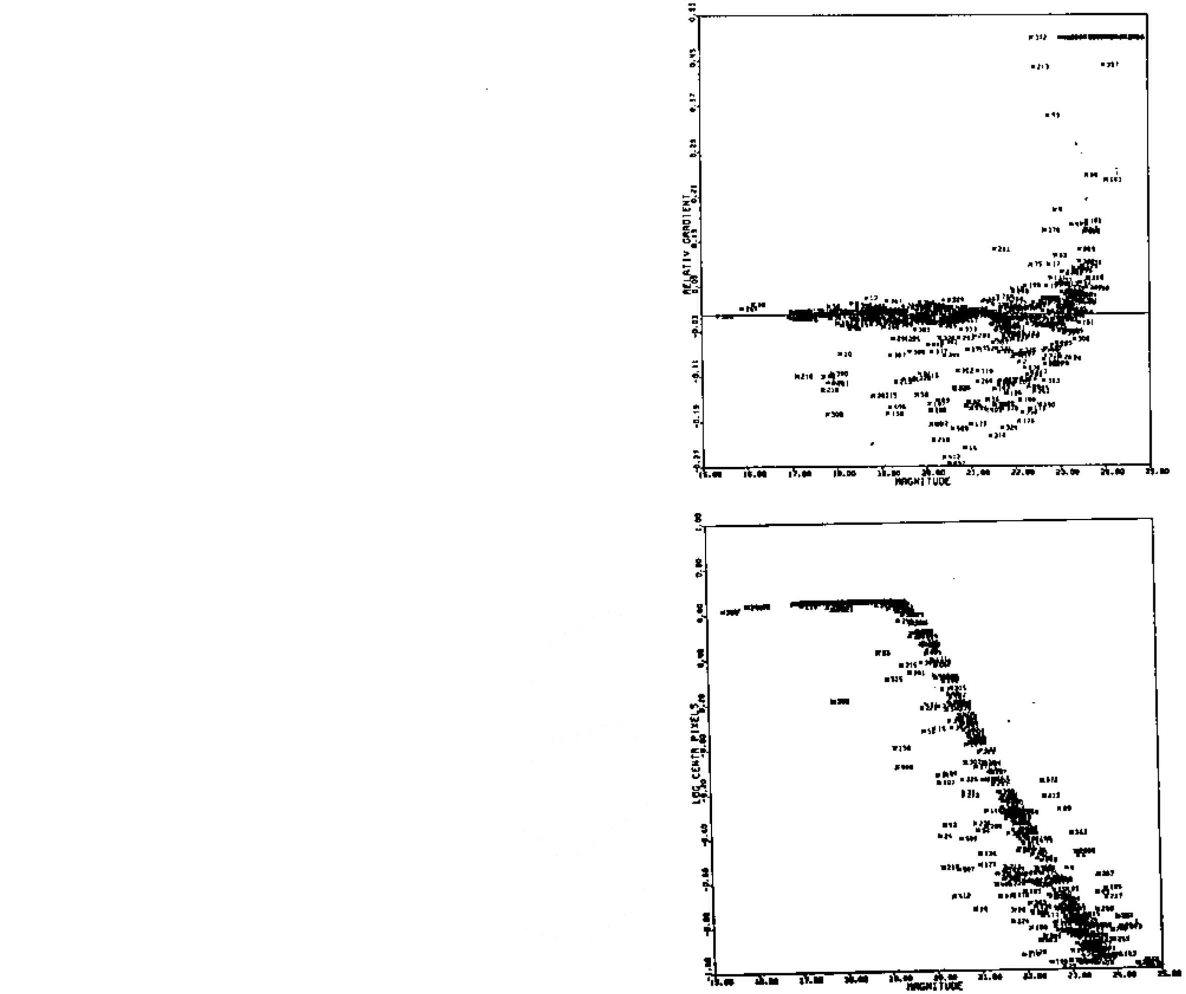
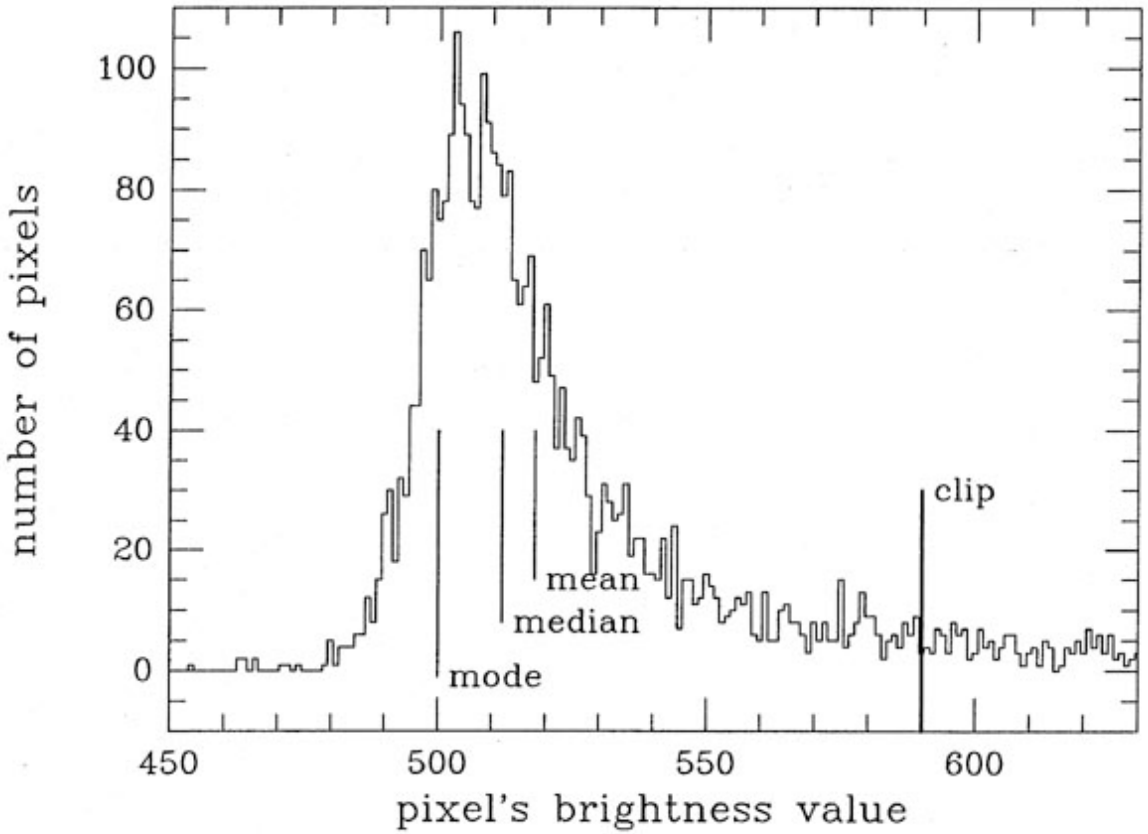


Figure 4. An example of plots of classification parameters in the field of cluster 1922-758, cf. Figure 3. The parameters shown here are: isophotal magnitude, relative gradient, and central surface brightness. The zero-point for the magnitude scale was set arbitrarily (but conservatively) by adopting a sky surface brightness level of 22.5 mag/arcsec². No corrections were made to remove the effect of saturation. The limiting isophote corresponds to 26.5 mag/arcsec². The relative gradient is calculated by a straight-line least-squares fit to the logarithmic deviation of the image profile from an average stellar image profile. The central surface brightness is calculated as an average of the intensity of the 9 central pixels in the image in units of sky background. It is here plotted on a logarithmic scale. The stars form narrow sequences in both diagrams. Galaxies lie below and to the left with respect to the stellar sequences. Plate defects fall above and to the right (e.g. ... the one-pixel defects in the upper right corner of the first plot and the line formed by

Background evaluation

The background measurement can be rather tricky (because of the crowding)

A good estimate of the local sky brightness is the mode of the distribution of the pixel counts in an annular aperture around the stars. Poisson errors make the peak of the histogram rather messy.

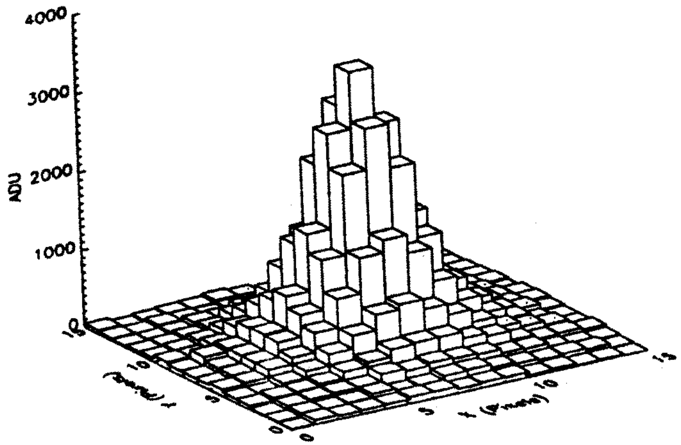


A good guess of the background level is:

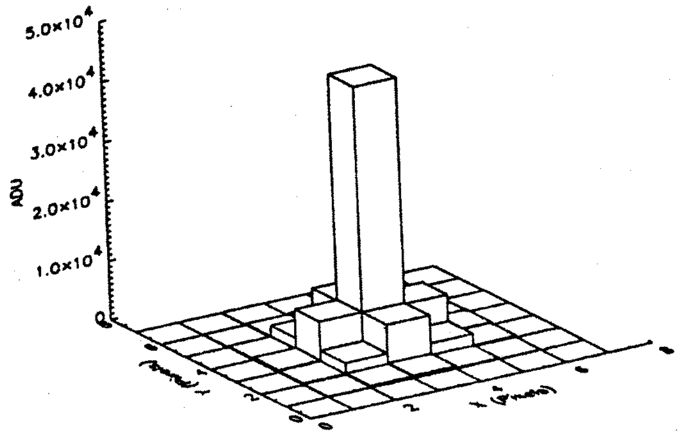
mode=3x(median)-2x(mean)

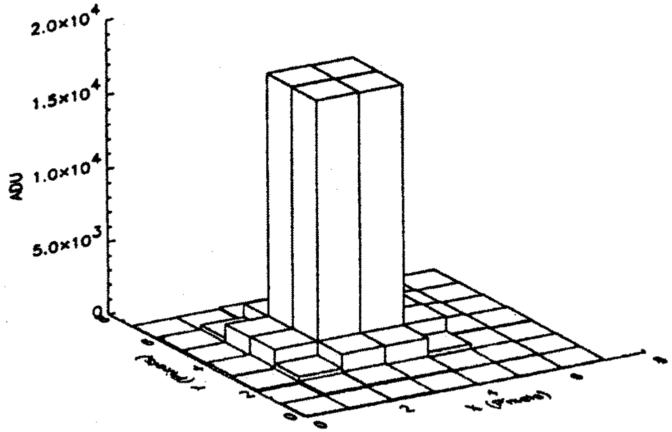
(which is striclty true for a gaussian distribution)

The background can be also derived from fitting.



Well sampled stars: ideal case
Limit around FWHM 2-3 pix.





Badly undersampled. Star profile strongly depends on the position of the center within the central pixel. The problem is worsened by the intra-pixel sensibility variation.

The stellar profile model: the PSF

The detailed shape of the average stellar profile in a digital frame must be encoded and stored in a format the computer can read and use for the subsequent fitting operations.

There are two possible approaches:

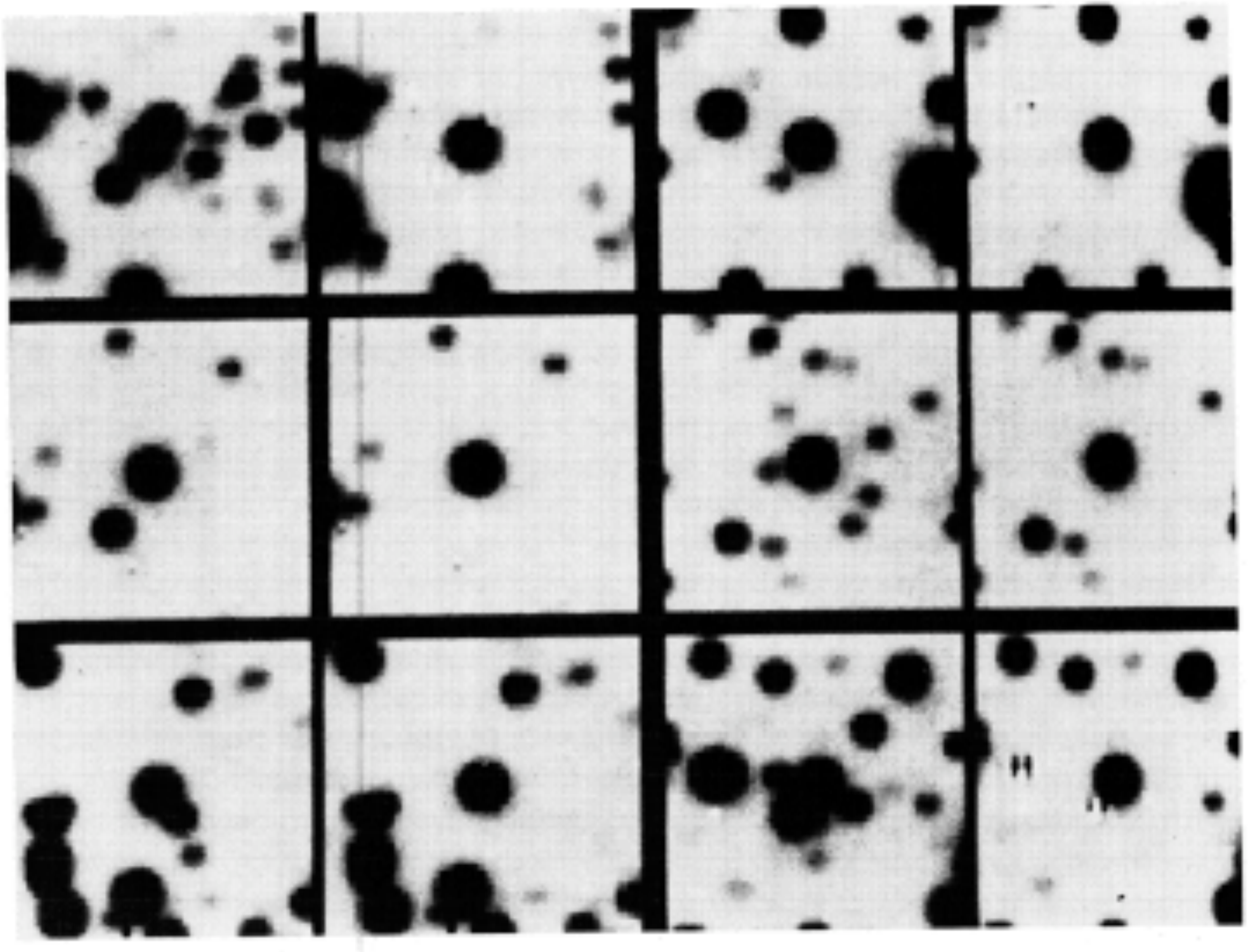
1. The analytic PSF. E.g. a gaussian, or, better a Moffat function:

$$S(r; C, B, R, \beta) = \frac{C}{\left(1 + \frac{r^2}{R^2}\right)^{\beta}} + B,$$

2. The empirical PSF. i.e. a matrix of numbers representing the stellar profile.

3. The hybrid PSF. i.e. a function in the core and a matrix of numbers in the outer regions.

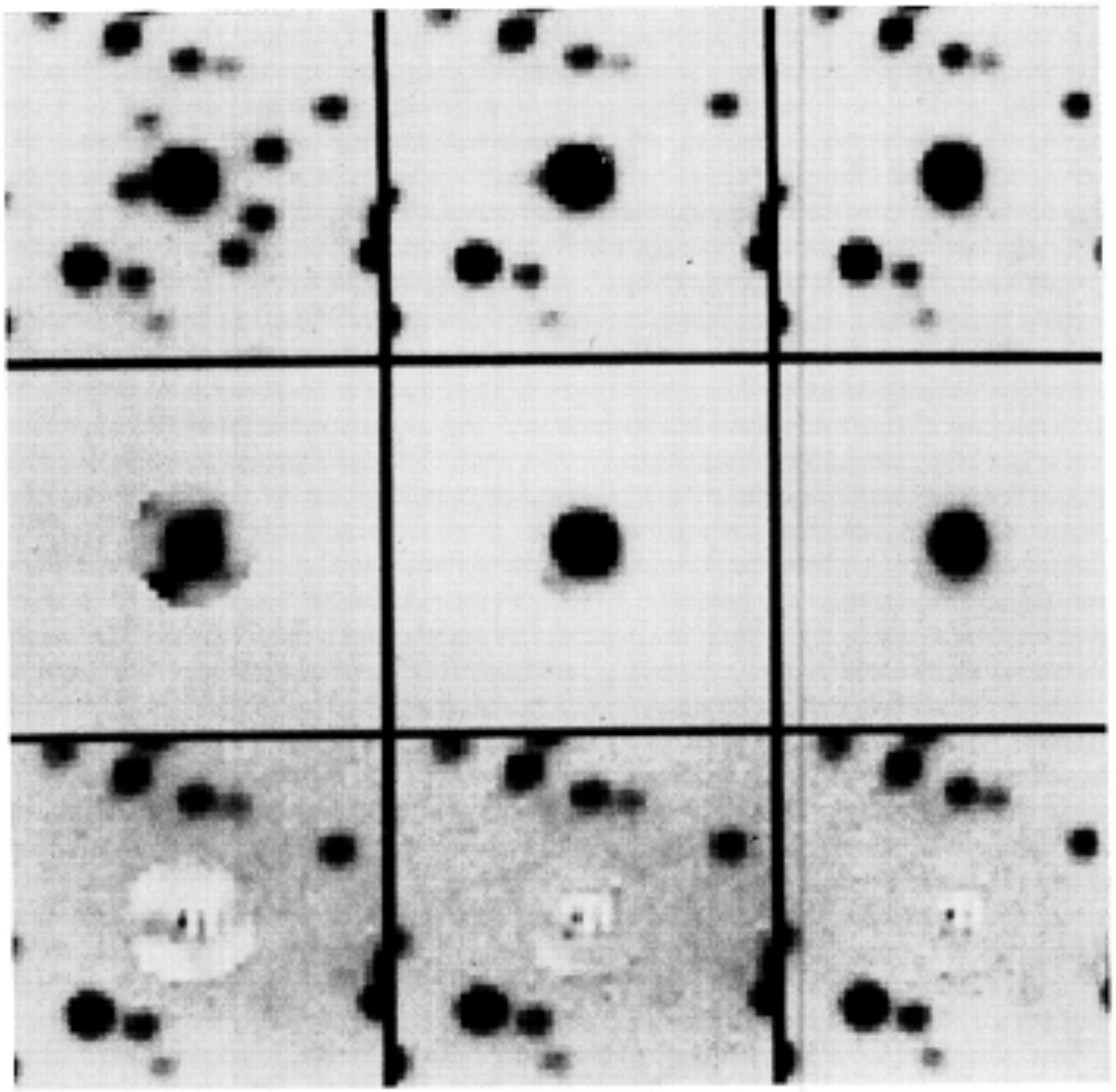
The PSF stars must be BRIGHT and CLEANED



Contaminating stars must be removed

This shows the relevance of the SUBTRACT routine

The PSF determination is an iterative process!



The PSF model after three iterations

After the starting guesses of the centroids (FIND) and brightness (PHOTOMETRY) are measured, and the PSF model determined (PSF), **the PSF is first shifted and scaled to the position and brightness of each star**, and each profile is subtracted, out to the profile radius, from the original image. This results in an array of residuals containing the sky brightness, random noise, **residual stars** and systematic errors due to inaccuracies in the estimate of the stellar parameters.

You may proceed further with a second search and analysis.

Matching stars between different digital images

Important astronomical information is often extracted from multiple images of the program object(s). These images could be taken with different pointings, orientations, filters, and even at different telescopes.

Once a list of common stars is constructed, the determination of the geometrical transformation parameters is a simple least-square problem.

The real problem is to find an efficent way to match many thousands of stars located in dozens of images.

There are two currently used methods: the “triangles” method (Stetson) and the staistical method (Lauberts, ESO-MIDAS).

THE PHOTOMETRIC ERRORS

Once we have the final photometry we have to determine the photometric errors for the single stars. This is not an obvious task because many error sources contributes to the final uncertainty of the data. Four different methods can be used:

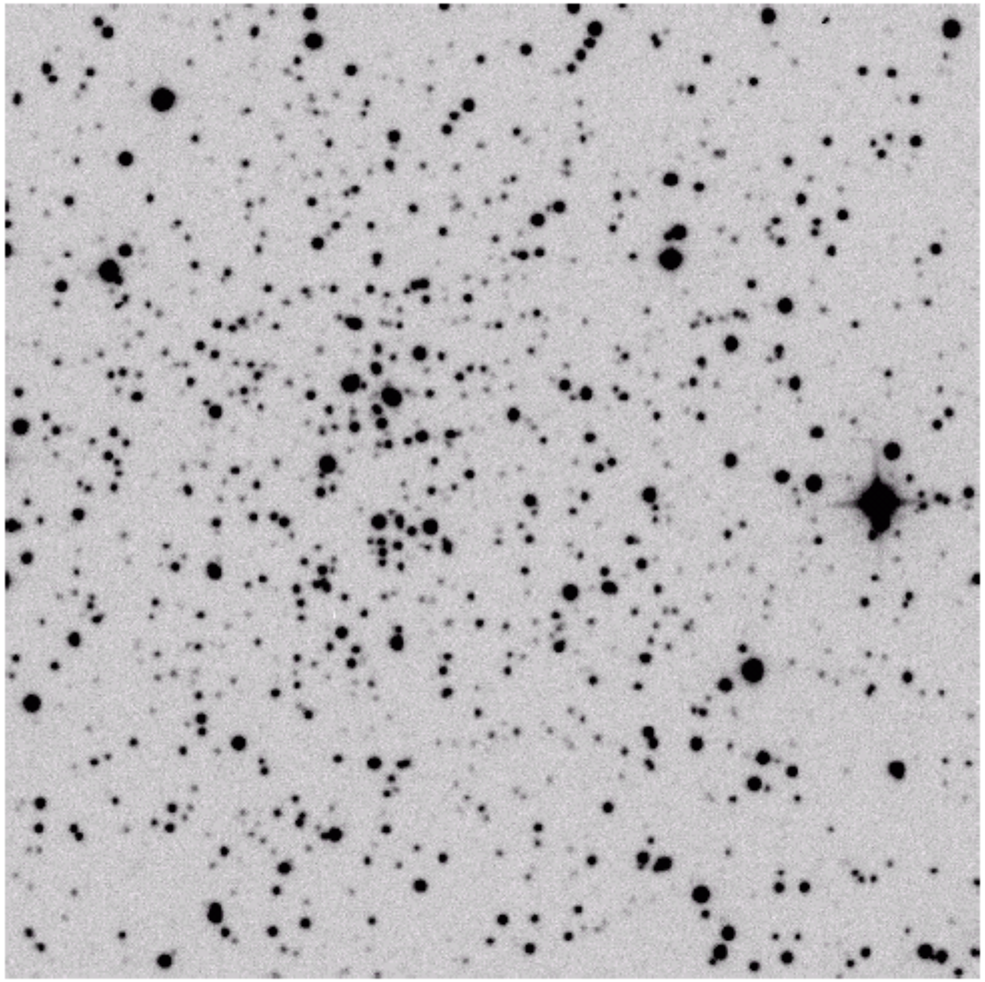
1) DAOPHOT gives the statistical error for each star.

2) Another obvious method is to compare the measurements from couples of images.

3) Daophot offers also the possibility to add artificial stars and to measure them simultaneously to the original stars.

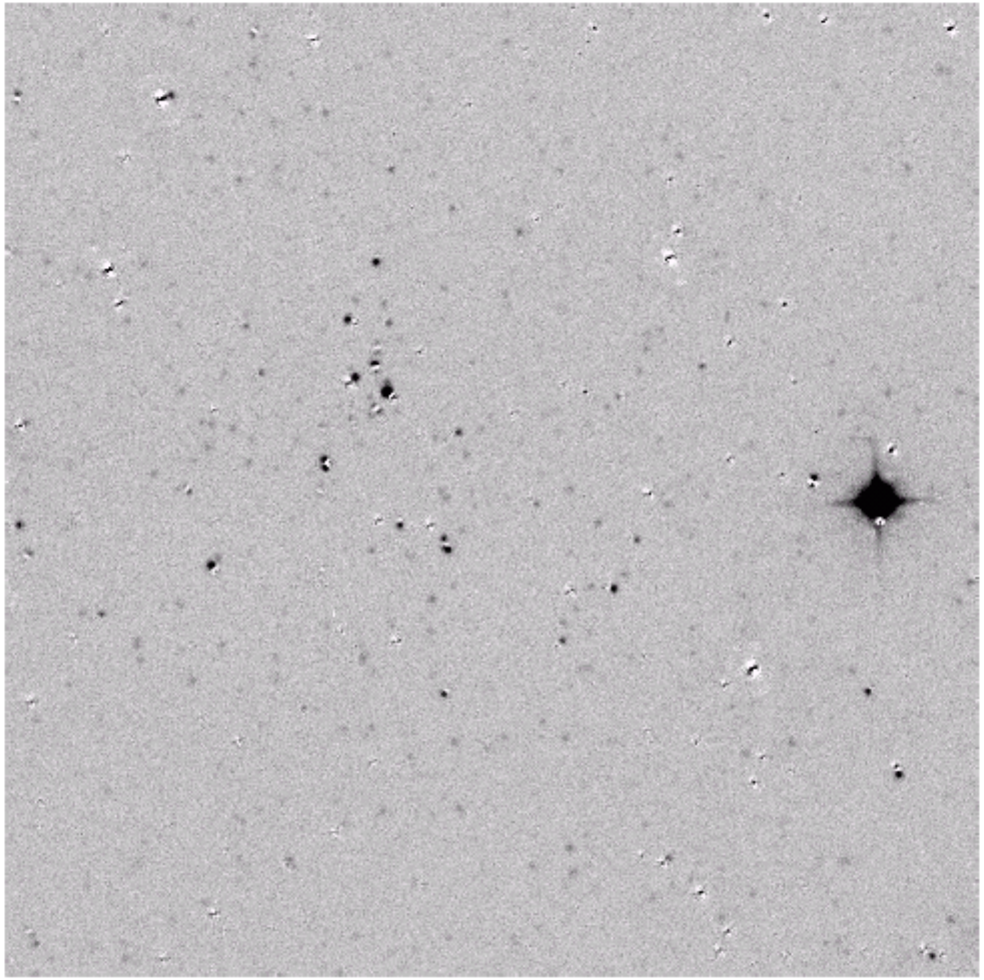
4) Finally the dispersion of the data can be derived from astrophysical considerations (for example from the dispersion of the CMDs).

Mo, 28 Aug 2006   15:07:23 MIDAS version: 99NOV

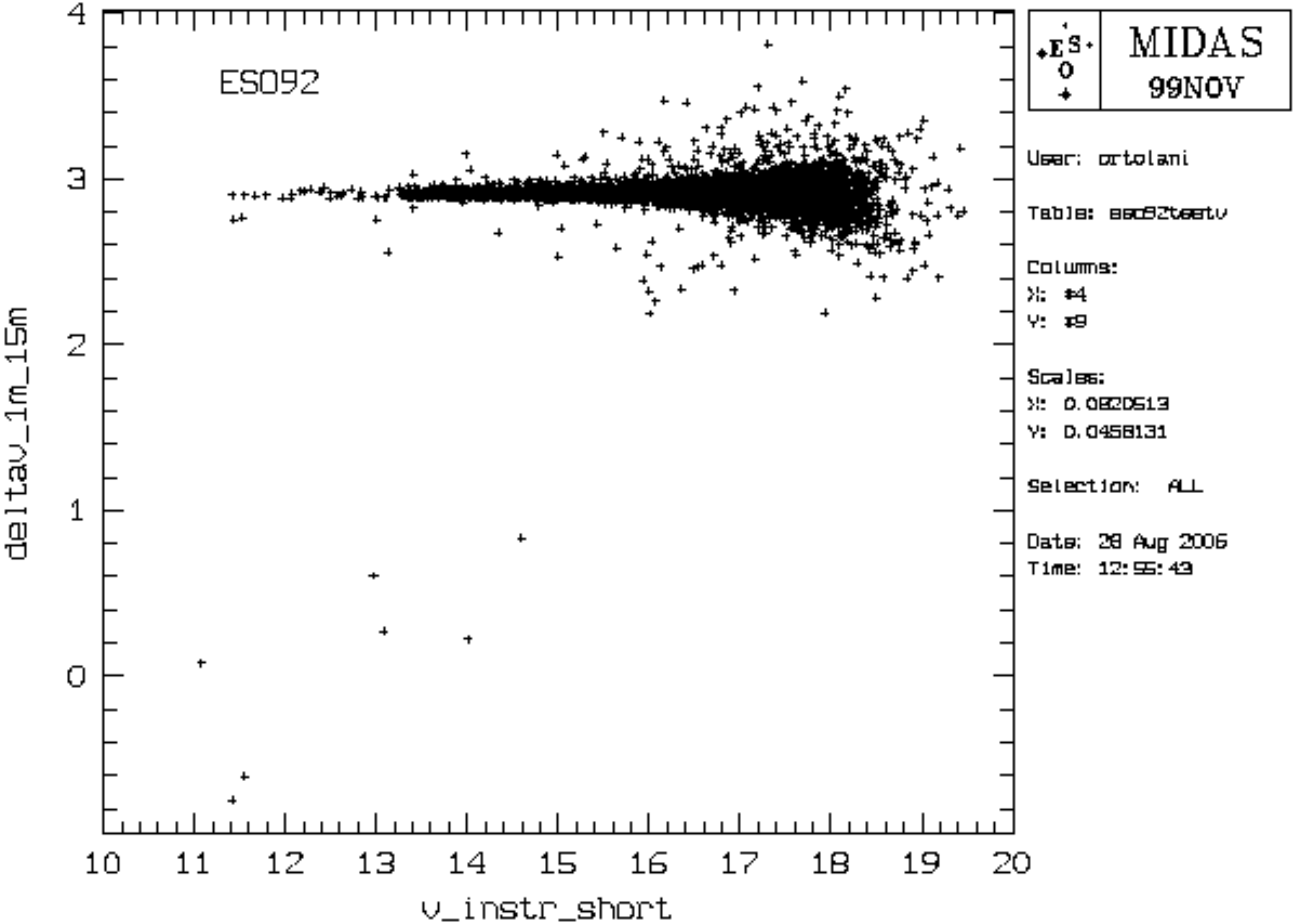


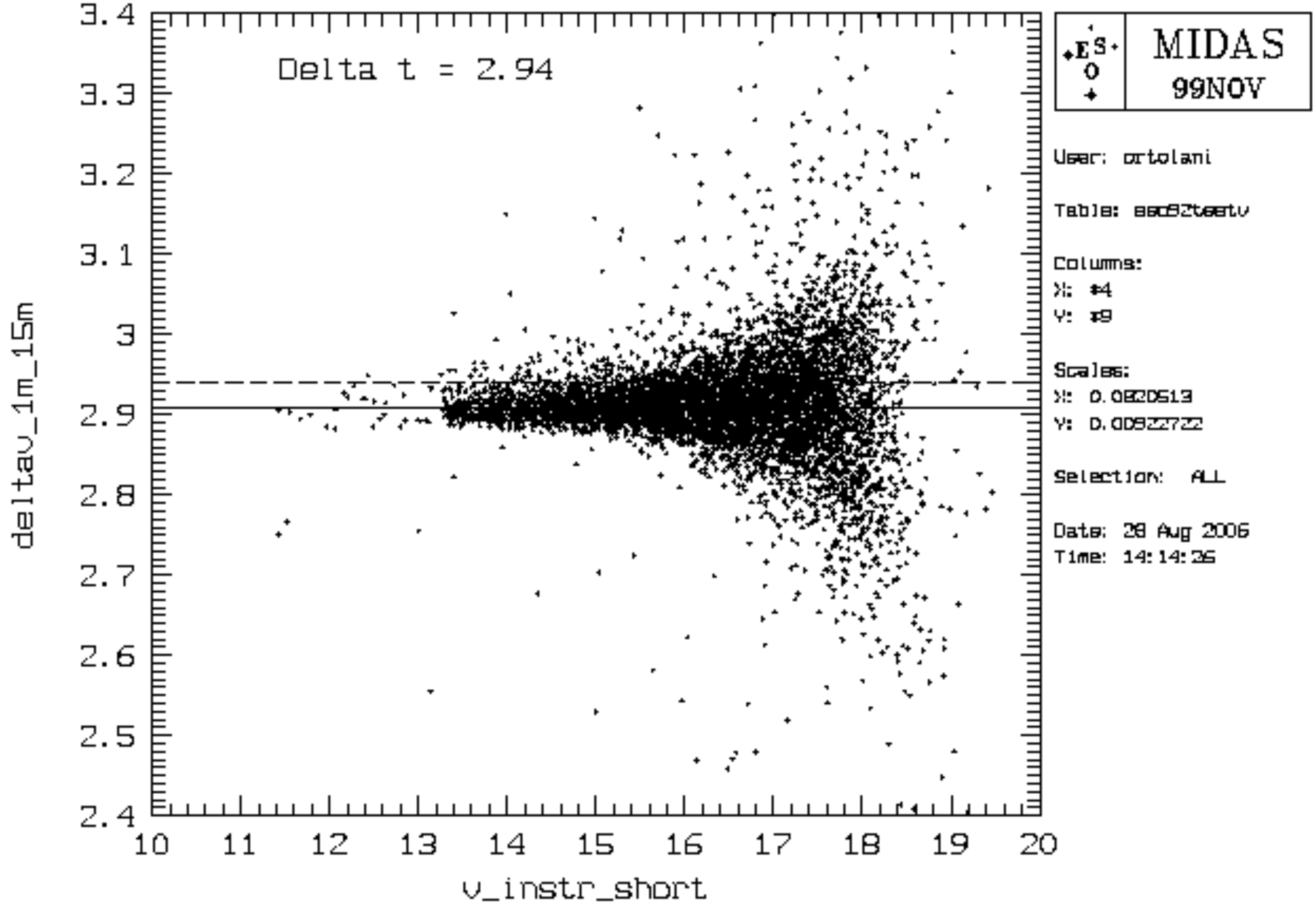
Frame : a50
Identifier : ESO92sc05/v/1
ITT-table : ramp.itt
Coordinates : 763, 755 : 1274, 1266
Pixels : 1, 1 : 512, 512
Cut values : 100, 400
User : ortolani

Mo, 28 Aug 2006 15:08:31 MIDAS version: 99NOV

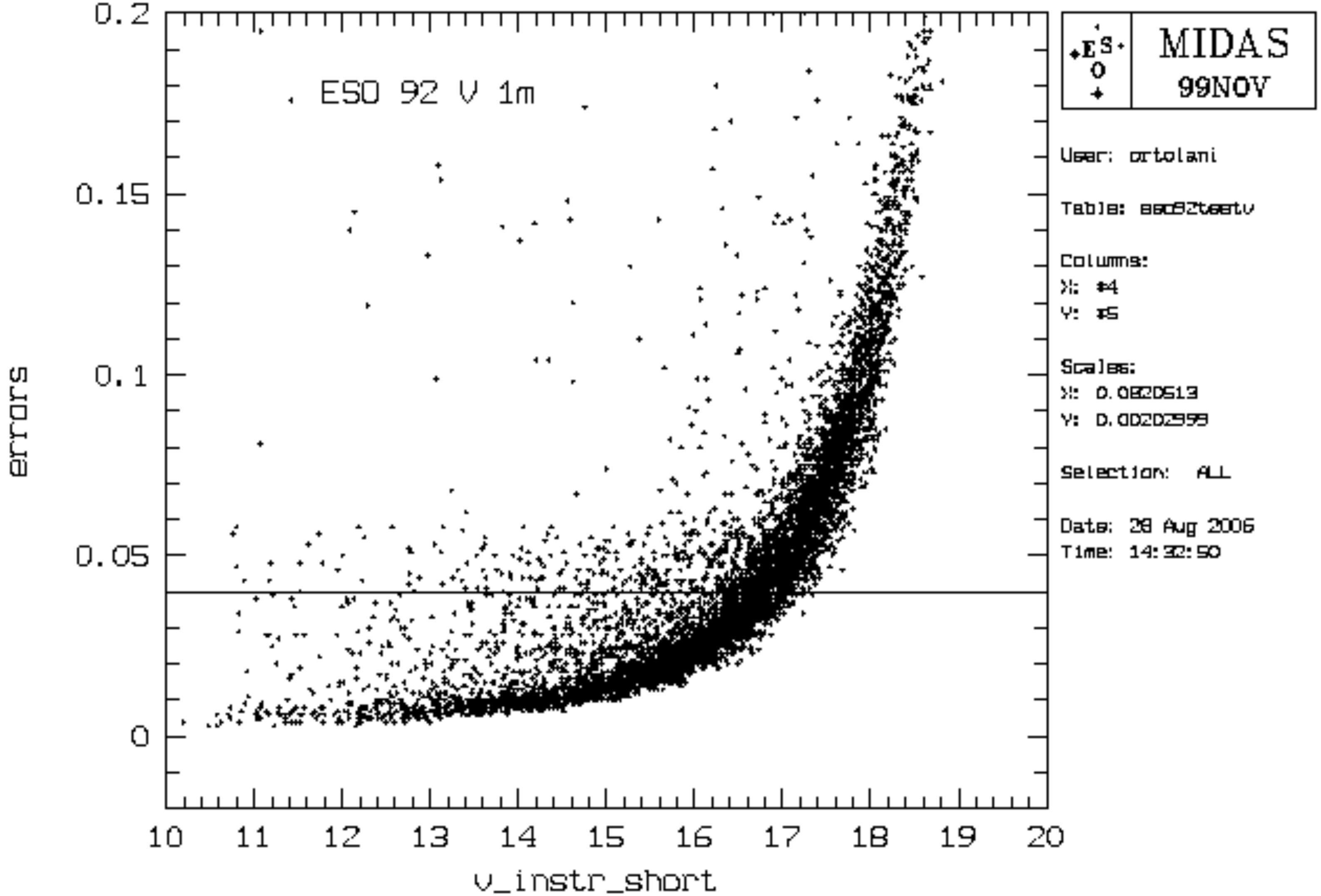


Frame : a50s
Identifier : ESO92sc05/v/1
ITT-table : ramp.itt
Coordinates : 763, 755 : 1274, 1266
Pixels : 1, 1 : 512, 512
Cut values : 100, 350
User : ortolani

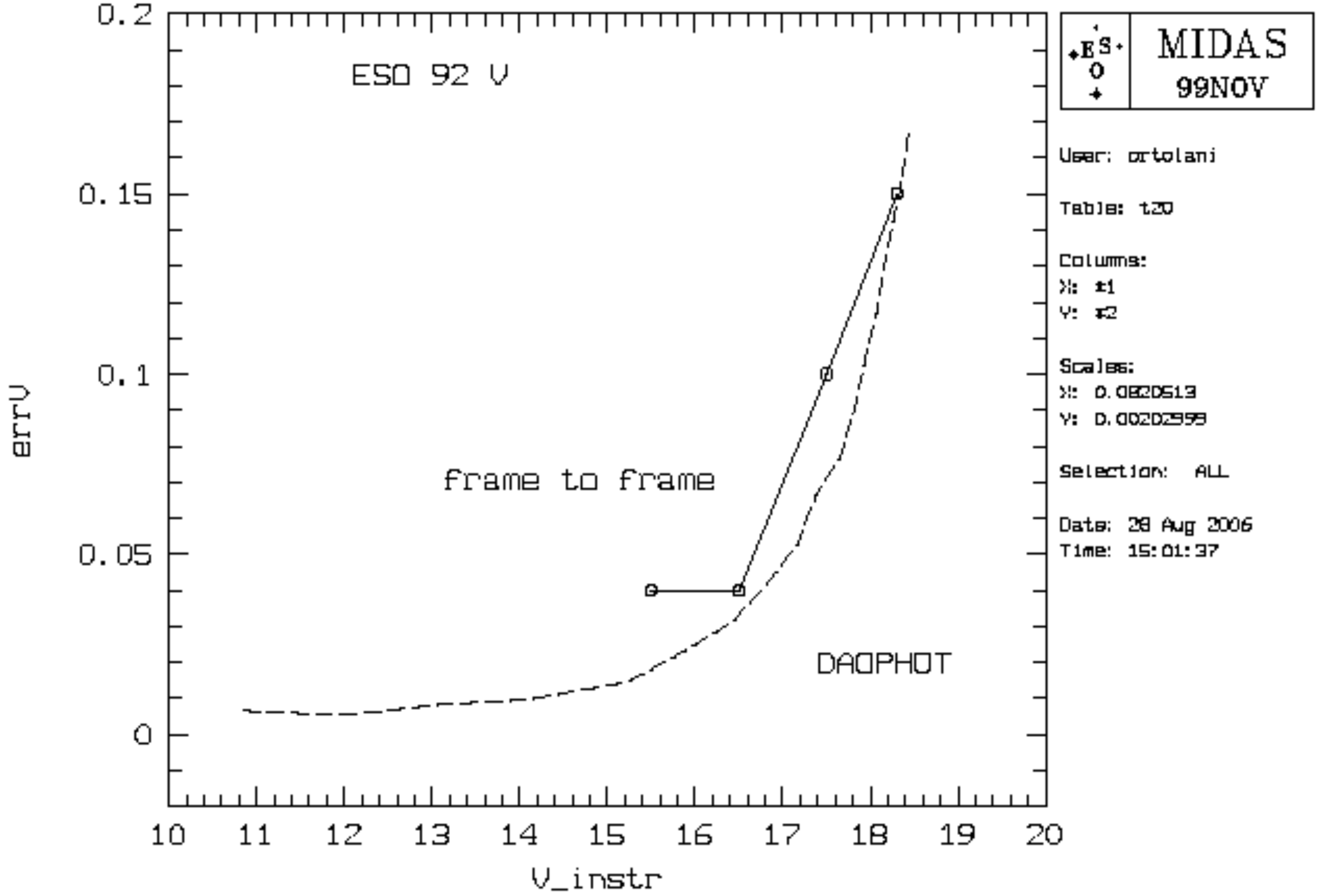

ESO92
deltav_1m_15m
v_instr_short
4
3
2
1
0
10
11
12
13
14
15
16
17
18
19
20
MIDAS
99NOV
User: ortolani
Table: eso92testv
Columns:
X: #4
Y: #9
Scales:
X: 0.0820513
Y: 0.0458131
Selection: ALL
Date: 28 Aug 2006
Time: 12:55:43



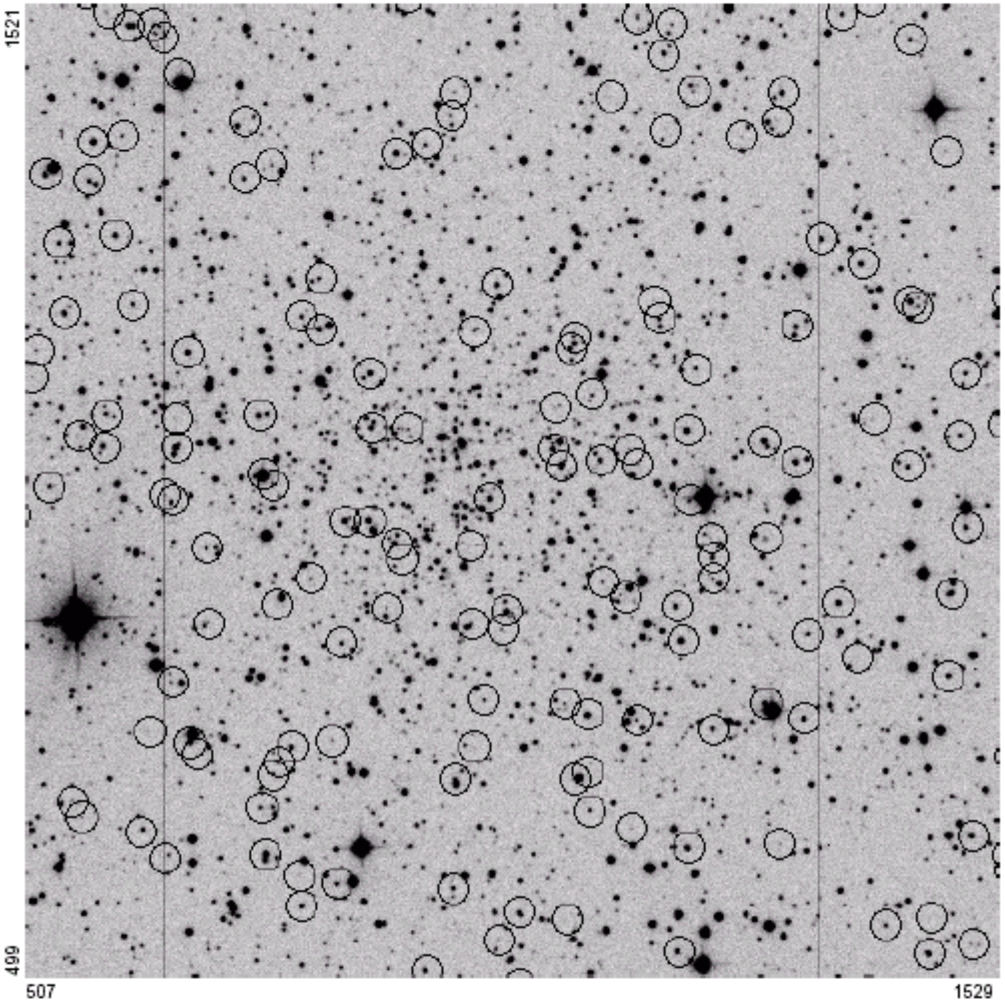
Delta t = 2.94
deltav_1m_15m
v_instr_short
MIDAS
99NOV
User: ortolani
Table: sec92tsetv
Columns:
X: #4
Y: #9
Scales:
X: 0.0820513
Y: 0.00922722
Selection: ALL
Date: 28 Aug 2006
Time: 14:14:26



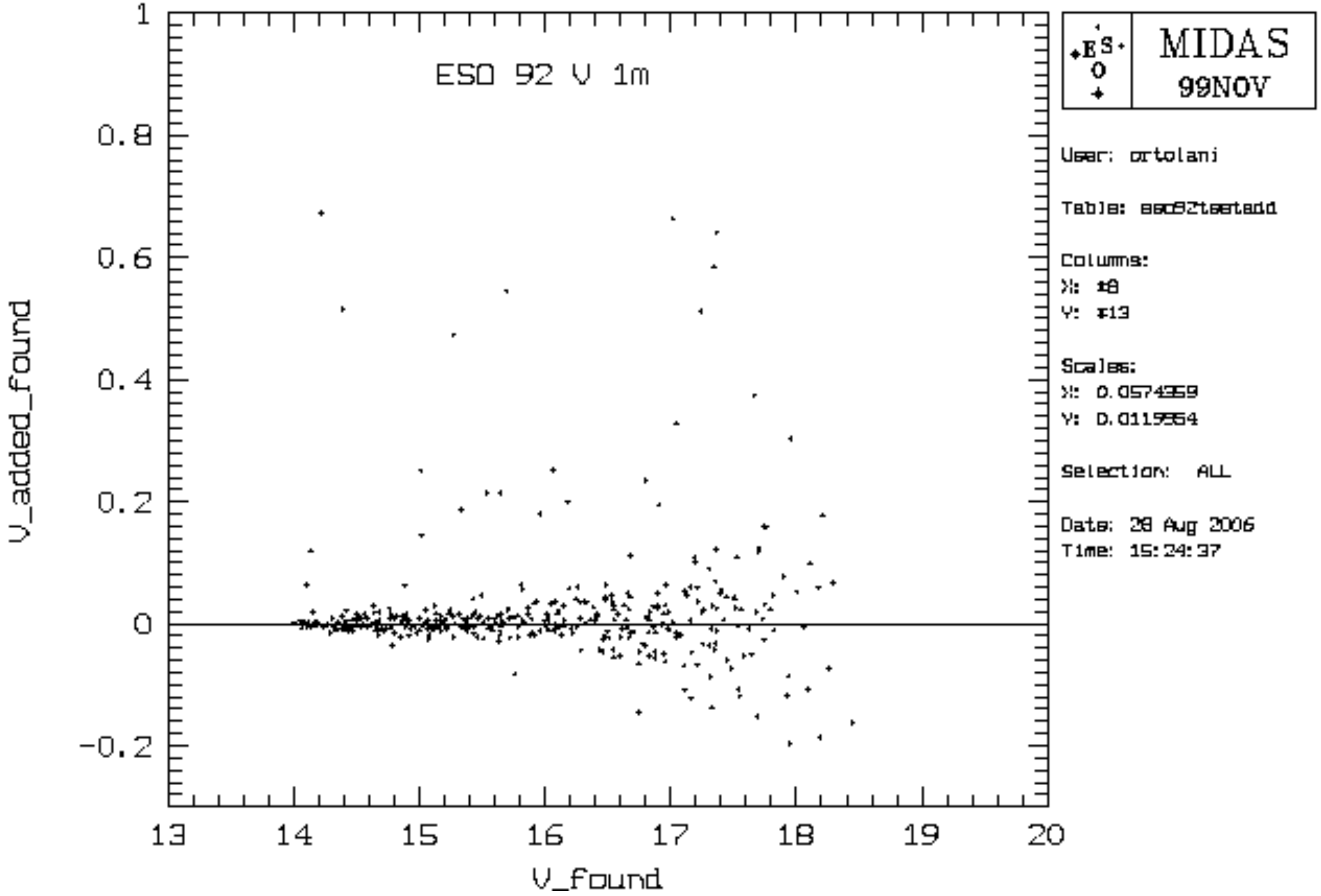
ESO 92 V 1m
errors
v_instr_short
0.2
0.15
0.1
0.05
0
10
11
12
13
14
15
16
17
18
19
20
MIDAS
99NOV
User: ortolani
Table: eso92testv
Columns:
X: #4
Y: #5
Scales:
X: 0.0820513
Y: 0.00202999
Selection: ALL
Date: 28 Aug 2006
Time: 14:32:50


ESO 92 V
frame to frame
DAOPHOT
errV
V_instr
0.2
0.15
0.1
0.05
0
10
11
12
13
14
15
16
17
18
19
20
MIDAS
99NOV
User: ortolani
Table: t20
Columns:
X: #1
Y: #2
Scales:
X: 0.0820513
Y: 0.00202999
Selection: ALL
Date: 28 Aug 2006
Time: 15:01:37

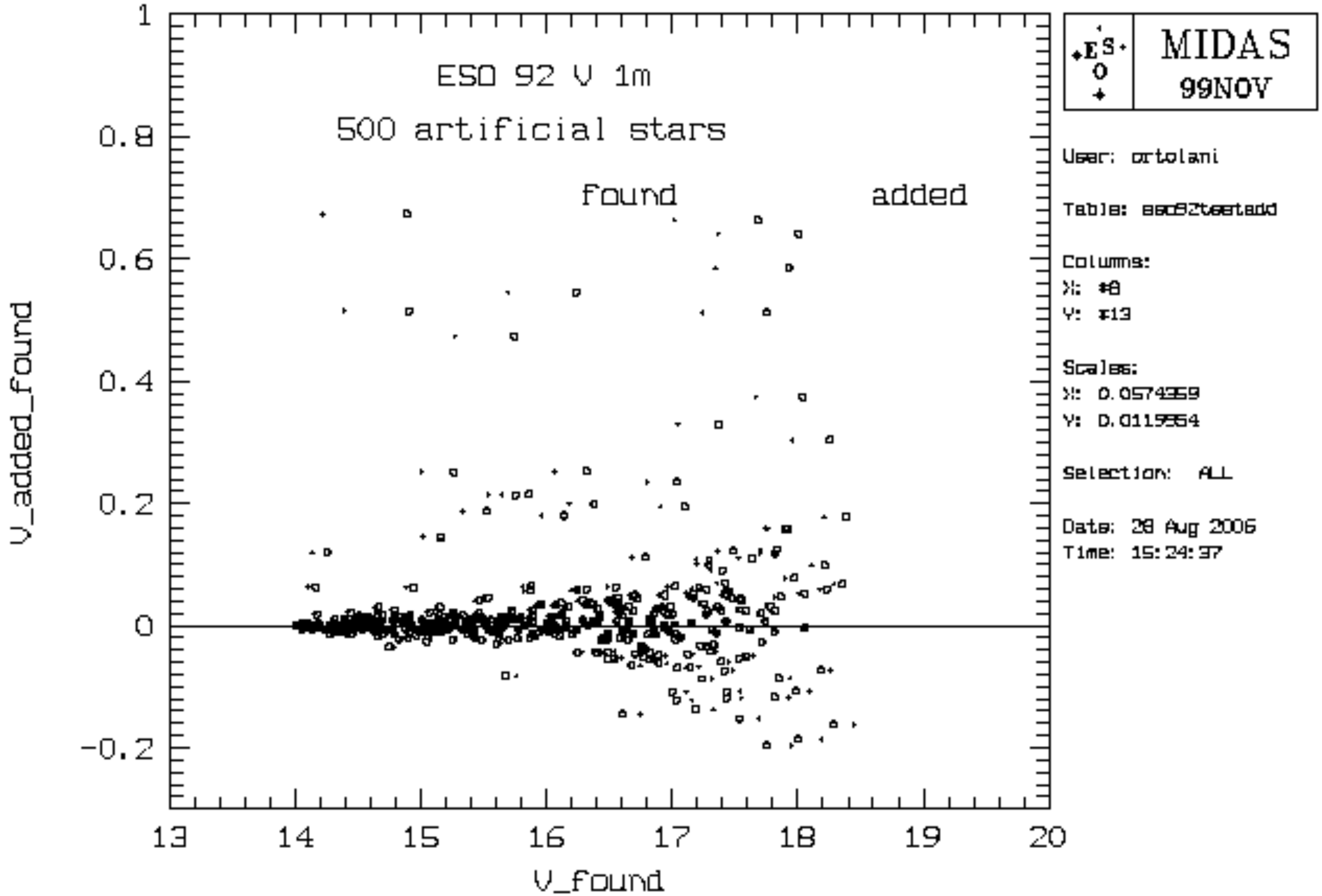
Mo, 28 Aug 2006 16:29:39 MIDAS version: 99NOV



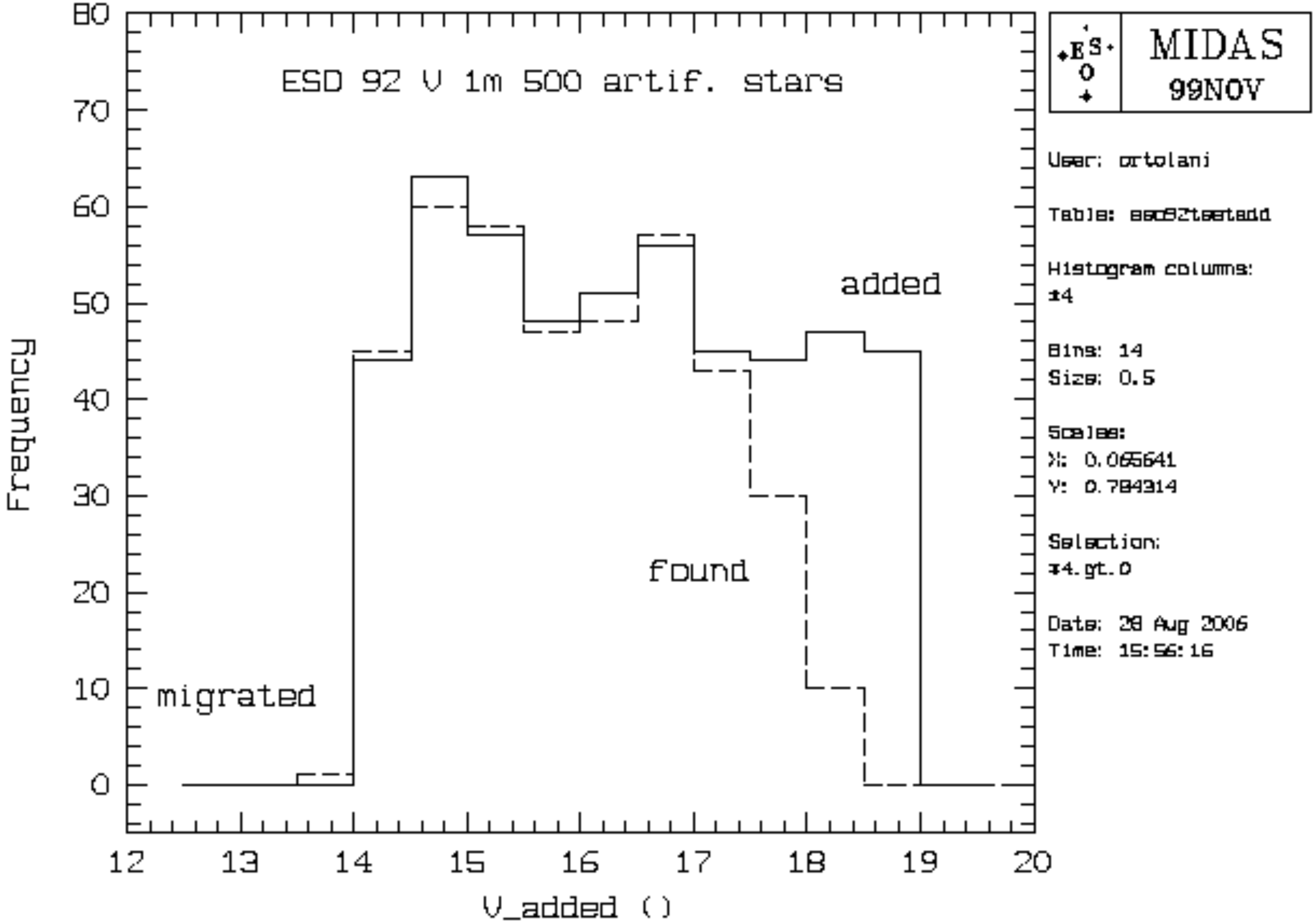
Frame : add01
Identifier : ESO92sc05/v/1
ITT-table : ramp.itt
Coordinates : 507, 499 : 1529, 1521
Pixels : 1, 1 : 512, 512
Cut values : 100, 350
User : ortolani



ESO 92 V 1m
V_added_found
V_found
1
0.8
0.6
0.4
0.2
0
-0.2
13
14
15
16
17
18
19
20
MIDAS
99NOV
User: ortolani
Table: eso92testadd
Columns:
X: #8
Y: #13
Scales:
X: 0.0574359
Y: 0.0119554
Selection: ALL
Date: 28 Aug 2006
Time: 15:24:37



ESO 92 V 1m
500 artificial stars
found
added
V_added_found
V_found
MIDAS
99NOV
User: ortolani
Columns:
X: #8
Y: #13
Scales:
X: 0.0574359
Y: 0.0115554
Selection: ALL
Date: 28 Aug 2006
Time: 15:24:37



ESO 92 V 1m 500 artif. stars
added
found
migrated
Frequency
V_added ()
MIDAS
99NOV
User: ortolani
Table: eso92testadd
Histogram columns:
#4
Bins: 14
Size: 0.5
Scales:
X: 0.065641
Y: 0.784314
Selection:
#4.gt.0
Date: 28 Aug 2006
Time: 15:56:16

SIGNAL TO NOISE RATIO
LIMITING MAGNITUDE WITH CCDs

$$S/N = \frac{s \times t}{N} \qquad \text{AT LIMIT } S/N < {}^{10}_{3}$$

$$N^2 = \sigma^2_{SHOT} + \sigma^2_{R.O.N.} + \sigma^2_{SPN} + \sigma^2_{DARK+COSMICS} + \sigma^2_{SKY}$$

$$N = \sqrt{s \times t + RON^2 \times A_{ST.} + SKY \times t \times A_{ST.} + (F \times SKY \times t)^2 + DARK \times t \times A_{ST}}$$

WITH: $A_{ST.} = FWHM^2 \times \pi$ (KING, PASP, 95, 163)

$s_{V=0} = R^2_{TEL.} \times \pi \times$ [redacted] $10^6 \times Q.E._{TOT.}$ (fot./sec.)

$F^2 = F_1^2 \times A_{ST} + F_2^2 \times A_{ST}/4 + F_3^2 \times A_{ST}/9 \ldots$

$F_1, F_2, F_3 \ldots$: SPATIAL NOISE COEFF. AT $\ell = 1, 2, \ldots$

$$m_{lim} = -2.5 \; \mathrm{LOG} \left(\frac{(S/N) \times N}{s_{m=0} \times t} \right)$$

WITH $N \propto \sqrt{A_t}, t, \sqrt{t}, \sqrt{Q.E.}$

$s \propto Q.E., A_{TEL}$, mag. zero point

$\rightarrow m_{lim} \propto \sqrt{A_{TEL}}, \sqrt{t}, \sqrt{Q.E.}$ IF SKY IS NOT VERY HIGH

LIMITING SIGNALS
NOISE SOURCES

- SHOT, READ OUT, SKY, SPATIAL NOISE, DARK, COSMICS

$$\sigma^2 = \sigma^2_{SHOT} + \sigma^2_{RON} + \sigma^2_{SKY} + \sigma^2_{SPN} + \sigma^2_{DARK}$$

$$N = \sqrt{RON^2 \times A + SKY \times t \times A + (SPN \times SKY \times t)^2 + S \times t + DARK \times t \times A}$$

$$A = FWHM^2 \times \pi$$

3.6 + EFOSC CCD #3

$FW = 1.''2$

$SPN = 0.3\%$

$Q.E. = 30\%$

$RON = 40$

$SKY = 21.5$ (V/□")

$S/N = 10$

CCD OBSERVATIONS: STARS + GALAXIES

ACCURACY

ACCURACY IS LIMITED BY SEVERAL ERROR SOURCES AFFECTING ABSOLUTE AND/OR RELATIVE CALIBRATION (MEASUREMENTS):

EXAMPES

ERROR SOURCE	MAG.	WHAT TO DO...
— CCD SHUTTER	~0.1 (~0.5s)	USE LONGER EXPOSURES CHECK SHUTTER TIMING
— NOISE	(...)	LONGER OR MULTIPLE EXPOSURES/DEFOCUS
— NON-UNIFORMITY	(~0.3-0.005)	CORRECT WITH PROPER FLAT FIELD
— COLOR/TEMP. OF STARS	(~0.3)	CHECK COLOR TERMS CHECK FILTERS AND RED LEAKS
— SKY TRANSPARENCY	~0.1	MEASURE STANDARDS ON LINE

CCD photometry evolution

IMPROVING

1. Dark current
2. Linearity
3. Cosmics
4. Readout noise
5. Cosmetics
6. Quantum efficiency and spectral coverage

STILL A PROBLEM (or getting worst):

1 Timing errors (large formats)
2 Internal reflections (due to focal reducers or flatteners)
3 Undersampling
4 DEVIATIONS FROM STANDARD SYSTEMS (big filters…)

Calibration of extended sources

The calibration for extended sources is still based on standard stars. The basic concept is that the flux of the star is compared to a fixed area.

Example: the sky background

$$\text{Sky(int./unit area)} = (\text{1/pixel area}) \times I_{sky}$$

$$m_{sky} = -2.5 \log \text{Sky} \qquad \text{(instr. mag./unit area)}$$

then use standard transformations.

Wide band calibrations are very difficult if the passband of the system is not standard.

EXAMPLES OF DAOPHOT INPUTS

INPUT PARAMETERS: GENERAL

READ NOISE (ADU; 1 frame) =	3.00	GAIN (e-/ADU; 1 frame) =	1.75
LOW GOOD DATUM (in sigmas) =	100.00	HIGH GOOD DATUM (in ADU) =	32000.00
FWHM OF OBJECT =	1.50	THRESHOLD (in sigmas) =	4.00
LS (LOW SHARPNESS CUTOFF) =	0.20	HS (HIGH SHARPNESS CUTOFF) =	1.00
LR (LOW ROUNDNESS CUTOFF) =	-0.70	HR (HIGH ROUNDNESS CUTOFF) =	0.70
WATCH PROGRESS =	-2.00	FITTING RADIUS =	2.00
PSF RADIUS =	14.00	VARIABLE PSF =	2.00
FRACTIONAL-PIXEL EXPANSION =	0.00	ANALYTIC MODEL PSF =	2.00
EXTRA PSF CLEANING PASSES =	3.00	USE SATURATED PSF STARS =	0.00
PERCENT ERROR (in %) =	0.75	PROFILE ERROR (in %) =	5.00

INPUT PARAMETERS: APERTURE PHOTOMETRY

File with aperture radii (default photo.opt):

A1	RADIUS OF APERTURE 1 =	1.50	A2	RADIUS OF APERTURE 2 =	1.64
A3	RADIUS OF APERTURE 3 =	1.82	A4	RADIUS OF APERTURE 4 =	2.03
A5	RADIUS OF APERTURE 5 =	2.28	A6	RADIUS OF APERTURE 6 =	2.56
A7	RADIUS OF APERTURE 7 =	2.88	A8	RADIUS OF APERTURE 8 =	3.23
A9	RADIUS OF APERTURE 9 =	3.62	AA	RADIUS OF APERTURE 10 =	4.05
AB	RADIUS OF APERTURE 11 =	4.51	AC	RADIUS OF APERTURE 12 =	5.00
IS	INNER SKY RADIUS =	14.00	OS	OUTER SKY RADIUS =	35.00