CAVEAT

THIS PRESENTATION INCLUDES 36 SLIDES. MANY OF THEM HAVE MORE WORDS THAN IS NORMAL FOR POWERPOINT.

NATHELESS, I HOPE TO SHOW ALL OF THEM IN 20 MINUTES OR LESS. MAY NOT SUCCEED, BUT WILL TRY.

The HST Treasury Program on Eta Carinae

Some data techniques developed for the Eta Car Treasury Program

Persons involved in this development sub-project:

Kris Davidson (UMN) Kazunori Ishibashi (MIT)

John C. Martin (UMN)

with considerable assistance from

Matt Gray (UMN, now at Clockwork)

Roberta M. Humphreys (UMN)

Further information: http://etacar.umn.edu/

*** PRELIMINARY REMARK ***

These tricks were devised for a specific STIS / CCD / spectroscopic data set ;

but

some of them are useful for a wide variety of 2-d image data.

THE ROLE OF ETA CAR
FOR DATA-PROCESSING CONCERNS

This has been an unusually demanding target for HST.

- Needs the best attainable spatial resolution, throughout an extended structure.
- Spatially and spectrally complex, with several distinct types of local spectra.
- Broad spectral coverage is also required.
- And it's time-dependent ! (Both cyclical and secular)
- Bright, so modest integration times give high S/N. With STIS we gathered a huge data volume quickly.

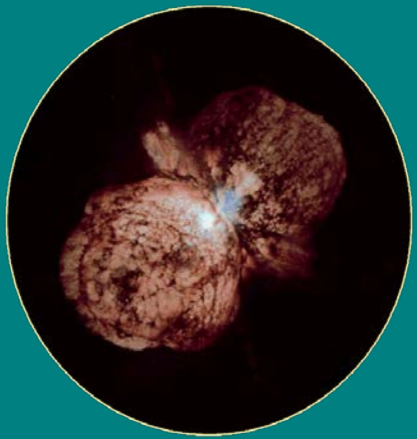
This set of characteristics is practically unique among major HST targets.

CONSEQUENTLY: IN SOME RESPECTS THIS HAS BEEN THE MOST INTENSIVE TARGET THROUGHOUT HST'S HISTORY.

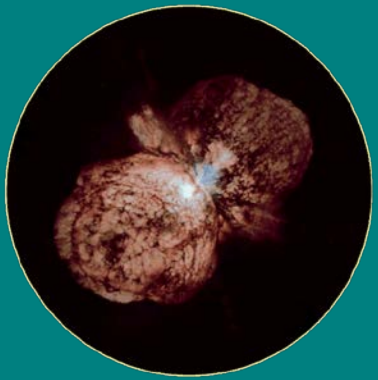
NON-ROUTINE OBSERVATIONS OF ETA REPEATEDLY PUSHED SEVERAL OF THE INSTRUMENTS CLOSE TO THEIR PRACTICAL LIMITS.

- Dense structure (lobes + skirt + granularity) produced one of the "iconic" HST images that resonated with the general public -- it even influenced Hollywood.

  Large dynamic range, with extraordinary surface brightnesses.



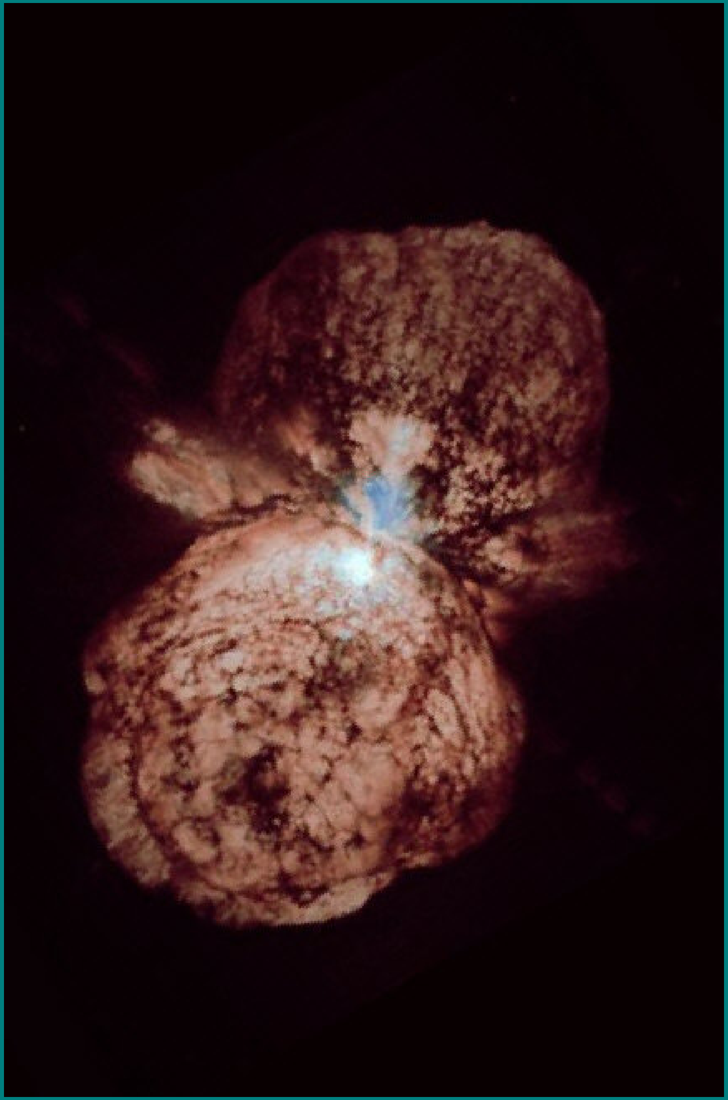
- Successive world records for high angular resolution in spectroscopy (FOS 1991 and 1996, GHRS 1997, STIS 1998 et seq)



"MOST INTENSIVE HST TARGET", CONTINUED ...

- 0.15″ resolution with the pre-COSTAR FOS, using a special trick. Later, practically the only target where the tiny 0.1″ FOS aperture was used (1991–1997)
- Another trick gave 0.1″ resolution with the 0.2″ GHRS aperture (1997)
- STIS / CCD: Best feasible resolution *on a complex extended structure.* (1998–2004. We'll see why this isn't easy.)

STIS OBSERVATIONS, 1998 -- 2004

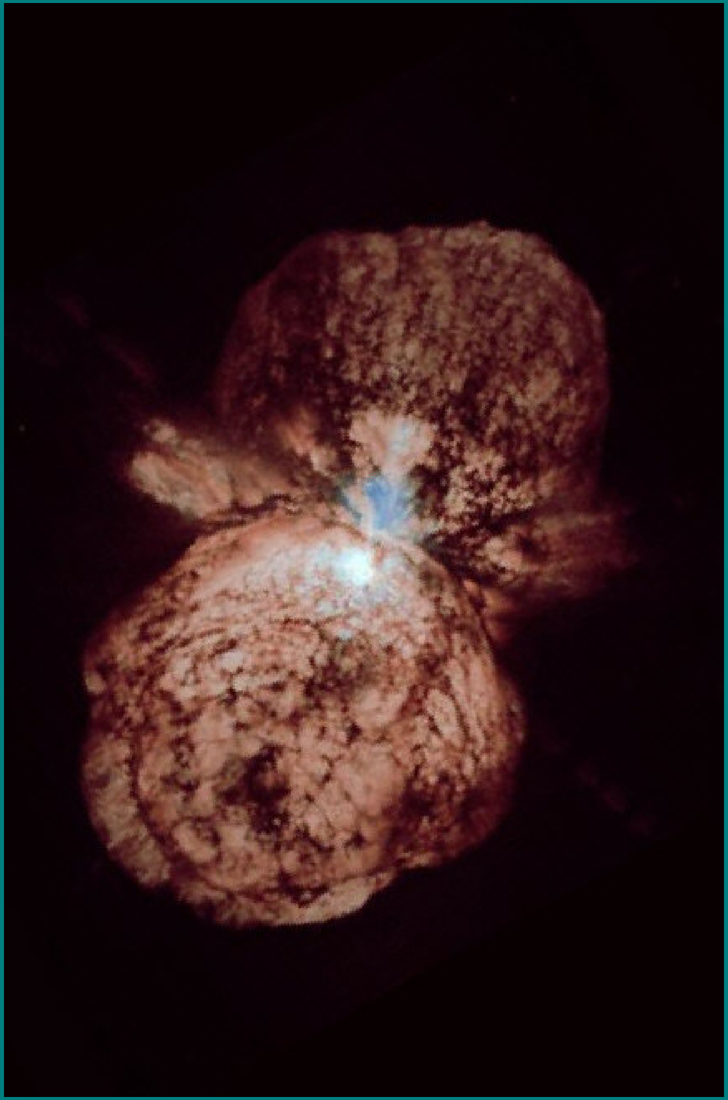


AT LEAST FIVE DISTINCT

TYPES OF SPECTRUM,

SPATIALLY DEPENDENT

STIS OBSERVATIONS, 1998 -- 2004



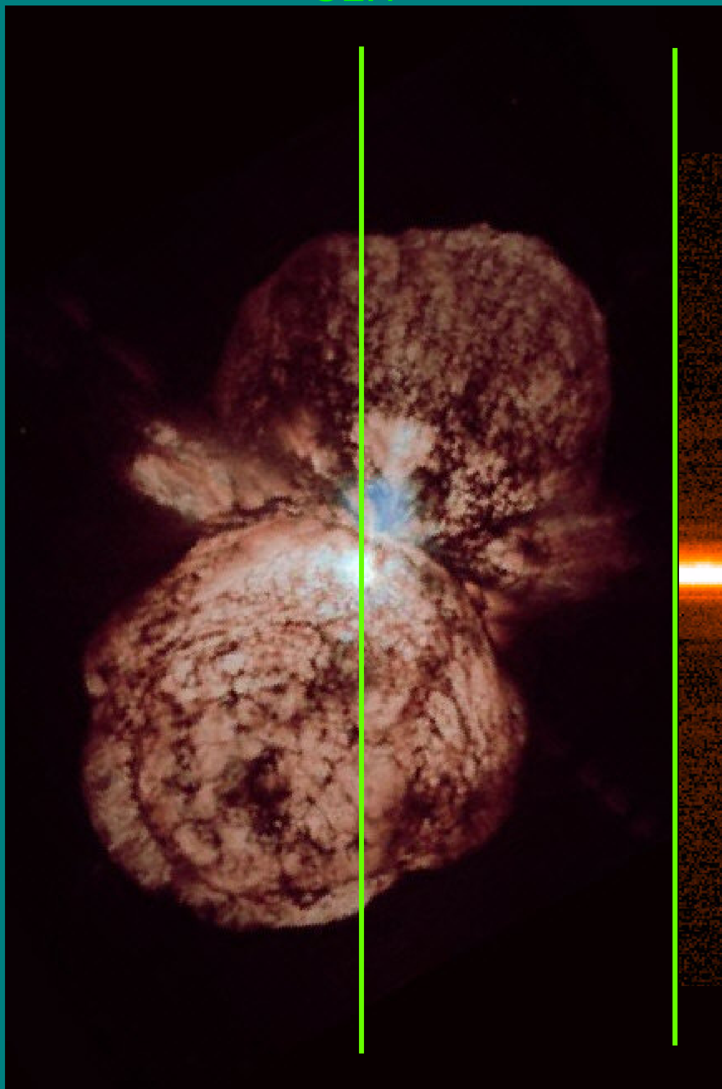
-- THOUSANDS OF EMISSION FEATURES

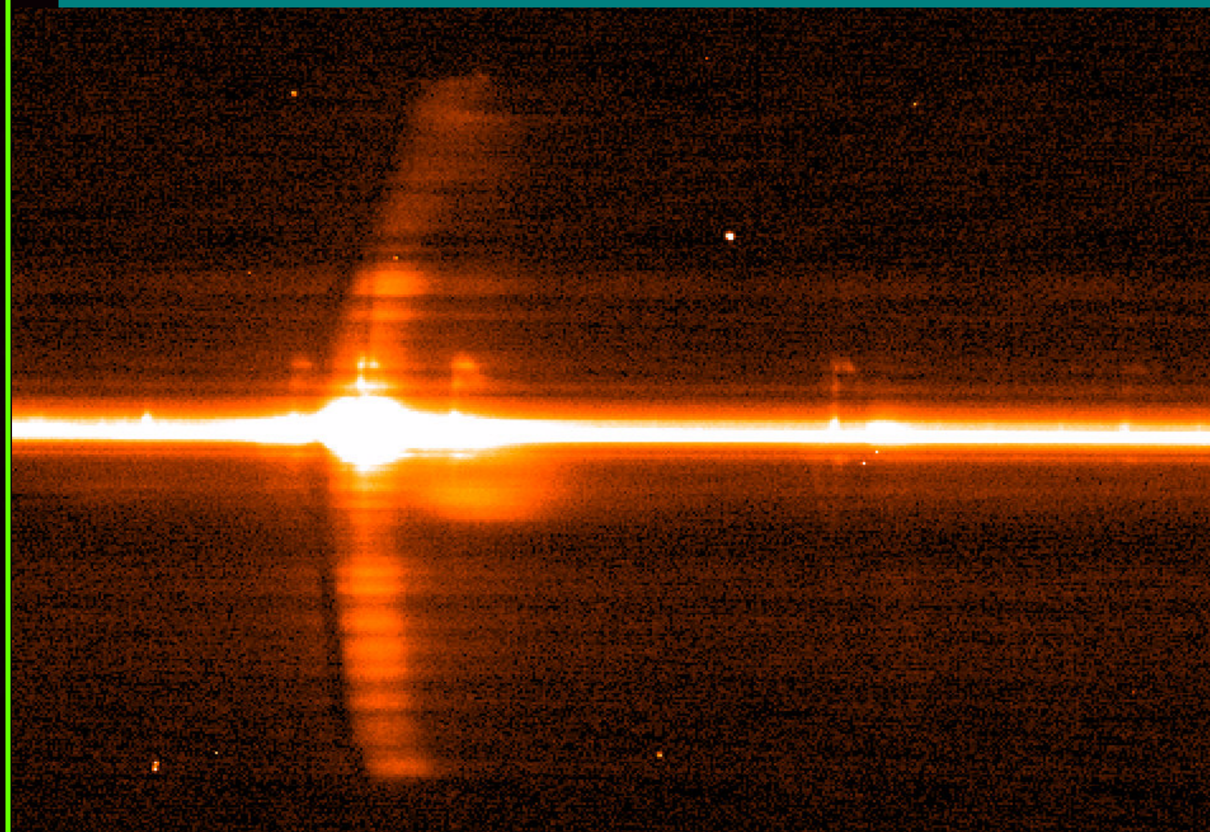
-- STRUCTURAL SIZE SCALES RANGE FROM 0.05″ TO 5″

-- LINE WIDTHS FROM 10 KM / S TO 600 KM / S

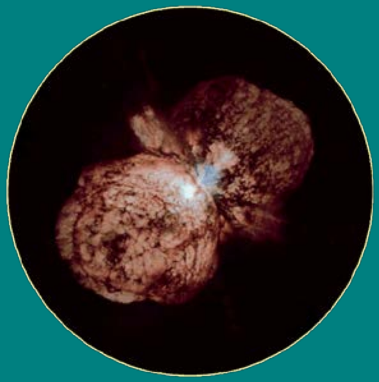
STIS OBSERVATIONS, 1998 -- 2004

SPECTROGRAPH SLIT



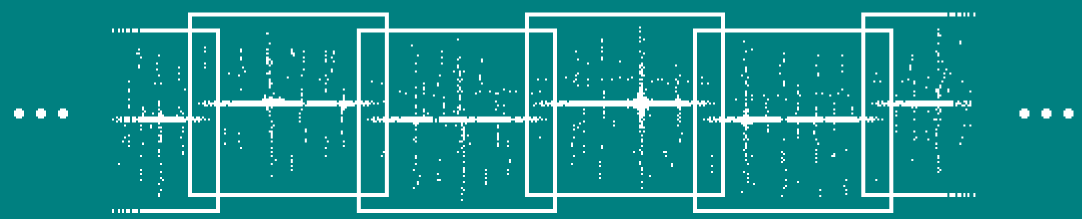


↑ ABOUT 4 % OF TOTAL WVL COVERAGE



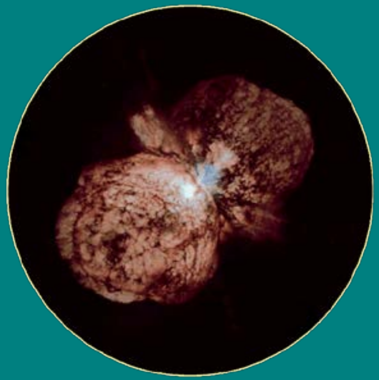
"MOST INTENSIVE HST TARGET", CONTINUED ...

- Practically the <u>only</u> target sampled with STIS's entire wavelength range, UV to 1 μm (CCD + MAMA)



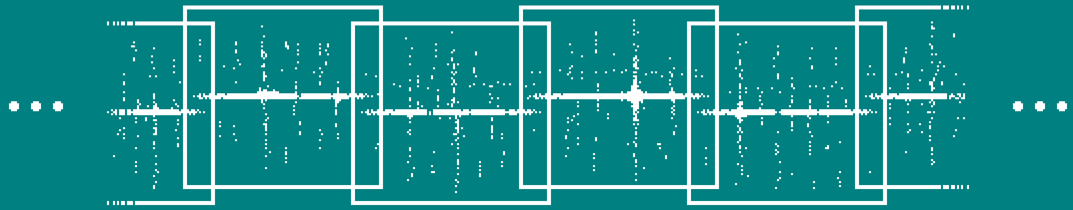
0.17 – 1 μm: ABOUT 30 GRATING TILTS

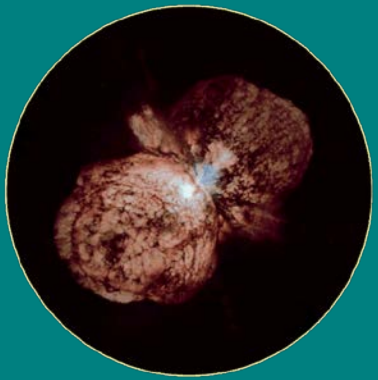
- Rich, position-dependent spectrum, > 2000 classified emission features. (They're even suitable for wavelength calibration.)



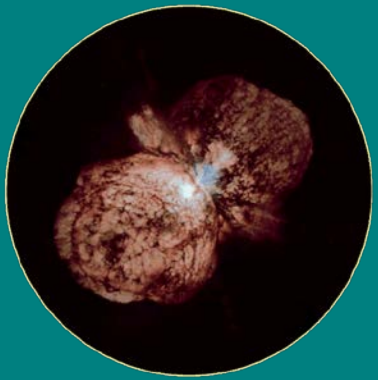
"MOST INTENSIVE HST TARGET", CONTINUED ...

- Some of the spectral images are less "sparse" than most astronomical images. A substantial fraction of the detector pixels contain significant data, not just background.





IN SHORT, HST DATA ON THIS OBJECT CONSTITUTE ONE OF THE BROADEST, MOST INTENSIVE SPECTROSCOPIC DATA SETS IN EXISTENCE.



SUMMARY: η CAR'S RELEVANCE TO DATA TECHNIQUES

(1) In several respects this object has consistently been one of the *very best* examples of HST's capabilities. For STIS it was probably the absolute best.

(2) The data acquisition rate for η Car (meaningful pixels per minute) is extraordinarily high.

(3) However, points (1) and (2) require non-routine data processing as well as unconventional observing plans. Standard software has often been inadequate.

HERE WE'LL SKETCH JUST ONE EXAMPLE --

MARGINAL SAMPLING

a.k.a. the Big Pixel problem,
common among modern instruments.

GOOD PIXELS HAVE WIDTHS LESS THAN 1/3 OF THE P.S.F.'S FWHM. FOR MANY REAL INSTRUMENTS, UNFORTUNATELY, THE RATIO EXCEEDS 1/2 .

EXAMPLES: HST'S WFPC2, STIS, ACS ...

(AT LEAST FOR $\lambda < 5000$ Å)

PRELIMINARY NOTE

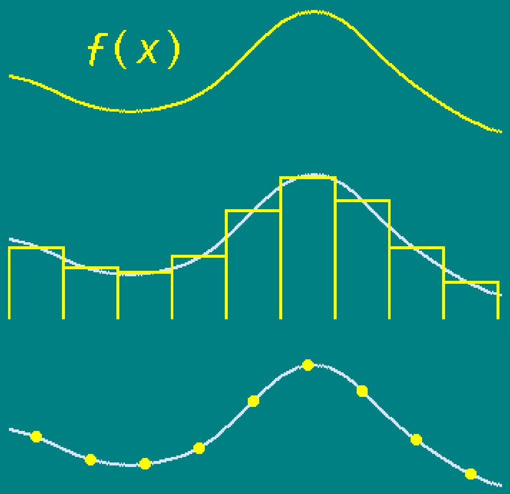
"SUBPIXEL MODELING" MEANS INTERPOLATION AND / OR SUBDIVISION INTO SMALLER PIXELS. IT IS USUALLY NEEDED, FOR –

- DISTORTION CORRECTIONS
- IMAGE ROTATION
- WAVELENGTH CALIBRATION (IF SPECTROSCOPY)
- CAREFUL ASTROMETRY
- COMBINING INDEPENDENT IMAGES
- SOME FORMS OF DECONVOLUTION
- ETC.

WITH MOST SOFTWARE THE SUBPIXEL MODELING IS IMPLICIT – BUT IT IS NECESSARY EVEN IF WE DON'T NOTICE IT !

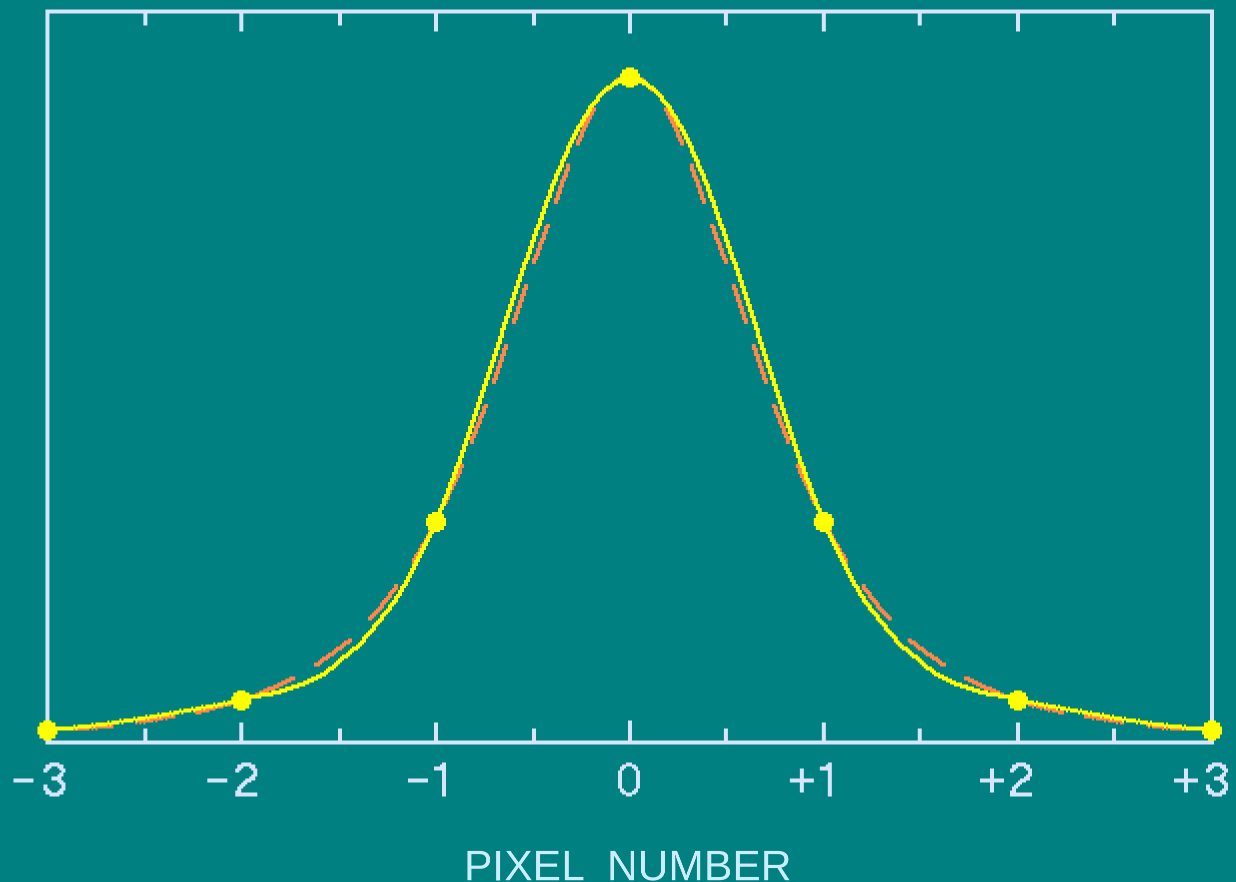
SUB-PIXEL MODELING IS EASIER TO EXPLAIN IF WE SIMPLIFY IN THREE WAYS.

- INSTEAD OF A 2-D IMAGE $f(x, y)$, CONSIDER A 1-DIMENSIONAL FUNCTION $f(x)$.
- INSTEAD OF PIXEL VALUES, TAKE DISCRETE SAMPLES $f(x_m)$.
- IGNORE NOISE.

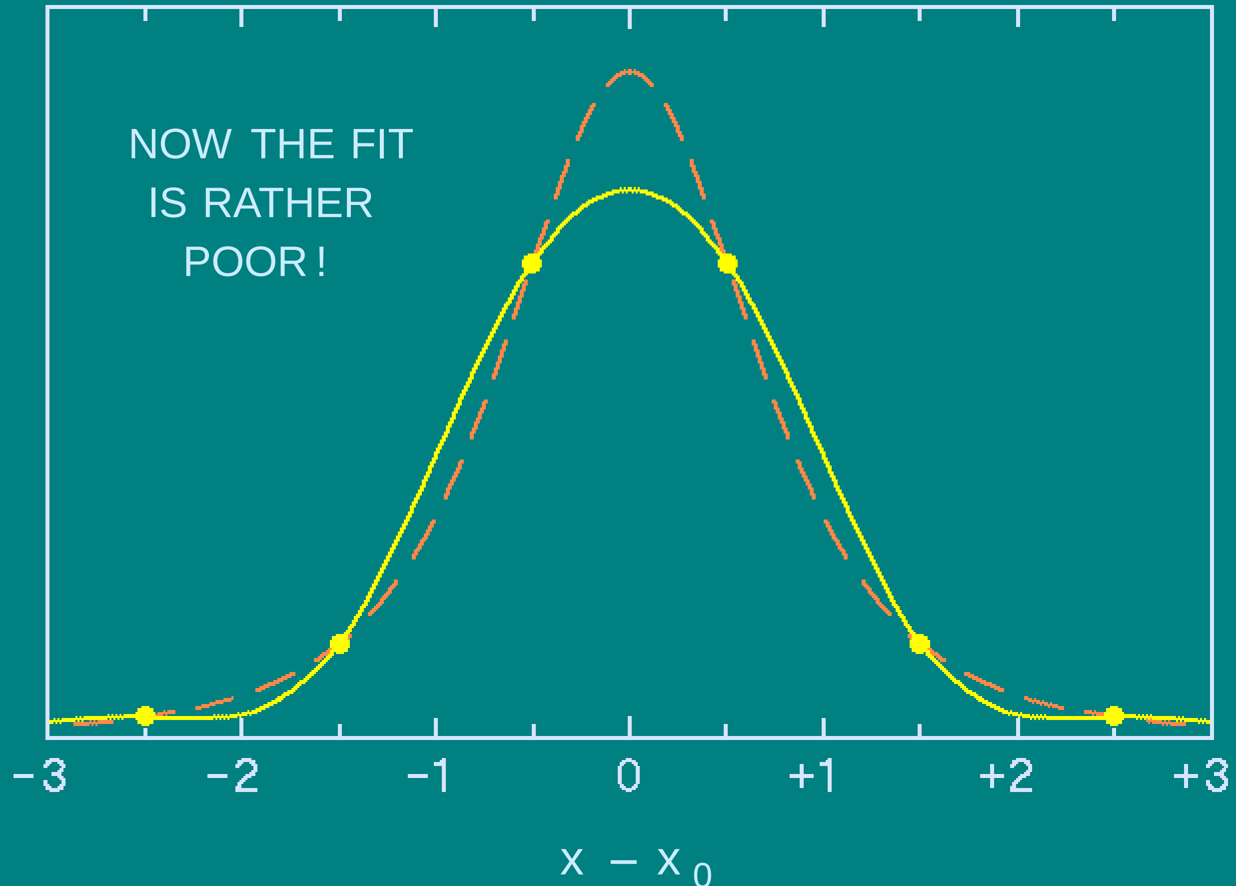


(SUBSEQUENT GENERALIZATION IS EASY.)

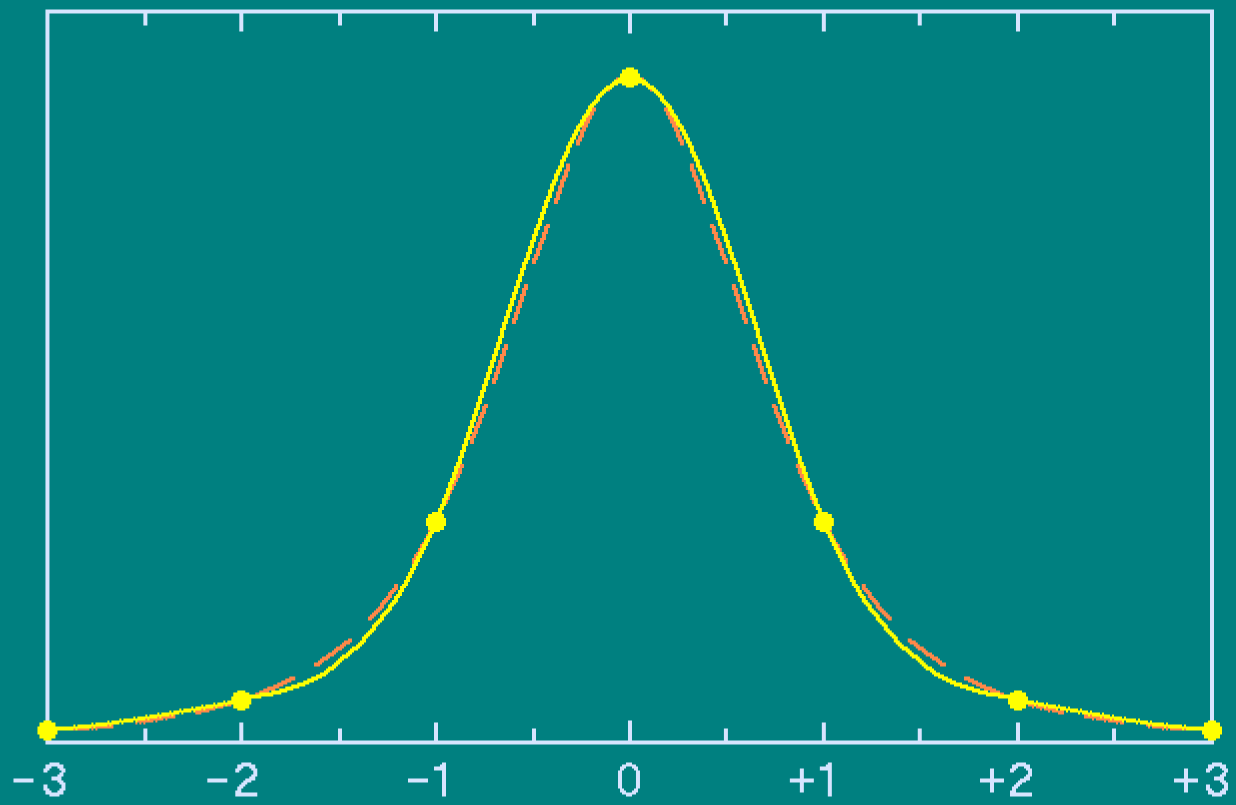
CASE 1. PEAK COINCIDES WITH A PIXEL CENTER



PEAK LOCATED MIDWAY BETWEEN TWO PIXEL CENTERS



VARYING P.S.F. !



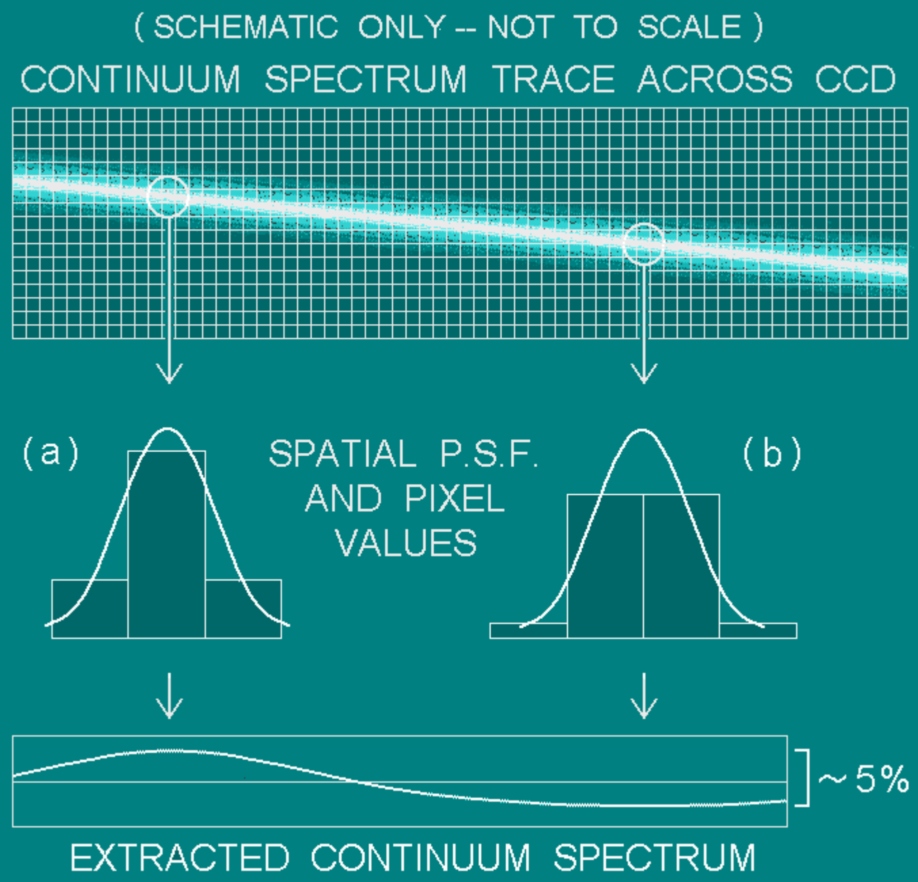
Implication:

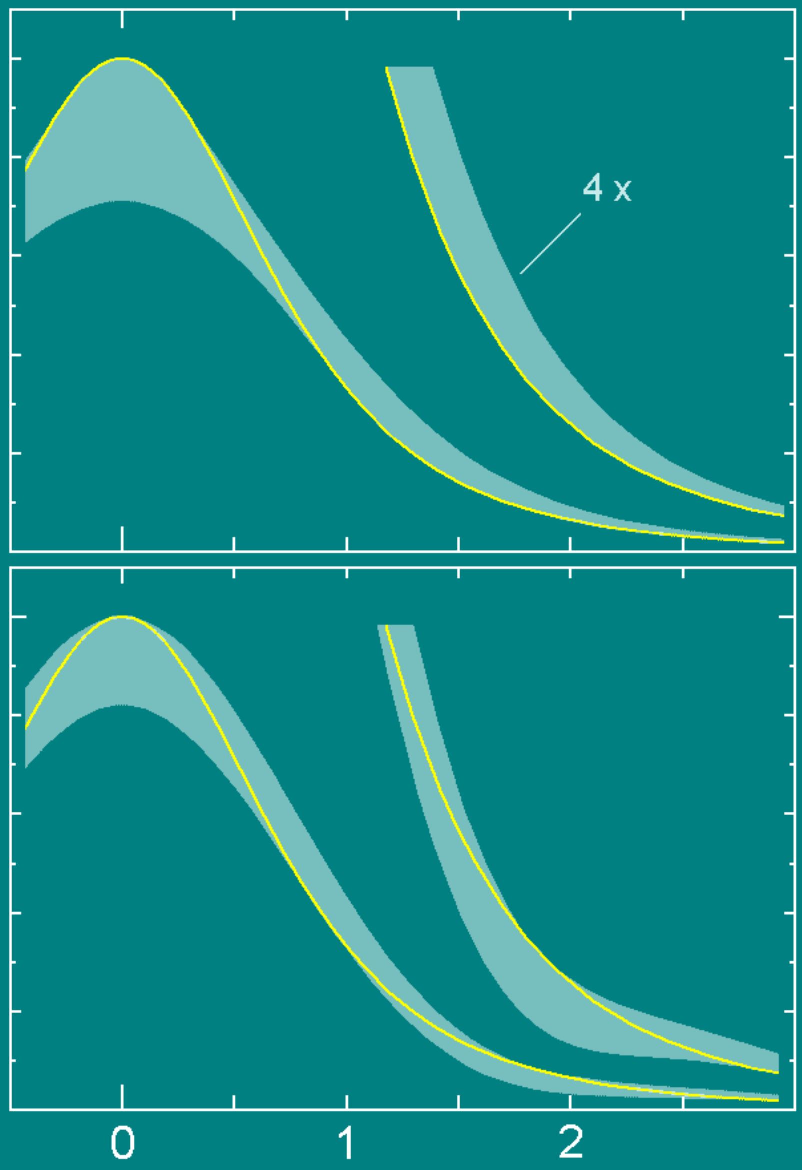
THE EFFECTIVE P.S.F. DEPENDS ON FRACTIONAL-PIXEL LOCATION.

- THIS IS NOT MERELY A CONSEQUENCE OF THE CHOSEN INTERPOLATION TECHNIQUE. IT IS FUNDAMENTALLY RELATED TO WHICH FOURIER PHASES ARE “MISSING” FOR ANY GIVEN PIXEL ALIGNMENT.
- “DITHERING” HELPS, BUT IS NOT ALWAYS FEASIBLE OR NECESSARY. “DECONVOLUTION” IS NOT PARTICULARLY HELPFUL IN THIS CONNECTION.
- WE GENERALLY DON’T NOTICE THIS EFFECT WHEN WE VIEW AN IMAGE, BUT IT CORRUPTS MEASUREMENTS. EXAMPLE: HST / STIS SPECTROSCOPY (NEXT SLIDE)

MOST USERS WHO ATTEMPTED HIGH SPATIAL RESOLUTION WITH STIS GOT WAVY OR “SCALLOPED” SPECTRA.

REASON: STANDARD SOFTWARE DIDN’T TAKE THE FOREGOING EFFECT INTO ACCOUNT.





ENVELOPE OF INTERPOLATED P.S.F. FOR ALL POSSIBLE LOCATIONS RELATIVE TO THE PIXEL GRID

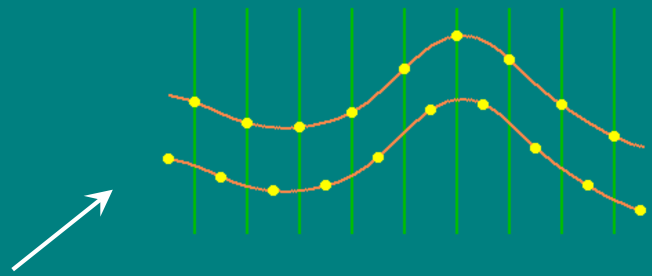
← LINEAR INTERPOLATION

← SPLINE INTERPOLATION

STRATEGY FOR SELF-CONSISTENT SUBPIXEL MODELING

THE DATA POINTS (PIXEL VALUES) ARE SAMPLES OF $f(x)$.
USE THEM TO GENERATE A NEW FUNCTION $g(x)$ WITH
THE FOLLOWING ATTRIBUTES:

(1) ACCURACY: $g(x)$ MATCHES $f(x)$ AS CLOSELY AS POSSIBLE,
CONSISTENT WITH REQUIREMENT 2;



(2) SELF-CONSISTENCY: $g(x)$ IS INSENSITIVE TO THE PIXEL
LOCATIONS x_m, TO WHATEVER PRECISION IS ALLOWED
BY REQUIREMENT 1.

STRATEGY FOR SELF-CONSISTENT SUBPIXEL MODELING

FOR GOOD MATHEMATICAL REASONS, REQUIREMENTS 1 AND 2 CONFLICT WITH EACH OTHER. CONSEQUENTLY, --

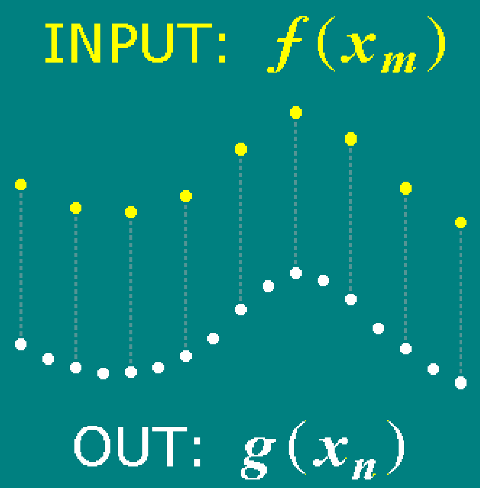
- THERE IS NO EXACT SOLUTION,
- THERE IS NO UNIQUE "BEST" APPROXIMATION,
- SO THIS IS AN EXERCISE IN COMPROMISE.

TO SOME EXTENT THE OPTIMUM COEFFICIENTS WILL DEPEND ON RESEARCH GOALS AND DATA STRUCTURE.

STRATEGY FOR SELF-CONSISTENT SUBPIXEL MODELING

WHEN GENERATING $g(x)$,

SUBDIVIDE THE PIXELS BY A FACTOR OF 2.



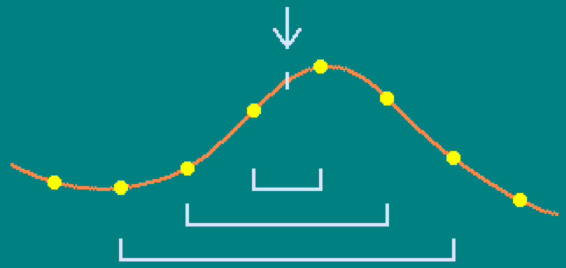
CASE A : OUTPUT PIXEL LOCATED AT SAME PLACE AS AN INPUT PIXEL.

CASE B : OUTPUT PIXEL LOCATED MIDWAY BETWEEN TWO INPUT PIXELS.

(WITH THIS REDUCED PIXEL SAMPLING, ORDINARY INTERPOLATION METHODS WILL BE GOOD ENOUGH TO ESTIMATE $g(x)$ CONTINUOUSLY.)

STRATEGY FOR SELF-CONSISTENT SUBPIXEL MODELING

FIRST STEP: CALCULATE THE INTERMEDIATE "CASE B" POINTS.

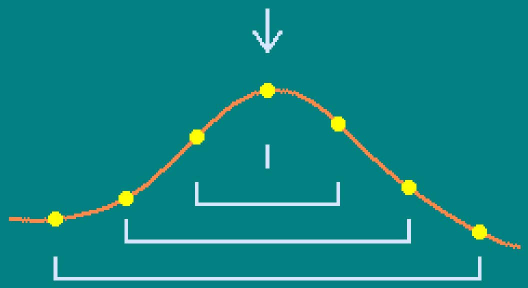


$$g(x) = B_0 \times \{ f(x-0.5) + f(x+0.5) \}$$
$$+ B_1 \times \{ f(x-1.5) + f(x+1.5) \}$$
$$+ B_2 \times \{ f(x-2.5) + f(x+2.5) \} + \ldots$$

THIS IS JUST *N*-POINT INTERPOLATION, WHERE USUALLY
$N = 4$ TO 8 (2 TO 4 *B*-COEFFICIENTS).

STRATEGY FOR SELF-CONSISTENT SUBPIXEL MODELING

NEXT: WE DO NOT ADOPT $g = f$ FOR THE COINCIDENT "CASE A" POINTS. INSTEAD, --



$$g(x) = A_0 \times f(x)$$
$$+ A_1 \times \{ f(x-1) + f(x+1) \}$$
$$+ A_2 \times \{ f(x-2) + f(x+2) \} + \ldots$$

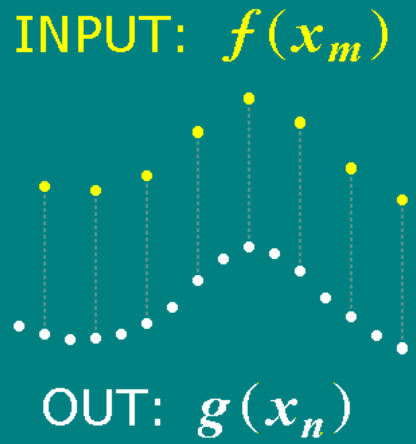
THIS AMOUNTS TO SMOOTHING, BUT IT APPLIES ONLY AT LOCATIONS WHERE THE ORIGINAL P.S.F. WAS UNSUSTAINABLY NARROW (FOR REASONS EXPLAINED EARLIER, RELATED TO SAMPLING) .

IN A PRACTICAL SENSE, NO USABLE INFORMATION IS LOST.

STRATEGY FOR SELF-CONSISTENT SUBPIXEL MODELING

THOSE TWO FORMULAE ARE THE ONLY FEASIBLE CHOICES IF WE WANT THE PROCESS TO BE LINEAR.

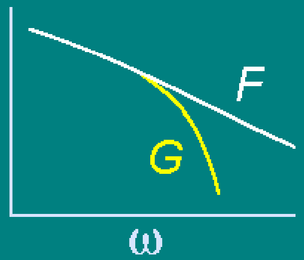
WE CAN MAKE THE PROBLEM SEEM DIFFERENT, E.G., BY WORKING IN FOURIER SPACE. BUT ALTERNATIVE, DIFFERENT-LOOKING PROCEDURES WILL BE ALMOST EQUIVALENT TO THIS ONE, MATHEMATICALLY SPEAKING.

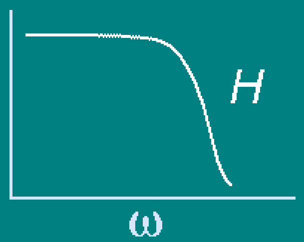


THEREFORE : THE PROBLEM BOILS DOWN TO A SEARCH FOR GOOD COEFFICIENTS A_n AND B_n THAT WORK WELL WITH EACH OTHER.

A FOURIER VIEW SHOWS WHY THERE'S NO PERFECT SOLUTION.

$F(\omega)$ AND $G(\omega)$ ARE THE F.T.'S OF $\boldsymbol{f(x)}$ AND $\boldsymbol{g(x)}$ ...





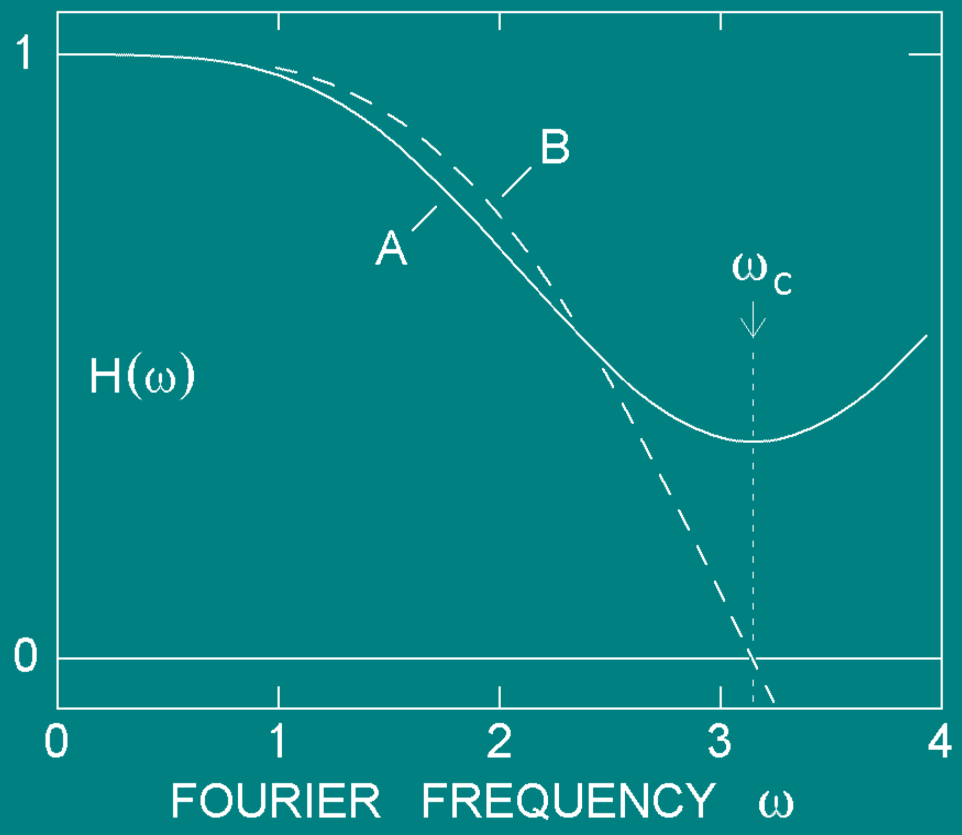
IF WE GENERATE $\boldsymbol{g}$ FROM $\boldsymbol{f}$ BY AN N-POINT LINEAR FORMULA, THEN

$$G(\omega) = H(\omega)\,F(\omega)$$

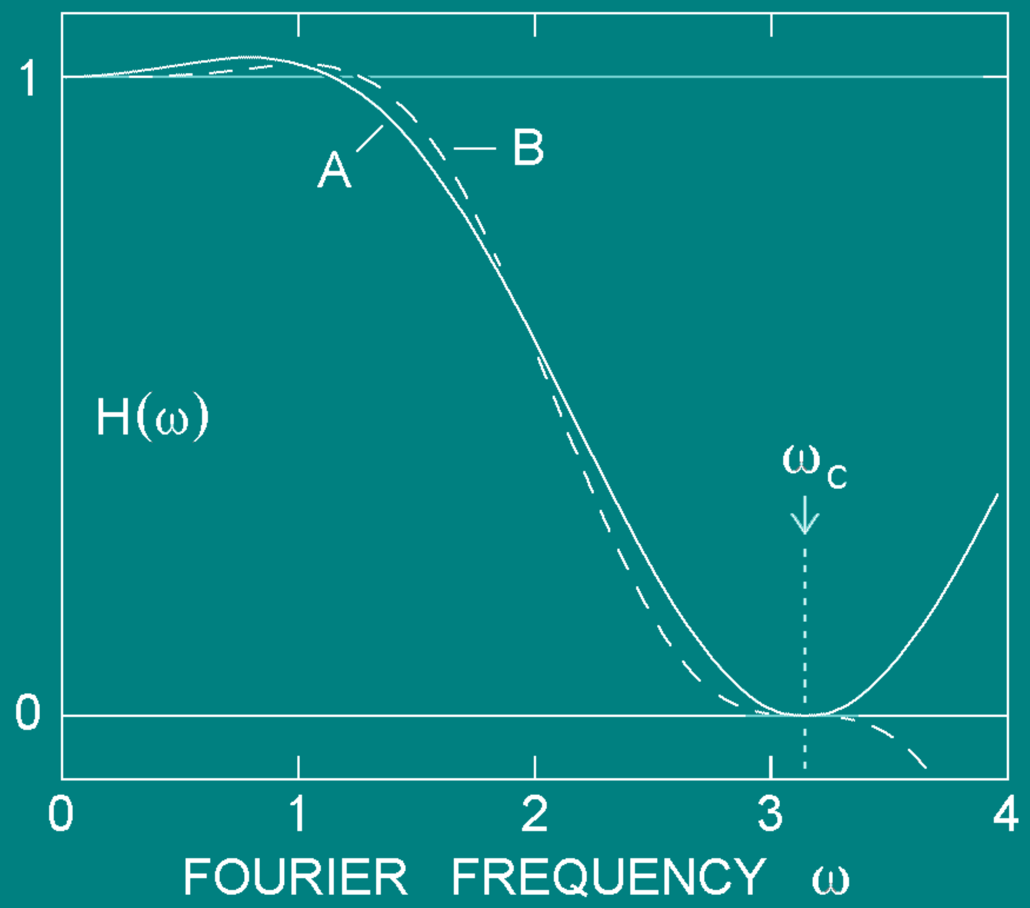
WHERE H IS A FILTERING FUNCTION THAT DEPENDS ON THE FORMULA COEFFICIENTS.

WE HAVE <u>TWO</u> FORMULAE, CASE A AND CASE B.
EACH HAS ITS OWN FILTER FUNCTION $H(\omega)$;

-- AND THEIR DIFFERENT SAMPLING MAKES THEM ALMOST INCOMPATIBLE NEAR THE CRITICAL FREQUENCY $\omega = \pi$.



(ONE SOLUTION, NOT VERY SATISFYING)

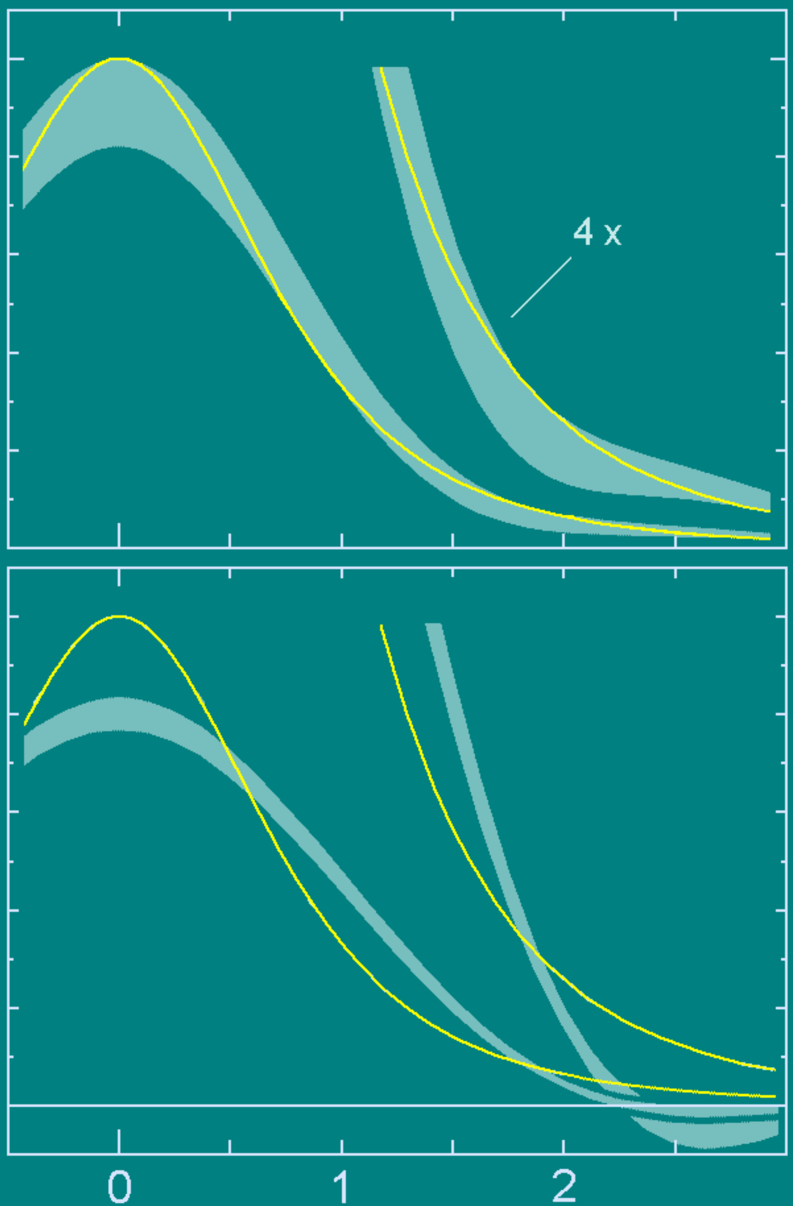


THE “BEST” COEFFICIENT SETS DEPEND SOMEWHAT ON INSTRUMENT PARAMETERS, AND ARE RATHER TEDIOUS TO CALCULATE.

HOWEVER, WE CAN IDENTIFY COEFFICIENTS THAT WORK FAIRLY WELL FOR A VARIETY OF DATA.

THE NEXT SLIDE WILL SHOW THE “P.S.F. ENVELOPE” FOR ONE SET OF COEFFICIENTS.

ENVELOPE OF PROCESSED P.S.F. FOR ALL POSSIBLE LOCATIONS RELATIVE TO THE PIXEL GRID



← SPLINE INTERPOLATION

← SUBPIXEL MODELING

If quantitative measurements are desired,

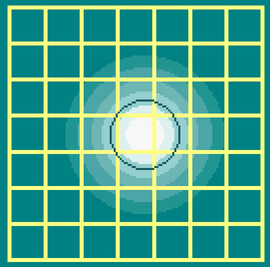
we recommend this technique for <u>most</u>

astronomical data images that have

(PSF FWHM)/3 < (PIXEL SIZE) < (PSF FWHM).

Past Examples:

WFPC2(PC), STIS, ACS, etc.



One can even argue that processing of this type should be standard.

THIS HAS BEEN ONLY ONE OF MANY DATA-TECHNIQUE CONCERNS FOR THE ETA TREASURY PROGRAM.

SOME OF THE OTHERS:

- IDENTIFICATION OF BAD PIXELS INDENDENT OF CR-SPLIT
- REALISTIC QUANTIFICATION OF RMS NOISE (IN SOME CASES THE PIPELINE IS VERY WRONG)
- ASYMMETRIC WINGS IN THE STIS SPATIAL P.S.F.
- SEVERAL TYPES OF “GHOSTS” IN STIS SPECTRAL IMAGES
- SPLICING SPECTRAL IMAGES WITH ADJACENT GRATING TILTS, EVEN THOUGH THE INSTRUMENT FOCUS VARIED ACROSS THE DETECTOR
- ETC.

The HST Treasury Program on Eta Carinae

FOR MORE INFORMATION

- John Martin's poster
- http://etacar.umn.edu/ , look for "Treasury Program" and then for "Technical Memos".   (Admittedly some of them need updates.)
- Contact us: kd@etacar.umn.edu , martin@etacar.umn.edu , bish@space.mit.edu
- We're preparing a paper on subpixel modeling.

(Coolest character in the alphabet.
Dramatic! Elegant! Mysterious!)