ERIM

PRELIMINARY

NOTES ON

VLA OPTICAL PROCESSOR

NOV 1976

SYSTEM PERFORMANCE OBJECTIVES

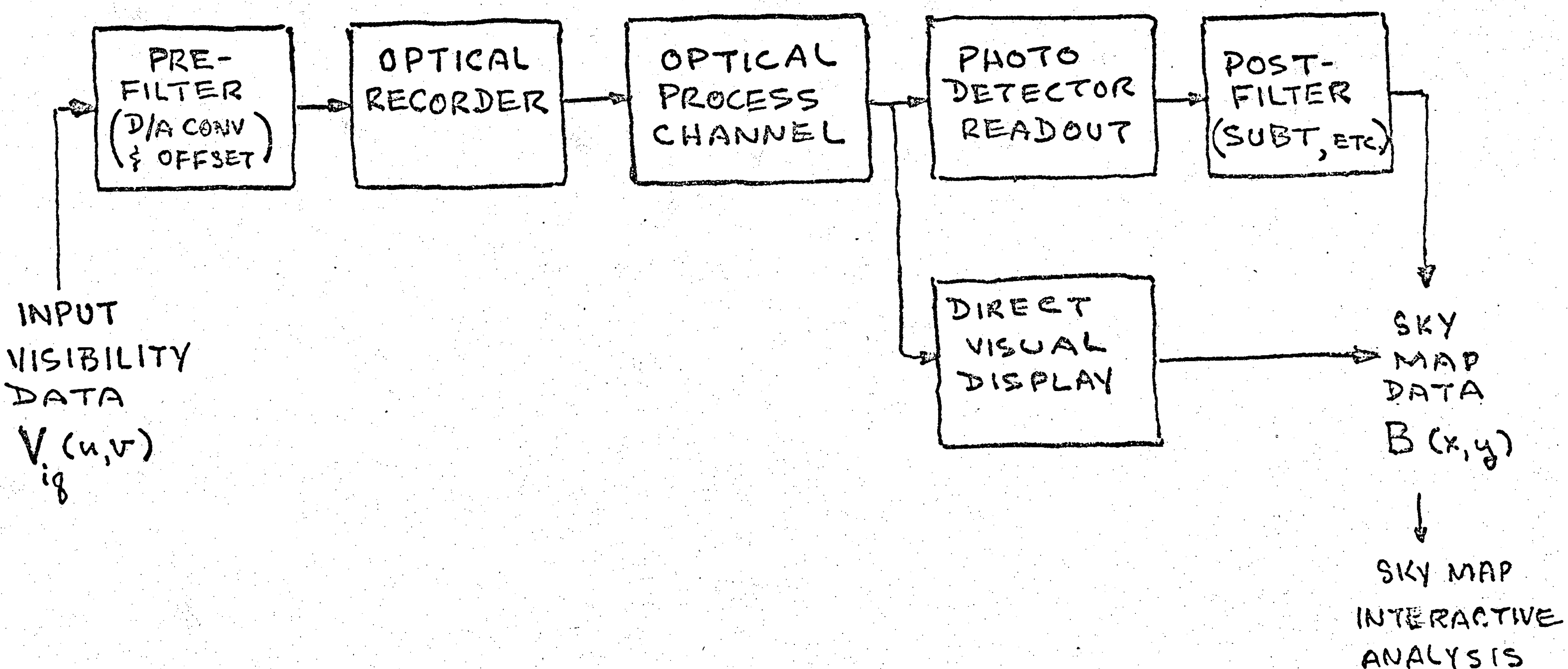
GENERATE SKY MAP DATA
BY OPTICAL FOURIER TRANSFORM
OF VISIBILITY DATA

$$V(u,v) \longrightarrow B(x,y) \sim F[V]$$

PROVIDE SUITABLE:

- ACCURACY
- RESOLUTION
- DYNAMIC RANGE
- OPERATING FEATURES

SYSTEM FUNCTIONAL ELEMENTS



CONCEPT SUMMARY

PRE-FILTER

$$V_{i,q}(u,v) \longrightarrow \mathcal{A}(u,v) = S(u,v) + S_*(u,v) + S_0(u,v)$$

OPTICAL RECORDER

$$\mathcal{A}(u,v) \longrightarrow t(u,v) = T(u,v) + T_*(u,v) + T_0(u,v)$$

OPTICAL F-T PROCESSOR

$$t(u,v) \longrightarrow I(x,y) \sim B(x,y)\,\mathrm{Cos}(\alpha) + n_T$$

$$B \sim F[V(u,v)]$$

MAP DATA READOUT (ELECTRONIC AND VISUAL)

$$I(x,y) \longrightarrow E(x,y) \sim B(x,y)\,\mathrm{Cos}(\alpha), \text{ ELECTRONIC}$$

$$ \longrightarrow I(x,y) \sim B(x,y)\,\mathrm{Cos}(\alpha), \text{ VISUAL}$$

POST FILTER (ELECTRONIC SKY MAP DATA)

$$\left.\begin{matrix} E_0(x,y) \\ -E_\pi(x,y) \end{matrix}\right\} \longrightarrow E_B(x,y) \sim B(x,y) + n_E$$

↑ SKY MAP DATA

PROPOSED DESIGN
KEY FEATURES

RECORDER

- ENCODE: REAL SIGNAL ON CARRIER
- FORMAT: ELLIPTICAL TRACKS (RECT RASTER IF POSSIBLE)
- APERTURE: 50 mm SQUARE
- BANDWIDTH: 60 c/mm
- MATERIAL: 70 mm WIDE FILM STRIPS
- TYPE: CRT/FILM

OPTICAL PROCESSING CHANNEL

- CONFIG: BEYOND LENS INPUT PLANE, WITH COMPENSATION FOR PHASE ERRORS
- FOCAL LGTH: ~ 3.3 M ; $\lambda \sim 0.5 \times 10^{-3}$ mm
- MAP SIZE: 100 X 100 mm
- RESOL SIZE: 80×10^{-3} mm (BETWEEN ZEROES)

SKY MAP ELECTRONIC READOUT

- COOLED PHOTO-DETECTOR ARRAY (LINEAR PUSH BRM)
- DETECTOR ELEMENT SIZE: 15×10^{-3} mm
- NO OF ELEMTS: ~ 7000
- DWELL TIME: ~ 0.03 SEC / LINE
- SAMPLES PER DIRTY BEAM MAIN LOBE: 5.5

SKY MAP DIRECT VISUAL READOUT (DISPLAY)

- DIRECT PROJECTION OF CONJUGATE MAP

CALIBRATION

- FOR SYSTEM GAIN AND SPATIAL SCALE FACTOR

ENVIROMENT:

- ENCLOSED OPTICAL CHANNEL
- TEMP & HUMIDITY CONTROLLED ROOM

SYSTEM OVERVIEW

INPUT (EXAMPLE FOR n STARS)

$$V_n(u,v) = \sum_n |V_n| e^{j\phi_n(u,v)}$$

OUTPUT (ELECTRONIC OUTPUT MAP DATA)

$$E_B(x,y) = K\,|V_n|\; a_T(x - \omega_u \lambda d,\, y - \omega_v \lambda d) \otimes p(x,y) \otimes g_d(x,y)$$

$a_T = F[A_T] \cdot F[\delta]$ TRANSFORM OF TRACK FUNCTION

$p = F[P \cdot P_1 \cdot P_2]$ TRANSFORM OF PHASE ERROR FUNCTION

g_d = READOUT ARRAY SAMPLING FUNCTION

$K = 4\, A_i A_r K_b K_f K_d \Delta\, G(x,y)$ GAIN CONSTANT

δ = TRACK ERROR FUNCTION

$G = F[g_b \otimes g_f]$

$$F[\;] = \iint [\;]\, e^{-j\left(\frac{2\pi x}{\lambda d} u + \frac{2\pi y}{\lambda d} v\right)}\, dx\, dy$$

PRE - FILTER

(D/A CONVERSION ; FREQUENCY OFFSET)

FROM INPUT $V_i(u,v)$, $V_q(u,v)$

$$V(u,v) = |V(u,v)| e^{j\phi(u,v)}$$

TO

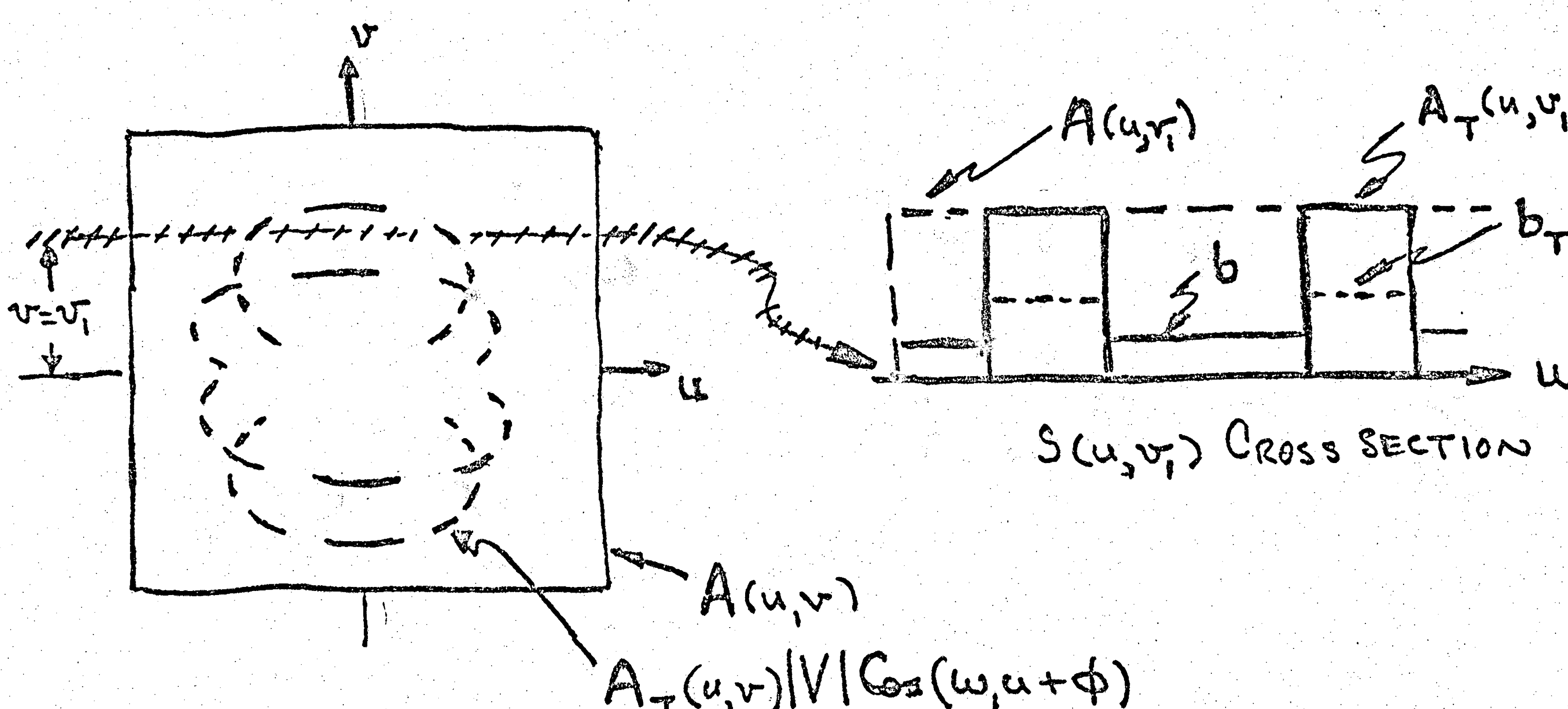
$$a(u,v) = A(u,v)\left\{A_T(u,v)\left[b_T + |V| \cos(\omega_1 u + \phi)\right]\right\}$$

$$+ A(u,v)\left\{b\left[1 - A_T(u,v)\right]\right\}$$

$$= A A_T |V| e^{j(\omega_1 u + \phi)} + A A_T |V| e^{-j(\omega_1 u + \phi)}$$

$$+ \left[A b + A A_T (b_T - b)\right]$$

S(u,v) DATA FRAME PROPERTIES



OPTICAL RECORDER

FROM:

$$s(u,v) = \underbrace{A(u,v)\,b + A_T(u,v)[b_T - b]}_{S_0(u,v)} + \underbrace{A_T(u,v)|V|e^{-j[\omega_1 u + \phi(u,v)]}}_{S_*(u,v)} + \underbrace{A_T(u,v)|V|e^{j[\omega_1 u + \phi(u,v)]}}_{S(u,v)}$$

TO:

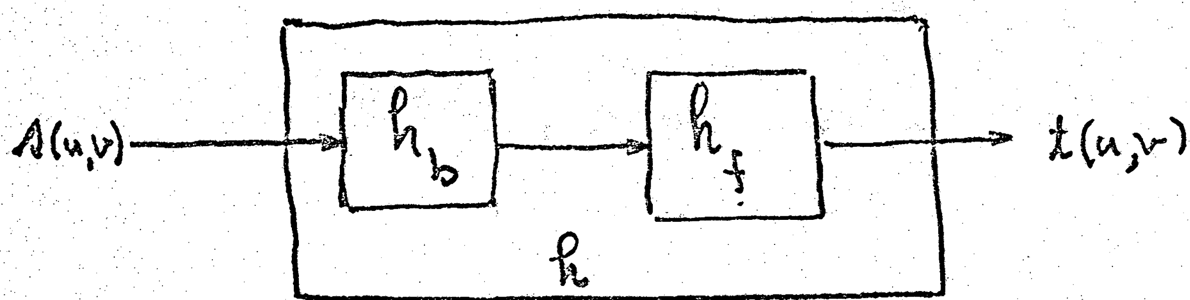
$$t(u,v) = s(u,v) \otimes h(u,v) + n_b \otimes h(u,v) + n_f(u,v)$$

$$= S_0(u,v) \otimes h(u,v) + S_*(u,v) \otimes h(u,v) + S(u,v) \otimes h(u,v) + n_b(u,v) \otimes h(u,v) + n_f(u,v)$$

$$\equiv T_0(u,v) + T_*(u,v) + T(u,v) + T_b(u,v) + T_f(u,v)$$

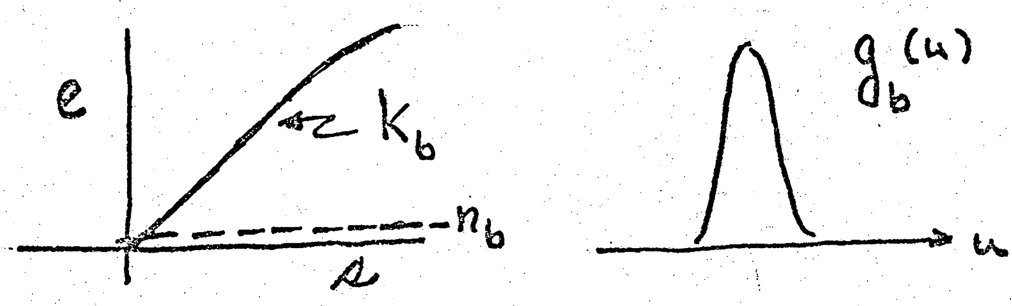
$h(u,v) = k\,g(u,v)$; n_b = WRITE BEAM NOISE ; n_f = RECORD MEDIUM NOISE

OPTICAL RECORDER IMPULSE RESPONSE PROPERTIES

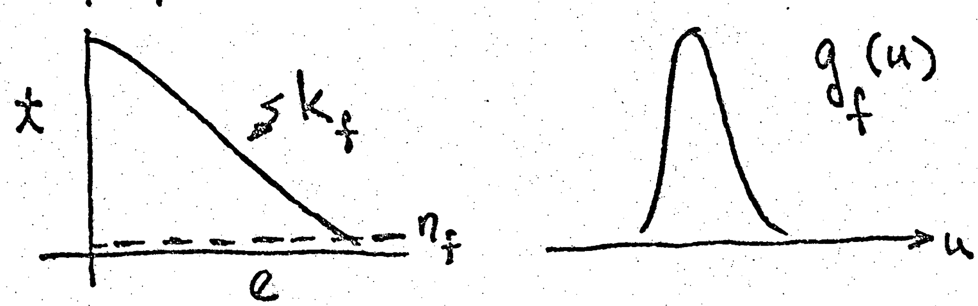


$$h(u,v) = h_b(u,v) \otimes h_f(u,v)$$

$$h_b(u,v) = K_b \, g_b(u,v)$$



$$h(u,v) = K_f \, g_f(u,v)$$



OPTICAL RECORDER

NOISE SOURCES

WRITING BEAM $n_b \sim$ .002 rms OF PK SIGNAL

INPUT AMPLIFIER (BW)

BEAM SOURCE (SHOT)(EXCIT, MODE) (PHOS)

RECORDING MATERIAL $n_f \sim$ .005 rms OF PK SIGNAL

FILM : GRAIN

GAIN LINEARITY

$k_b \cdot k_f$

- LINEARIZED .001 FOR $\simeq T_0 \pm \frac{1}{2} T_0$
- MAGNITUDE MEASURED FOR EACH DATA RUN

OPTICAL RECORDER
GEOMETRIC ACCURACY

WRITING BEAM

ϵ_u, ϵ_v POSITION ERROR FUNCTIONS

$$\left.\begin{array}{l} u \rightarrow u + \epsilon_u \\ v \rightarrow v + \epsilon_v \end{array}\right\} \sim .00002 \text{ OF SCAN LENGTH MAX}$$

FILM SHRINK-STRETCH

m_u, m_v POSITION DISTORTION FUNCTIONS

M_u, M_v UNIFORM SIZE CHANGE FACTOR

$$\left.\begin{array}{l} u \rightarrow u + m_u \\ v \rightarrow v + m_v \end{array}\right\} \sim .00002 \text{ OF FILM WIDTH}$$

M_u, M_v SCALE ALL u, v } $\sim 1 \pm .03$

RECORDER IMPULSE RESPONSE

$$h_b(u,v) \rightarrow h_b(u+\epsilon_u, v+\epsilon_v)$$

$$h_f(u,v) \rightarrow h_f(u+m_u, v+m_v)$$

OPTICAL RECORDER

GEOMETRIC ERROR MODEL

$$t(u,v) = s(u,v) \otimes h_b(u+\epsilon_u, v+\epsilon_v) \otimes h_f(u+m_u, v+m_v)$$

WITH u,v SCALED BY M_u, M_v

LET :

$$h_b(u+\epsilon_u, v+\epsilon_v) = h_b(u,v) \otimes \delta(u+\epsilon_u, v+\epsilon_v)$$

$$h_f(u+m_u, v+m_v) = h_f(u,v) \otimes \delta(u+m_u, v+m_v)$$

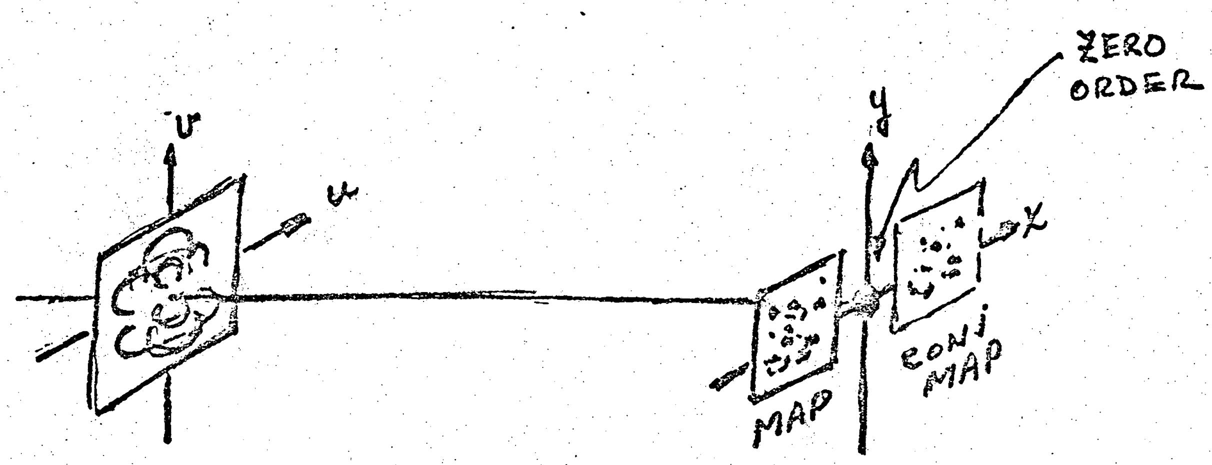
WHERE δ ≡ DELTA FUNCTION,
$\delta_\epsilon(u,v) \equiv \delta(u+\epsilon_u, v+\epsilon_v)$, ETC..

THEREFORE :

$$t(u,v) = s(u,v) \otimes h_b(u,v) \otimes h_f(u,v) \otimes \underbrace{\delta_\epsilon(u,v) \otimes \delta_m(u,v)}_{\text{RECORDER POSITION ERROR FUNCTIO[N]}}$$

$$= \underbrace{s(u,v) \otimes \delta_\epsilon(u,v) \otimes \delta_m(u,v)}_{\text{ERROR MODELED AS MODIFIED INPUT SIGNAL}} \otimes h_b(u,v) \otimes h_f(u,v)$$

OPTICAL PROCESSING CHANNEL



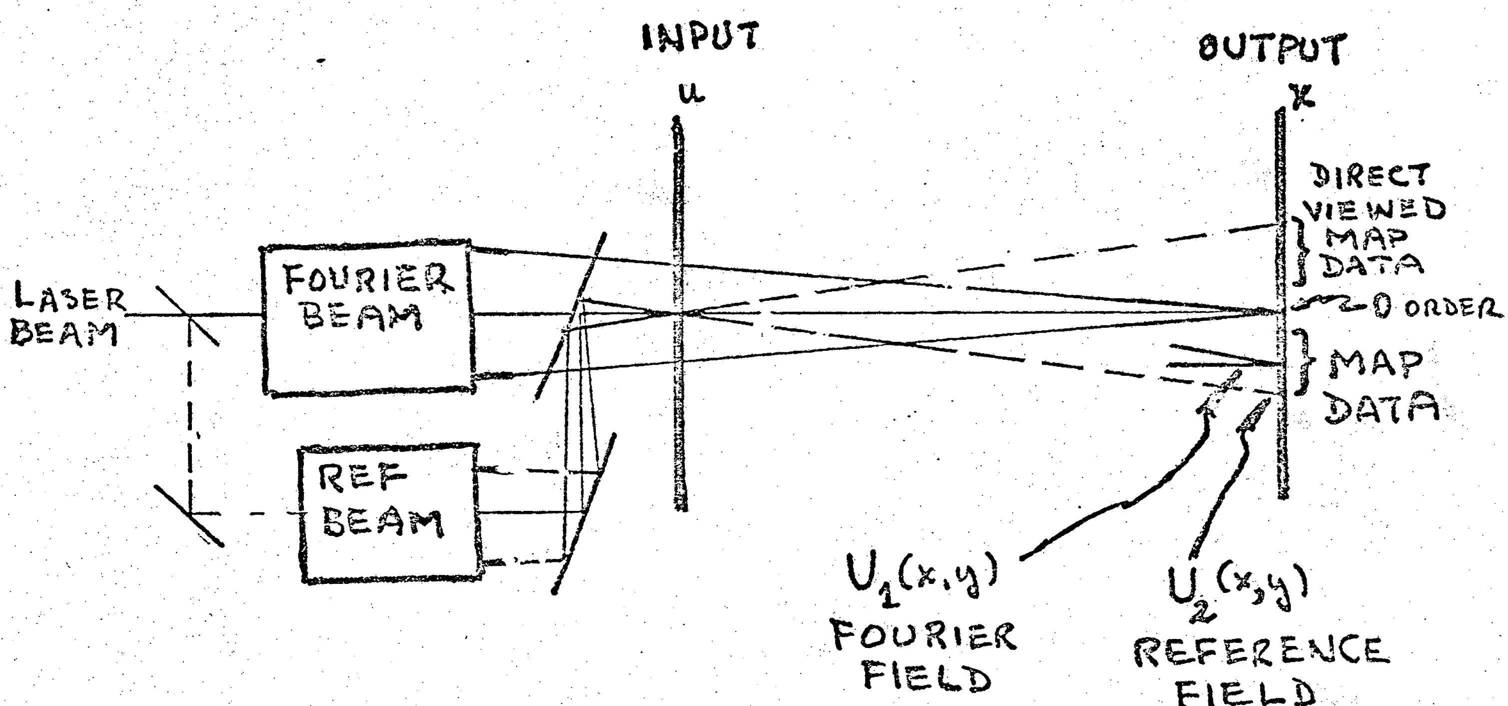
INPUT PLANE

$t(u,v)$

OUTPUT MAP PLANE

$I(x,y)$

OPTICAL PROCESSING CHANNEL SCHEMATIC



FROM INPUT DATA RECORD $t(u,v)$

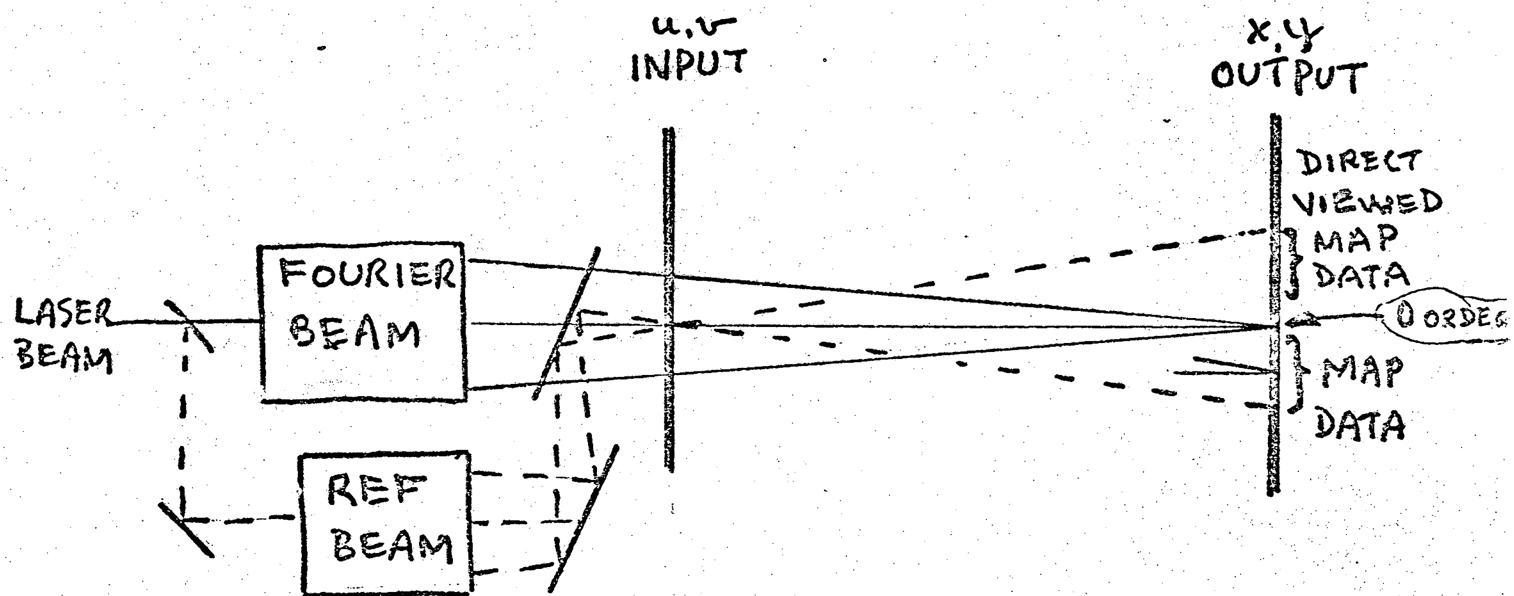
$$t(u,v) = T_0(u,v) + T_*(u,v)\,P_* + T(u,v)\,P + T_b(u,v) + T_f(u,v)$$

TO OUTPUT LIGHT INTENSITY $I(x,y)$

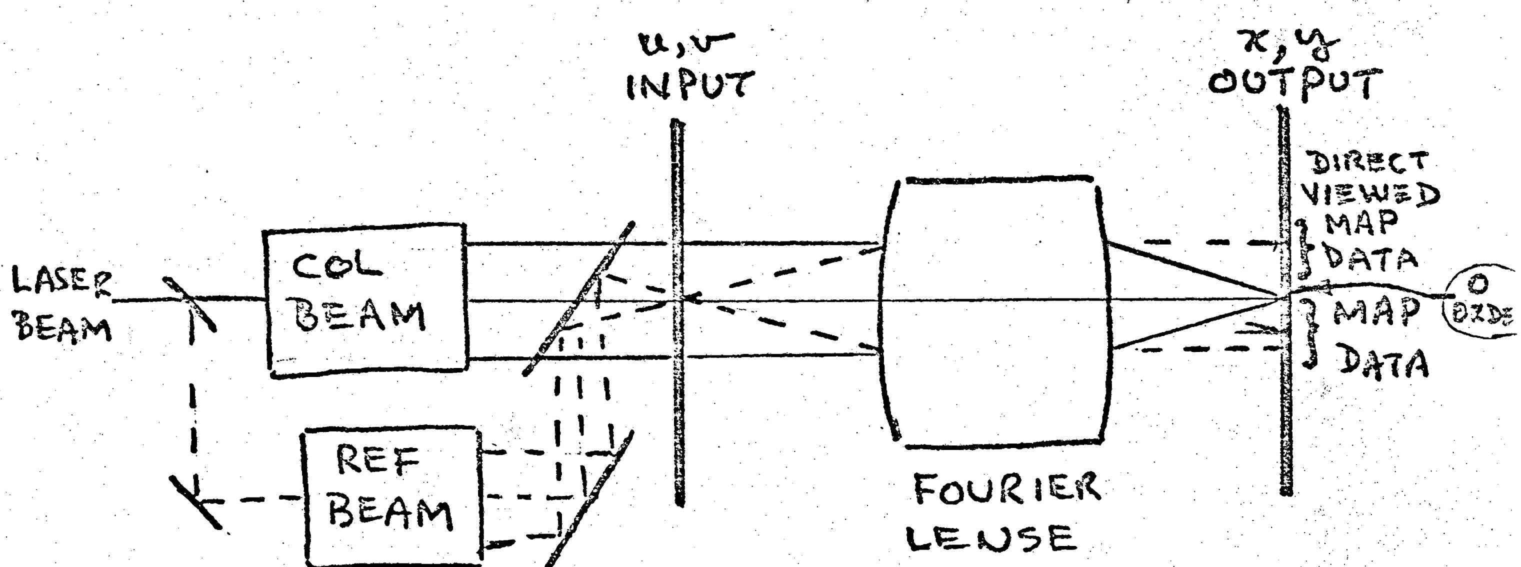
$$I(x,y) = \left| U_1(x,y) + U_2(x,y) \right|^2$$

$$\equiv \underbrace{I_B(x,y)}_{\text{SKY MAP DATA}} + \underbrace{I_N(x,y)}_{\text{NOISE AND BACKGROUND}}$$

OPTICAL CHANNEL CONFIGURATION CANDIDATES



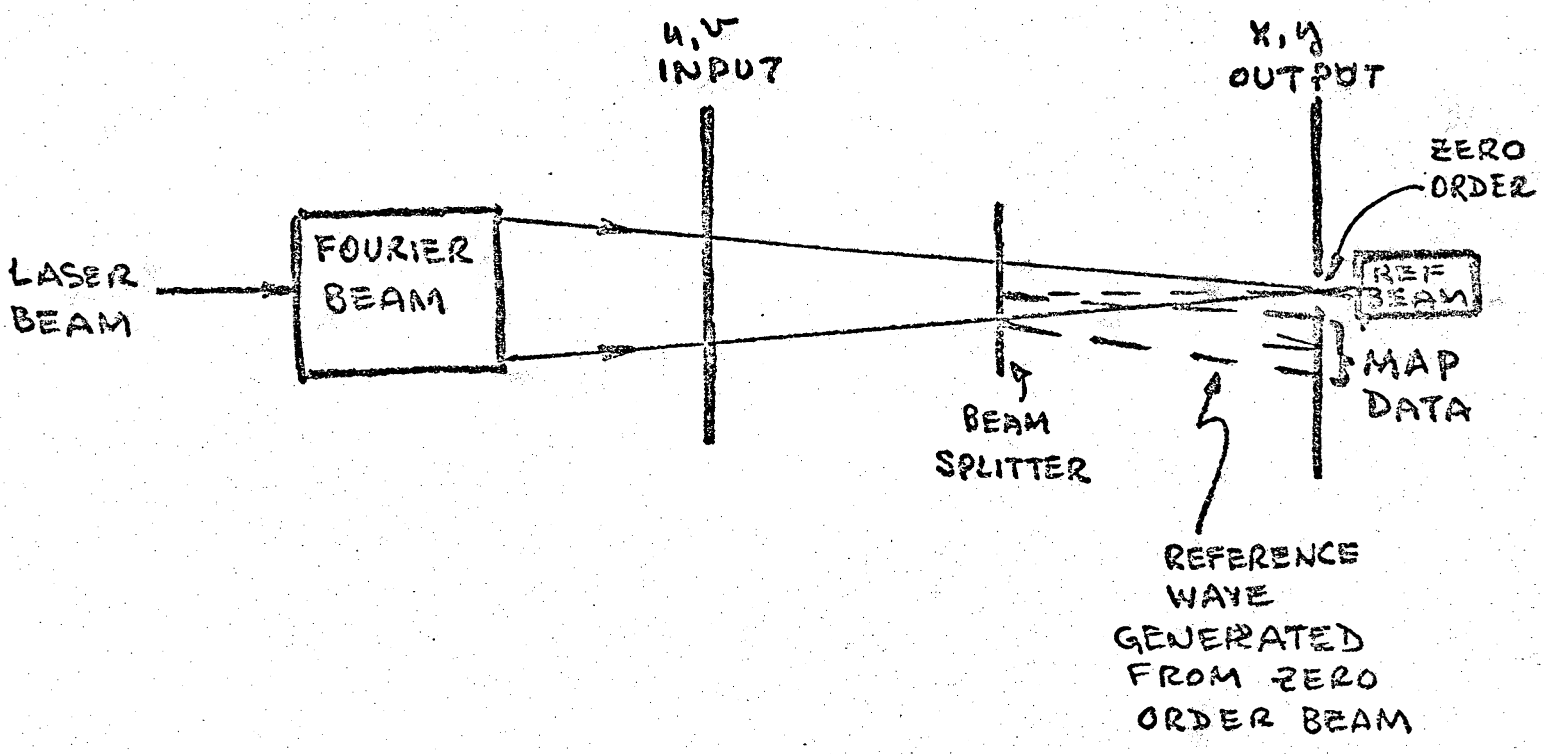
BEYOND THE LENSE INPUT PLANE



BEFORE THE LENSE INPUT PLANE

OPTICAL CHANNEL

CONFIGURATION CONSIDERATIONS



USE OF THE ZERO ORDER
OUTPUT PLANE BEAM
AS THE REFERENCE BEAM
SOURCE

(ALSO USEFUL WITH BEFORE THE
LENSE INPUT PLANE)

OPTICAL PROCESSING
CHANNEL OUTPUT $I(x,y)$

$$I(x,y) = \left| U_1(x,y) + U_2(x,y) \right|^2$$

SIMPLIFIED CASE (NO NOISE)

$$U_1(x,y) = A_i e^{j\Theta_i(x,y)} F\{t(u,v)\}$$

$$U_2(x,y) = A_r e^{j\Theta_r(x,y)}$$

$$F\{t(u,v) = F\{T(u,v)\} + F\{T_*(u,v)\} + F\{T_0(u,v)\}$$

$$= B(x,y) + B_*(x,y) + B_0(x,y)$$

$$I(x,y) = \left[A_r e^{j\Theta_r} + A_i e^{j\Theta_i} F\{t\}\right]\left[A_r e^{-j\Theta_r} + A_i e^{-\Theta_i} F^*\{t\}\right]$$

$$= 2A_iA_r B(x,y)\cos(\Theta_i - \Theta_r)$$ ← MAP DATA

$$+ 2A_iA_r B_*(x,y)\cos(\Theta_i - \Theta_r)$$ ← CONJ-SEP MAP

$$+ A_i B(x,y) + A_r$$ ← SUBT / NOT SEP

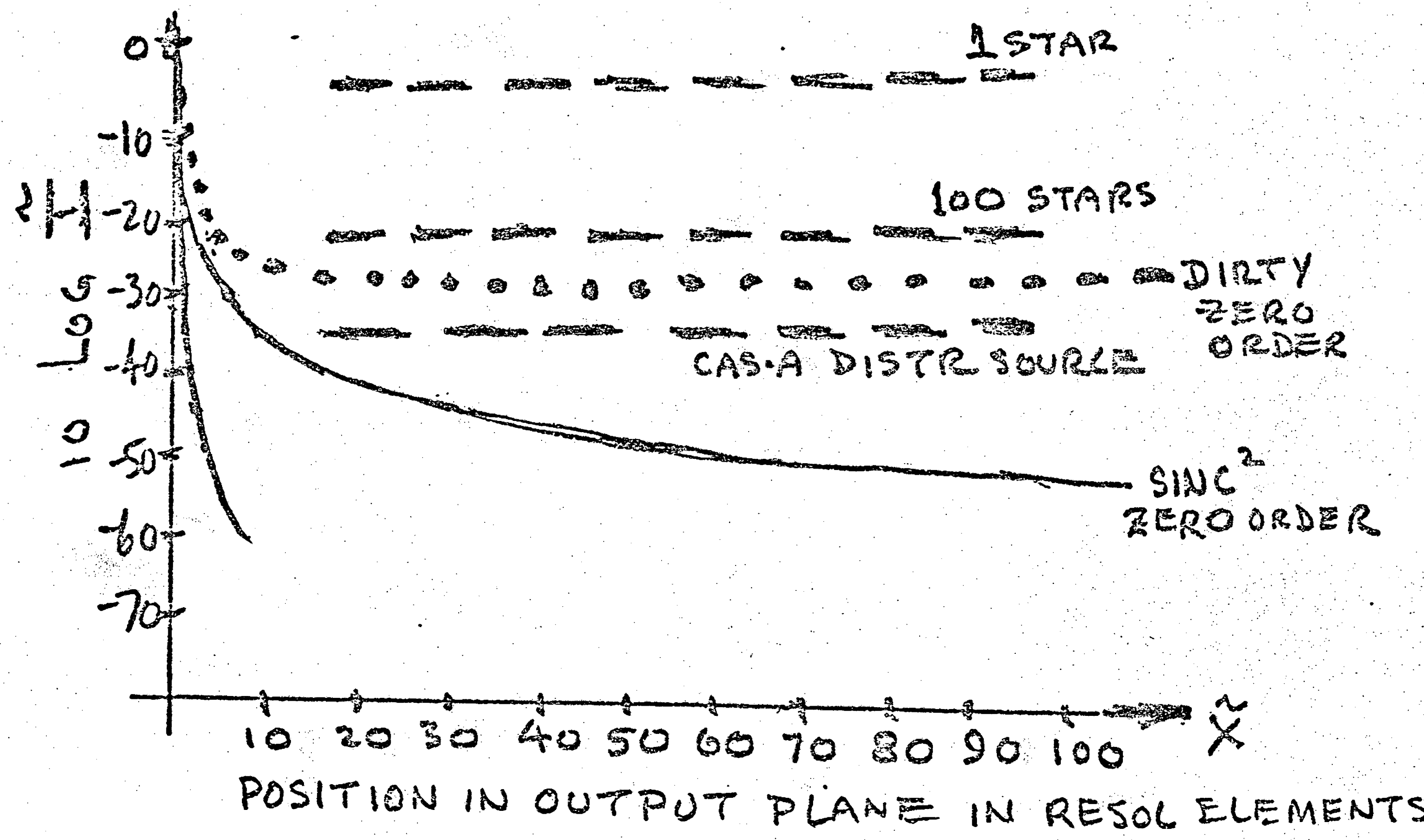
$$+ A_i^2 B_*^2(x,y) + A_i^2 B_0^2(x,y)$$ ← SUBT / SEP

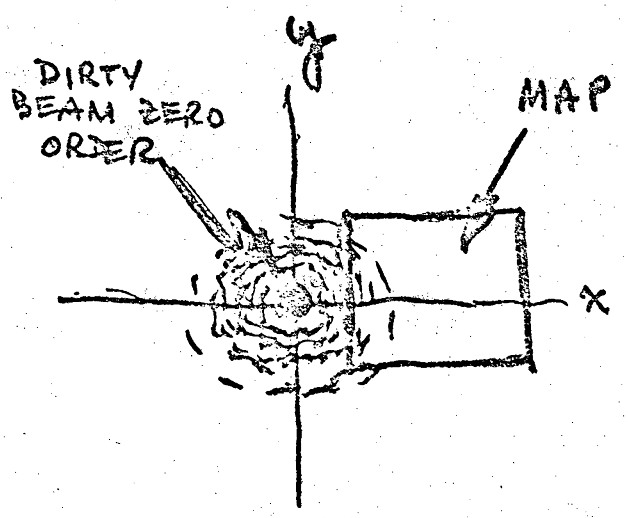
$$+ A_i^2\left[B_*(B^* + B_0^*) + B_*^*(B + B_0)\right]$$ ← SUBT / PAR SEP

$$+ 2A_iA_r\left[B_0\right]\cos(\Theta_i - \Theta_r)$$ ← NOT SUBT / SEP

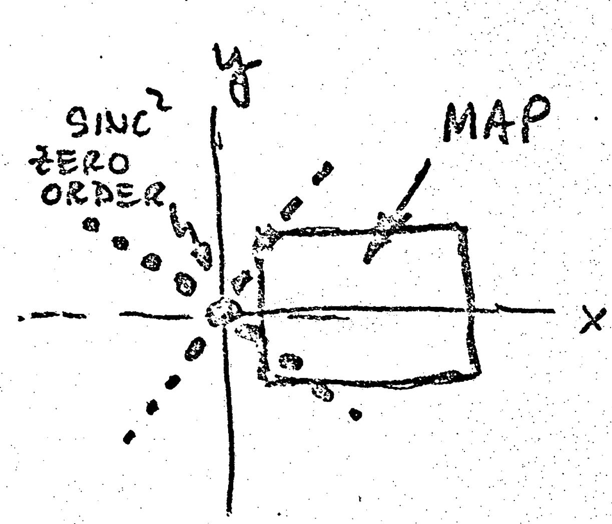
RELATIVE LIGHT INTENSITY AT THE MAP PLANE

$$\tilde{I} = I / I_{B_0}$$





OUTPUT PLANE WITH UNMATCHED BIAS ($b \neq b_T$) WITH $b = 0$



OUTPUT PLANE WITH MATCHED BIAS ($b = b_T$) AND $A(u,v) = RECT(u), RECT(v)$

OPTICAL PROCESSING CHANNEL

INTENSITY OUTPUT $I(x,y)$ AS A FUNCTION OF $U_1(x,y)+U_2(x,y)$

$$I(x,y) = \left| U_1(x,y) + U_2(x,y) \right|^2$$

$$U_1(x,y) = [A_i + \eta_i(t)]\, e^{j\,\Theta_i(x,y)+W_i(x,y)} \cdot F\left\{ t(u,v)\, e^{j[W_1(u,v)+W_2(x,y,u,v)]} \right\} + \eta_{si}(x,y)$$

$$\equiv U_i(x,y) + U_{ni}(x,y,t)$$; WITH U_{ni} AMPLITUDE NOISE TERMS

$$U_2(x,y) = [A_r + \eta_r(t)]\, e^{j[\theta_r(x,y)+W_r(x,y)]} + \eta_{sr}(x,y)$$

$$\equiv U_r(x,y) + U_{nr}(x,y,t)$$; WITH U_{nr} AMPLITUDE NOISE TERMS

$$I(x,y) = [U_i + U_r + U_{ni} + U_{nr}] \cdot [U_i^* + U_r^* + U_{ni}^* + U_{nr}^*]$$

$$= [U_i U_r^* + U_i^* U_r] + \underbrace{\left[U_i U_i^* + U_r U_r^* + (U_{ni}+U_{nr})(U_{ni}^*+U_{nr}^*) + (U_i+U_r)(U_{ni}^*+U_{nr}^*) + (U_i^*+U_r^*)(U_{ni}+U_{nr}) \right]}_{\equiv I_N(x,y)}$$

OPTICAL PROCESSING CHANNEL

OUTPUT $I(x,y)$

$$I(x,y) = U_i(x,y)\,U_r^*(x,y) + U_i^*(x,y)\,U_r(x,y) + \tilde{I}_N(x,y)$$

$$U_i(x,y) = A_i\, e^{j[\Theta_i + W_i]}\, F\{ t(u,v)\cdot P_1(u,v)\cdot P_2(u,v,x,y)\}$$

$$t(u,v) = [T(u,v)\cdot P(u,v)] + [T_0(u,v) + T_b(u,v) + T_f(u,v) + T_*(u,v)\cdot P_*(u,v)]$$

$$F\{t\cdot P_1\cdot P_2\} = [B(x,y)\otimes p(x,y)] + \Big[B_0(x,y)\otimes p_{12}(x,y) + B_b(x,y)\otimes p_{12}(x,y$$
$$+ B_f(x,y)\otimes p_{12}(x,y) + B_*(x,y)\otimes p_{12*}(x,y)\Big]$$

$$\equiv B(x,y)\otimes p(x,y) + [\;\tilde{B}(x,y)\;]$$

$$p(x,y) \equiv F\{P\cdot P_1\cdot P_2\} \quad ; \quad p_{12}(x,y) = F\{P_1\cdot P_2\}$$

$$U_i(x,y) \equiv U_B(x,y) + U_{\tilde{B}}(x,y) \quad ; \quad U_B(x,y) = A_i\, e^{j\Theta_i + W_i}\, B(x,y)\otimes p(x,y)$$

OPTICAL PROCESSING CHANNEL

OUTPUT $I(x,y)$

$$I(x,y) = \left[U_B(x,y) + U_{\tilde{B}}(x,y)\right] U_r^*(x,y) + \left[U_B^*(x,y) + U_{\tilde{B}}^*(x,y)\right] U_r(x,y) + \tilde{I}_N(x,y)$$

$$= \left[U_B U_r^* + U_B^* U_r\right] + \left[U_{\tilde{B}} U_r^* + U_{\tilde{B}}^* U_r + \tilde{I}_N\right]$$

$$\equiv \underbrace{I_B(x,y)}_{\text{SKY MAP DATA}} + \underbrace{I_N(x,y)}_{\text{NOISE AND BACKGROUND}}$$

$$I_B(x,y) = A_i A_r \; B(x,y) \otimes p(x,y) \cdot e^{j[\Theta_i - \Theta_r + W_i - W_r]}$$
$$+ A_i A_r \; B^*(x,y) \otimes p^*(x,y) \cdot e^{-j[\Theta_i - \Theta_r + W_i - W_r]}$$

$$= 2A_i A_r [B \otimes p]' \cos(\alpha) + 2A_i A_r [B \otimes p]'' \sin(\alpha)$$

WITH $\alpha = (\Theta_i - \Theta_r + W_i - W_r)$, $[\;]' \Rightarrow$ REAL, $[\;]'' \Rightarrow$ IMAG

PHASE ERRORS

THEY APPEAR AS W's IN

$$F\left\{T \cdot e^{j(W+W_1+W_2)}\right\} = B(x,y) \circledast p(x,y)$$

RECORDER ABERRATIONS

$$W(u,v) = \omega_u(\epsilon_u + m_u) + \omega_v(\epsilon_v + m_v)$$

ω_u OR ω_v = MAX FREQ COMPONENT

u,v PLANE OPTICAL COMPONENT ABBRRATIONS

$$W_1(u,v) = \frac{2\pi}{\lambda}\,\delta_1(u,v)$$

$$\delta(u) \sim \underline{au},\ bu^2,\ \underline{cu^3}, \ldots$$

u,v – x,y PLANE COUPLED ABERR EFFECTS

$$W_2(u,v,x,y) = \frac{2\pi}{\lambda}\,\delta_2(u,v,x,y)$$

$$\delta_2(u,x) \sim au^3x,\ \underline{bu^2}x^2,\ \underline{cux^3}$$

PHASE ERROR TOLERANCES FOR ONE PERCENT ACCURACY AT PEAK AND 1st SIDELOBE+ FOR DIRTY BEAM

WITH $I_0 - I_\pi$ PROCEDURE USED

FOR $W(u,v)$ AND $W_1(u,v)$ ERRORS

$$au \leq \frac{\lambda}{50} \quad *$$

$$cu^3 \leq \frac{\lambda}{10}$$

$$(bu^2 + du^4 + eu^5 + \ldots) \leq \frac{\lambda}{8}$$

FOR NON-PARAXIAL ERROR

$W_2(u,v,x,y)$

$$cux^3 \leq \frac{\lambda}{50} \quad *$$

$$bu^2x^2 \leq \frac{\lambda}{10} \quad *$$

OTHERS TOLERABLE

* LARGER ERRORS ARE COMPENSATABLE AT X,Y OUTPUT

PHASE ERRORS

THEY ALSO APPEAR IN THE PROCESSOR FRINGE PATTERN FUNCTION $\cos\alpha$

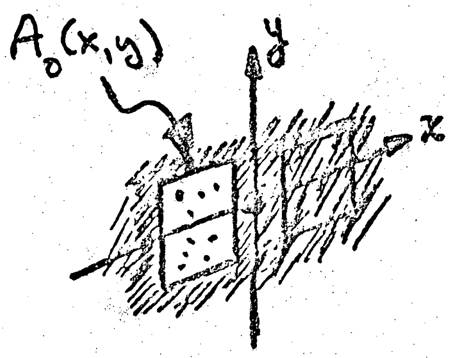
$$\cos(\alpha) = \cos[\theta_i - \theta_r + W_i - W_r]$$

AS $W_i(x,y) - W_r(x,y)$

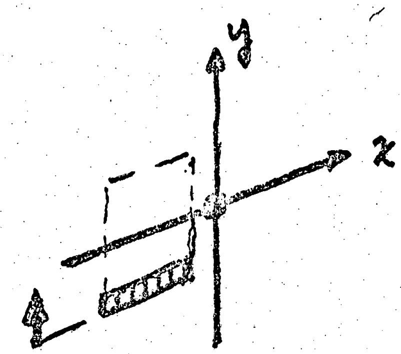
CAUSED BY AIR PATH OPTICAL PROPERTY FLUCTUATIONS

CONTROLLED BY PROCESSOR OPTICAL CHANNEL ENCLOSURE

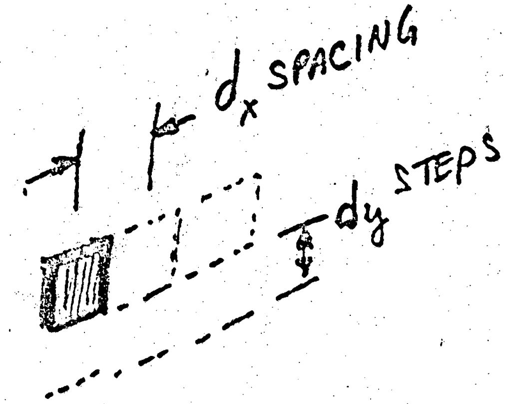
PHOTO-DETECTOR ARRAY READOUT OF MAP DATA



OUTPUT MAP DATA $A_o(x,y)\, I(x,y)$



LINEAR PUSH-BROOM ARRAY



INDIVIDUAL DETECTOR ELEMENT RESPONSE

$$h_d(x,y) = k_d\, g_d(x,y)$$

FROM INPUT $I(x,y)$ AND DETECTOR DWELL TIME Δ

TO OUTPUT $E(x,y)$

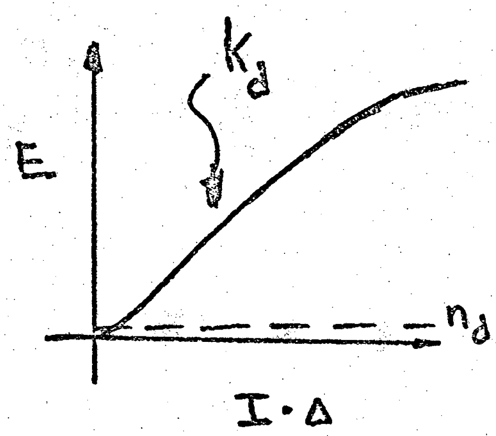
$$E(x,y) = \left[A_o(x,y)\, I(x+\epsilon_x, y+\epsilon_y) * h_d(x,y)\right] \mathrm{III}\left(\frac{x}{d_x}\right) \mathrm{III}\left(\frac{y}{d_y}\right) \cdot \Delta$$

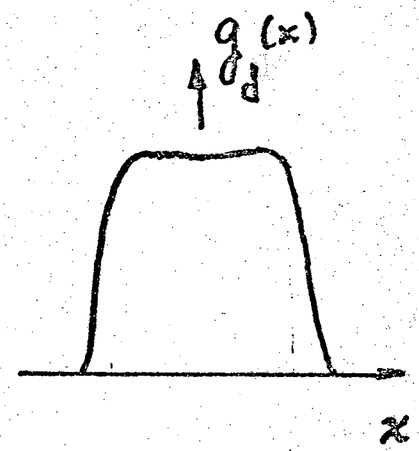
$$+ \; n_d$$

PHOTO-DETECTOR ARRAY
IMPULSE RESPONSE

FOR INDIVIDUAL ELEMENTS

$$h_d(x,y) = k_d\, g_d(x,y)$$





- Δ = INTEGRATION TIME ~ 10^{-1} SEC PER LINE AND ELEMENT
- n_d = RESET NOISE (SHOT) + AMPLIFIER NOISE (BW) + DARK LEVEL (TEMP) } ~ .0002 rms OF PK SIGNAL
- PATTERN NOISE k_d VARIATION FROM ELEMENT TO ELEMENT.
- k_d LINEARIZED TO .001 → .0005 OVER FINITE SIGNAL RANGE

POST FILTER

SUBTRACTION OF (BALANCED MIXER) MAP FRAMES

$$E_B(x,y) = E_0(x,y) - E_\pi(x,y)$$

WHERE $E_0 \Rightarrow \alpha = 0$ IN $I(x,y) \equiv I_0$

$E_\pi \Rightarrow \alpha = \pi$ IN $I(x,y) \equiv I_\pi$

AND

$$I(x,y) = 2A_i A_r (B \otimes p)' \cos\alpha + 2A_i A_r (B \quad)'' \sin\alpha + I_N$$

$$E_B(x,y) = \text{III}\left(\frac{x}{d_x}\right)\text{III}\left(\frac{y}{d_y}\right)\Big[A_0(x,y)\, I_0(x+\epsilon_x, y+\epsilon_y) * h_d(x,y) - A_0(x,y)\, I_\pi(x+\epsilon_x, y+\epsilon_y) * h_d(x,y)\Big]\cdot\Delta + n_{d0} - n_{d\pi}$$

EXPERIMENTAL BREADBOARD OPTICAL PROCESSOR ACTIVITY

OPTICAL PROCESSING CHANNEL

- BEYOND LENSE INPUT PLANE
- 3.3 M FOCAL LENGTH
- FILM + GATE DATA ENTRY
- READOUT DETECTOR ARRAY (1024 RETICON LINEAR)
- HE-NE (100 mw) AND ARGON LASER

DATA INPUT

- CRT / FILM RECORDER
- DATA CONVERSION
  CCT → D/A → CRT/FILM

DATA OUTPUT

- DIODE ARRAY → CCT → RAMTEK COMPUTER
- DIODE ARRAY → SCAN RECORDER → INVERSE FT

EXPERIMENTAL RESULTS

CRT / FILM RECORDING

SIMULATED VLA DATA (STAR)

PULSE TRAIN

PROCESSOR OUTPUT

FOR VLA DATA INPUT
WITH MATCHED BIAS

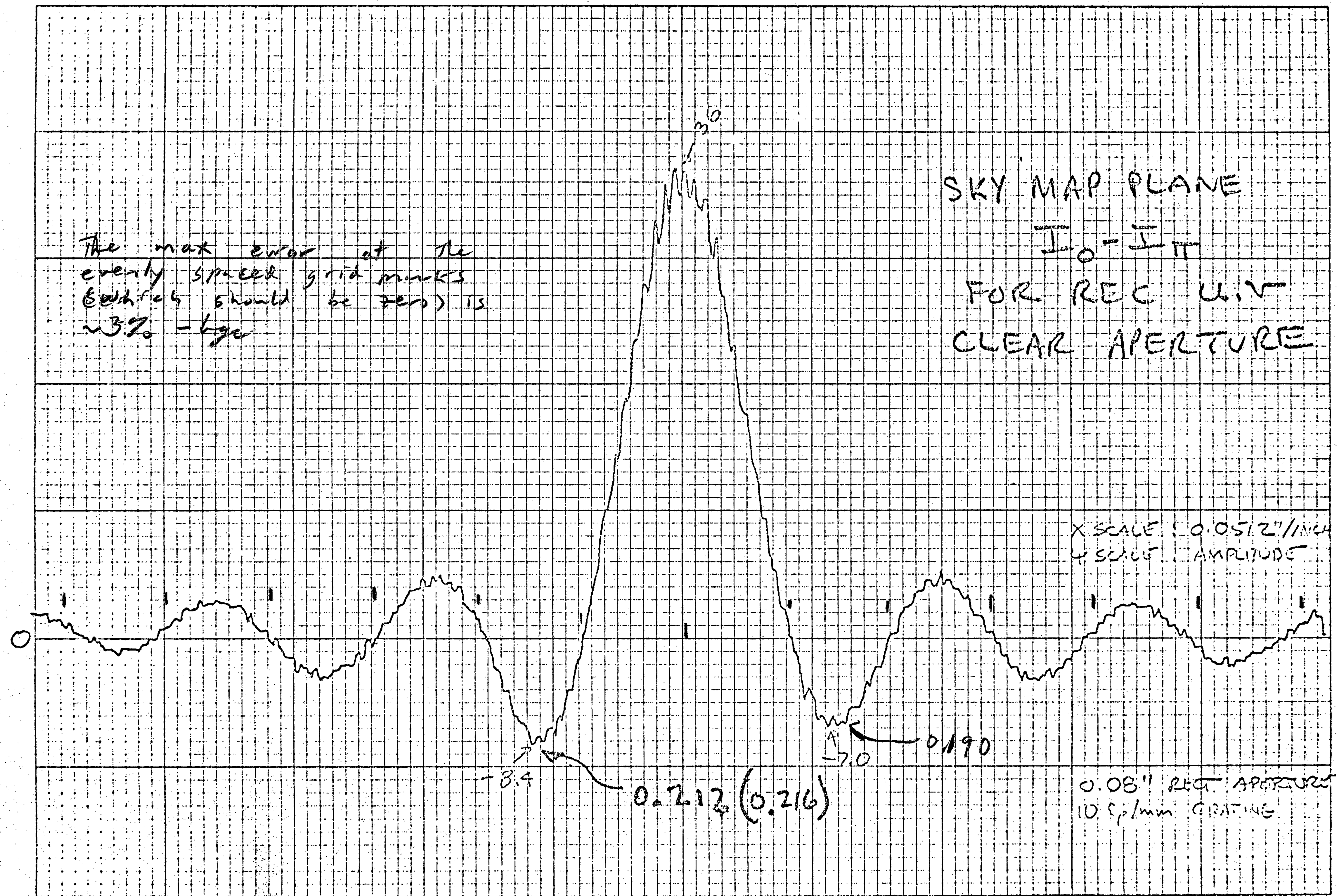
SKY MAP PLANE PHOTOS

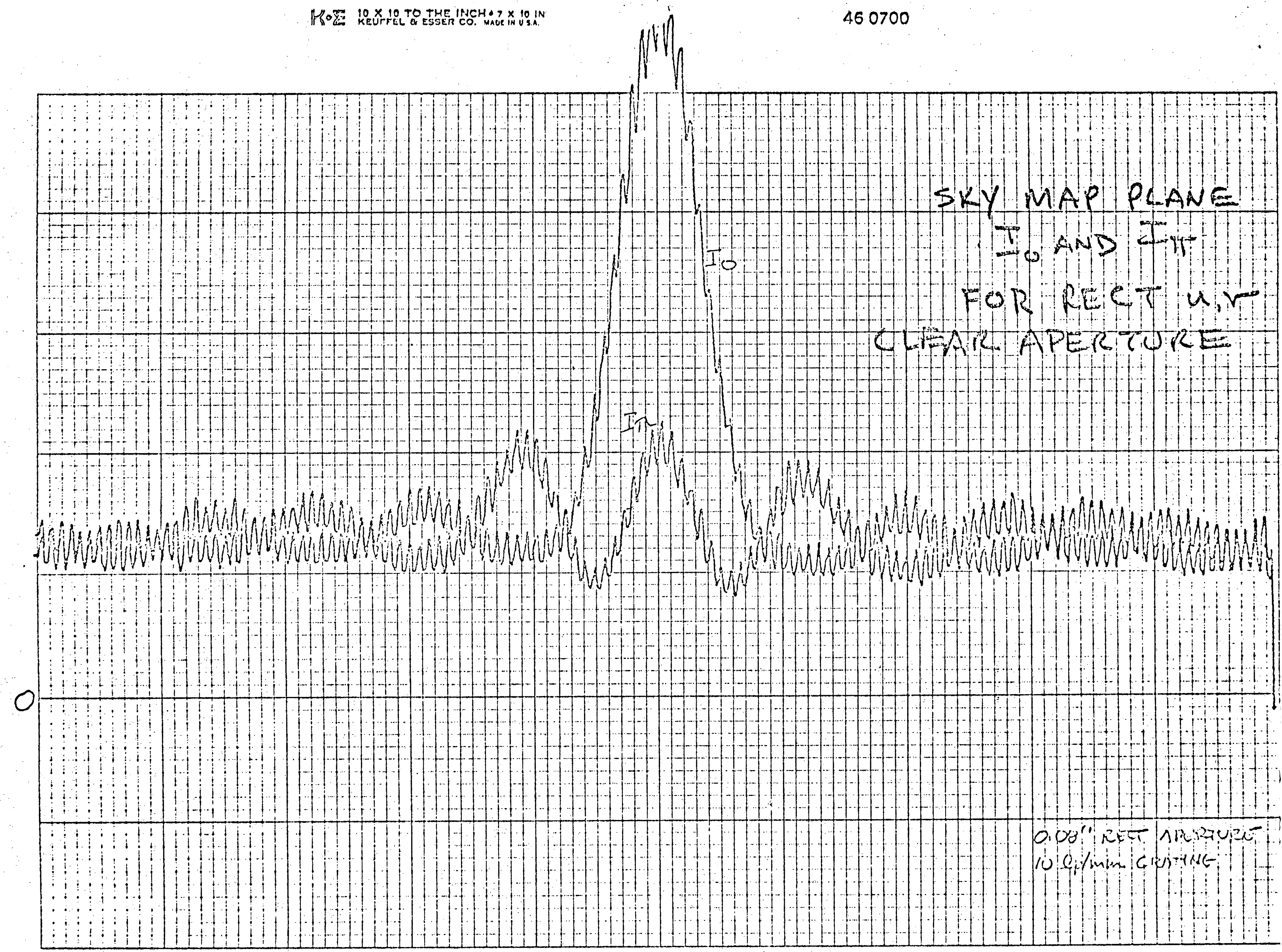
SKY MAP (ARRAY) OUTPUT
WITH $I_0 - I_\pi$ POST
FILTER STEP

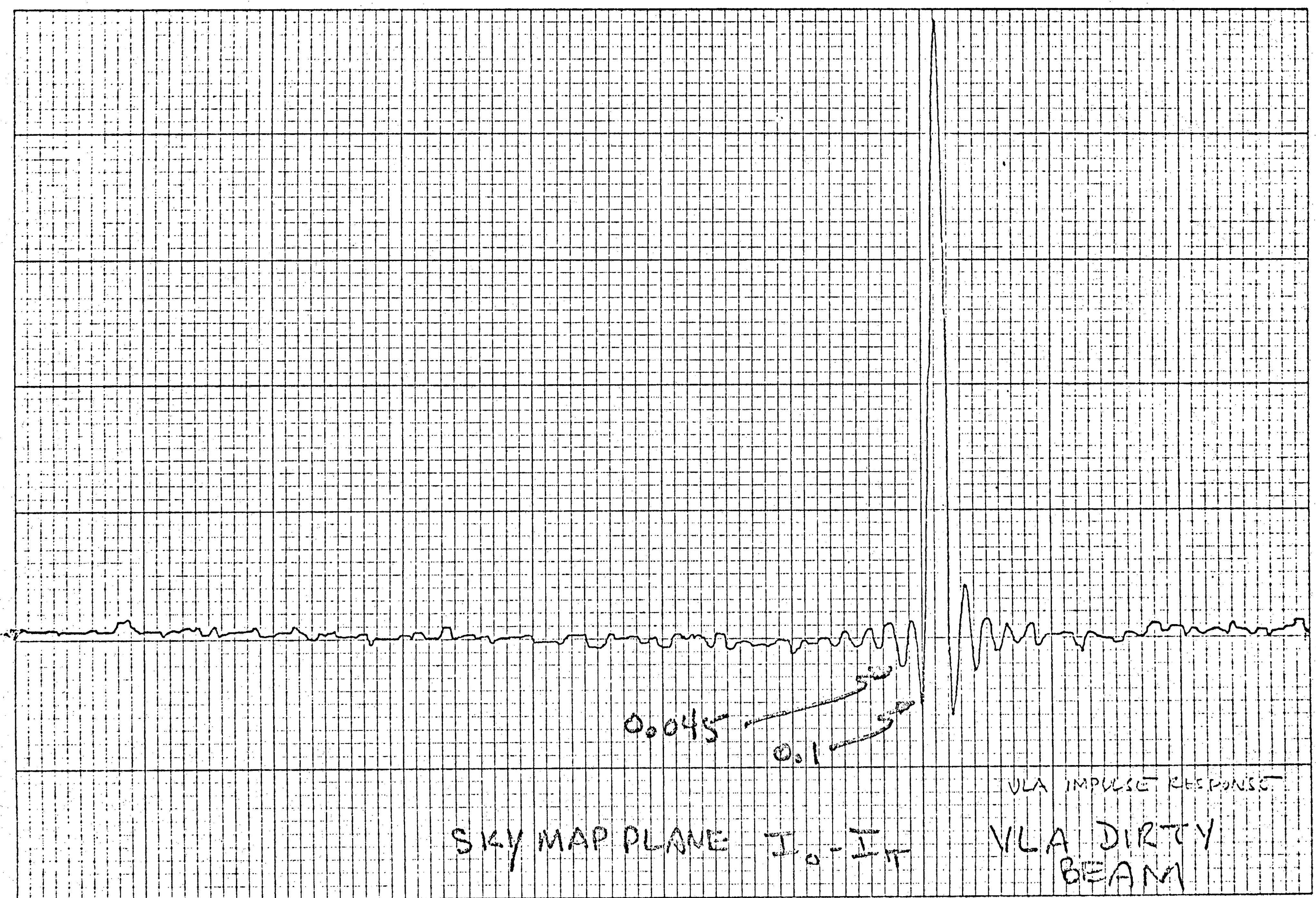
FOR CLEAR REST
AND CIRC u,v APERTURES

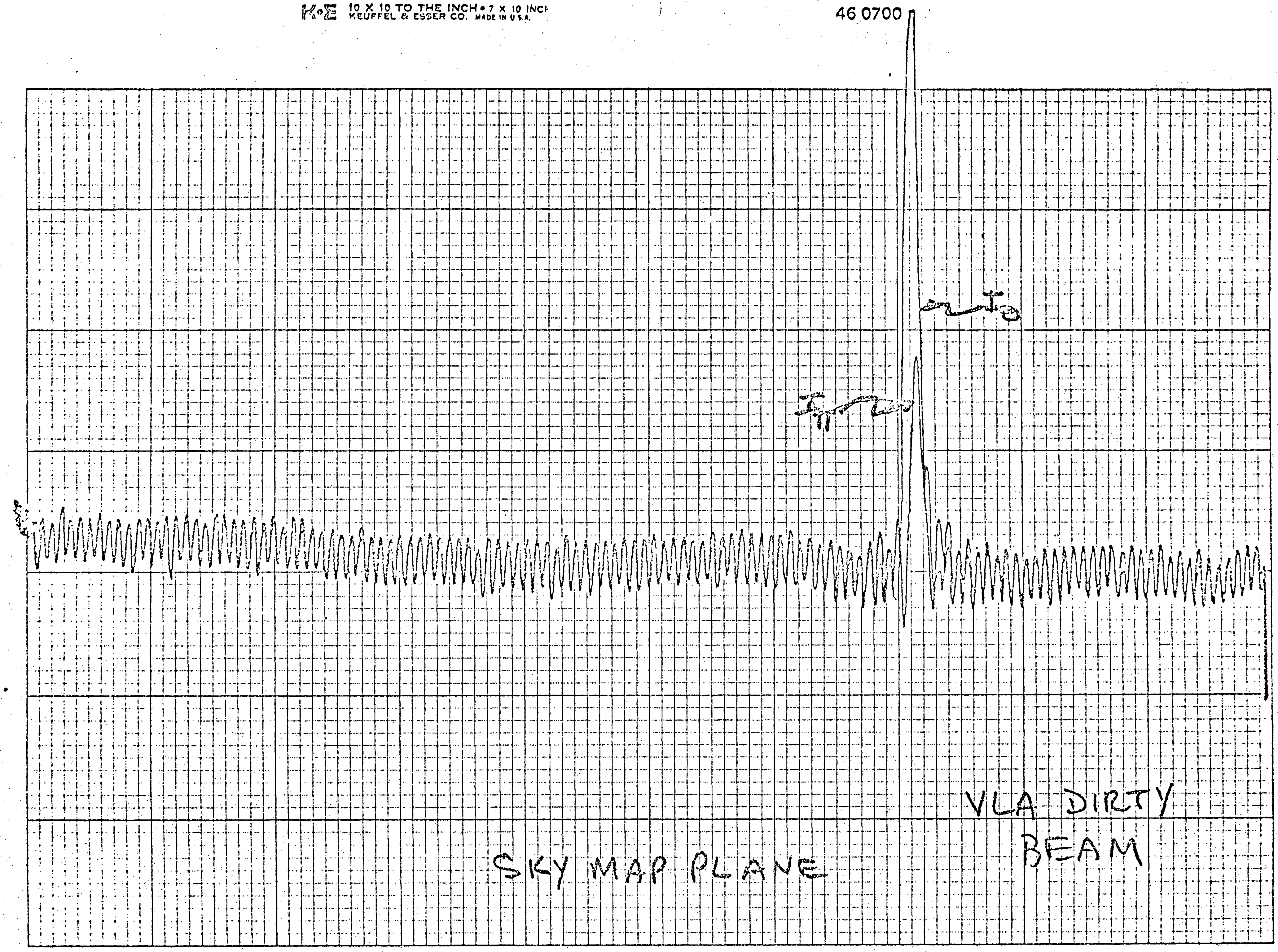
K+E 10 X 10 TO THE INCH • 7 X 10 IN
KEUFFEL & ESSER CO. MADE IN U.S.A.

46 0700




K+E 10 X 10 TO THE INCH • 7 X 10 IN
KEUFFEL & ESSER CO. MADE IN U.S.A.
46 0700
SKY MAP PLANE
I0 AND Iπ
FOR RECT u,v
CLEAR APERTURE
I0
Iπ
0
0.08" RECT APERTURE
10 lp/mm GRATING


0.045
0.1
VLA IMPULSE RESPONSE
SKY MAP PLANE
VLA DIRTY BEAM


VLA DIRTY
BEAM
SKY MAP PLANE

PROPOSED PROGRAM

CURRENT EFFORT

- ESTABLISH CONCEPTUAL APPROACH
- SYSTEM MODEL AND ERROR BUDGET
- PRELIMINARY PERFORMANCE SPECIFICATIONS AND COST ESTIMATES

FUTURE EFFORT

- DEFINE DETAILED DESIGN; ESTABLISH FIRM COSTING
- DESIGN & TEST "SUB-SYSTEMS"
- INTEGRATE & TEST "SYSTEM"