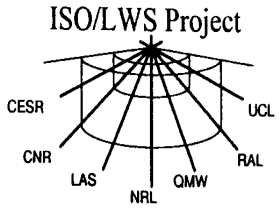

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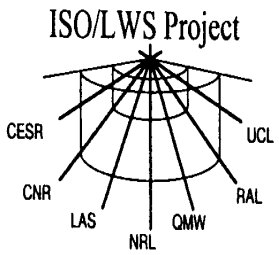
Overview of all the techy bits!

By Bruce Swinyard.....

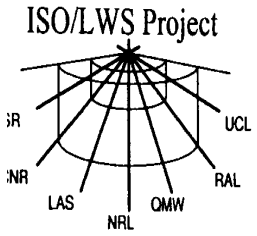
What we can cover.....

- Overview of the instrument operation.
- Overview of the calibration - how its done and how are we doing in terms of accuracy and repeatability.
- Propagation of flux uncertainties - estimating the uncertainty on your fluxes.
- Drift correction.
- Detector non-linearity and time response.
- Fringing - what causes it and can we get rid of it?
- Beam size - what is the LWS beam size and why?
- Fabry Perot range scans.



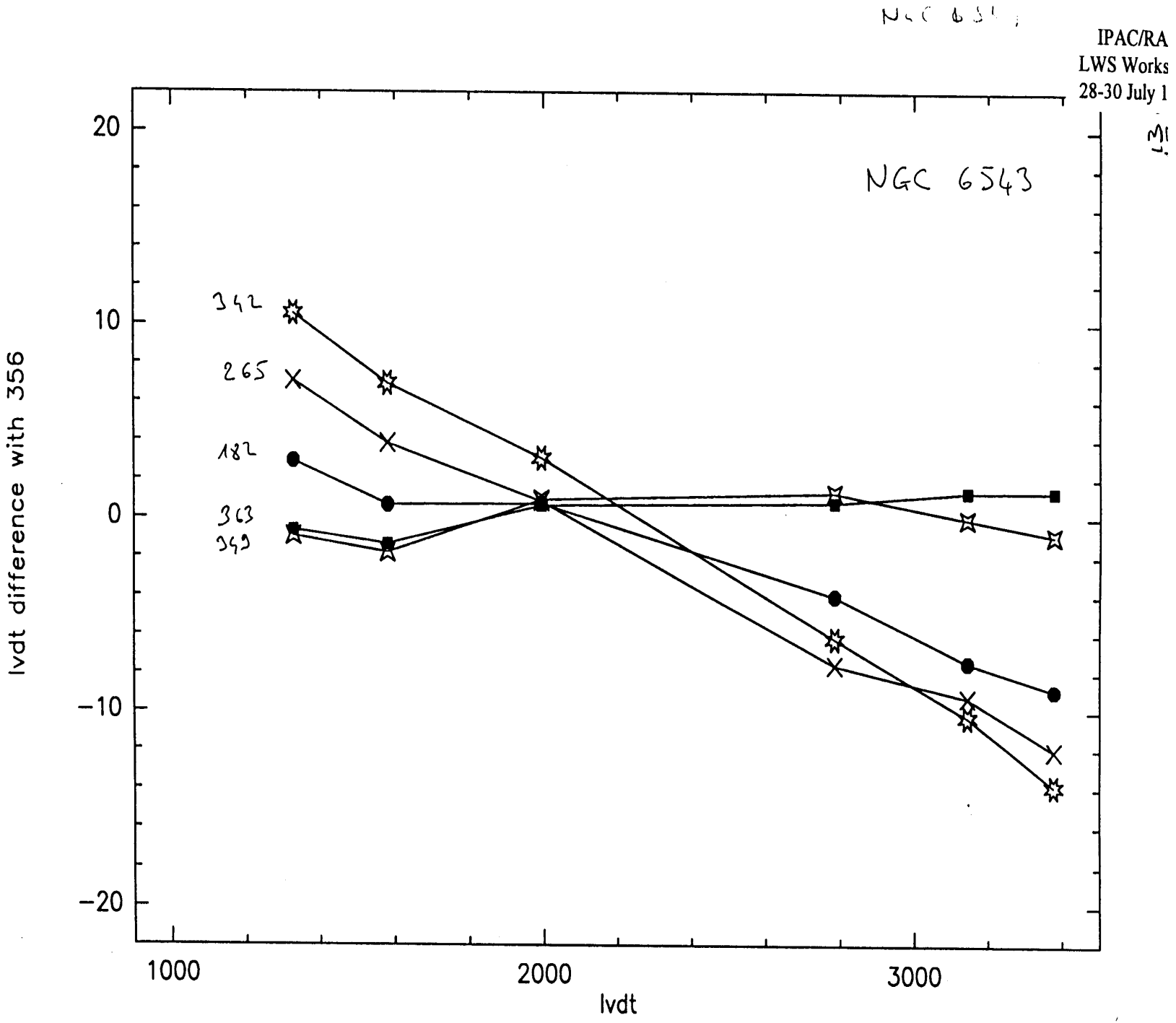
Instrument Calibration

- The basic flux calibration scheme relies on observations of astronomical objects with known continua (Uranus, Mars + secondary standards).
- To maintain the flux calibration as a function of time the response of the detectors to the internal calibrators is measured before and after every AOT (illuminator flashes).
- The wavelength calibration of both the grating and the FP's relies on the measurement of sources with known lines at known relative velocities.
- Both the flux and wavelength calibrations are monitored on at least a weekly basis - this has shown up some problems over the course of the mission but has also allowed us to solve them.



Grating Wavelength Calibration

- Weekly monitoring of the wavelength calibration began to show serious deviations in grating behaviour in the middle of 1996.
- This is manifested by changes in the LVDT position of the centroid of a given line on a given source.
- The behaviour grew worse towards the Autumn but appears(!) to have righted itself.
- A solution has been found whereby the coefficients that convert the LVDT into optical position have been derived for three (so far) different time periods.
- However OLP V6 does not have this implemented - therefore there may be wavelength inaccuracy in the grating calibration.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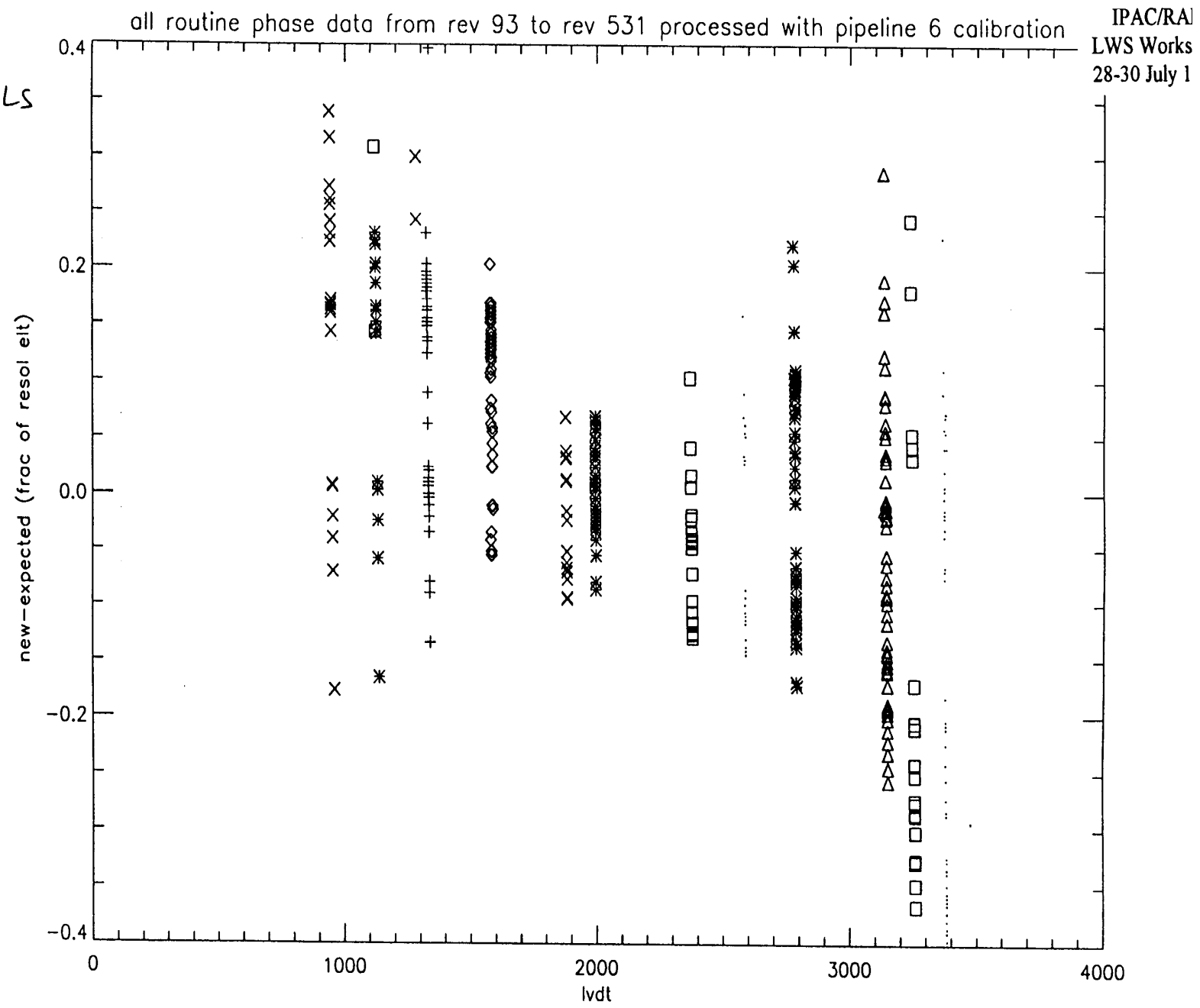
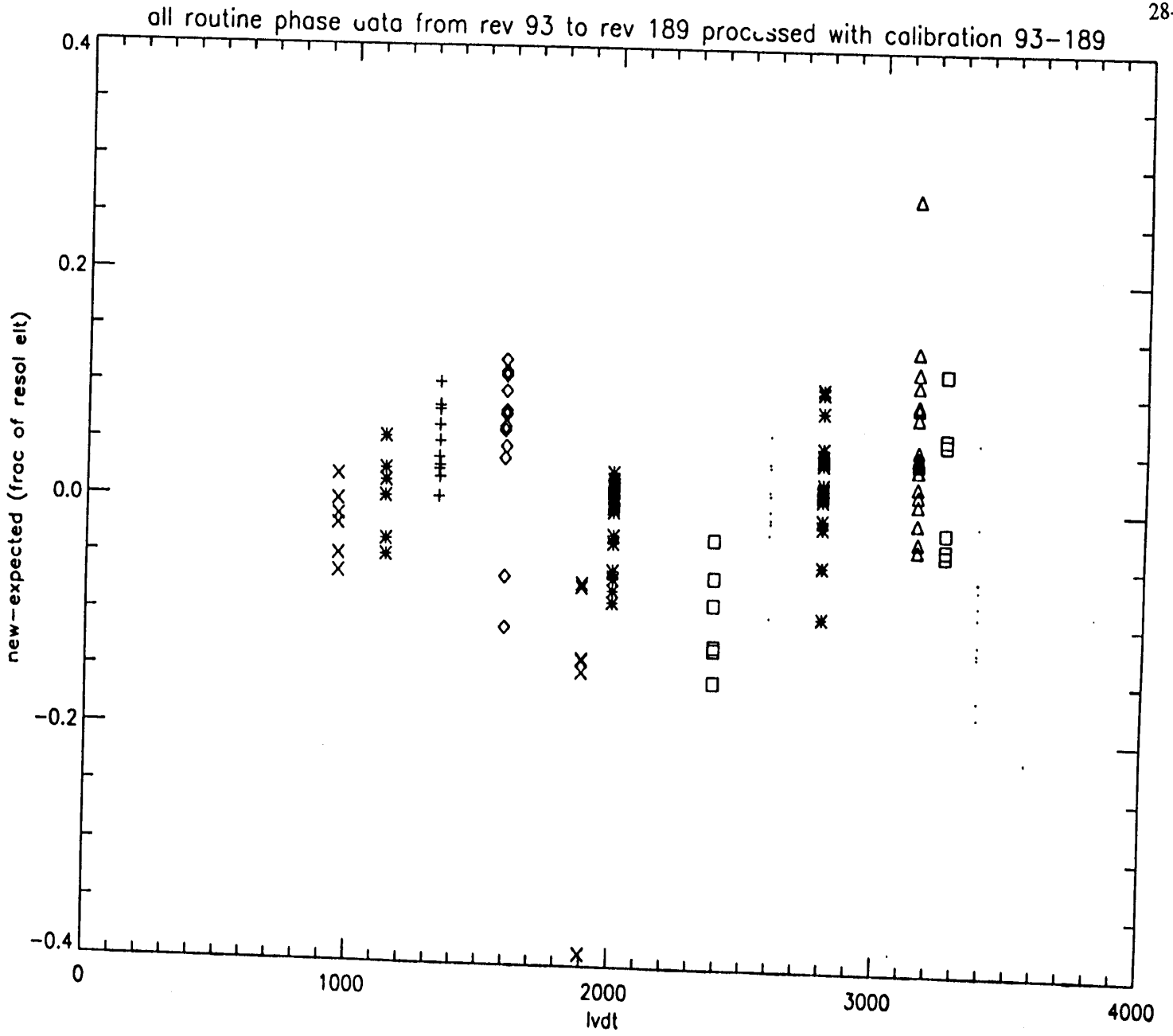
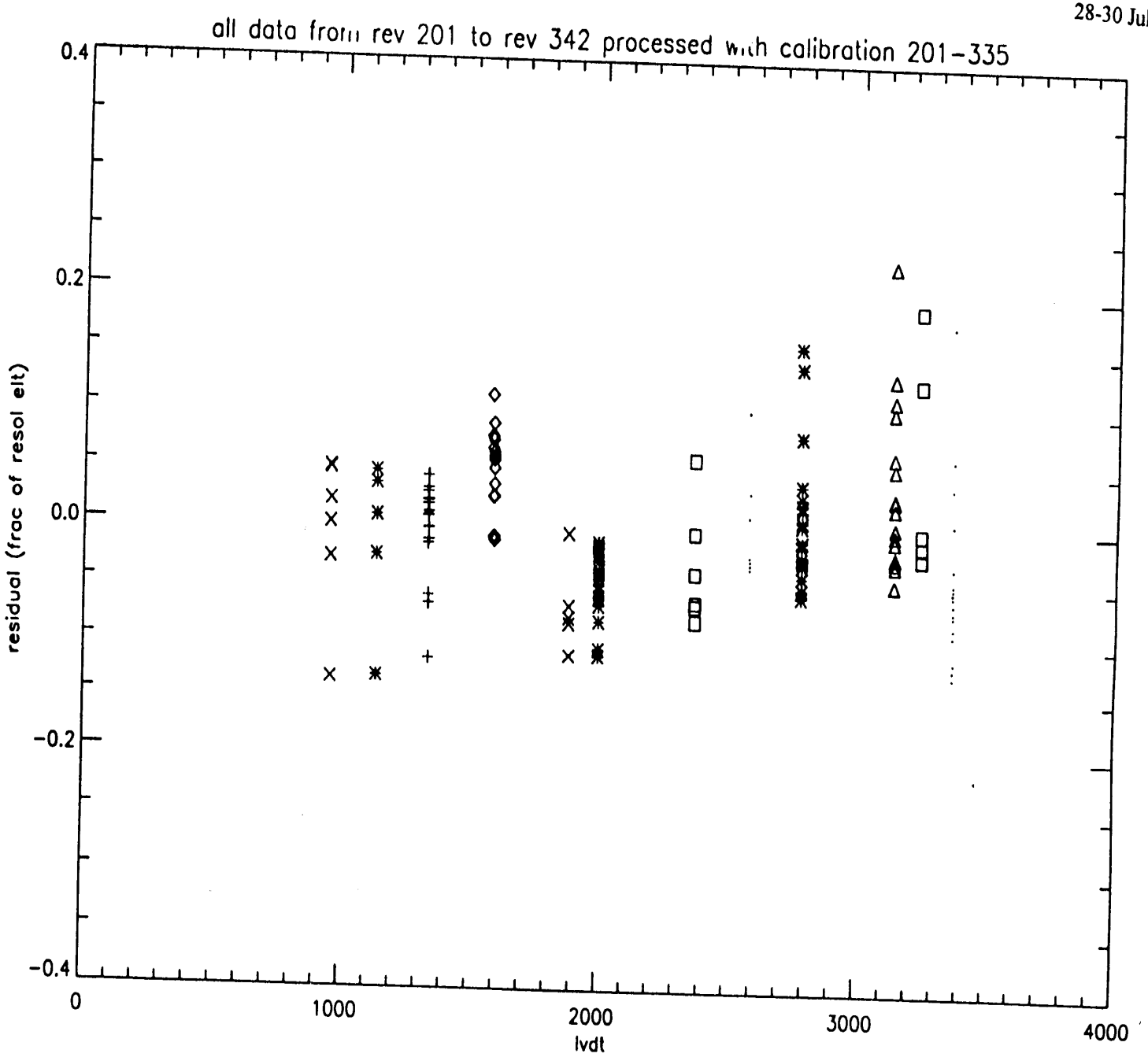
LWS Works
28-30 July 1
NGC 6543
342
265
182
363
349
lvdt difference with 356
lvdt
20
10
0
−10
−20
1000
2000
3000

DUALS

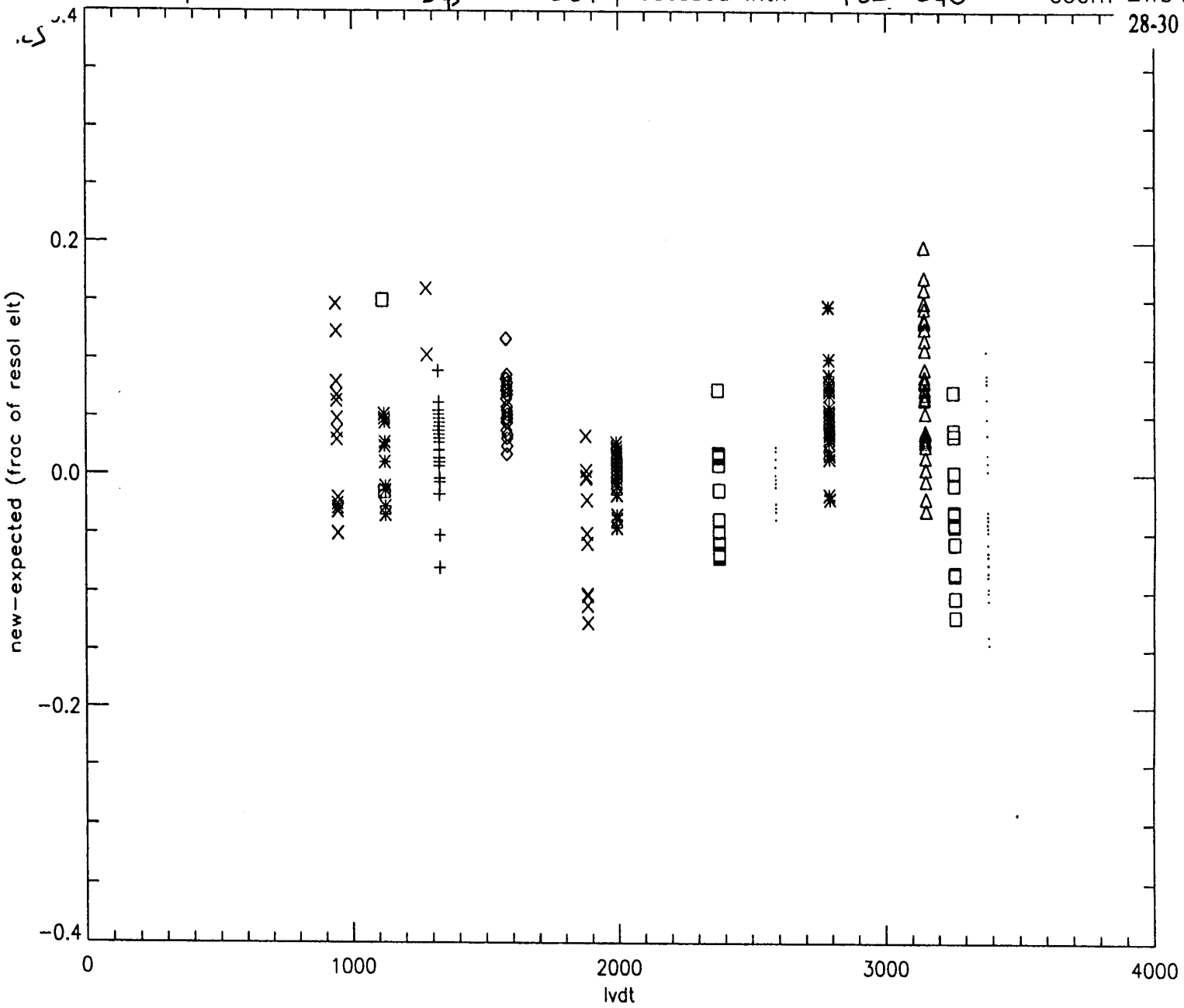

all routine phase data from rev 93 to rev 531 processed with pipeline 6 calibration
IPAC/RA
LWS Works
28-30 July 1
new−expected (frac of resol elt)
0.4
0.2
0.0
−0.2
−0.4
0
1000
2000
3000
4000
lvdt

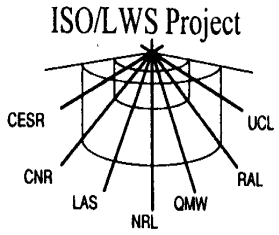
4


all routine phase data from rev 93 to rev 189 processed with calibration 93-189
new-expected (frac of resol elt)
0.4
0.2
0.0
-0.2
-0.4
0
1000
2000
3000
4000
lvdt


all data from rev 201 to rev 342 processed with calibration 201-335
residual (frac of resol elt)
0.4
0.2
0.0
-0.2
-0.4
0
1000
2000
3000
4000
lvdt

outine phase data from rev349 to rev531 processed with Post-342 coeffi



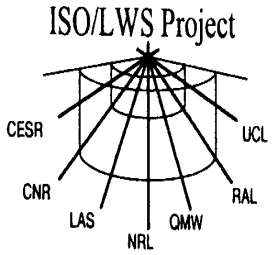


FP wavelength calibration

Internal consistency - FPS.....

Peak	Laser WL (um)	Calc WL (um)	Deviation (x10-3um)
303.72	51.82062	51.81990	0.72
1362.51	51.82062	51.82058	0.04
324.52	51.82873	51.82945	-0.72
1380.21	51.82873	51.82888	-0.15
2410.51	51.82873	51.82932	-0.59
1439.96	63.18231	63.18203	0.28
2691.24	63.18231	63.18250	-0.19
2701.17	63.18908	63.18827	0.81
3926.97	63.18908	63.18914	-0.05

Wavelength RMS = 5.235E-04 um



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FP wavelength calibration

Internal consistency - FPL.....

Peak	Laser WL (um)	Calc WL (um)	Deviation (x10-3um)
826.70	88.36593	88.36614	-0.21
2196.17	88.36593	88.36586	0.07
851.73	88.38027	88.38015	0.12
2221.50	88.38027	88.38028	-0.01
311.73	145.52181	145.52170	0.11
2568.12	145.52181	145.52186	-0.05

Wavelength RMS = 1.279E-04 um

Test of new FP wavelength calibration Gal-G file

RV determined from data processed using the new Fabry Perot wavelength calibration Cal-G file.
(vacuum wavelengths from van der Hucht and Koornneef.

NGC 3603

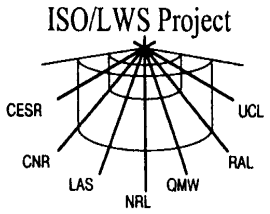
	$\lambda_{obs}(\mu m)$	$\lambda_{vac}(\mu m)$	*RV (km/s)*	*ion*
52	51.819	51.815	23.1	[O III]
57	57.336	57.330	31.4	[N III]
88	88.367	88.356	37.3	[O III]
157	157.760	157.741	36.1	[C II]

NGC 6543

	$\lambda_{obs}(\mu m)$	$\lambda_{vac}(\mu m)$	*RV (km/s)*	*ion*
57	57.316	57.330	-73.2	[N III]
88	88.336	88.356	-67.9	[O III]

NGC 6357 I

	$\lambda_{obs}(\mu m)$	$\lambda_{vac}(\mu m)$	*RV (km/s)*	*ion*
52	51.819	51.815	-5.8	[O III]
57	57.336	57.330	0	[N III]
63	63.185	63.184	4.7	[O I]
88	88.361	88.356	17.0	[O III]
122	121.90	121.889	27.1	[N II]
145	145.535	145.5255	19.6	[O I]
157	157.746	157.741	9.5	[C II]



Stability of the Photometric Calibration

- Calibration observations are made weekly on sources with fluxes that are known to constant.
- These show the stability of the calibration to be very good on sources with moderate fluxes.

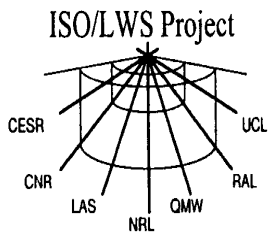
Repeatability of Auto Analysis Results (S106)

Auto Analysis products from OLP version 6.0.

The following values are determined by median averaging all the scans, clipping at 3 sigma.

Detector	126	182	189	203	210	223	314
SW1	0.97	0.97	0.95	0.95	0.95	0.96	1.00
SW2	0.85	0.88	0.90	0.90	0.90	0.88	1.00
SW3	0.90	0.89	0.90	0.90	0.90	0.89	1.00
SW4	0.93	0.93	0.91	0.94	0.93	0.94	1.00
SW5	0.98	0.99	0.99	0.99	1.00	0.99	0.89
LW1	0.98	0.97	1.00	0.99	1.00	0.98	0.99
LW2	0.96	1.00	0.99	0.98	0.98	1.00	0.93
LW3	0.89	0.99	0.95	1.00	0.99	0.99	0.94
LW4	0.90	0.99	0.96	1.00	0.95	0.97	0.82
LW5	0.96	0.99	0.98	1.00	0.99	0.99	0.85

Detector	Sigma/mean Whole Detector	Sigma/mean Single wavelength
SW1	0.02	0.02
SW2	0.05	0.02
SW3	0.04	0.04
SW4	0.03	0.03
SW5	0.04	0.04
LW1	0.01	0.03
LW2	0.02	0.02
LW3	0.04	0.04
LW4	0.06	0.07
LW5	0.05	0.05



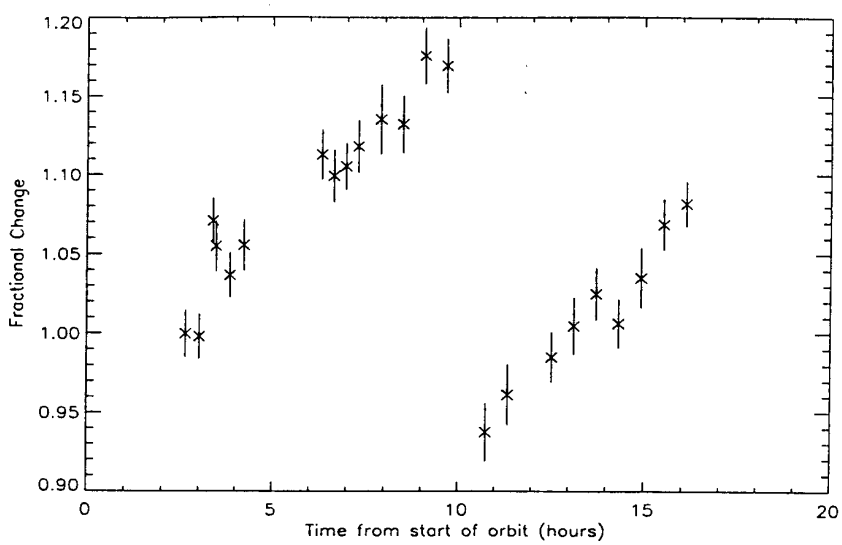
Responsivity Drift Correction

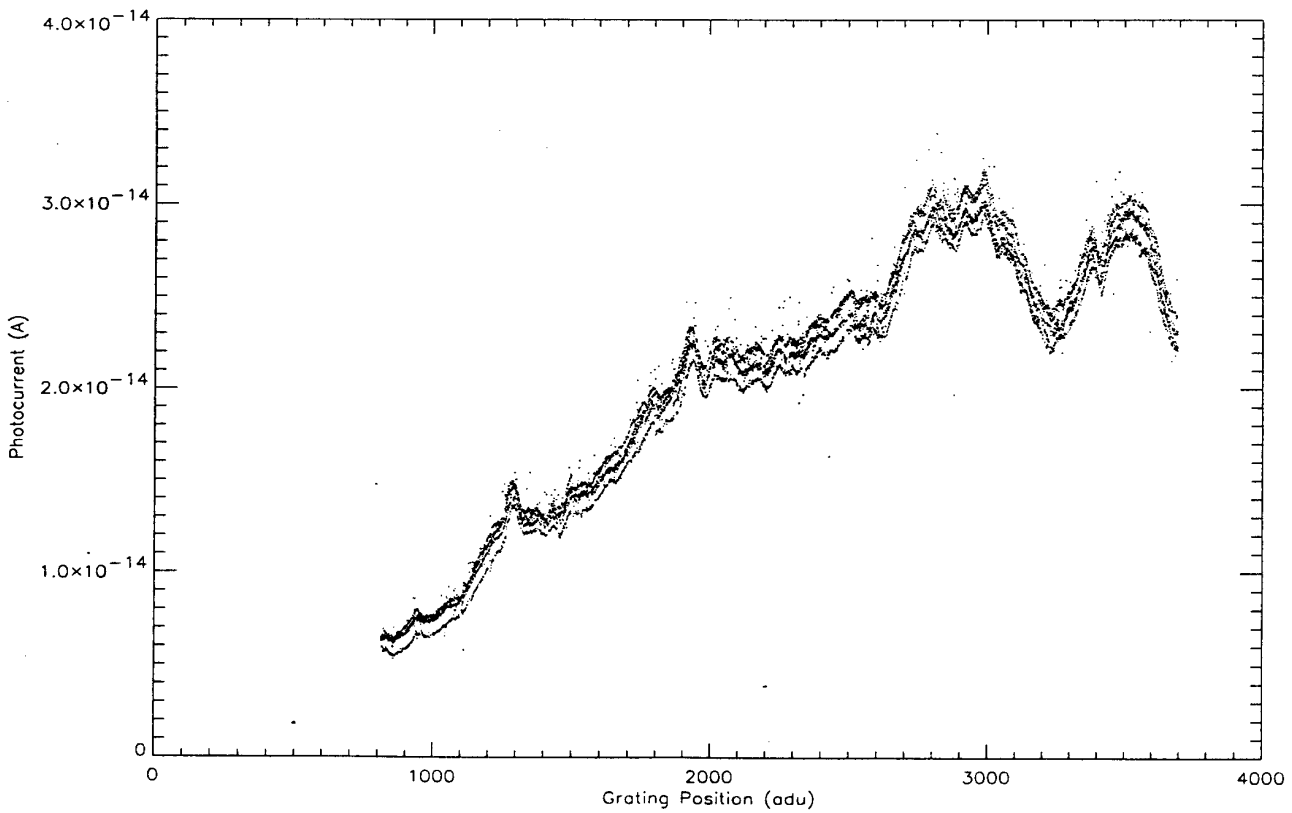
- Calibration measurements made at the beginning and end of each observation show that the responsivity of the detectors drifts more or less linearly with time around the orbit.

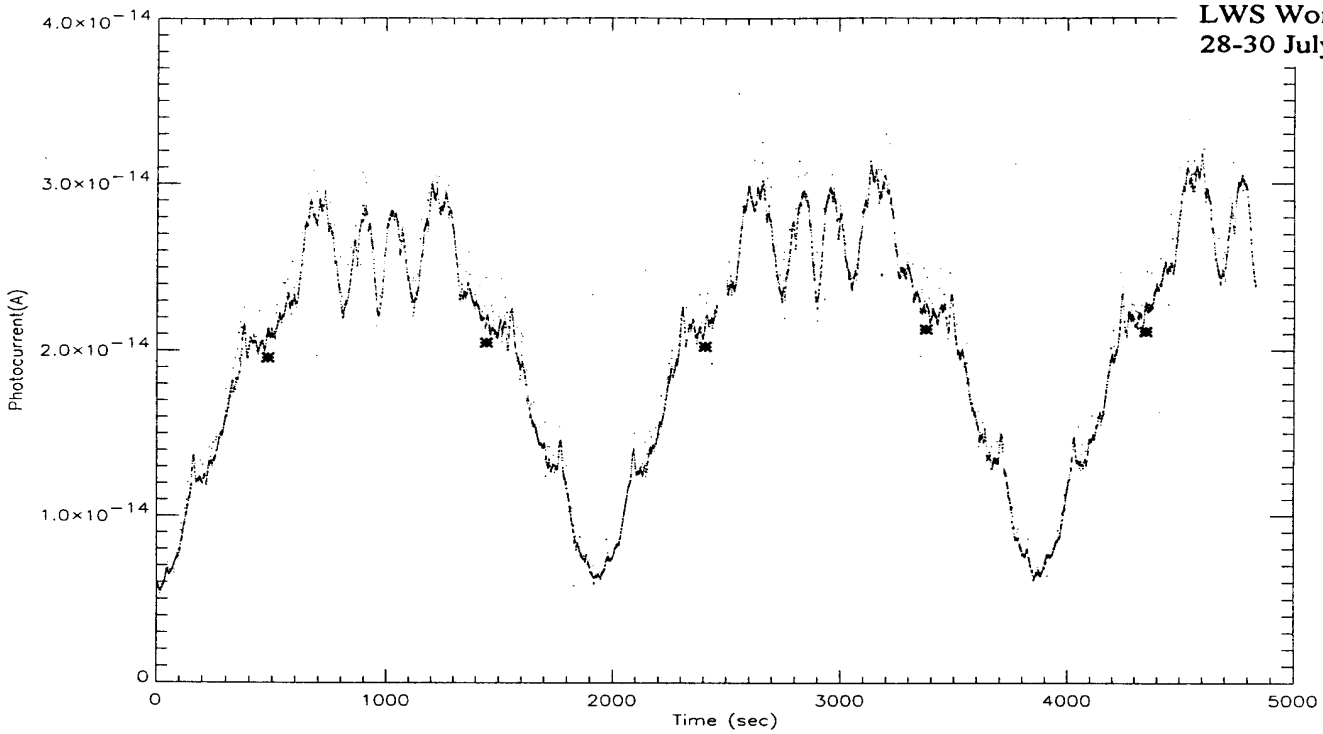
- Attempts to correct this drift using the calibration measurements have been dogged by poor signal/noise.

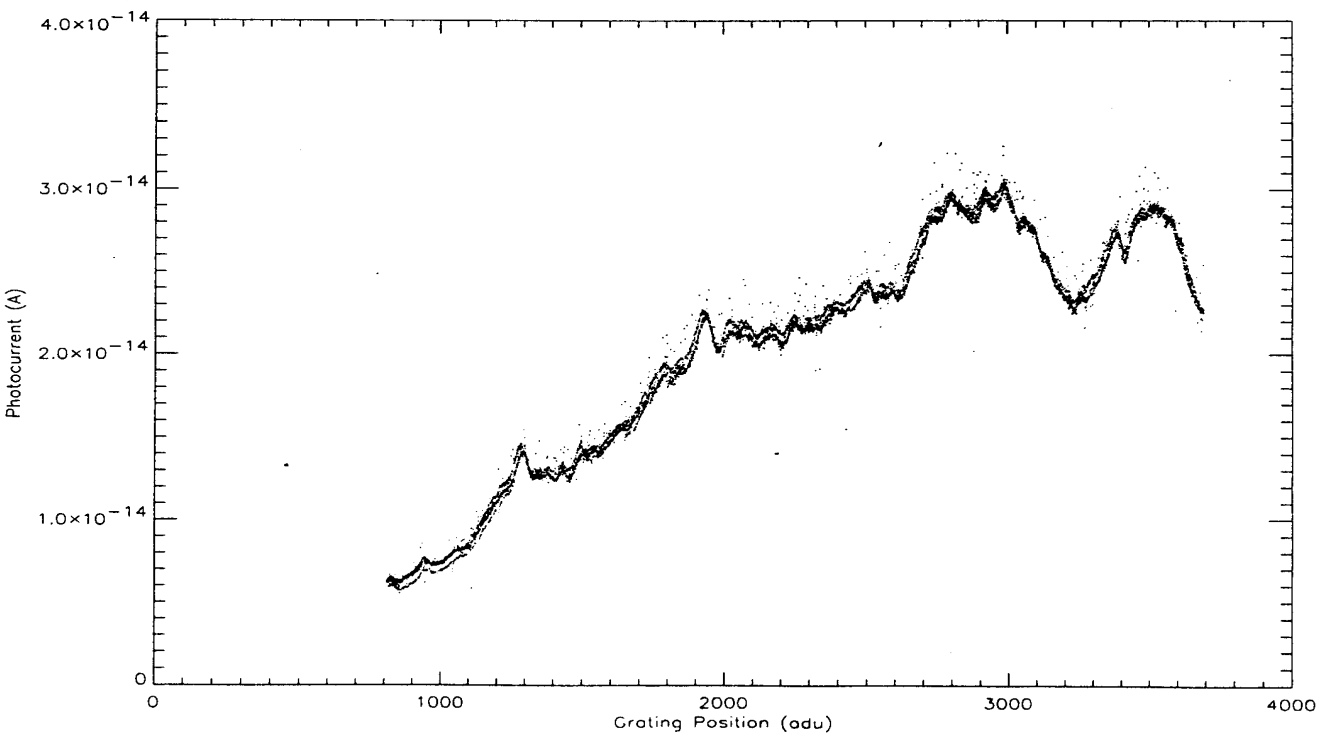
- The current scheme uses the observed source flux as a measure of the relative change in the responsivity.

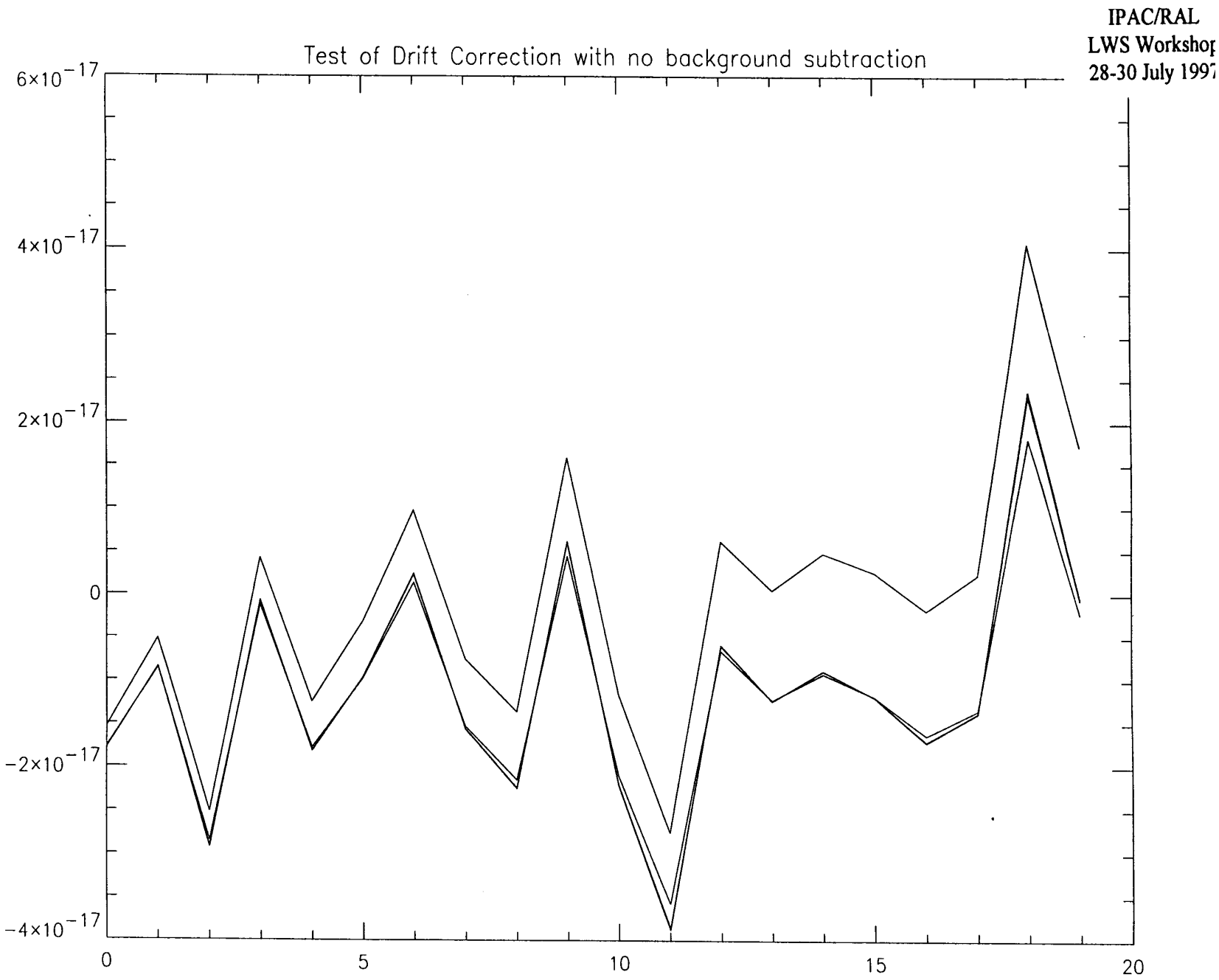
- The calibration measurements are used to correct to an absolute responsivity scale based on observations of sources with known fluxes (Uranus and (later) Mars).


Fractional Change
1.20
1.15
1.10
1.05
1.00
0.95
0.90
0
5
10
15
20
Time from start of orbit (hours)


Photocurrent (A)
4.0×10⁻¹⁴
3.0×10⁻¹⁴
2.0×10⁻¹⁴
1.0×10⁻¹⁴
0
0
1000
2000
3000
4000
Grating Position (adu)


4.0×10⁻¹⁴
3.0×10⁻¹⁴
2.0×10⁻¹⁴
1.0×10⁻¹⁴
0
Photocurrent(A)
0
1000
2000
3000
4000
5000
Time (sec)


4.0×10⁻¹⁴
3.0×10⁻¹⁴
2.0×10⁻¹⁴
1.0×10⁻¹⁴
0
Photocurrent (A)
0
1000
2000
3000
4000
Grating Position (adu)


Test of Drift Correction with no background subtraction
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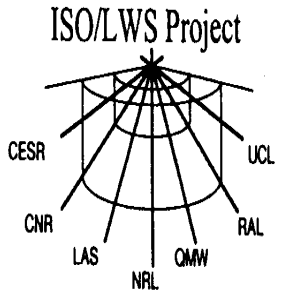
6×10⁻¹⁷
4×10⁻¹⁷
2×10⁻¹⁷
0
-2×10⁻¹⁷
-4×10⁻¹⁷
0
5
10
15
20



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Detector Time Response

- Differences are seen in some sources in the flux derived when the grating is going forwards compared to when it is going backwards.
- These are due to the time response of the detector.
- This is a complex function of the illumination history on the detector and the steepness of the rise of the "photocurrent spectrum" being measured.
- Emannuel Caux of CESR Toulouse is working on a practical solution to the problem.....

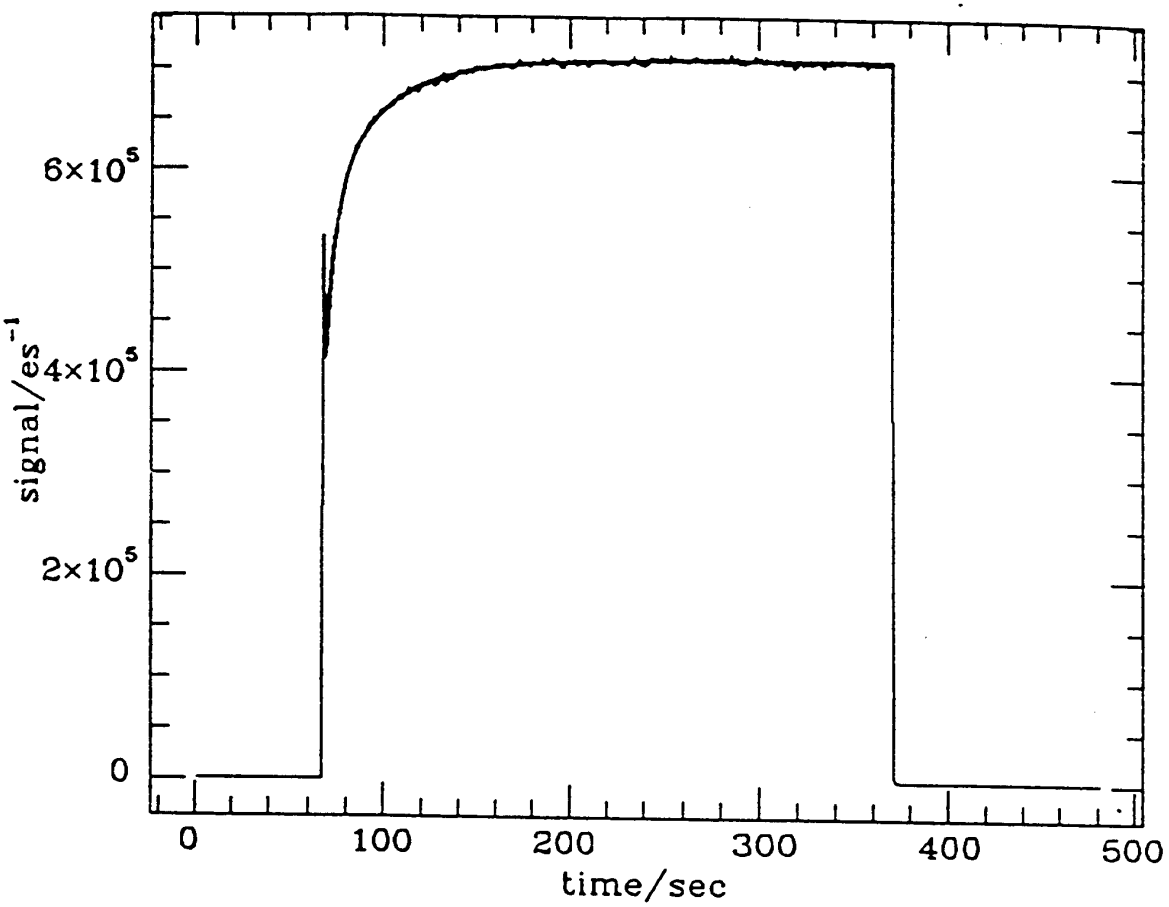

Figure 5: *Transient response in a Ge:Ga(u) at 3K and 200mV bias, to a step change in illumination at 85μm. The time response has been fitted with a model containing three time-constants (bold line).*

From Church et al., 1992

$I(t)$: Input Flux (sky)

$S(t)$: Instrument Response

$$S(t) = \alpha I(t) + (1-\alpha) * \int_{-\infty}^{t} I(t') e^{-\frac{(t-t')}{\tau}} dt'$$

with : α = constant,

$$\tau = f(I(t)) \quad [\text{in fact } \tau = g(S(t))]$$

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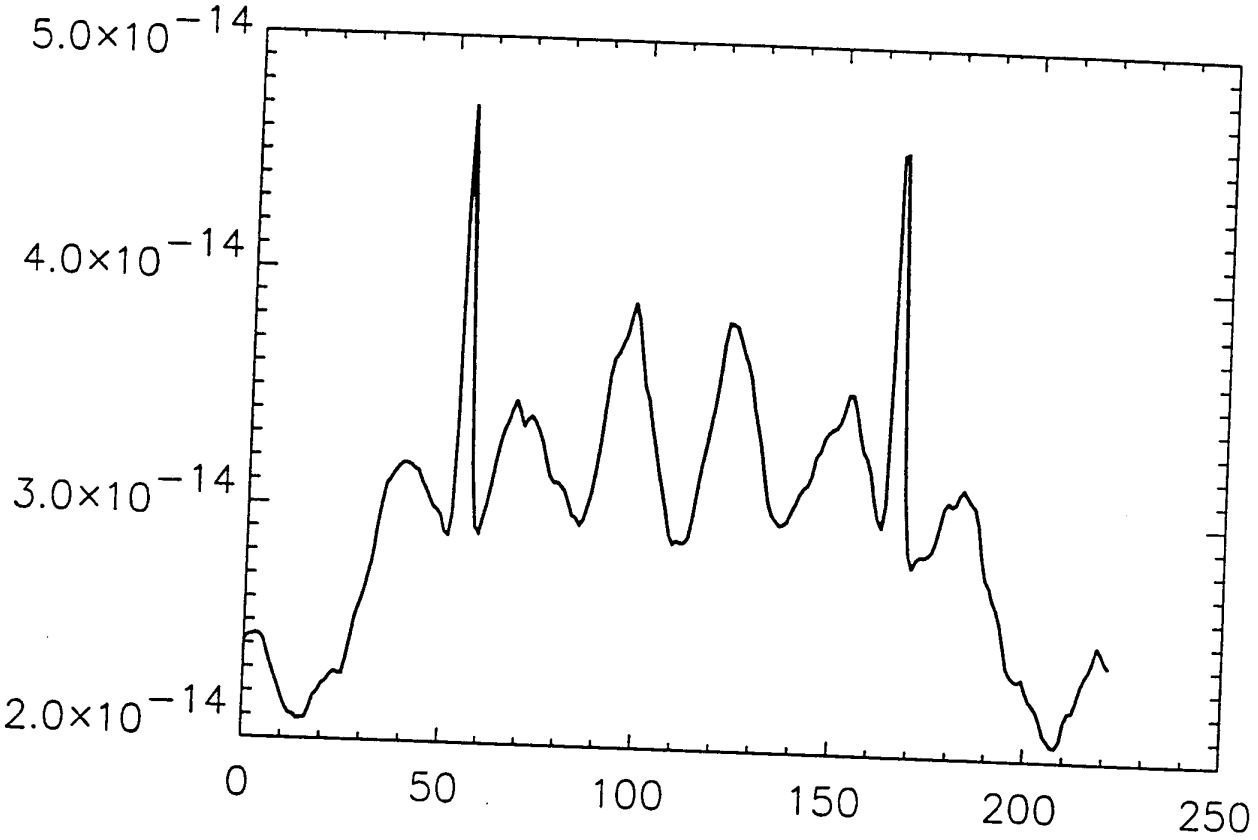

LW4 Extended Source

Oversampling = 2

$N_{scans\ forward} = N_{scans\ backward} = 22$

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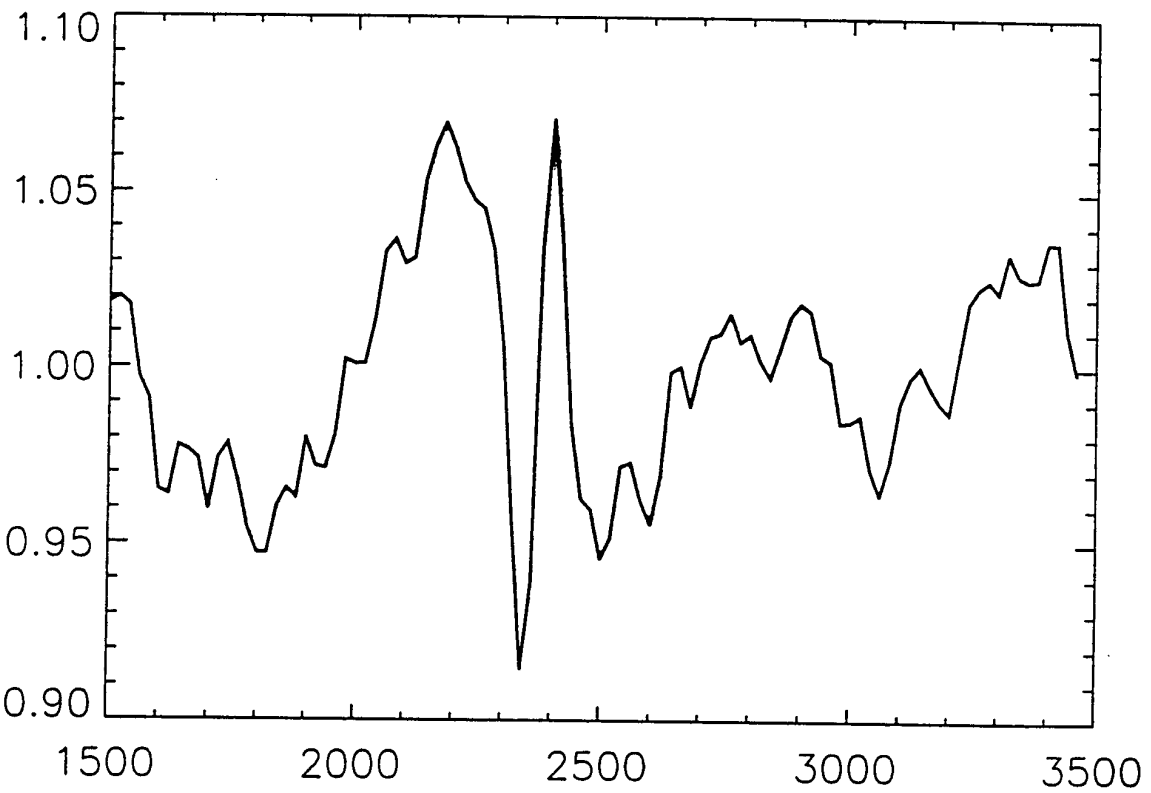

LWL

forward / backward

Noise = $3.2\ 10^{-3}$

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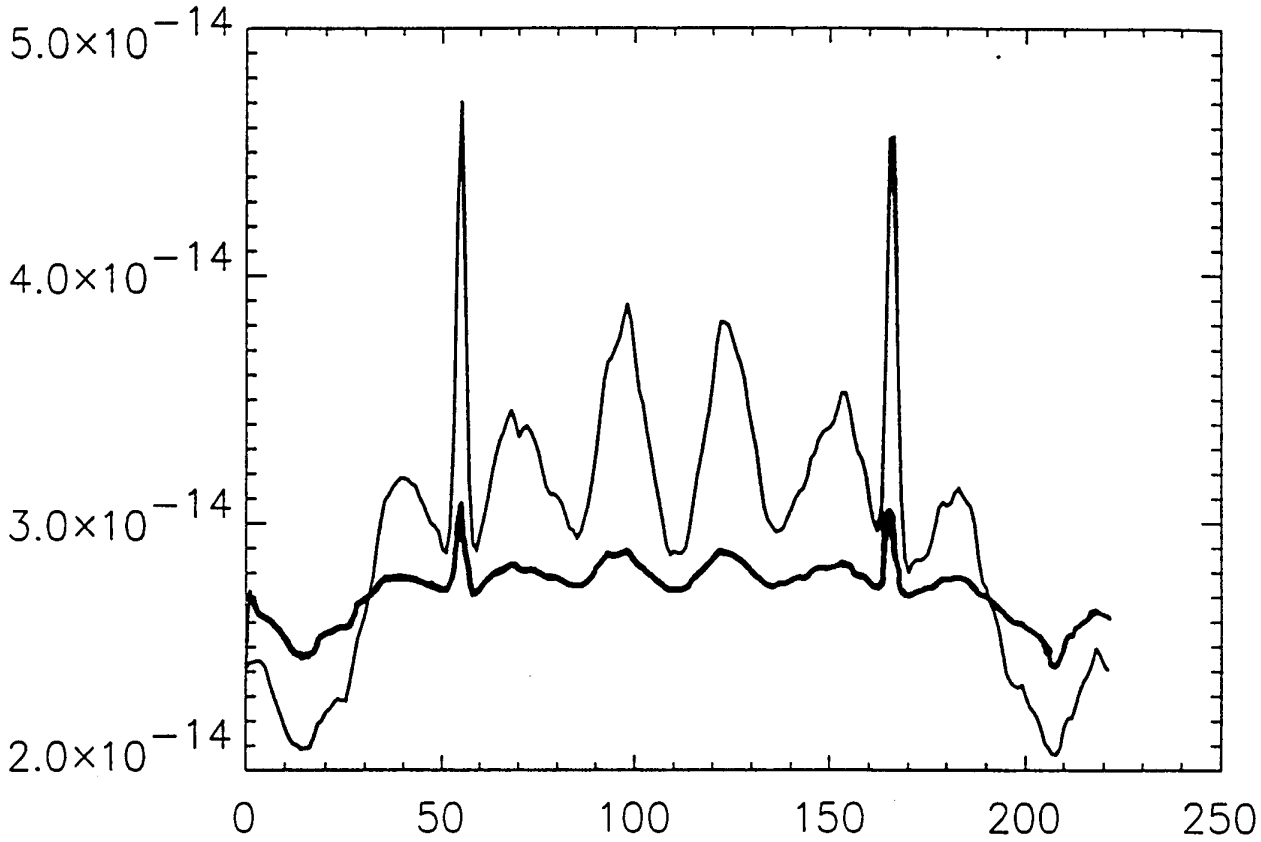

LW4

~~Noise = 3.2 10^-15~~

After memory effect Correction

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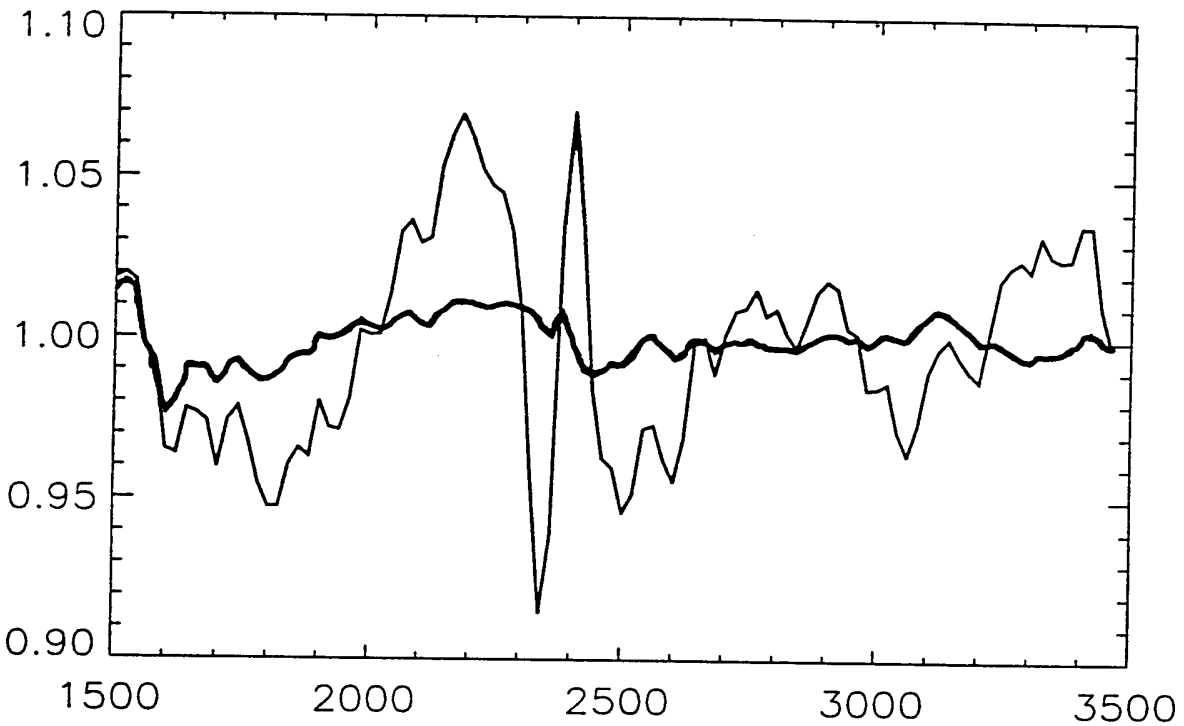
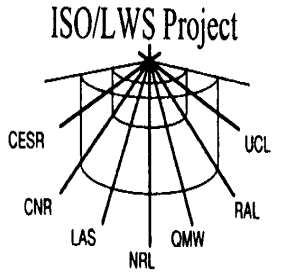


LW4

Noise = $3.2\ 10^{-3}$ }
Noise = $7.4\ 10^{-4}$ } gain = 4.3

One band combard, linear dependance with Flux.

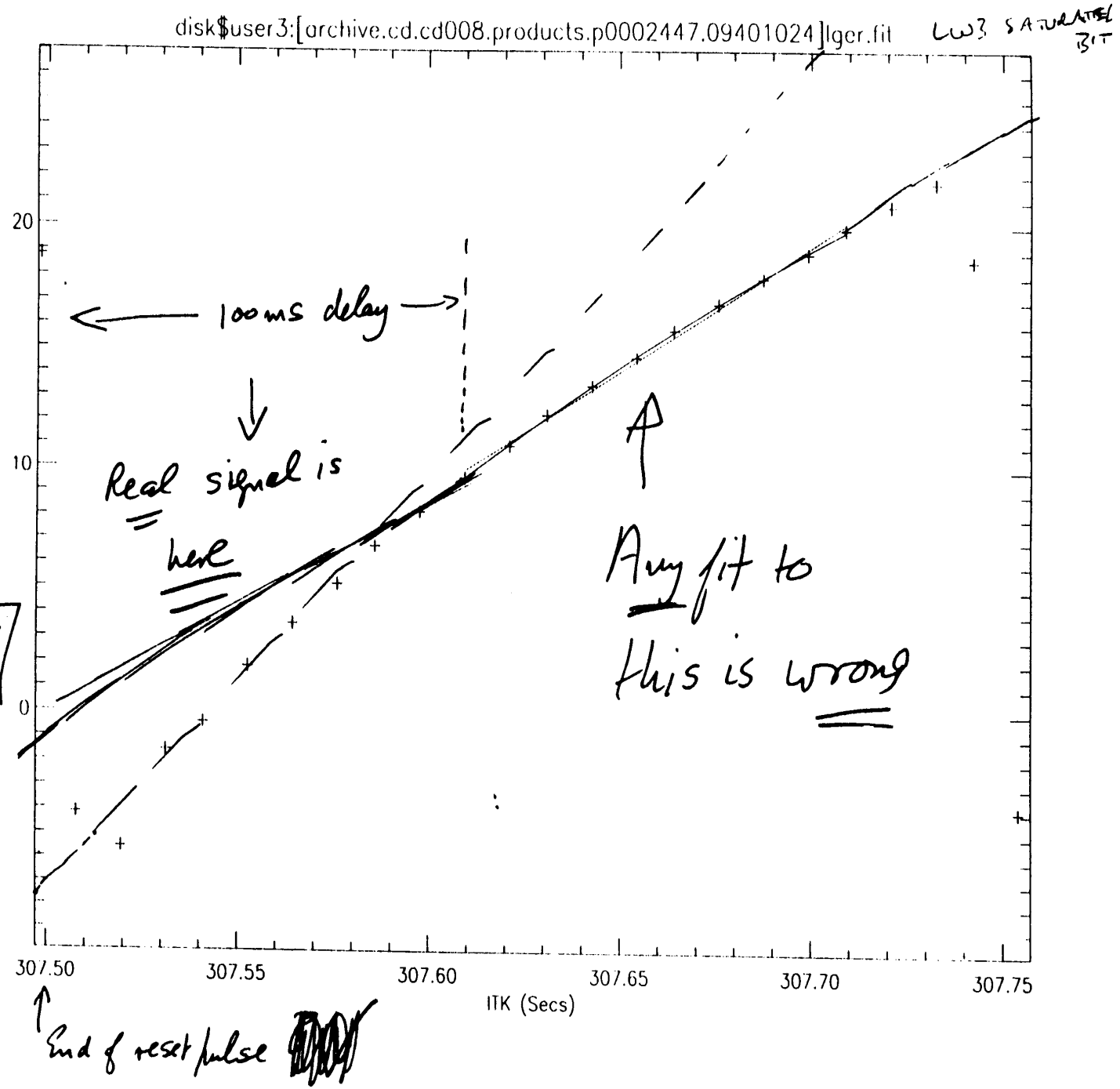


Non-Linear Response to Strong Sources

- The photoconducting detectors are read out using integrating amplifiers - as the charge builds up on the integrating node of the amplifier, the net bias across the detector is reduced.

- This leads to a non-linear response when the flux is high enough that the bias is reduced by a significant fraction (5-10% depending on the detector).

- To compensate for this, observations of Saturn have been used to predict the percentage change in responsivity as a function of photocurrent.



ms:

$= \frac{33}{0.2} = 165$

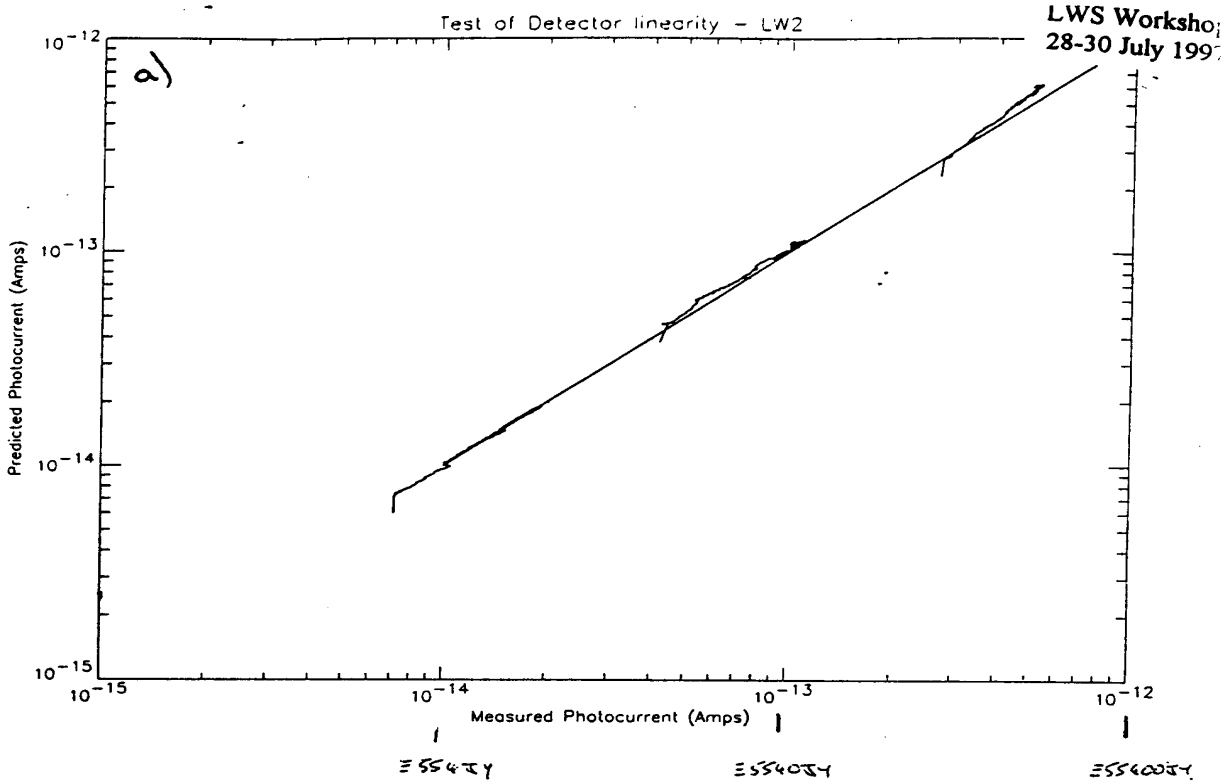
that:

$= \frac{24}{0.25}$

≈ 100

factor of 1.7

Fig 4.



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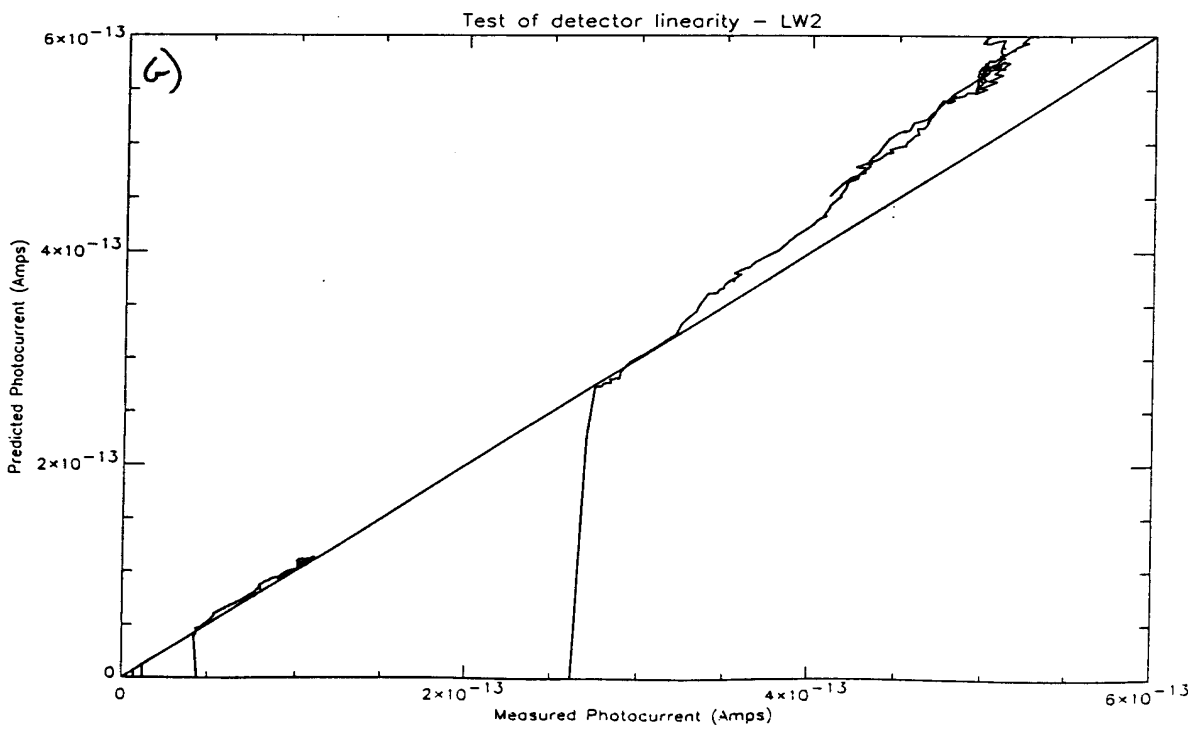
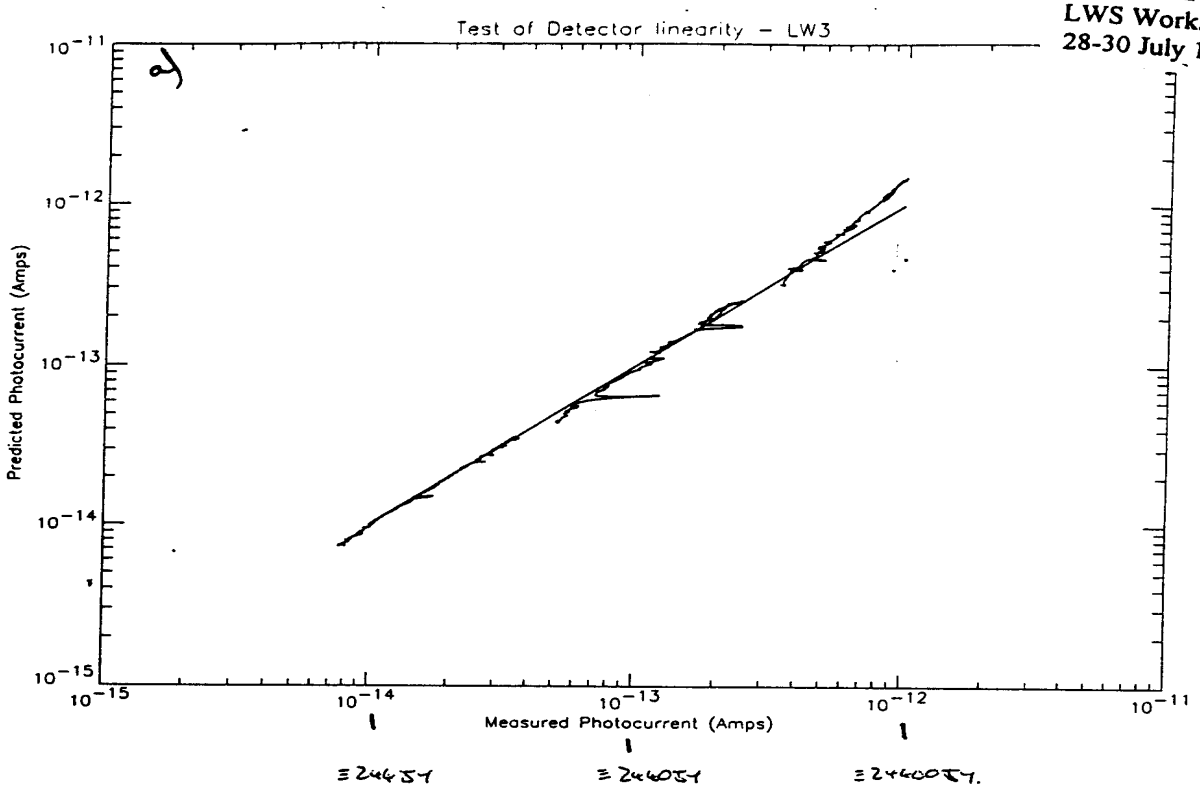


Fig 5


Test of Detector linearity – LW3
a)
Predicted Photocurrent (Amps)
Measured Photocurrent (Amps)
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
≡ 24654
≡ 246054
≡ 2460054.

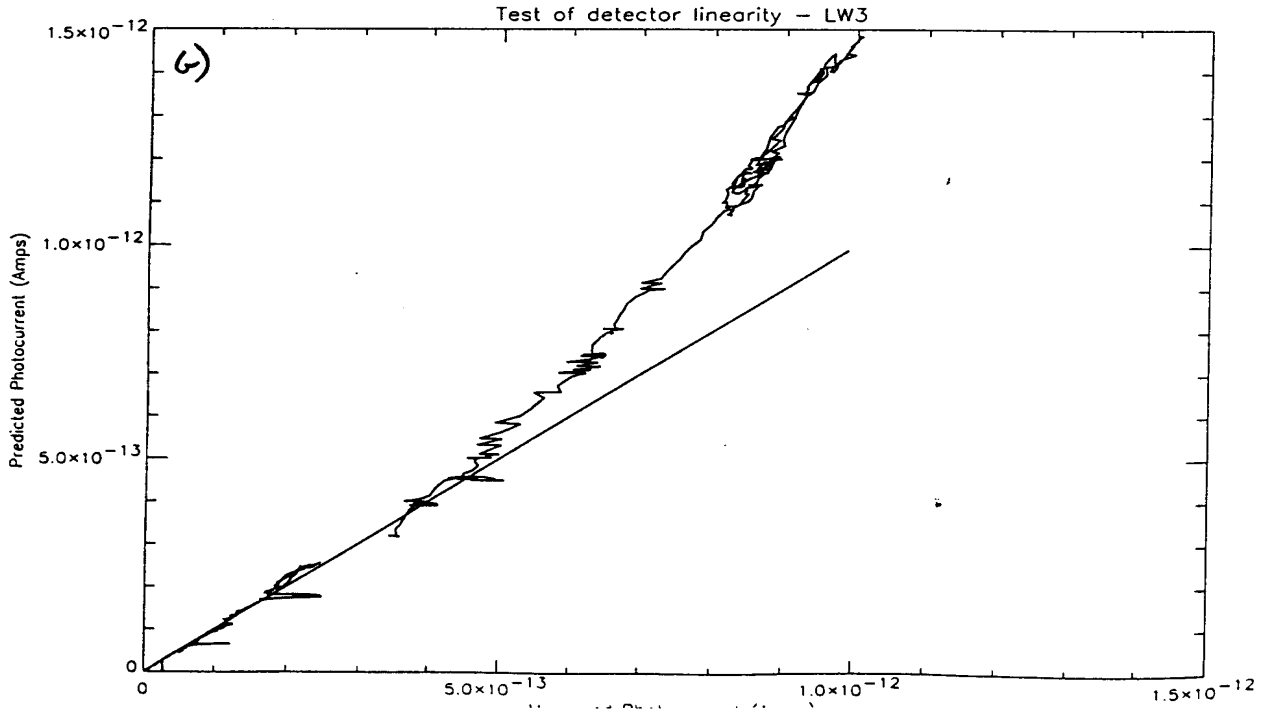
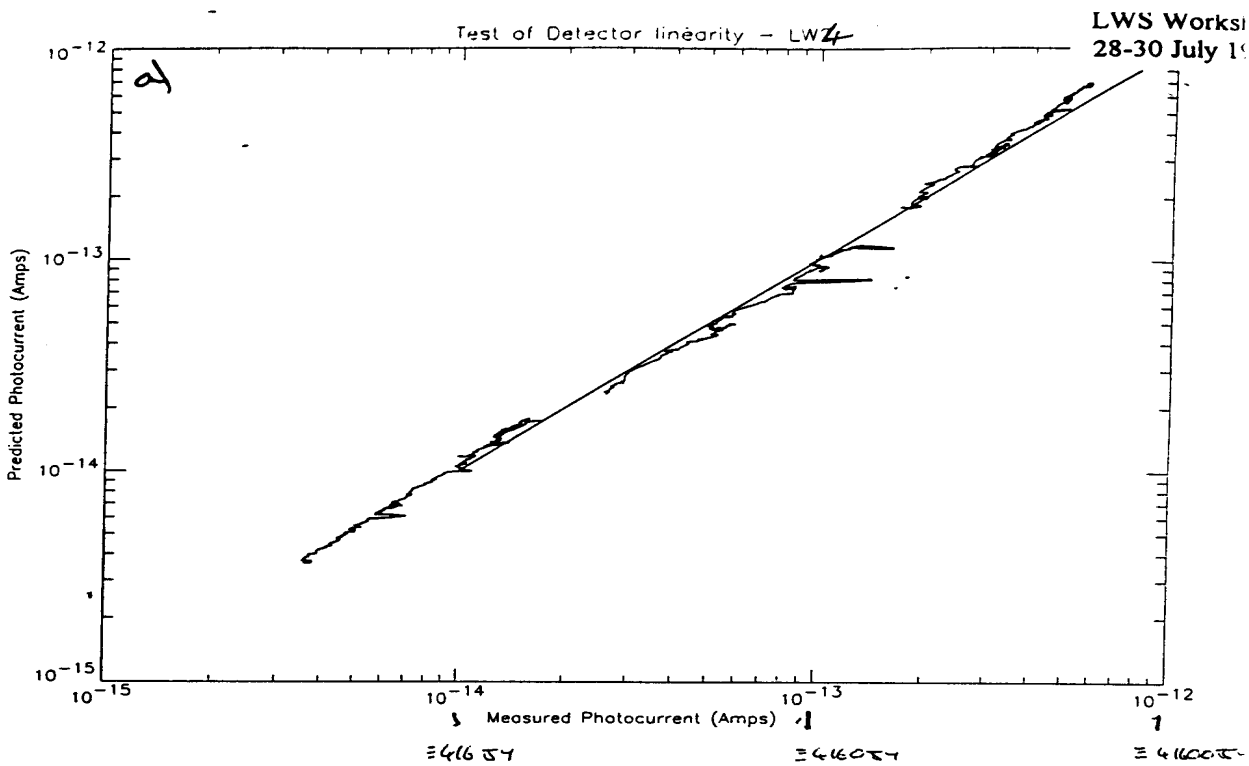
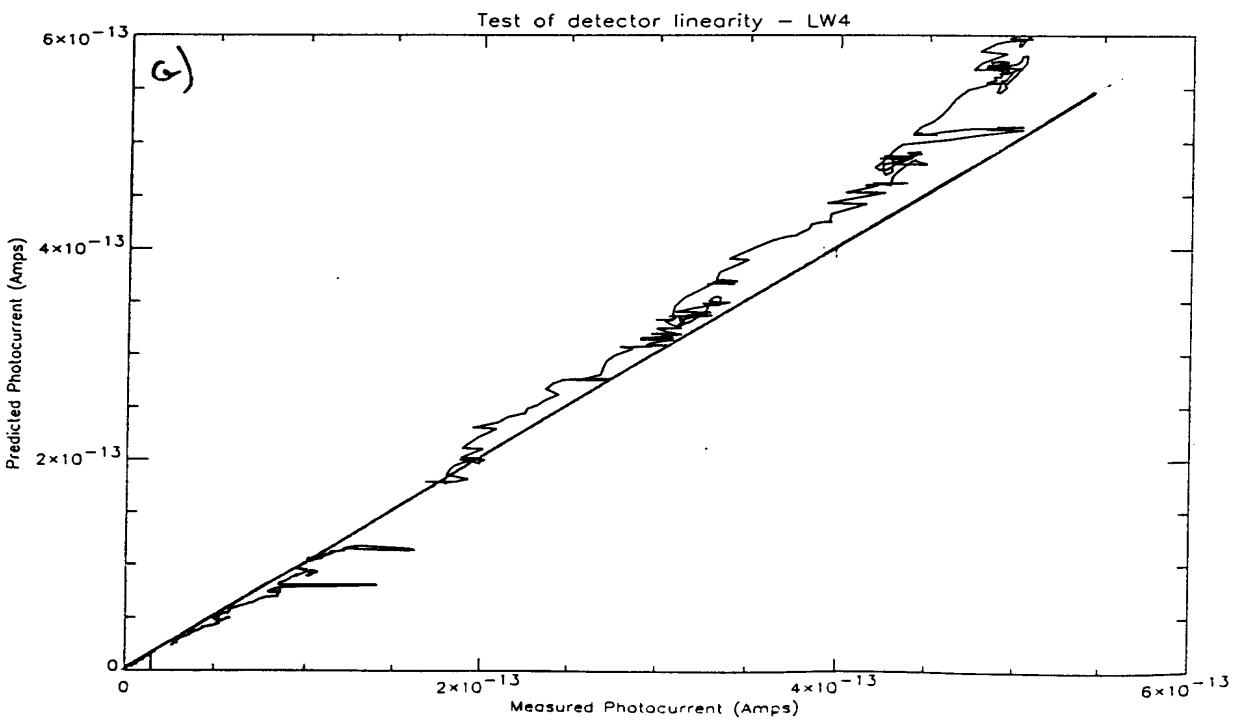
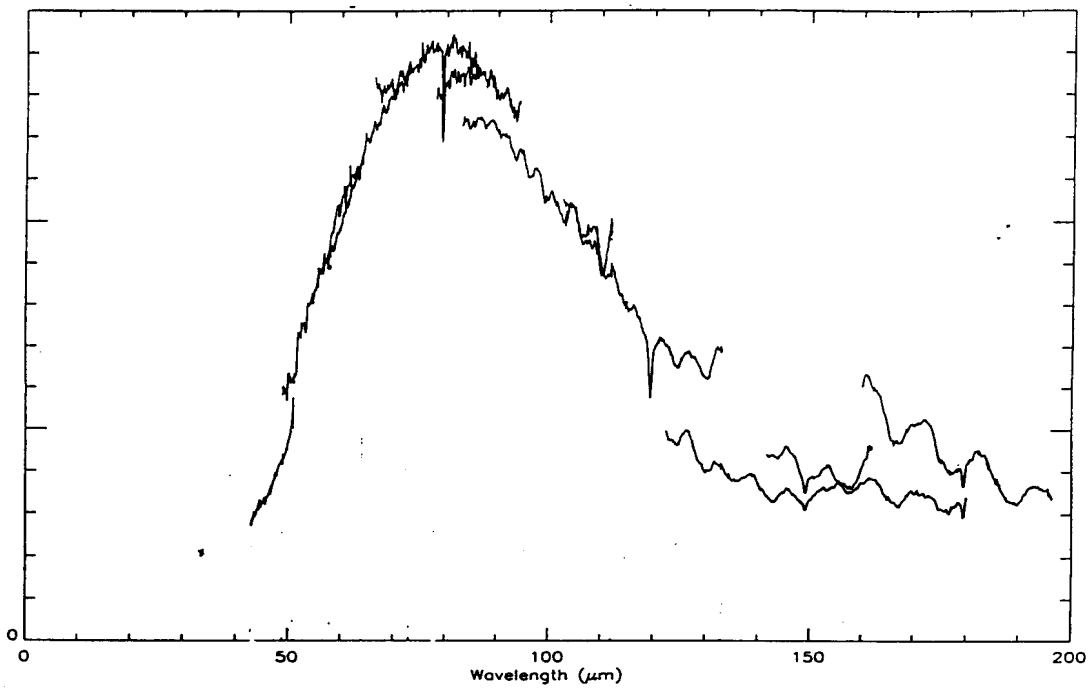
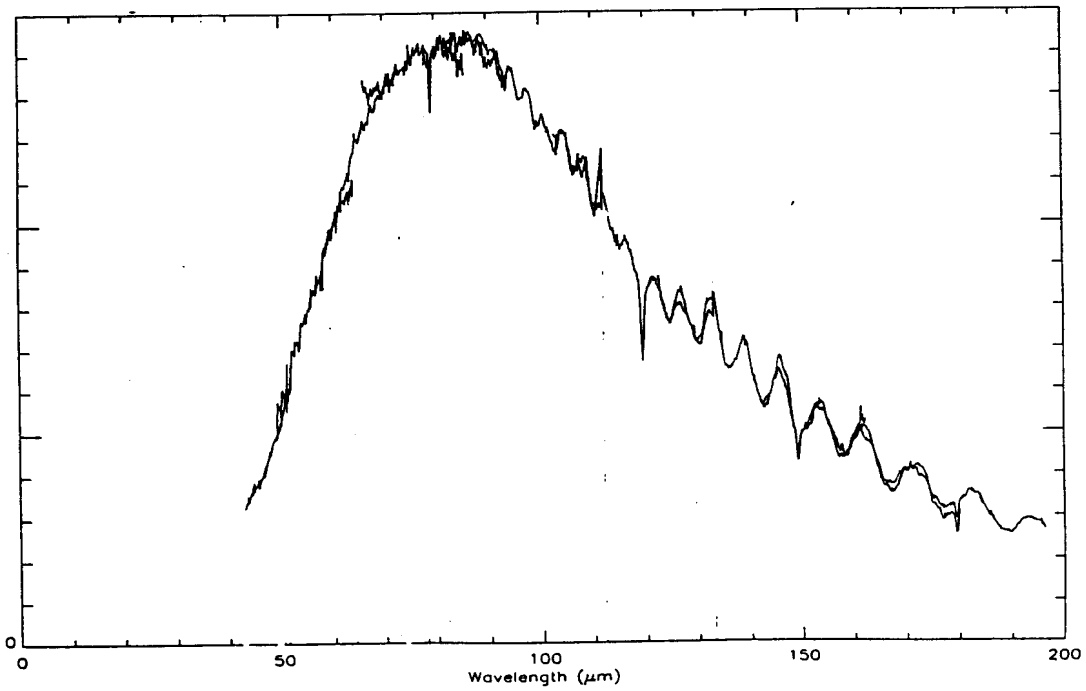

Test of detector linearity – LW3
b)
Predicted Photocurrent (Amps)
1.5×10^{-12}
1.0×10^{-12}
5.0×10^{-13}
0
5.0×10^{-13}
1.0×10^{-12}
1.5×10^{-12}

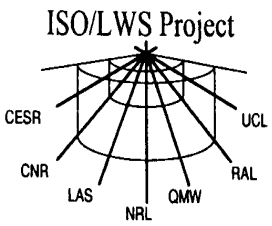
FIG6.


Test of Detector linearity – LW4
a)
Predicted Photocurrent (Amps)
Measured Photocurrent (Amps)
10^{-12}
10^{-13}
10^{-14}
10^{-15}


Test of detector linearity – LW4
G)
Predicted Photocurrent (Amps)
Measured Photocurrent (Amps)
6×10^{-13}
4×10^{-13}
2×10^{-13}
0

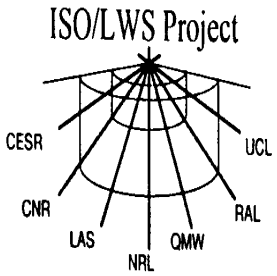

0
0
50
100
150
200
Wavelength (μm)


0
0
50
100
150
200
Wavelength (μm)



Fringing

- Sinusoidal fringes are observed on the spectra of extended sources and off axis point sources.
- They arise because of the interference between two beams propagating in the instrument with a time delay between.
- The two beams in question arise from the "normal" reflections from the field mirror M2 and from the substrate holding M2 which is ~1.45 mm behind the front surface of M2.
- This was supposed to be black - but what's black at >100 μm!?
- They can mostly be identified and removed using a program developed for detection of periods in spectroscopic binaries which solves for the period, phase and wavenumber dependent amplitude of a sine wave fitted to the data.
- Detector time response can lead to poor removal of the fringes as can lines.



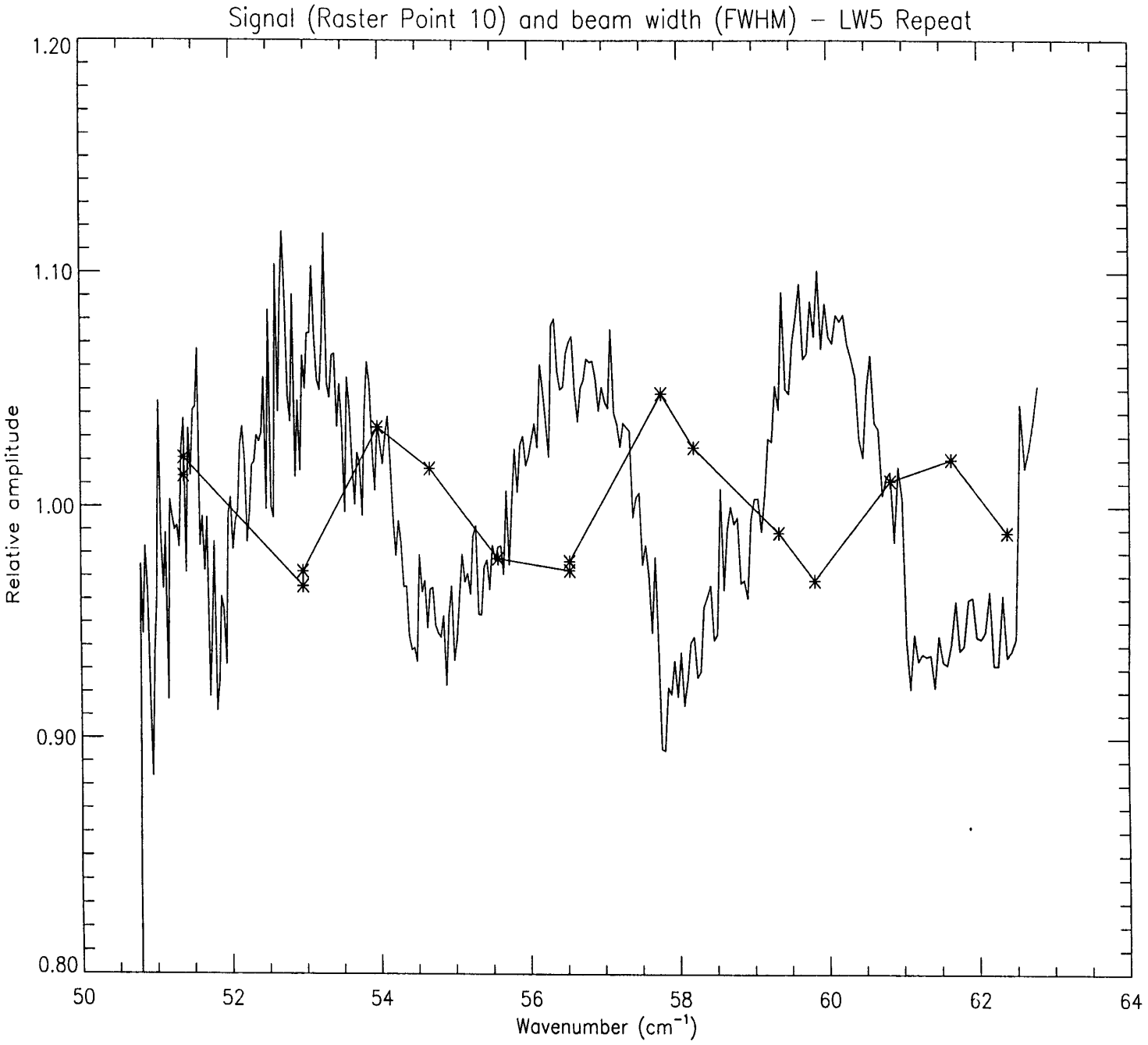
Fringing ctd.....

- The way the fringe is removed depends to a great extent on interpretation of the source distribution:

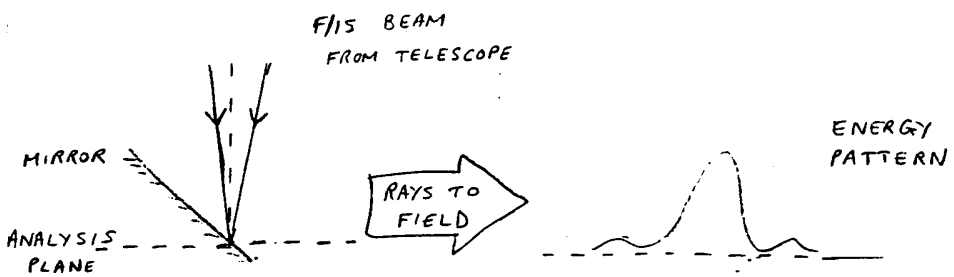
CASE 1: Point like source with lines and fringed continuum from extended region:
>>>> SUBTRACT the fringed continuum

CASE 2: Fully extended source for lines and continuum OR off axis point source with no significant contribution from extended continuum:
>>>> DIVIDE OUT the fringe

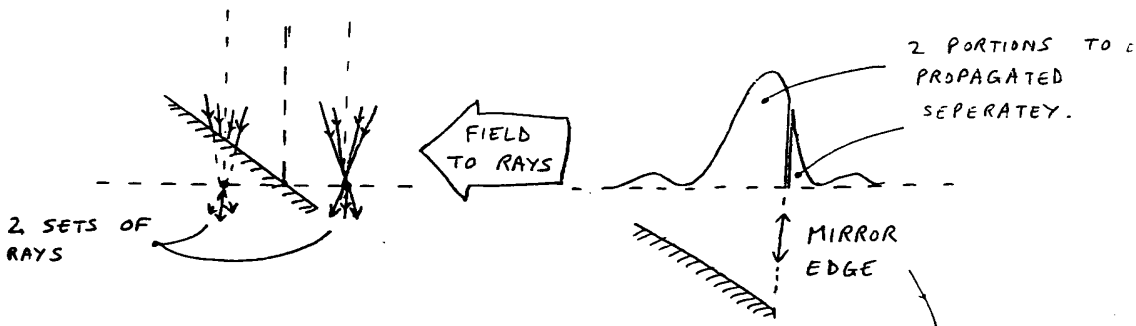
CASE 3: A mixture of point like off axis and extended emission for both lines and continuum:
>>>> VERY TRICKY!


Signal (Raster Point 10) and beam width (FWHM) – LW5 Repeat
Relative amplitude
1.20
1.10
1.00
0.90
0.80
50
52
54
56
58
60
62
64
Wavenumber (cm^{-1})

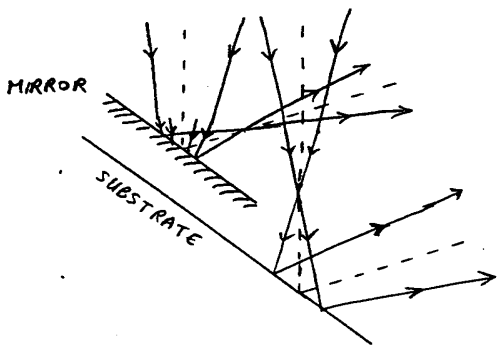
Analyse Input Field



Split field at mirror

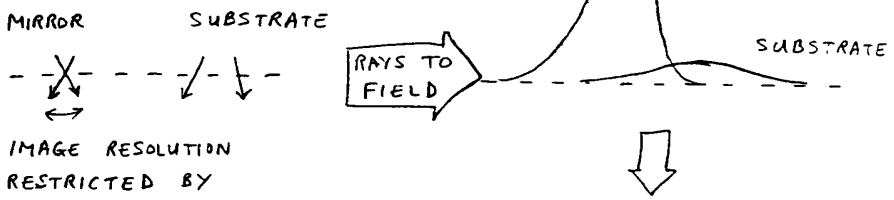


Propagate



IMAGING RESOLUTION RESTRICTED TO F/15.

Analyse at image plane



Record energy of total pattern (coherent sum of the 2 sets)

$$U = \int E \, dA$$

MISO2IM3C.DAT detected energy versus wavelength

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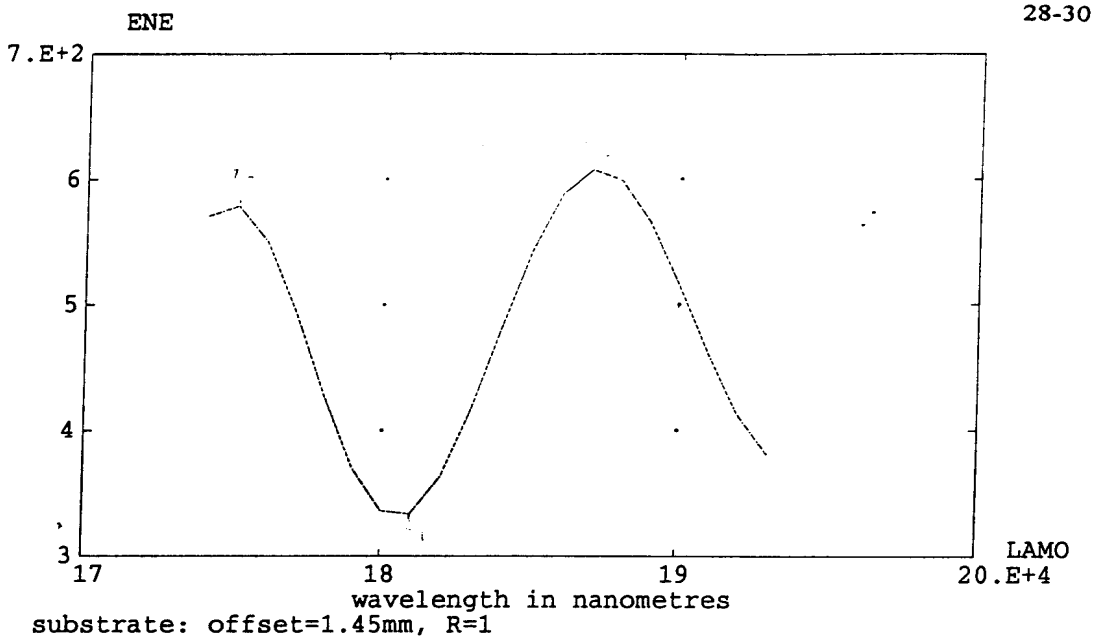
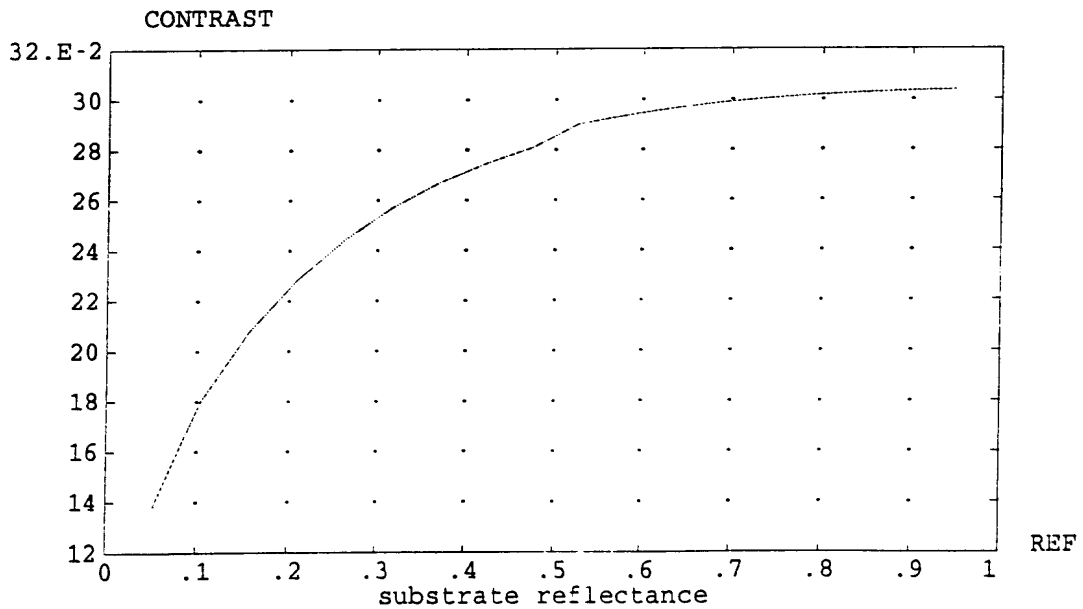


substrate: offset=1.45mm, R=1

ASAP v5.0 11-27-96 11:08

fringe contrast versus substrate reflectance $\lambda = 182, 189$.



field angle (m) 0.1557 deg.

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"INFRARED BLACK LAWS FOR ROOM + CRYOGENIC TEMPERATURES"

• MARTIN BLACK
▲ NEXTEL
△ CORNELL BLAC
▯ ECP 2200
* HERBERT

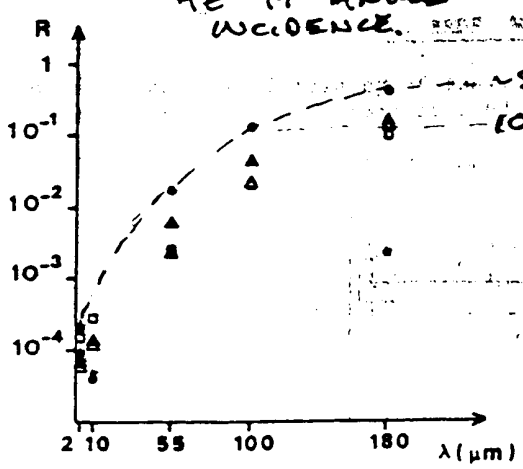


Fig.4a

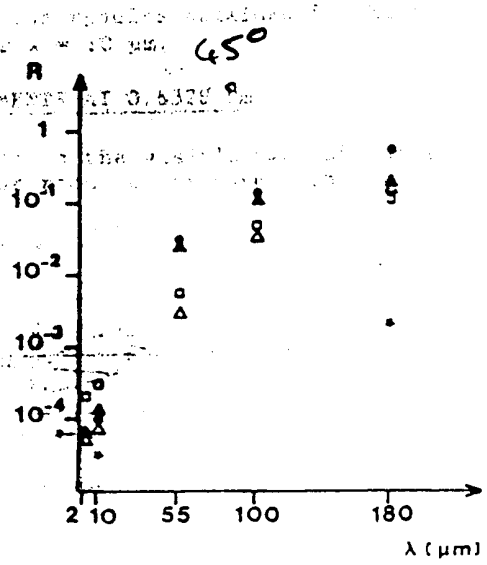
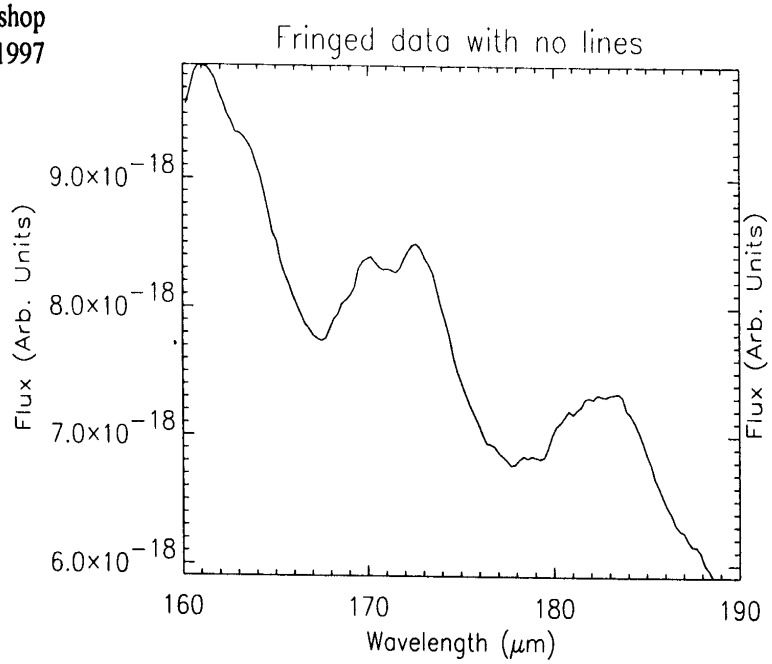
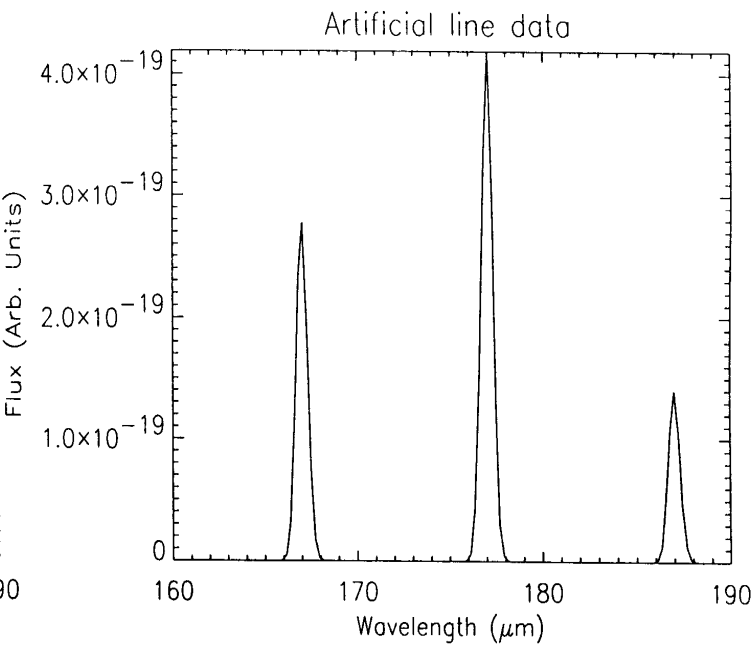
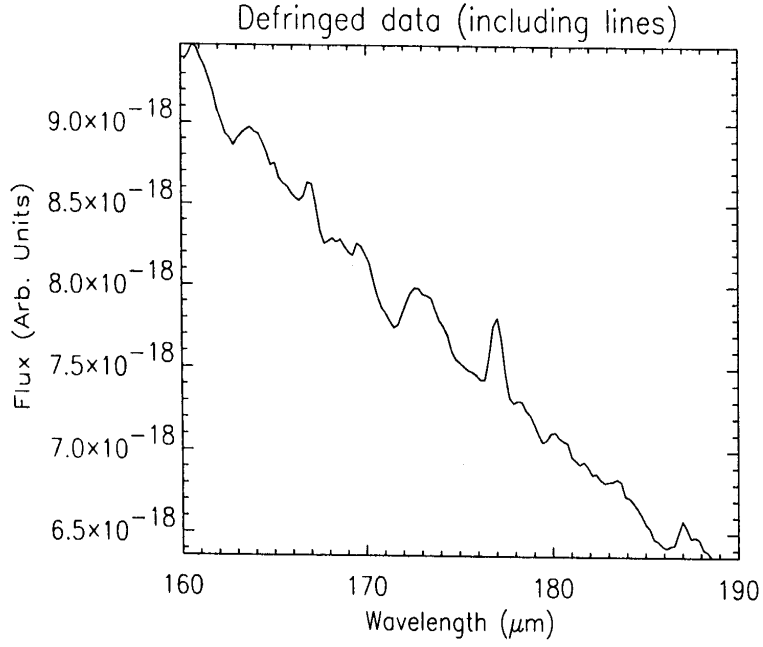
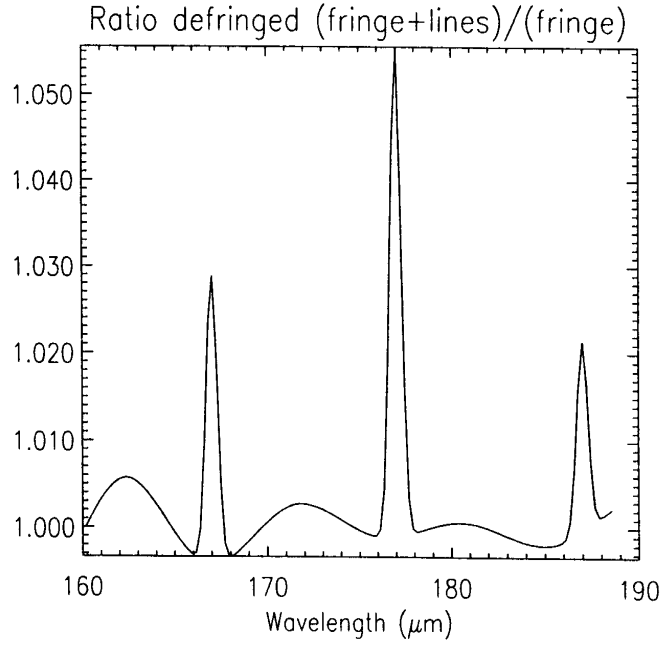


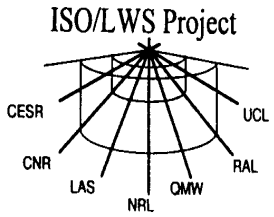
Fig.4b


Fringed data with no lines
Flux (Arb. Units)
9.0x10⁻¹⁸
8.0x10⁻¹⁸
7.0x10⁻¹⁸
6.0x10⁻¹⁸
160
170
180
190
Wavelength (μm)


Artificial line data
Flux (Arb. Units)
4.0x10⁻¹⁹
3.0x10⁻¹⁹
2.0x10⁻¹⁹
1.0x10⁻¹⁹
0
160
170
180
190
Wavelength (μm)


Defringed data (including lines)
Flux (Arb. Units)
9.0x10⁻¹⁸
8.5x10⁻¹⁸
8.0x10⁻¹⁸
7.5x10⁻¹⁸
7.0x10⁻¹⁸
6.5x10⁻¹⁸
160
170
180
190
Wavelength (μm)


Ratio defringed (fringe+lines)/(fringe)
1.050
1.040
1.030
1.020
1.010
1.000
160
170
180
190
Wavelength (μm)



Dark current uncertainties and error propagation

One can write the final uncertainty on the flux for any given point as:

$$\Delta F = F \times \left(\frac{(\delta P^2 + \delta D^2)}{(P - D)^2} + \left(\frac{\delta P_U}{P_U}\right)^2 + \left(\frac{\delta M_U}{M_U}\right)^2 + \left(\frac{\delta R}{R}\right)^2 \right)^{1/2} \qquad (1)$$

where:

δP = the statistical uncertainty on the photocurrent
P = the average value of the photocurrent
δD = the statistical uncertainty on the measured dark current
D = the average dark current
δP_U = the statistical uncertainty on the photocurrent on Uranus
P_U = the photocurrent on Uranus
δM_U = the uncertainty on the accuracy of the Uranus model spectrum
M_U = the value of the model spectrum
δR = the statistical uncertainty on the measured illuminator ratio
R = the value of the illuminator ratio

Dark current uncertainties and error propagation

- We know some of these things:

$\delta P_U/P \simeq 0.01$

$\delta M_U/M \simeq 0.05$

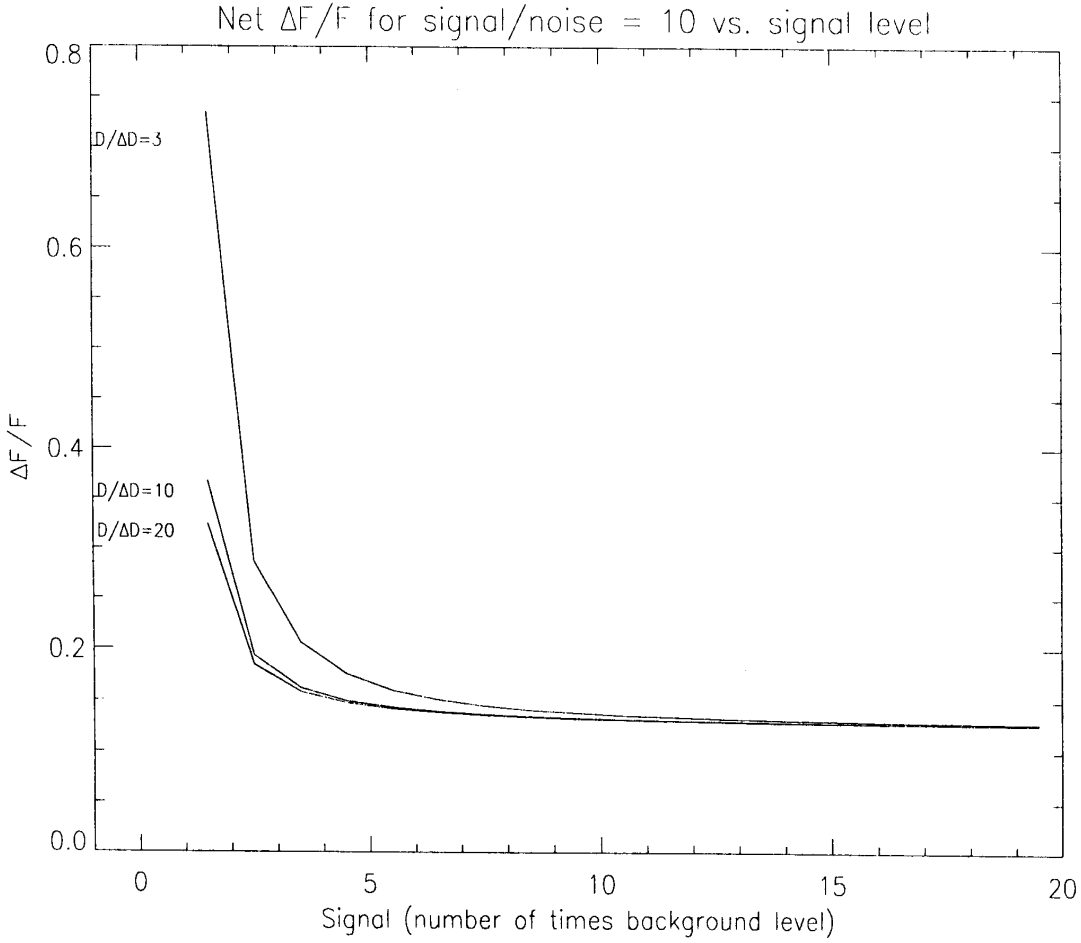
$\delta R/R \sim 0.05$ (generally can be factor of two bigger or smaller!)

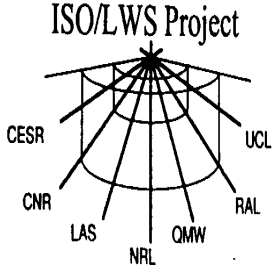
So we can rewrite (1) as:

$$\Delta F = F \times \left(\frac{(\delta P^2 + \delta D^2)}{(P - D)^2} + 0.0051 \right)^{1/2} \qquad (2)$$

The clear implication of this is that the final accuracy of the derived flux depends critically on how close the measured photocurrent is to the dark current and how well the dark current can be measured.

Dark current uncertainties and error propagation





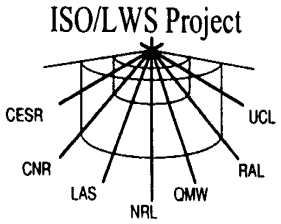
Dark current uncertainties and error propagation

Measuring the dark current:

Up to REV 237 we used ~16 1/2 sec ramps; after this (owing to an uplink mistake) we used ~8 one sec ramps.

For both of these a random sample of dark current measurements shows that $\langle \delta D/D \rangle$ ~ 5-6, but can be as low as 2.

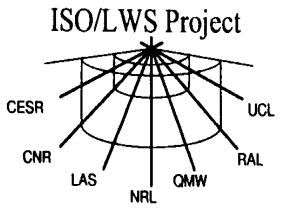
From REV 3?? we use 30 (ish) 1/2 sec ramps and $\langle \delta D/D \rangle$ ~ 12-14 and no worse than 6.



Dark current uncertainties and error propagation

What does it mean in flux? The table gives the equivalent fluxes and flux densities at the centre of the detector band for "typical" detector dark currents:

Detector	Dark Current (e/s)	Dark Current (Amps)	Flux (W cm^{-2} μm^{-1})	Flux Density (Jy)
SW1	3250	5.20e-16	5.52e-18	39.1
SW2	1240	1.98e-16	4.02e-18	42.4
SW3	1240	1.98e-16	3.13e-18	45.7
SW4	710	1.14e-16	2.04e-18	39.1
SW5	924	1.48e-16	3.14e-18	75.4
LW1	1470	2.35e-16	7.45e-19	26.1
LW2	332	5.32e-17	5.56e-20	2.77
LW3	647	1.03e-16	3.74e-20	2.51
LW4	1650	2.64e-16	1.29e-19	11.1
LW5	1059	1.69e-16	5.24e-19	55.4



Dark current uncertainties and error propagation

Estimation of the uncertainty on the flux without using the SPD.....

The flux is given by

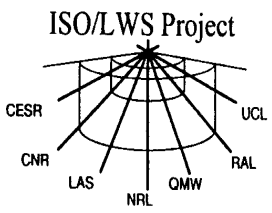
$$F(\lambda) = \frac{P(\lambda) - D}{f_R R(\lambda)\,\Delta\lambda}$$

$P(\lambda)$ - Photocurrent
D - dark current
f_R - responsivity correction factor from illuminator flash
$R(\lambda)$ - detector responsivity ($A/(W\,cm^{-2})$)
$\Delta\lambda$ - grating resolution element

one can write the uncertainty on this as

$$\Delta F(\lambda) = \left(\Delta\left(\frac{P(\lambda)}{f_R R(\lambda)\,\Delta\lambda} \right)^2 + \Delta\left(\frac{D}{f_R R(\lambda)\,\Delta\lambda} \right)^2 \right)^{1/2} \qquad (1)$$

ctd.....



Dark current uncertainties and error propagation

where

$$\Delta\left(\frac{D}{f_R R(\lambda)\,\Delta\lambda}\right)=\left(\frac{\delta D^2}{D}+\frac{\delta f_R{}^2}{f_R}+\frac{\delta R(\lambda)^2}{R(\lambda)}\right)^{1/2} x\left(\frac{D}{f_R R(\lambda)\,\Delta\lambda}\right) \qquad (2)$$

and we can estimate

$$\Delta\left(\frac{P(\lambda)}{f_R R(\lambda)\,\Delta\lambda}\right)\approx\left(\frac{\delta F(\lambda)^2}{F(\lambda)}+\frac{\delta f_R{}^2}{f_R}+\frac{\delta R(\lambda)^2}{R(\lambda)}\right)^{1/2} x\, F(\lambda) \qquad (3)$$

We know everything to calculate (2) precisely - we can estimate $\delta F(\lambda)$ from the spectrum and thus calculate (3).

Equation (3) is a very good approximation when $P(\lambda) >> D$ and - because $F(\lambda) \to 0$ as $P(\lambda)$ approaches D - it doesn't matter that it is a bad approximation at low fluxes because the dark current uncertainties will dominate anyway.

What happens between times - well you can always go back and do it properly!

LWS OPTICS MODEL

B. Swinyard

Overview

- Measurement of the FWHM of the LWS beam gives a maximum of 82" - even at 46 μm - and a peculiar response versus wavelength.
- This is STILL not explained by the ASAP model - which is restricted to the ISO telescope, M2 and the acceptance angle of the collimator.
- To add in all the surfaces to the ASAP and run for all cases will be extremely laborious.
- Observers will need a parametric model at some point in order to fully calibrate extended and complex sources.
- Standard Fraunhofer diffraction theory can be used to shed light on what might be happening - ultimately a full ASAP model must be used to calibrate the parametric model.

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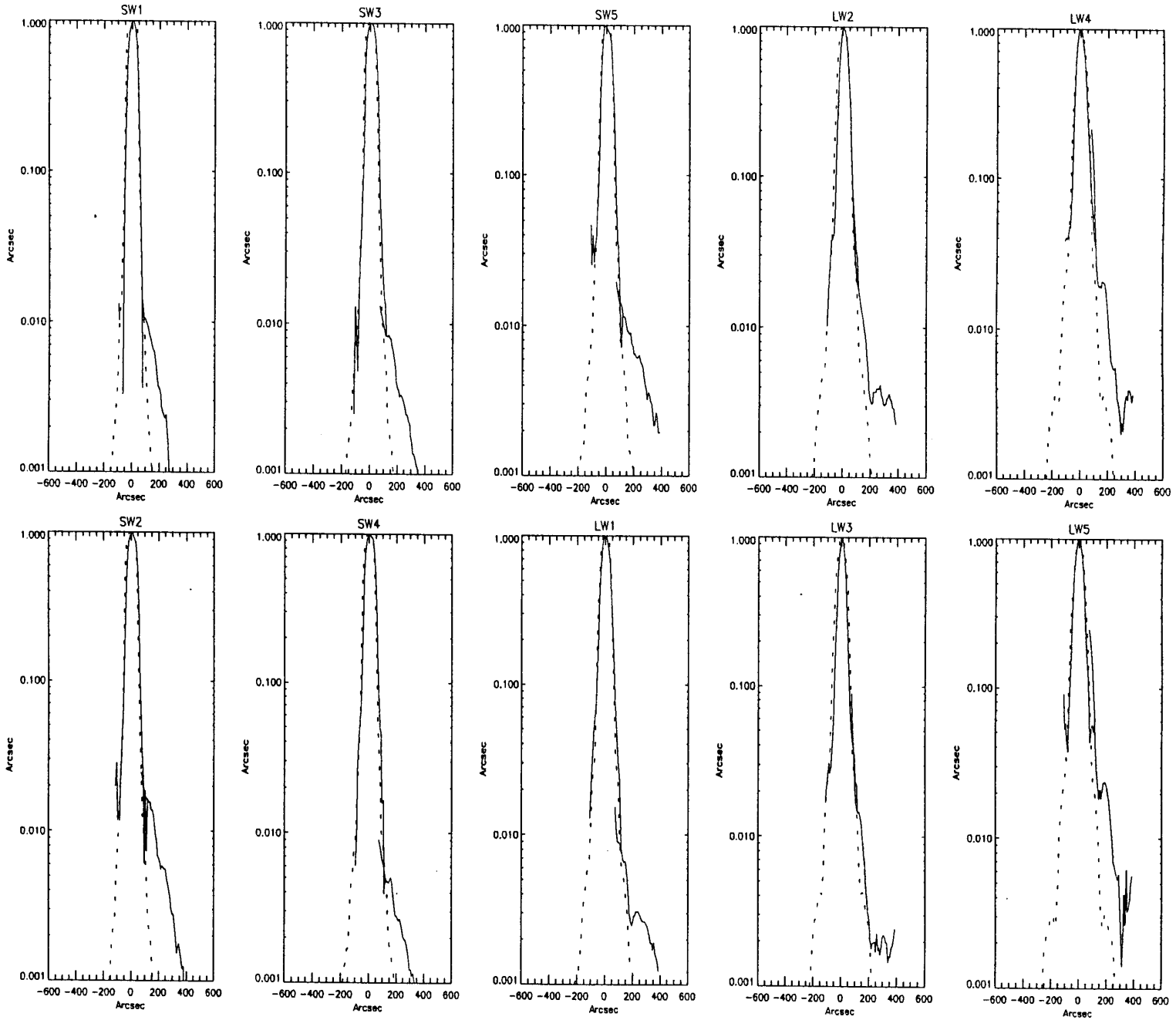
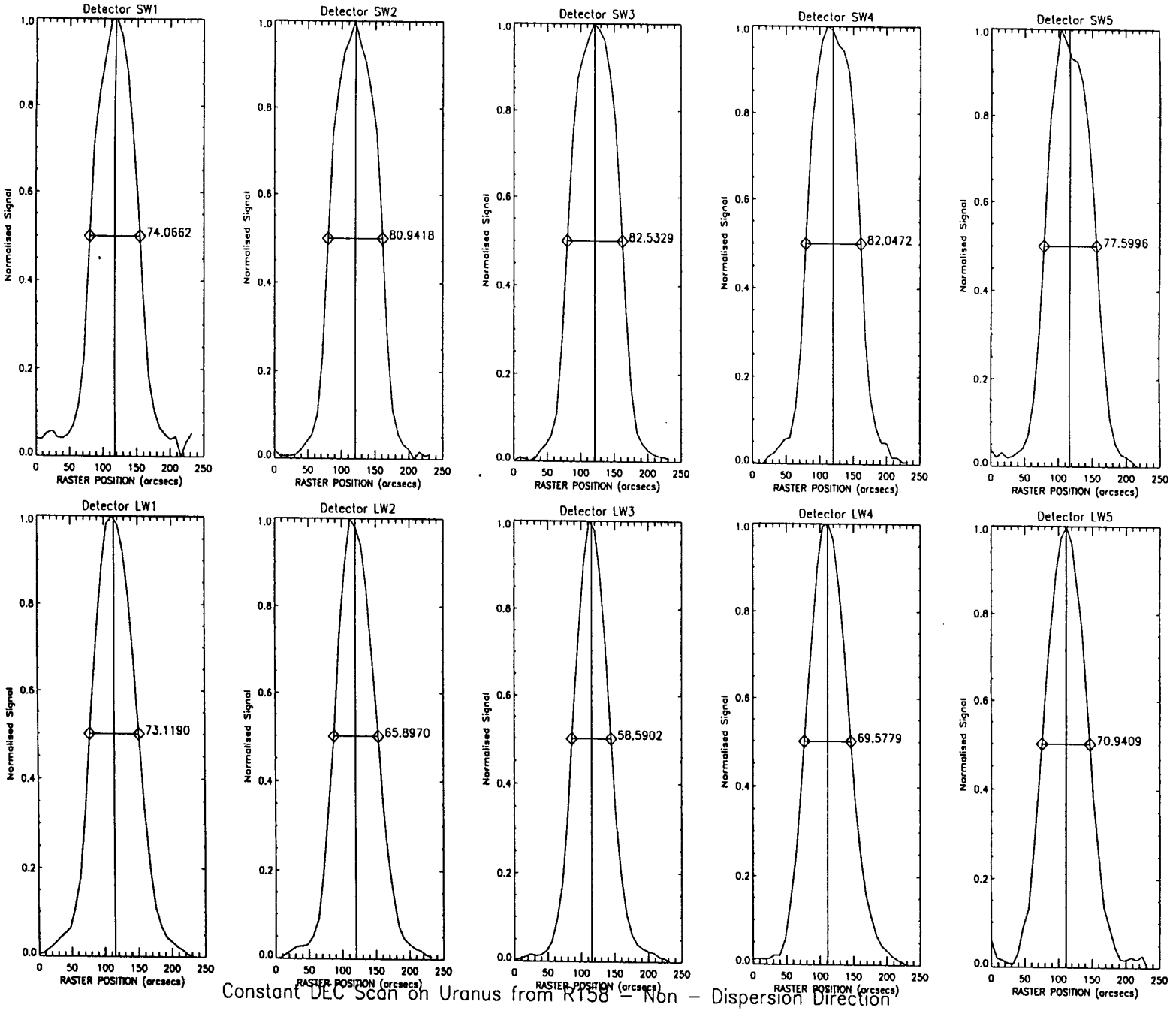

SW1
SW3
SW5
LW2
LW4
SW2
SW4
LW1
LW3
LW5
1.000
0.100
0.010
0.001
Arcsec
-600 -400 -200 0 200 400 600



Constant DEC Scan on Uranus from R158 – Non – Dispersion Direction

LWS OPTICS MODEL

B. Swinyard

Measured FWHM and "standard" convolution

Approximate Wavlength (μm)	Measured FWHM in Y-axis (",^)	Measured FWHM in Z-axis (",^)	Expected FWHM in Y-axis from M2 (",^)
46	82 +,_ 1 (0)	70 +,_ 4 (0)	105.8
56	83 +,_ 1 (0)	79 +,_ 2 (0)	105.8
66	83 +,_ 1 (0)	82 +,_ 1 (0)	105.5
76	82.5 +,_ 1.5 (0)	78.5 +,_ 3.5 (0)	105.2
84	82 +,_ 1 (0)	75.5 +,_ 2.5 (0)	105.3
102	77 +,_ 1 (2)	71 +,_ 2 (3)	106.2
122	69.5 +,_ 1.5 (3)	67.5 +,_ 0.5 (3)	105.9
140	63 +,_ 3 (3)	58.5 +,_ 0.5 (3)	103.9
160	71.5 +,_ 0.5 (4)	68 +,_ 3 (5)	101.9
176	72 +,_ 3 (5)	71 +,_ 1 (8)	100.4

LWS OPTICS MODEL

B. Swinyard

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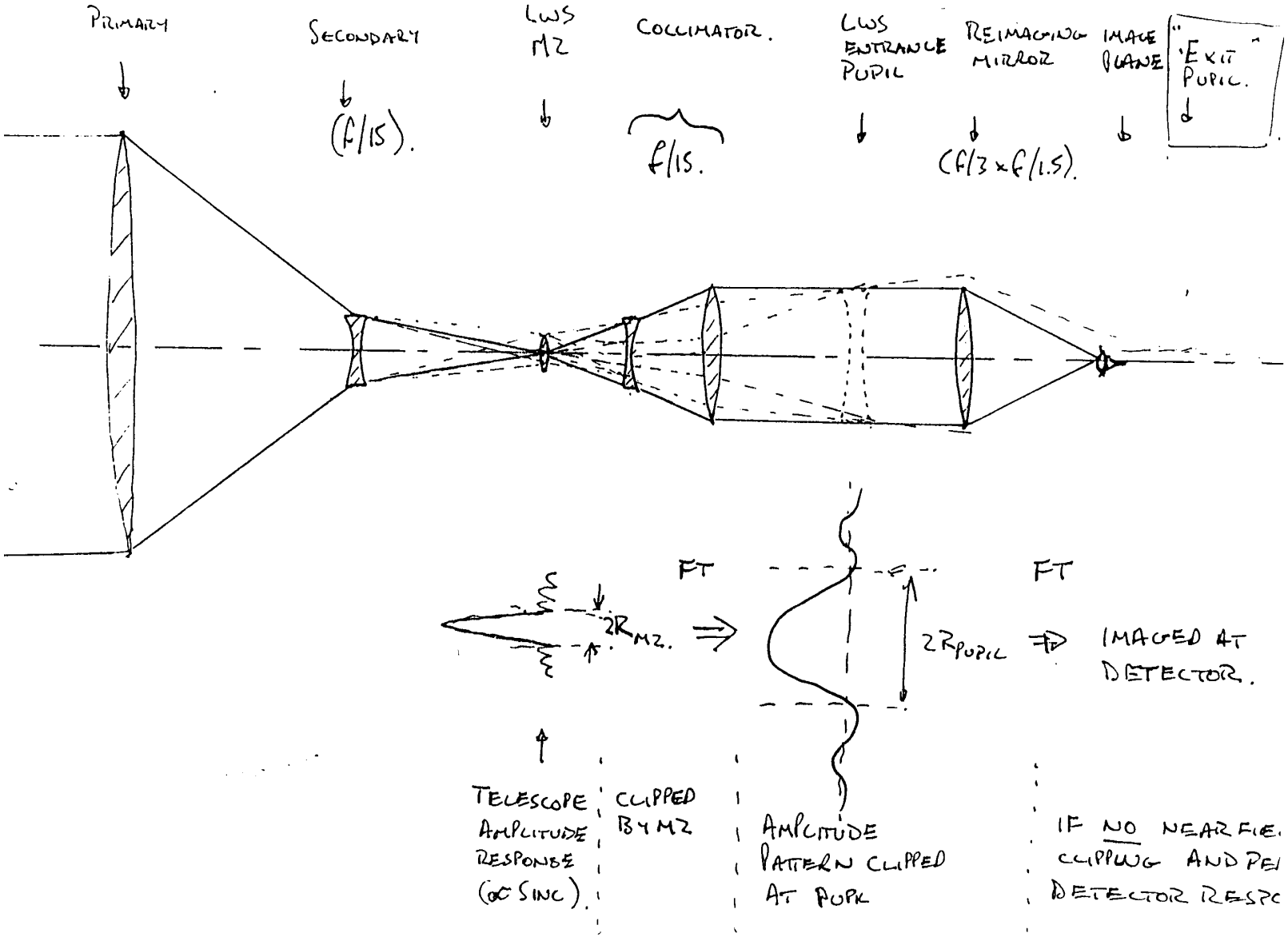
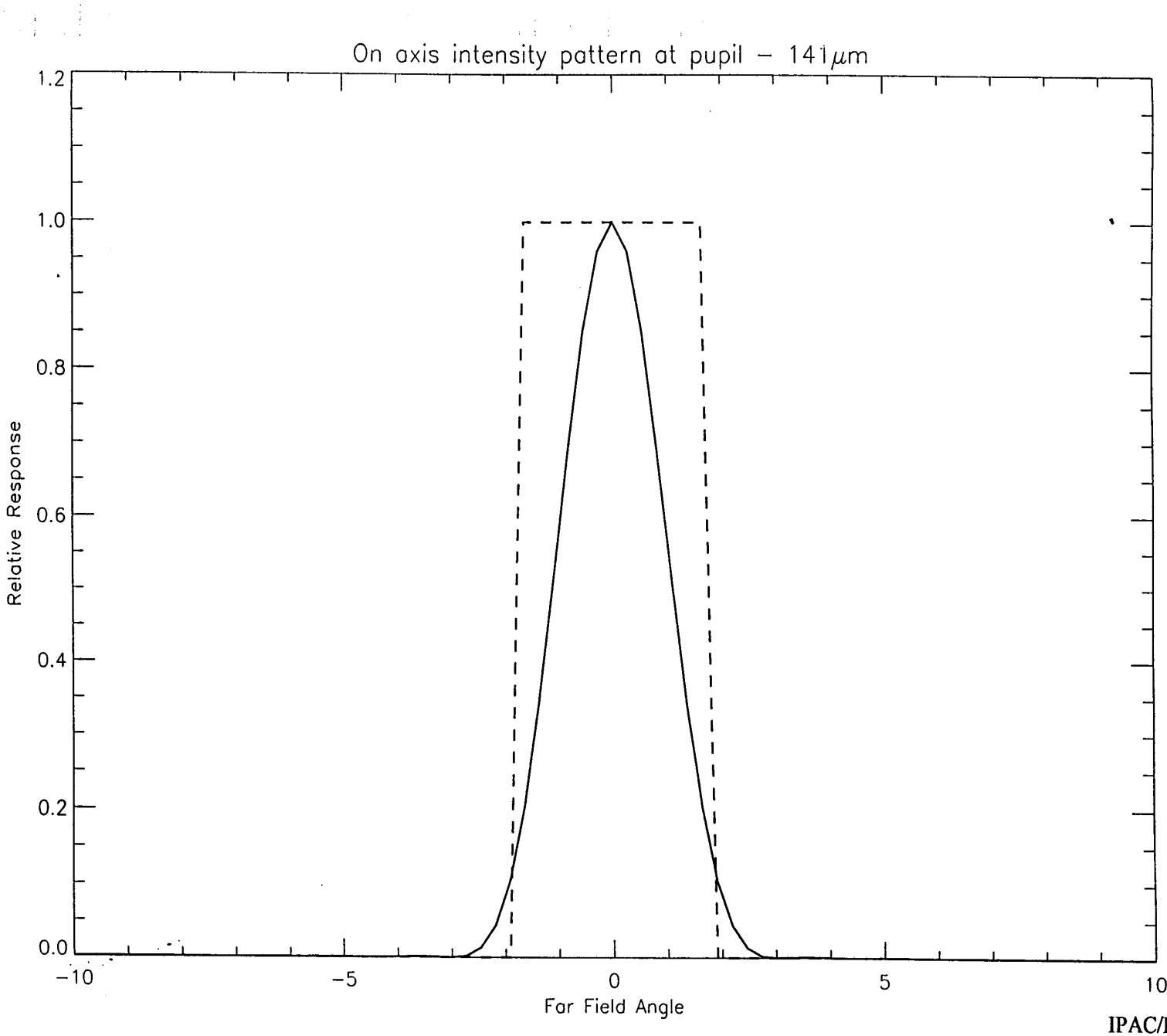
Optical Train





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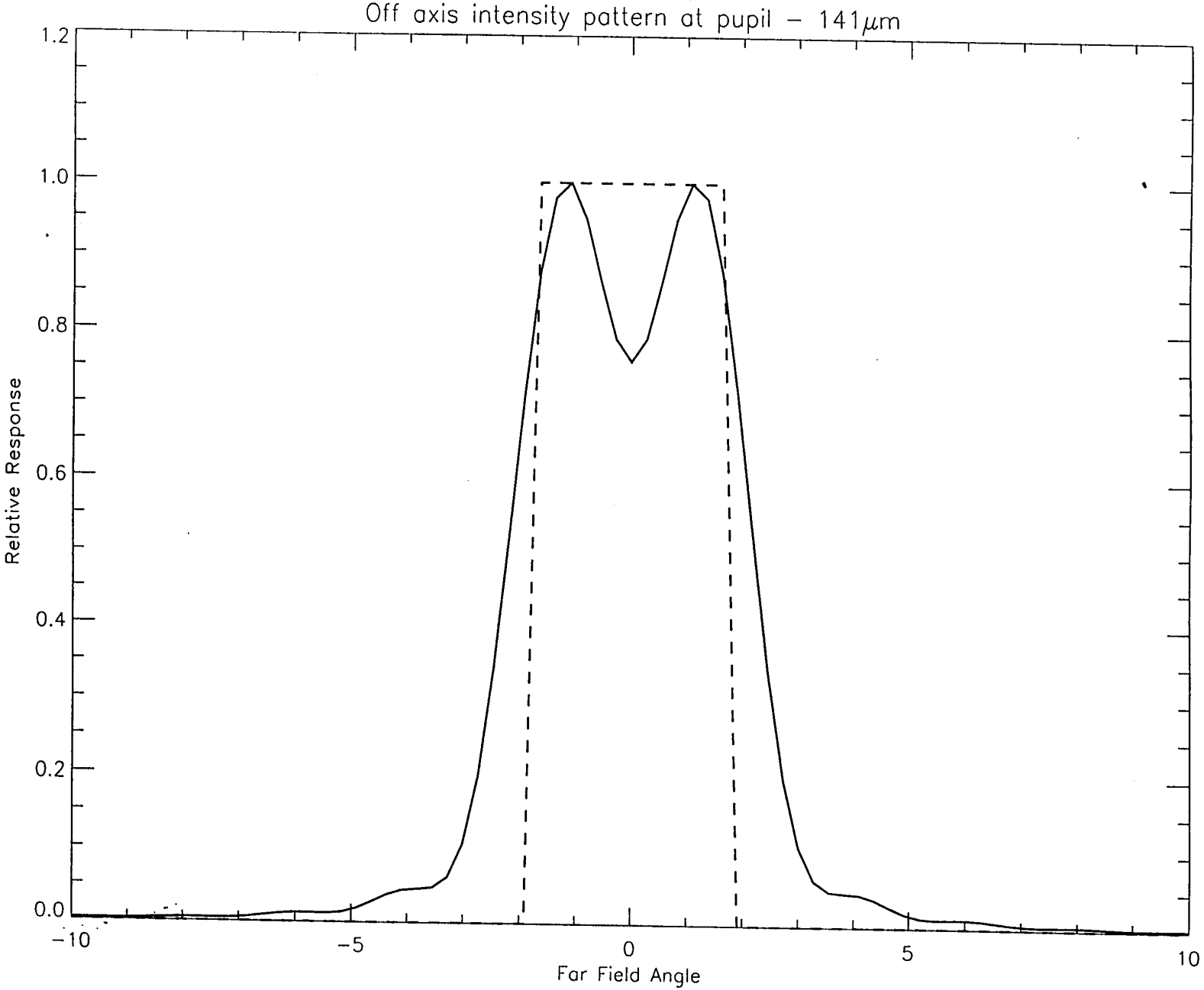
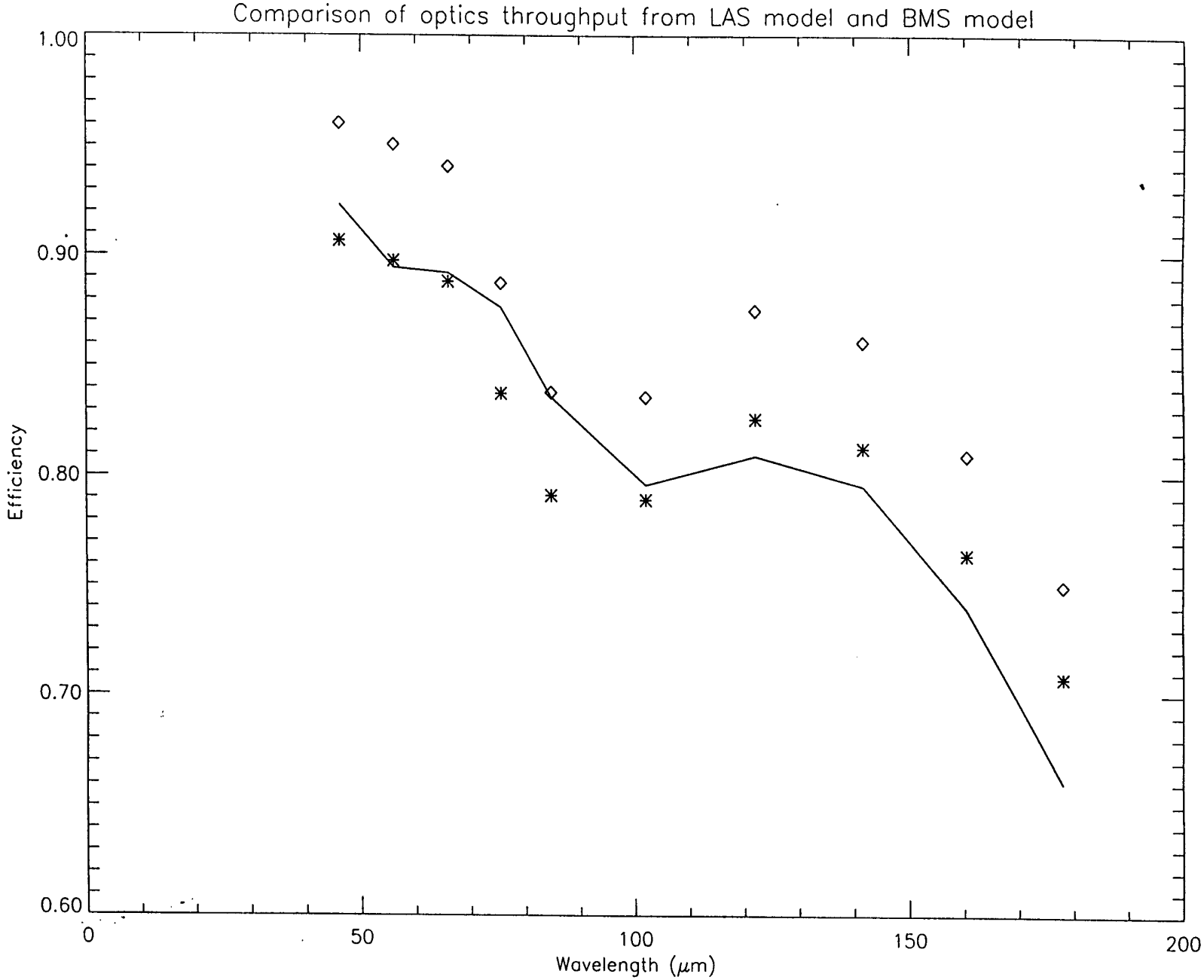

Off axis intensity pattern at pupil – 141μm
Relative Response
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−10
−5
0
5
10
Far Field Angle



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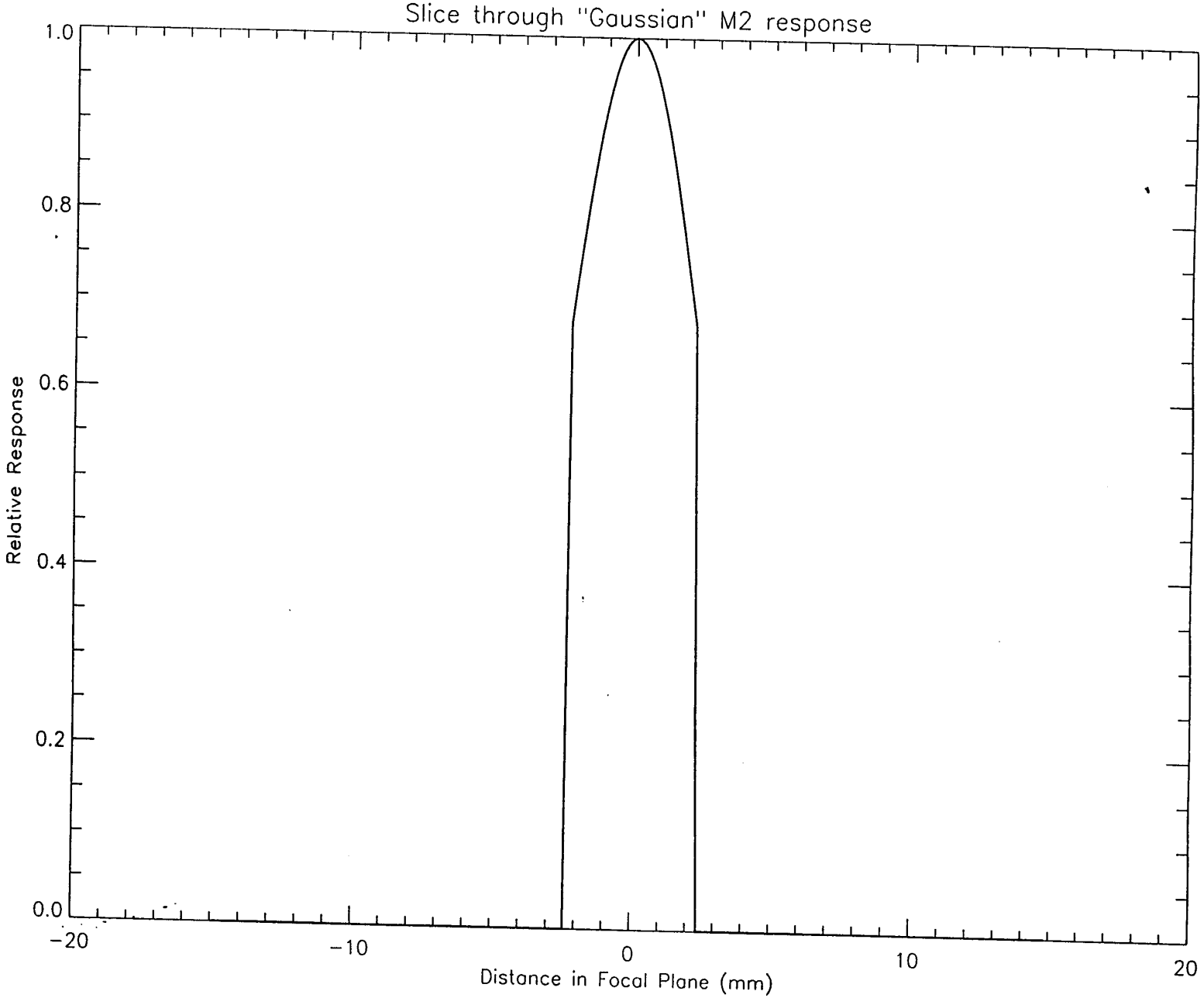
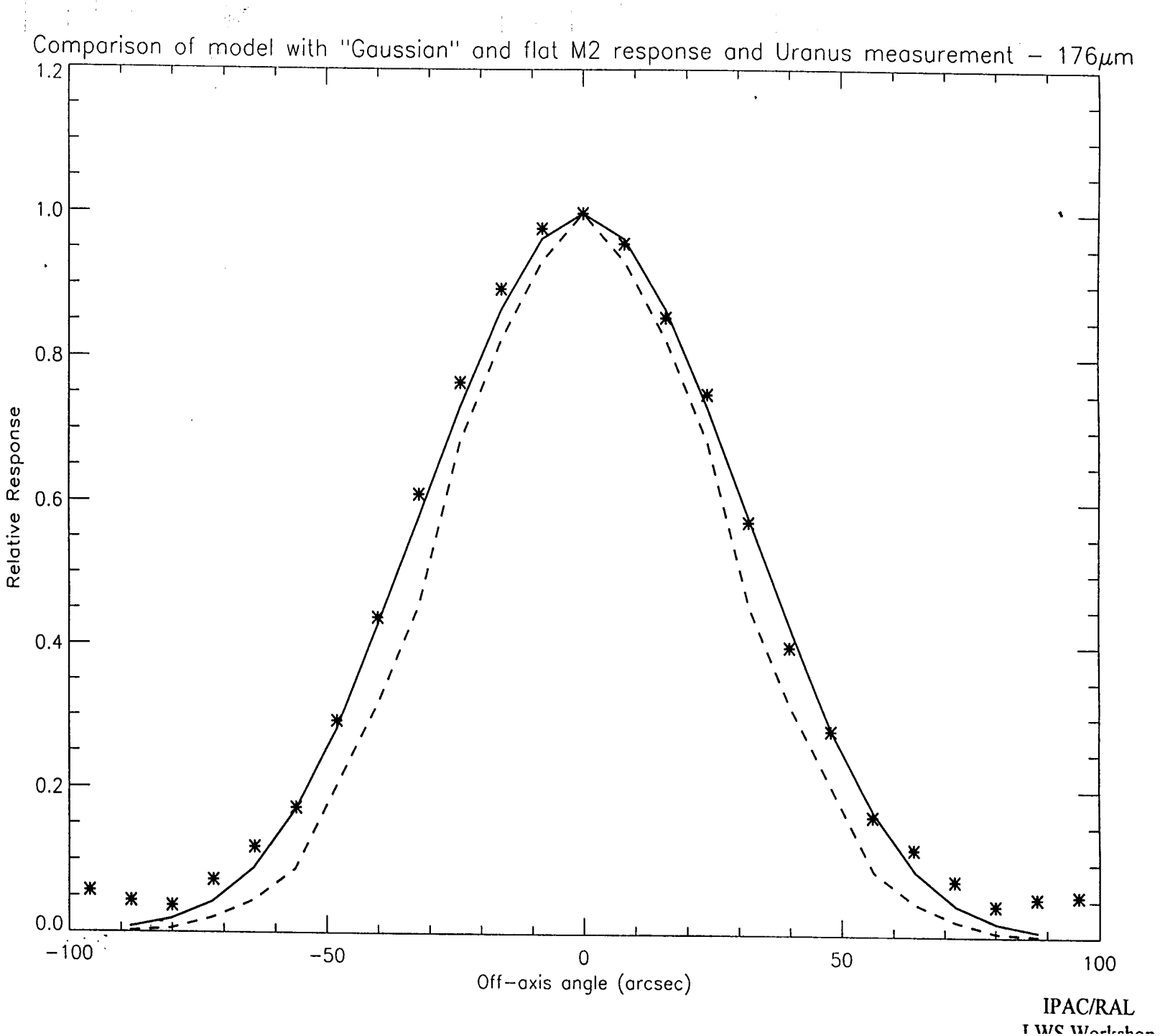
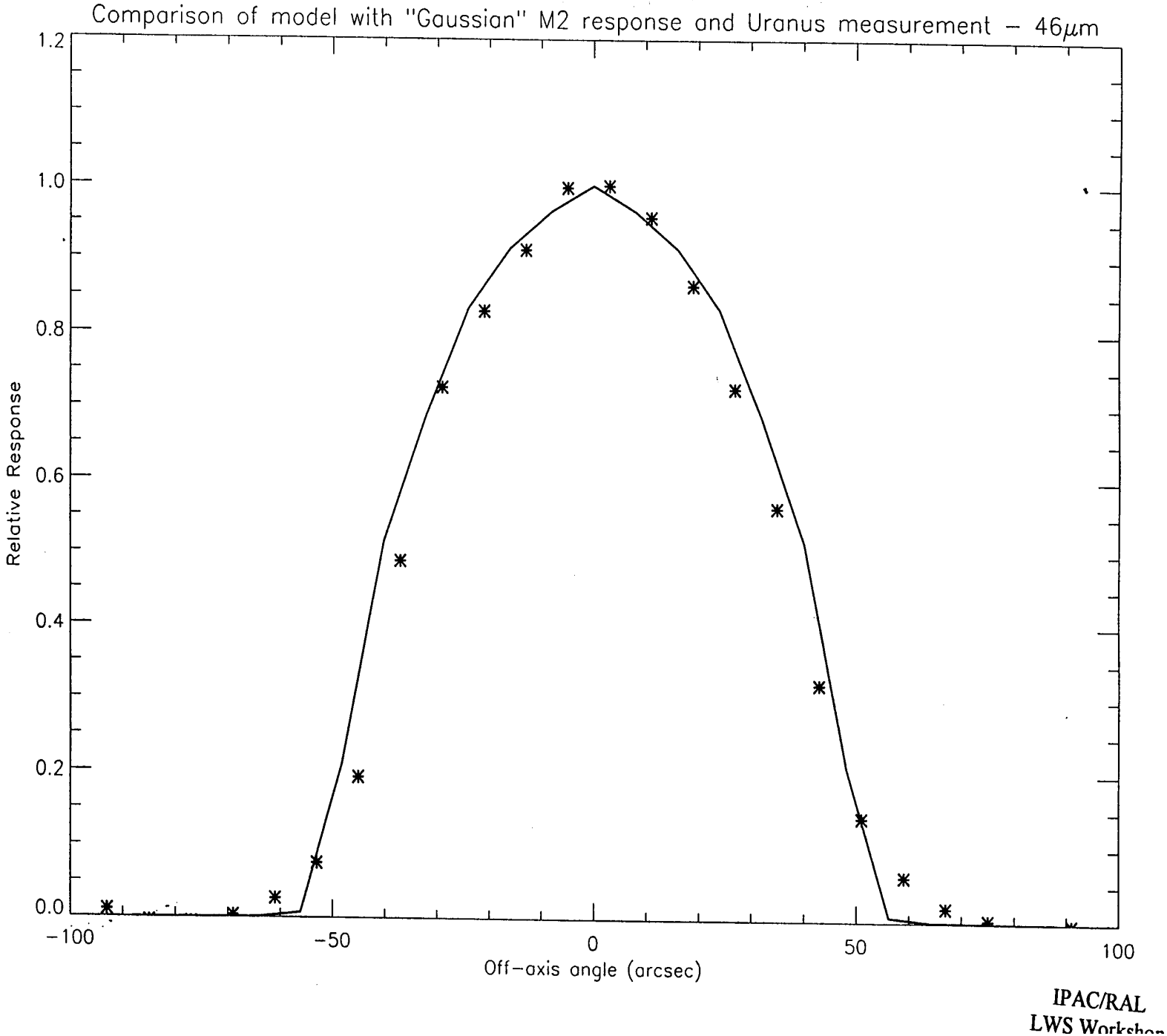

Slice through "Gaussian" M2 response
Relative Response
1.0
0.8
0.6
0.4
0.2
0.0
-20
-10
0
10
20
Distance in Focal Plane (mm)


Comparison of model with "Gaussian" and flat M2 response and Uranus measurement – 176μm
Relative Response
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−100
−50
0
50
100
Off−axis angle (arcsec)
IPAC/RAL



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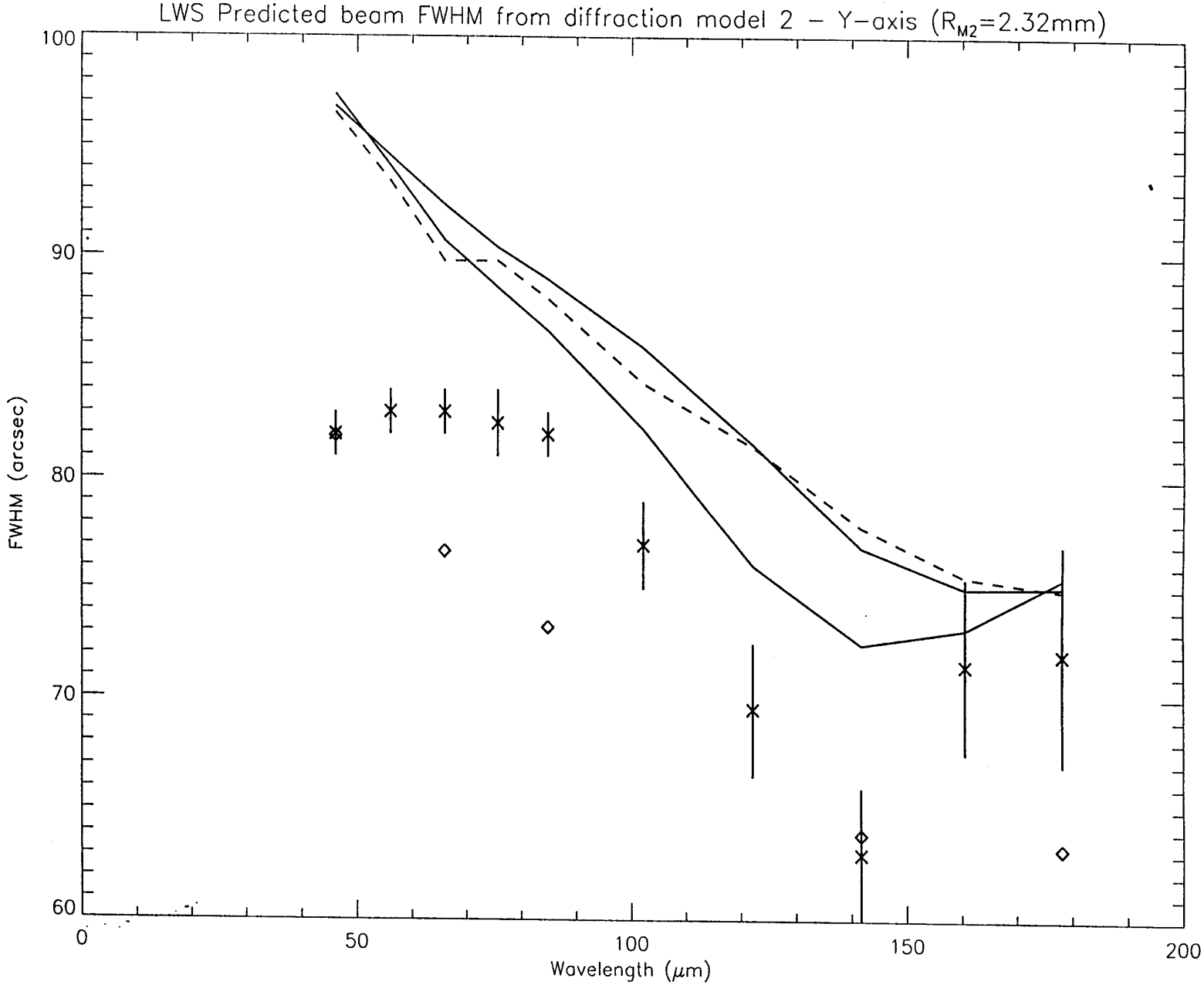
LWS Workshop



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LWS OPTICS MODEL

B. Swinyard

What is going on!

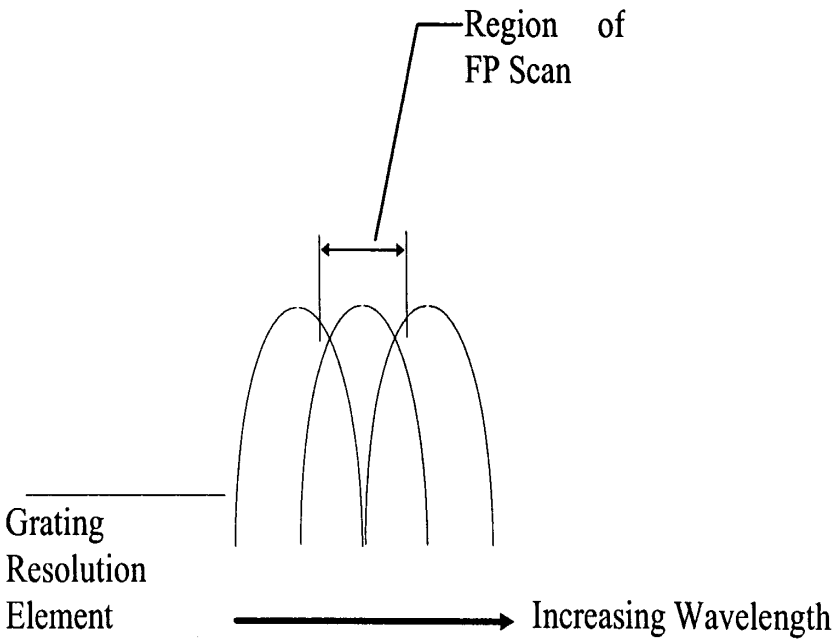
- The "standard" model agrees with the results of the original calculations (hurrah!)
- It does not explain the beam width.
- Changing parameters within the model does have an affect on the beam width but only explain the response versus wavelength if they too are somehow wavelength dependent.

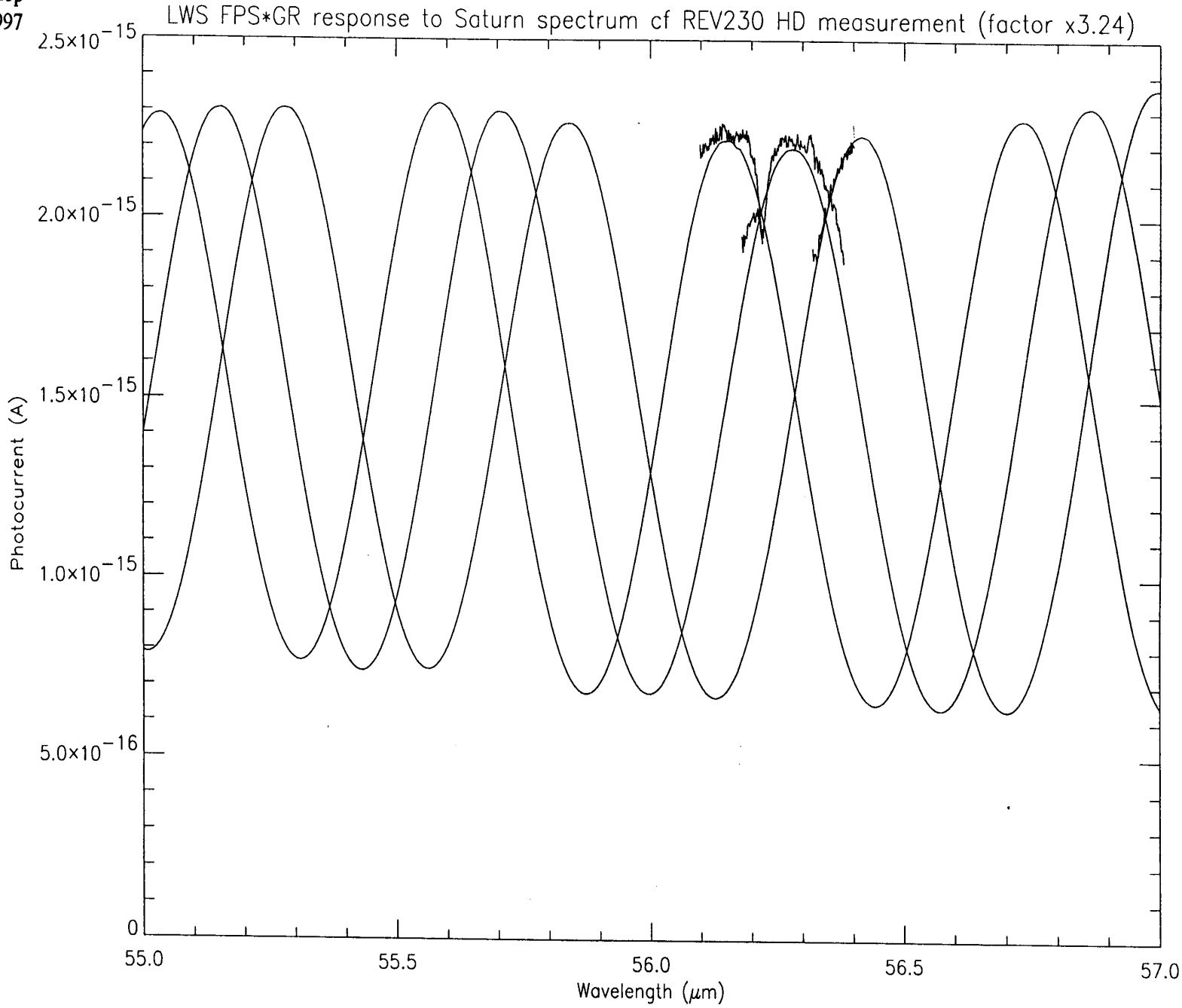
What doesn't work systematically:

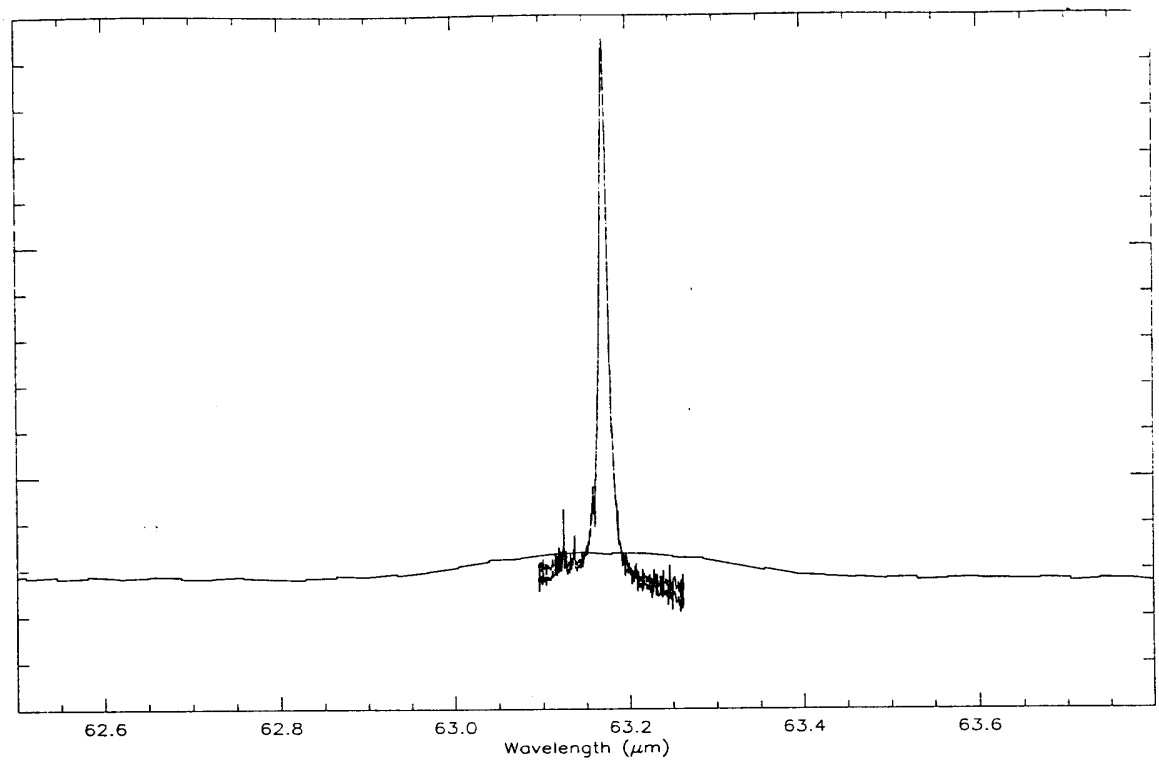
- Simplistic model of the grating
- "Pupil" response - can be used to explain the LW response.
- Detector slit width - only changes the throughput(?)
- Re-imaged detector or "M2 response" - may work if the detector response isn't as published (?)
  Is it "Clipped" through the system?
  What is the affect of the M2 mirror mount?
- Biggest mystery is the "flat response" at short wavelengths.

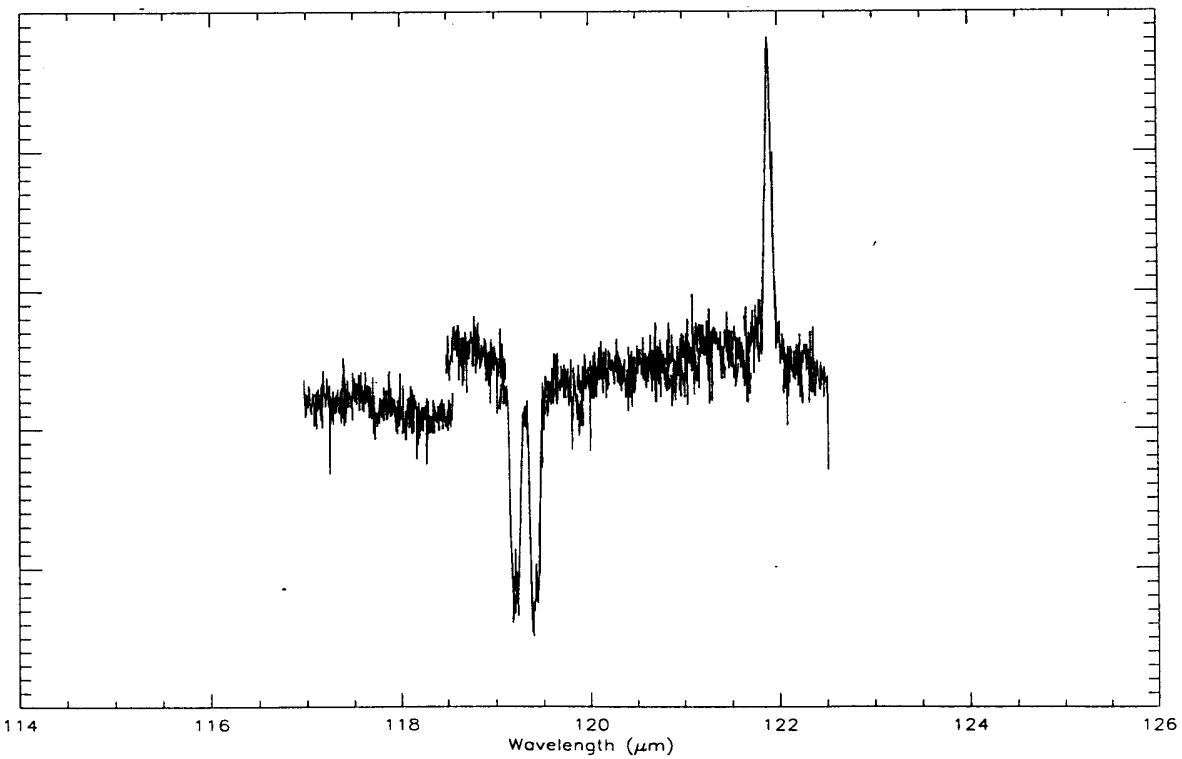
Fabry-Perot Wide Wavelength Scans (L03)

- The Fabry-Perots can be used to cover large wavelength regions by stepping the grating and scanning the FP over the commensurate wavelength:

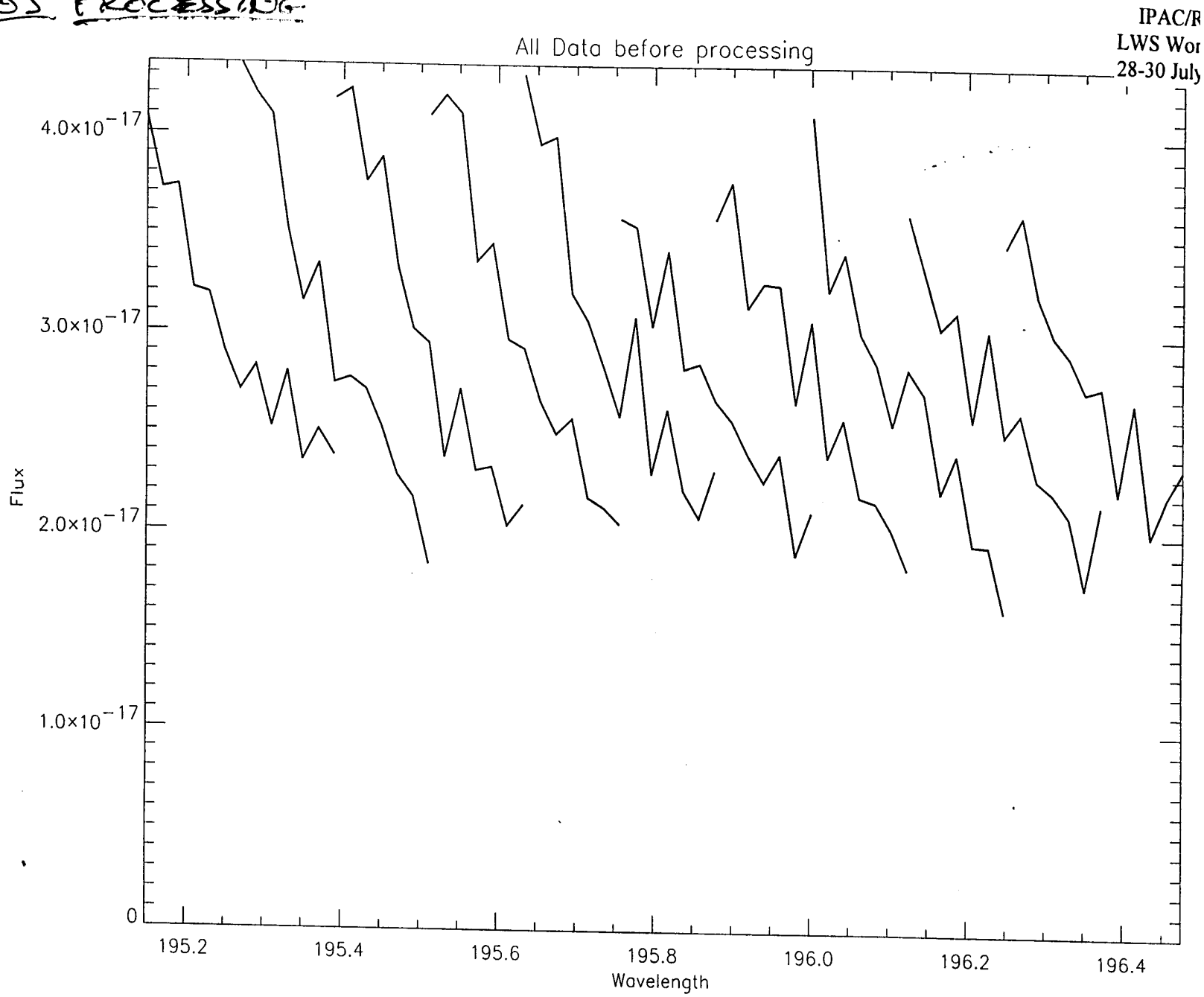



LWS FPS*GR response to Saturn spectrum cf REV230 HD measurement (factor x3.24)
2.5×10⁻¹⁵
2.0×10⁻¹⁵
1.5×10⁻¹⁵
1.0×10⁻¹⁵
5.0×10⁻¹⁶
0
Photocurrent (A)
55.0
55.5
56.0
56.5
57.0
Wavelength (μm)


62.6
62.8
63.0
63.2
63.4
63.6
Wavelength (μm)

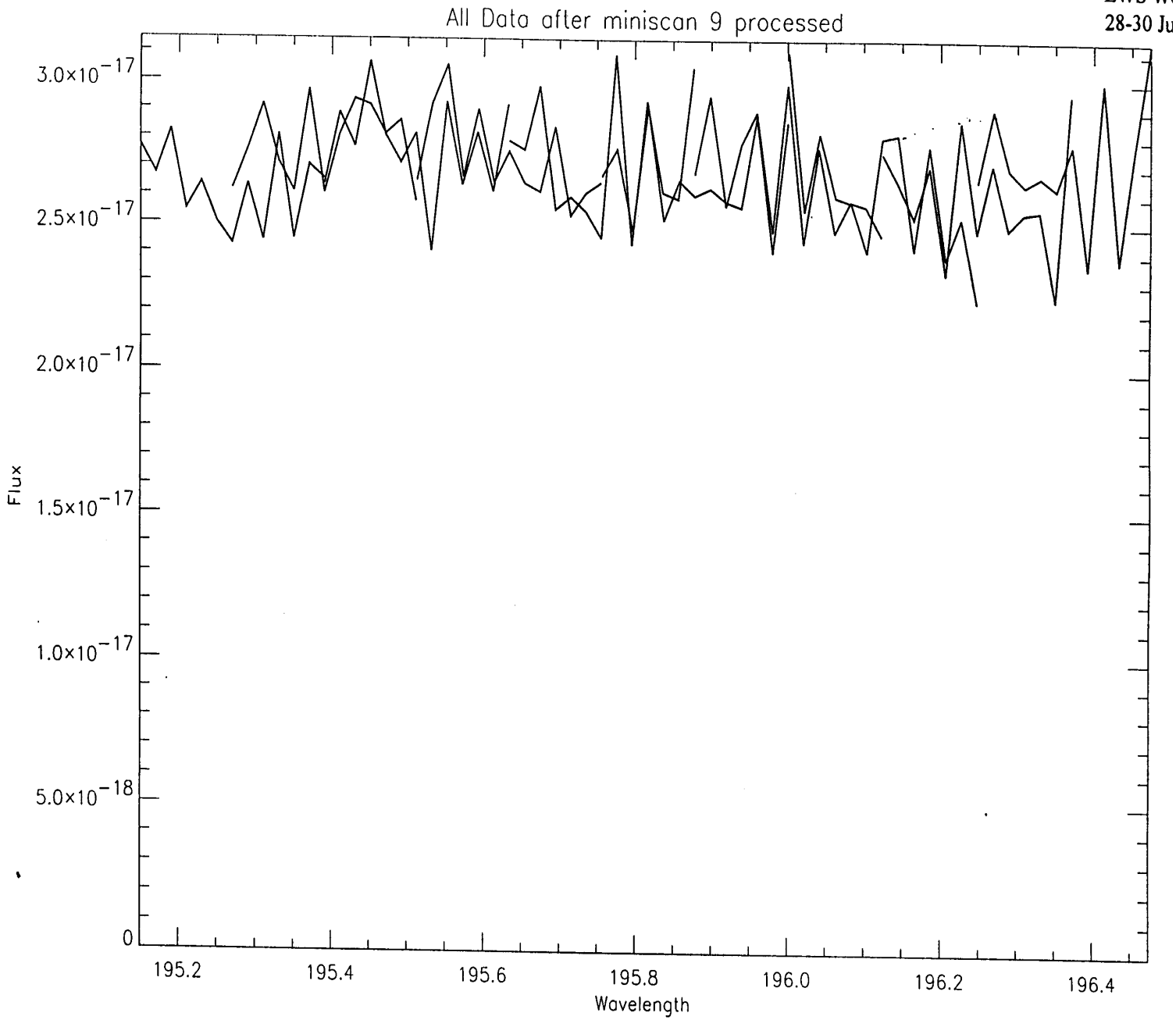

114
116
118
120
122
124
126
Wavelength (μm)

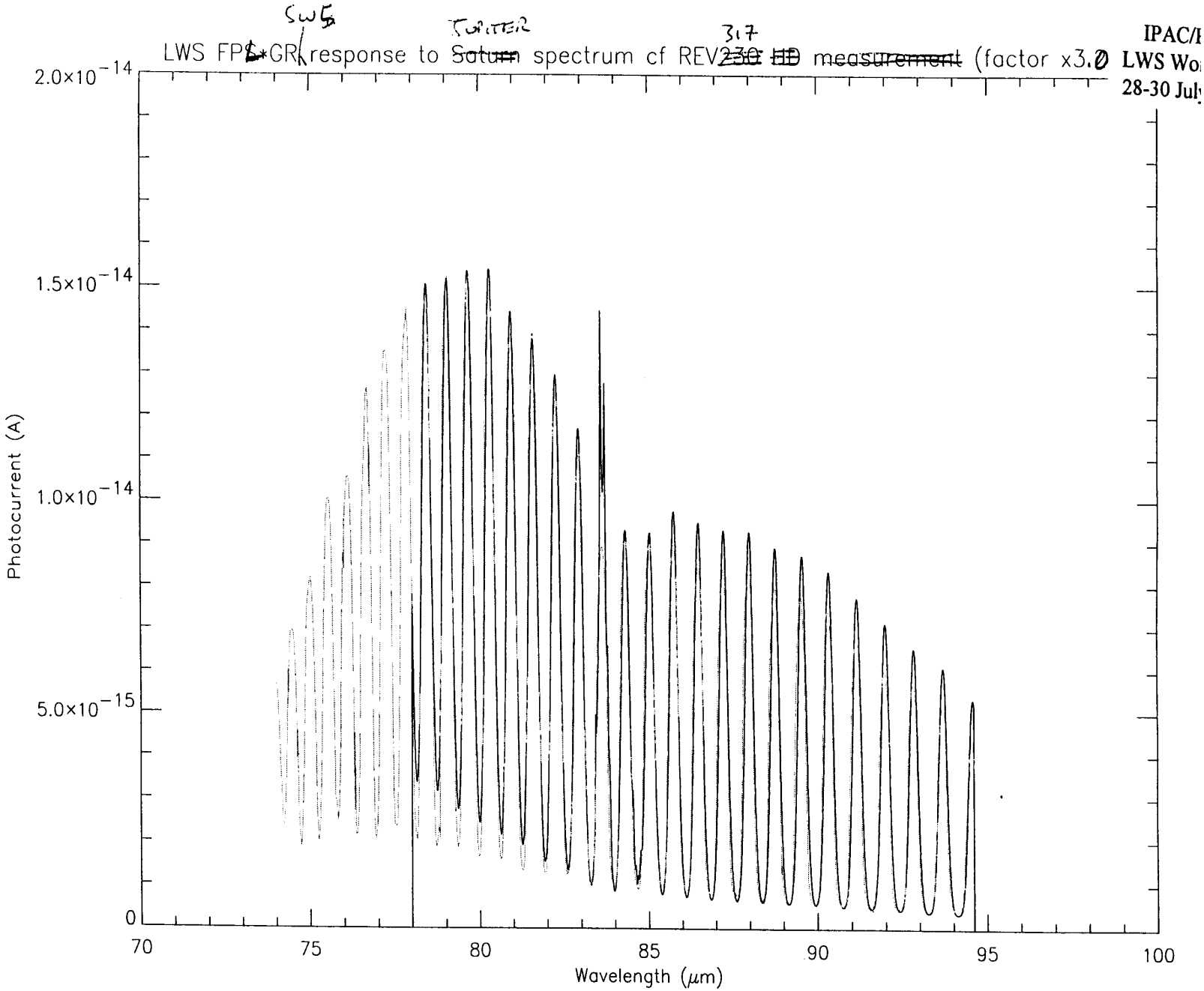
LO3 PROCESSING



L03 Processing

IPAC
LWS W
28-30 Ju




LWS FP SW5 GR response to Jupiter spectrum of REV 317
IPAC/I
LWS Wo
28-30 Jul
2.0×10⁻¹⁴
1.5×10⁻¹⁴
1.0×10⁻¹⁴
5.0×10⁻¹⁵
0
Photocurrent (A)
70
75
80
85
90
95
100
Wavelength (μm)