THE UNIVERSITY OF KANSAS SPACE TECHNOLOGY CENTER
Raymond Nichols Hall
2291 Irving Hill Drive—Campus West Lawrence, Kansas 66045
Telephone:

NASA CR-156721

USE OF A MULTI-LOOK UNFOCUSSED SAR PROCESSOR ON SPACECRAFT

Remote Sensing Laboratory
RSL Technical Memorandum 295-10

(NASA-CR-156721) USE OF A MULTI-LOOK UNFOCUSSED SAR PROCESSOR ON SPACECRAFT (Kansas Univ.) 26 p HC A03/MF A01 CSCL 17I N78-20391
Unclas
G3/32 12132

Richard K. T. Fong

April, 1976

Supported by:

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Goddard Space Flight Center
Greenbelt, Maryland 20771

CONTRACT NAS 5-22384

REMOTE SENSING LABORATORY

TABLE OF CONTENTS

LIST OF FIGURES

ABSTRACT

This paper considers two methods of processing signals from a multi-look unfocussed synthetic-aperture radar. A saving in the processor complexity is achieved in comparison to a fully focussed SAR system at the expense of slightly greater clutter levels and poorer along-track resolution. In addition, lower power consumption enables the unfocussed processor to increase the number of looks to compensate in part for the reduced resolution.

An example of a processor for 150 m resolution at 435 km height with 138 km swath (7° to 22°) uses only 33 watts for 4 looks (most of the power is used by 4 A/D converters).

USE OF A MULTI-LOOK UNFOCUSSED SAR PROCESSOR ON SPACECRAFT

Richard K. T. Fong

1.0 INTRODUCTION

A synthetic aperture radar (SAR) array is achieved by suitably processing radar echoes from a single mobile antenna moved along the line of a hypothetical linear array, resulting in beam sharpening and consequent fine resolution along a line parallel to the array.

Focussing requires that the effective phase length between each of the array elements and the target is the same. The total received signal from such a target is the result of phase-coherent summing of the received signals from all elements of the array. For a fully-focussed SAR, linear along-track resolution is:

$$r_x = \frac{D}{2} \quad ,$$

independent of frequency and range [1], where D is the physical length of the antenna.

Now consider the comparable case for the unfocussed SAR. Each element of the synthetic array illuminates and receives a return signal from a target independent of every other array element. Here linear along-track resolution is (for minimum processing):

$$r_x \approx \left[\frac{1}{2}\ (\lambda R)\right]^{1/2}$$

at slant range R and wavelength λ [2].

For the unfocussed SAR, resolution in the along-track direction is dependent on range and frequency. In this case, the coherent echoes are summed without compensation for the phase shifts. This simplifies the processor but limits the maximum admissable length of the synthesized antenna. This arises from the fact that the phase difference of the received signals in the center and on the edges of the synthesized aperture must not exceed 90 degrees [3], i.e.

$$L < (\lambda R)^{1/2}$$

Unfocussed signal processing provides along-track resolution which is considerably poorer than fully-focussed signal processing. Nevertheless for requirements in sea-ice, soil-moisture, and snow imaging it may be adequate. One method of improving the image quality is to provide for multi-looks. That is, multiple independent coherent looks are made of each cell, and these coherent looks are non-coherently combined to provide a better quality image.

As the real antenna is progressively moved along the line of a hypothetical linear array, there is a certain amount of overlapping of beam coverage. This overlapping permits multi-looks at a specified picture or target cell area, enabling averaging to be done to give a better image and reduce speckle (Figure 1).

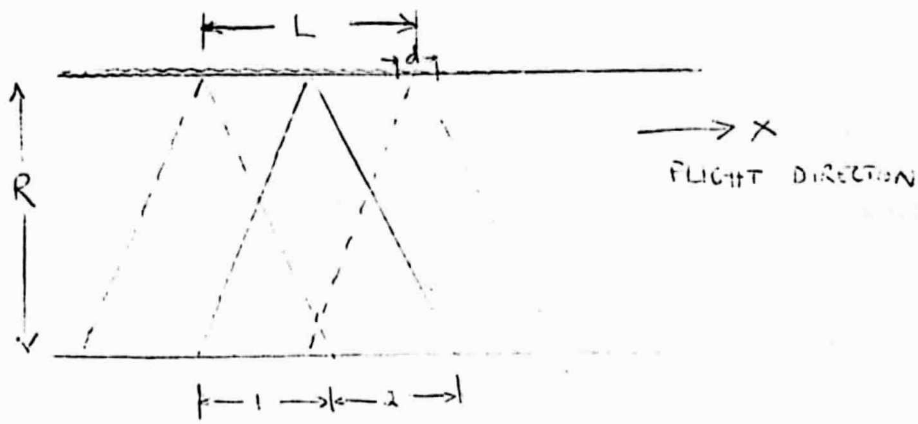


Figure 1. System for two looks on a pixel.

When processing synthetic-aperture radar data, all or part of the Doppler bandwidth may be processed for resolution. If the total bandwidth is used for resolution, the resultant processed signal contains all the information about the target which can be obtained (assuming the system is linear). Therefore, a multi-look system can never gather more information about any target than a one-look system having the same bandwidth (when the system is linear).

If the bandwidth is divided into sections, several signals may be derived from the total bandwidth, each of which when processed yields proportionately less resolution. Combining the multiple looks will result in a better-looking image than any look itself because the speckled appearance of the picture will be improved.

The independent looks can also be obtained by processing different look angles or different polarizations. The effect on the processor is to increase its complexity by the number of looks. Thus, for four looks, the memory and arithmetic rate each increase by a factor of four. If one Doppler filter is required for one look as in the unfocussed processor, then four filters are required for four looks.

Two methods for the production of multiple looks, illustrated in Figure 2, are:

1. Filtering to form multiple bandwidth sections, with each section processed coherently and the results detected and summed.
2. Processing for ultimate resolution and low-pass filtering detected outputs to the desired resolution.

Both methods give virtually identical results in terms of the quality of the resulting image. However, preference is for method 1 which requires the least amount of storage [4].

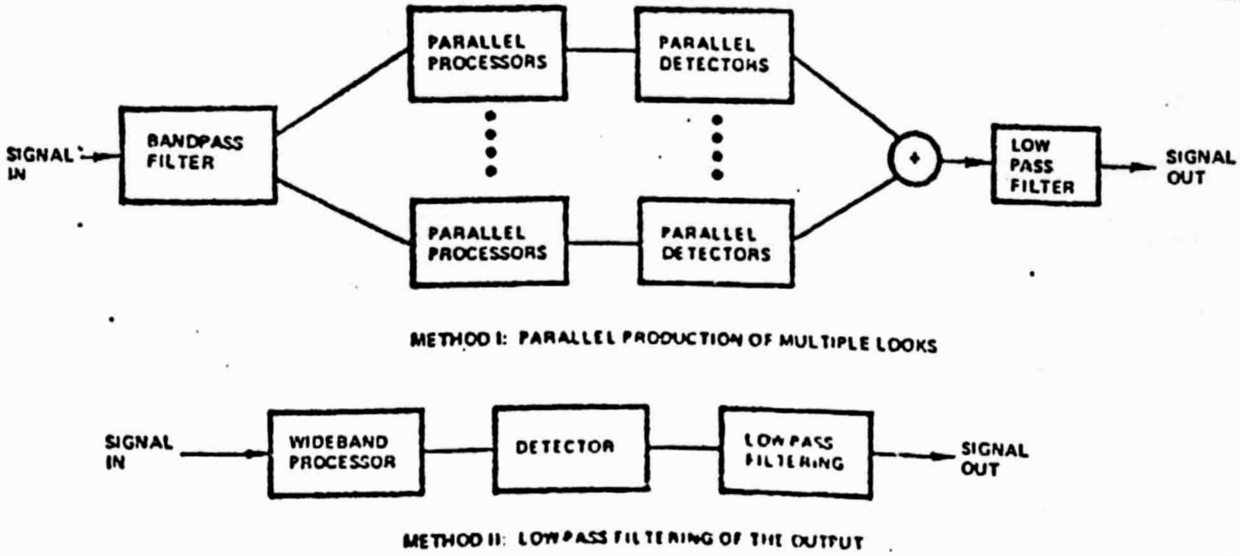


Figure 2. Two methods used for producing multi-looks.

The basic elements of a spaceborne SAR system are shown in Figure 3. Since the unfocussed SAR processor is relatively simple, it is possible to use it as the on-board system.

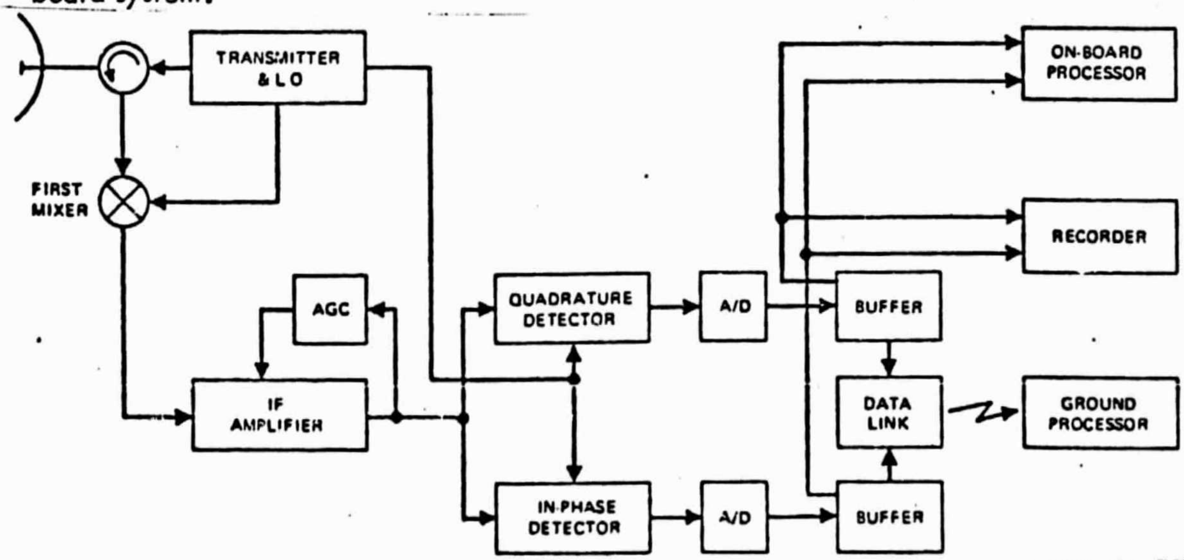


Figure 3. Basic radar block diagram.

ORIGINAL PAGE IS OF POOR QUALITY

2.0 SAR SIGNAL PROCESSING

SAR systems employ signal processing to convert stored radar signals into fine-resolution images. Signal processing in radar systems is analogous to modulation theory in communication systems. Both fields continuously emphasize communicating a maximum of information in a specified bandwidth and minimizing the effect of interference.

The fundamental aperture synthesis process is carried out by storing and summing reflected radar signals observed at the sequence of positions,

$$(x_1, x_2, x_3 \cdots\cdots\cdots x_n)$$

Since the unfocussed SAR processing does not introduce a phase-shift factor, it merely sums the signals over the length of the synthetic aperture. Summation of the signals is limited to the first Fresnel zone if severe sidelobe degradation is to be avoided.

All SAR systems provide the same target histories for processing (filtering). Each method of processing offers a trade in the suitability of its final image to satisfy user requirements against the engineering and economic requirement of a SAR system.

Unfocussed SAR systems (i.e., those which do not require range-dependent quadratic phase corrections) can be implemented using recirculating delay lines, Doppler filters and other analogous networks.

Unfocussed SAR processing can also be described as "Zone Plate" processing employing matched-filtering or reference functions which include only the first Fresnel zone [5]. The use of modified reference functions gives rise to slightly greater clutter levels and poorer along-track resolution but this is the trade-off leading to the design of simpler processors.

3.0 RECIRCULATING DELAY LINES

In this method, the various range elements are processed sequentially as a signal circulates around a delay line and is added to the incoming signal.

This recirculation is continued until the signals in N cycles of the input have been added together. Only signals having the proper period add up each

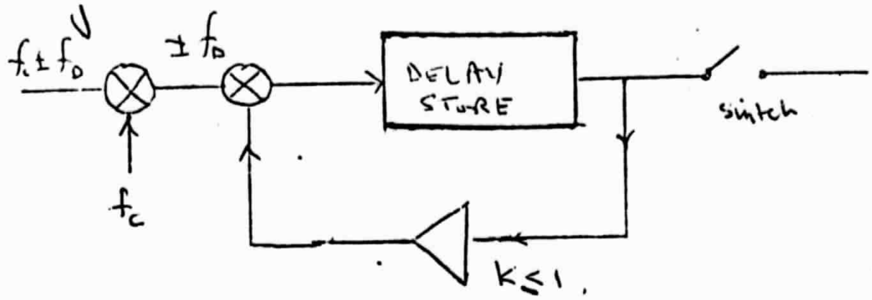


Figure 4. Active comb filter.

time, while signals with different periods drift in and out of phase in the addition process.

Consider a train of N pulses (see Figure 5) for which the first train pulse is denoted by $f_p(t)$ and its Fourier transform by $F_p(w)$. Then the Fourier transform $F(w)$ of the pulse train through the comb filter in Figure 4 is given by:

$$F(w) = F\left\{f_p(t) + K f_p(t-T_p) + K^2 f_p(t-2T_p) + \ldots K^{N-1} f_p(t-(N-1)T_p)\right\}$$

$$= F_p(w)\,(1 + Ke^{-jwTp} + K^2 e^{-2jwTp} + \ldots\ldots)$$

$$= F_p(w)\,\frac{1 - K^N e^{-jwNTp}}{1 - Ke^{-jwTp}}$$

$$= F_p(w)\,\frac{1 - e^{-jwNTp} - (K^N - 1)\,e^{-jwNTp}}{1 - e^{-jwTp} - (K-1)\,e^{-jwTp}}$$

$$= F_p(w)\,\frac{e^{-jwNTp/2}\,e^{jwNTp/2} - e^{-jwNTp/2}\,e^{-jwNTp/2} - (K^N-1)\,e^{-jwNTp}}{e^{-jwTp/2}\,e^{jwTp/2} - e^{-jwTp/2}\,e^{-jwTp/2} - (K-1)\,e^{-jwTp}}$$

$$= F_p(w)\,\frac{2je^{-jwNTp/2}\sin\left(\frac{wNTp}{2}\right) - (K^N-1)\,e^{-jwNTp}}{2je^{-jwTp/2}\sin\left(\frac{wTp}{2}\right) - (K-1)\,e^{-jwTp}}$$

$$F(w) = F_p(w)\,\frac{\left[2j\sin\left(\frac{wNTp}{2}\right) - (K^N-1)\,e^{\frac{-jwNTp}{2}}\right] e^{\frac{-jwNTp}{2}}}{\left[2j\sin\left(\frac{wTp}{2}\right) - (K-1)\,e^{\frac{-jwTp}{2}}\right] e^{\frac{-jwTp}{2}}}$$

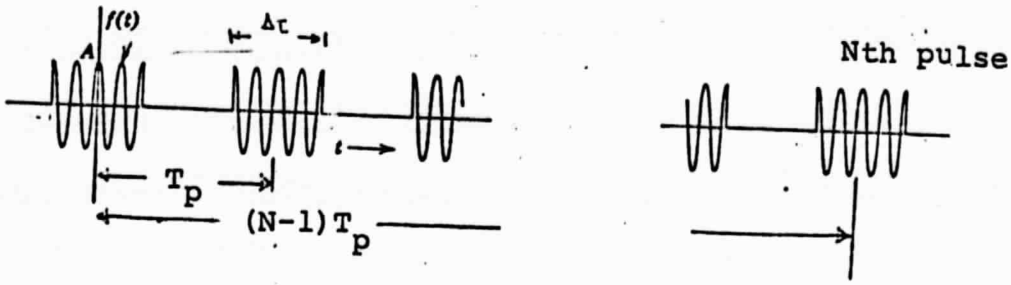


Figure 5. Train of N rf pulses.

$$F(w) = F_p(w) \frac{[2j \sin(\frac{wNTp}{2}) - (K^N - 1)\{\cos(\frac{wNTp}{2}) - j \sin(\frac{wNTp}{2})\}] e^{\frac{-jw(N-1)Tp}{2}}}{[2j \sin(\frac{wTp}{2}) - (K - 1)\{\cos(\frac{wTp}{2}) - j \sin(\frac{wTp}{2})\}]}$$

For K = 1, the expression reduces to

$$F(w) = F_p(w) \frac{\sin(wNTp/2)}{\sin(wTp/2)} e^{\frac{-jw(N-1)Tp}{2}} \quad (1)$$

a typical plot of which is shown in Figure 6 where

$$F_p(w) = \frac{A\Delta T}{2} \left[\frac{\sin(w - wo)\Delta T/2}{(w - wo)\Delta T/2} + \frac{\sin(w + wo)\Delta T/2}{(w + wo)\Delta T/2}\right] \quad (2)$$

The filtering of a train of pulses is therefore called a comb-filter because of the shape of the frequency spectrum of the signal.

The carrier frequency $wo = \frac{2\pi m}{Tp}$ where 'm' is an integer. The width of the overriding envelope is $\frac{2\pi}{\Delta T}$ and is related to the spectrum of a single pulse, i.e., $\sin(w - wo)\Delta T/2 = 0$ or $(w - wo) = \frac{2\pi}{\Delta T}$ when w is the value at the first null of the single-pulse spectrum. The centers of the teeth of a comb are spaced by $\frac{2\pi}{Tp}$ and have a width of 4π times the reciprocal of the total pulse-train length.

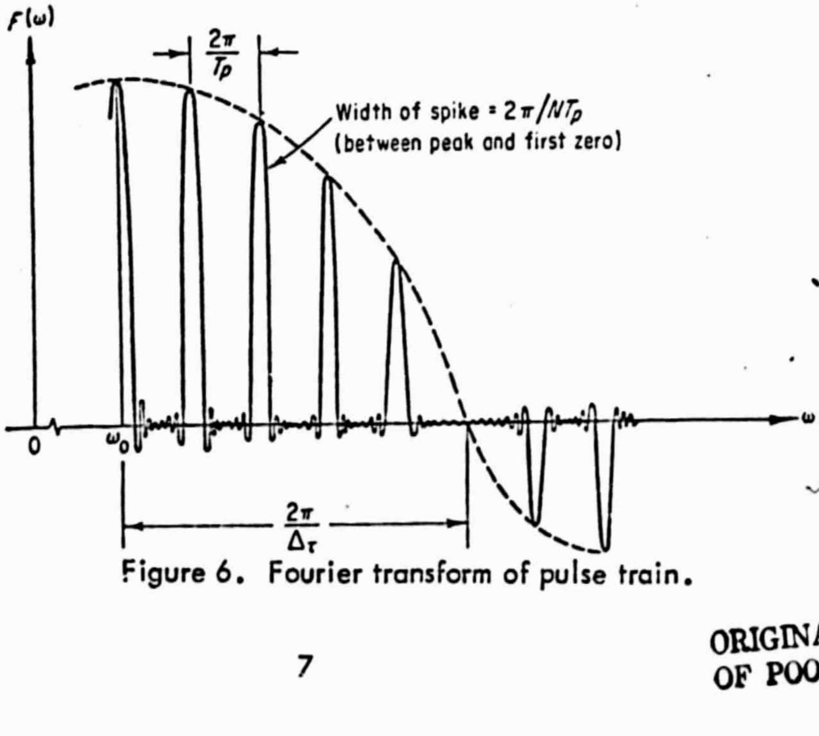


Figure 6. Fourier transform of pulse train.

Expanding F(w) further we obtain

$$F(w) = F_p(w) \frac{[(K^N-1)\cos(\frac{wNTp}{2}) - j(K^N+1)\sin(\frac{wNTp}{2})]\, e^{\frac{-jw(N-1)Tp}{2}}}{[(K-1)\cos(\frac{wTp}{2}) - j(K+1)\sin(\frac{wTp}{2})]} \qquad (3)$$

A switch or inhibit gate as shown in Figure 4, limits the pulse train to N pulses. The gates are usually used to clear the delay line after (N-1) recirculations of the first pulse. By employing a feedback loop around the delay line with loop gain K less than unity, we can do without the input or output gates. In fact, some unfocussed SAR systems use this method and omit the switch, with the effective N determined by the decay associated with the repeated passage of the signals through the gain K.

Another effect of the feedback loop is to reduce the sidelobes. The teeth of the comb filter have a $\frac{\sin x}{x}$ shape if all pulses summed are weighted the same.

By adjusting the amplifier gain K in the feedback loop for less than unity, this shape can be changed to achieve any of the standard weighting functions and resulting passband shapes. Hence to optimize integrator performance, the value of K, loop gain must be optimized. [6]

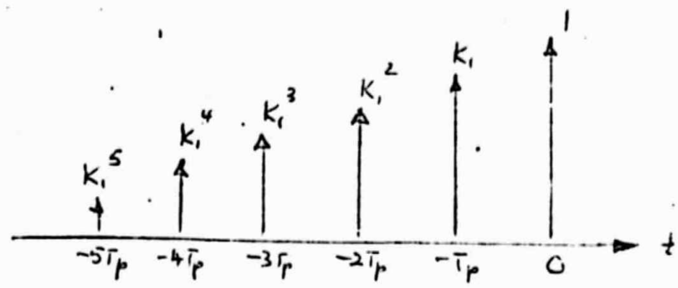


Figure 7. Weighting function for feedback loop gain K.

To demonstrate the effect on a SAR system, equations (1) and (3) were plotted using SAR specifications and illustrated on Figure 8. The computer print-out results are in Appendix A.

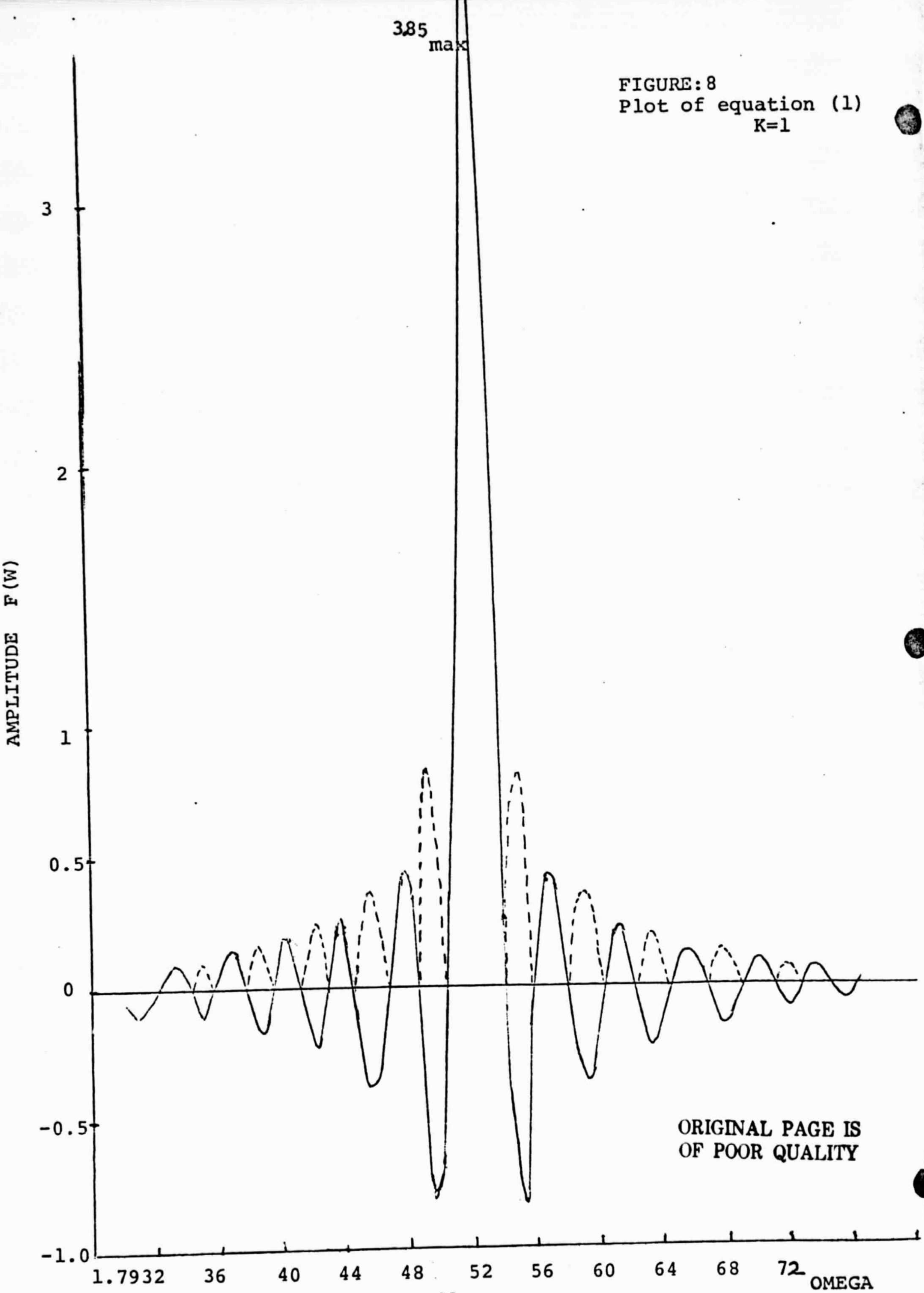
Advantages in recirculating delay line processors include the need for no physical range gating since target range is determined by the time of appearance of echo pulses at Doppler outputs. The comb filter has a set of passbands spaced by the same spacing as the Fourier components of the received pulse. This permits narrow-band Doppler filtering while retaining the wide-band characteristics of the pulse train necessary to retain range resolution.

Disadvantages include the necessity for stringent requirements on loop gain, bandwidth, delay time, and spurious responses.

If the delay line is implemented by a sampled-data system using either an analog or a digital shift register, the delay is established by the clock driving the register, which can be made very accurate. The use of a digital system also eliminates the loop-gain stability problem.

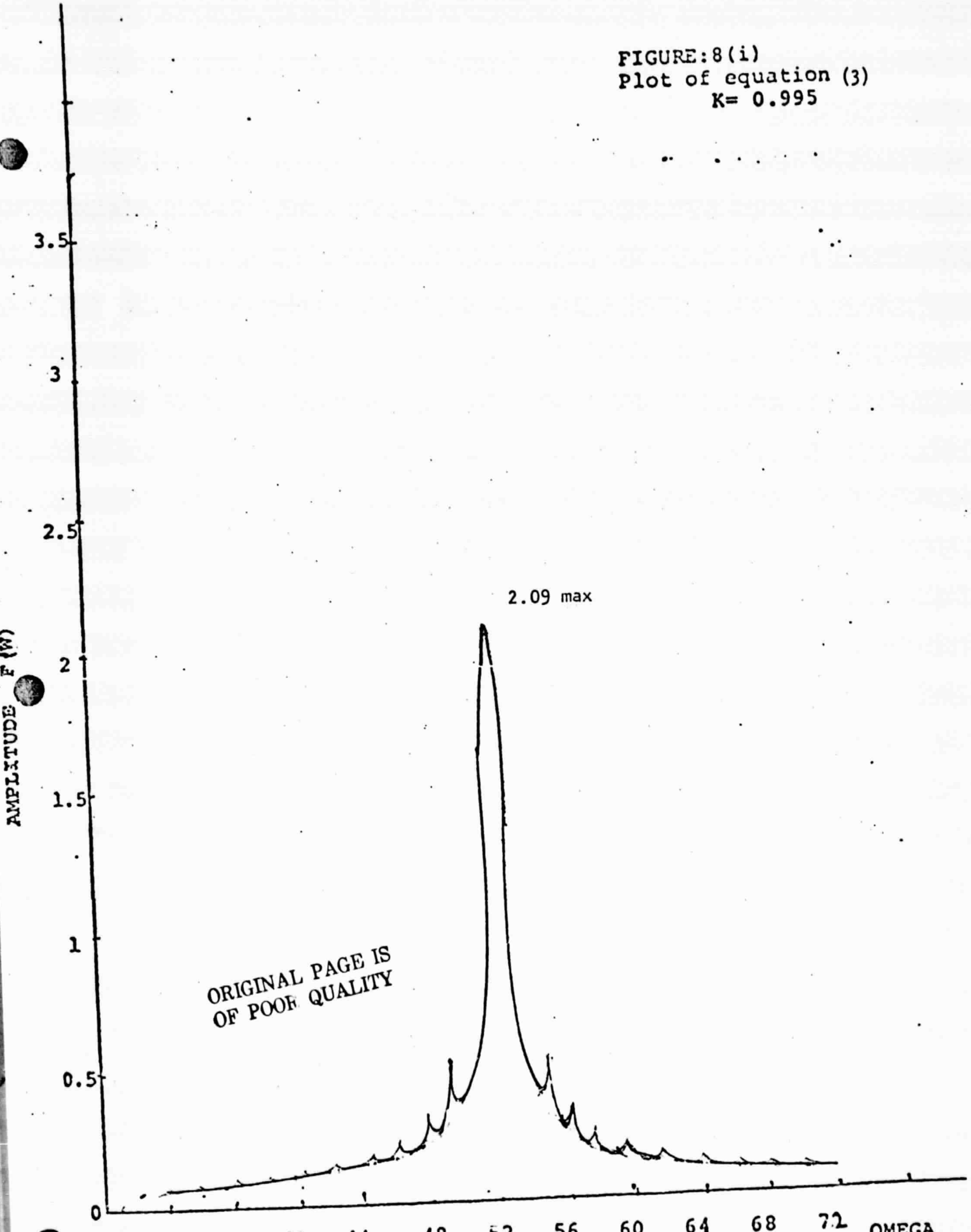
4.0 DOPPLER FILTERS AND RANGE GATES

The infusion of digital techniques into radar processing in recent years is



3.85 max
FIGURE: 8
Plot of equation (1)
K=1
AMPLITUDE F(W)
3
2
1
0.5
0
-0.5
-1.0
1.7932
36
40
44
48
52
56
60
64
68
72
OMEGA
ORIGINAL PAGE IS
OF POOR QUALITY

FIGURE:8(i)
Plot of equation (3)
K= 0.995



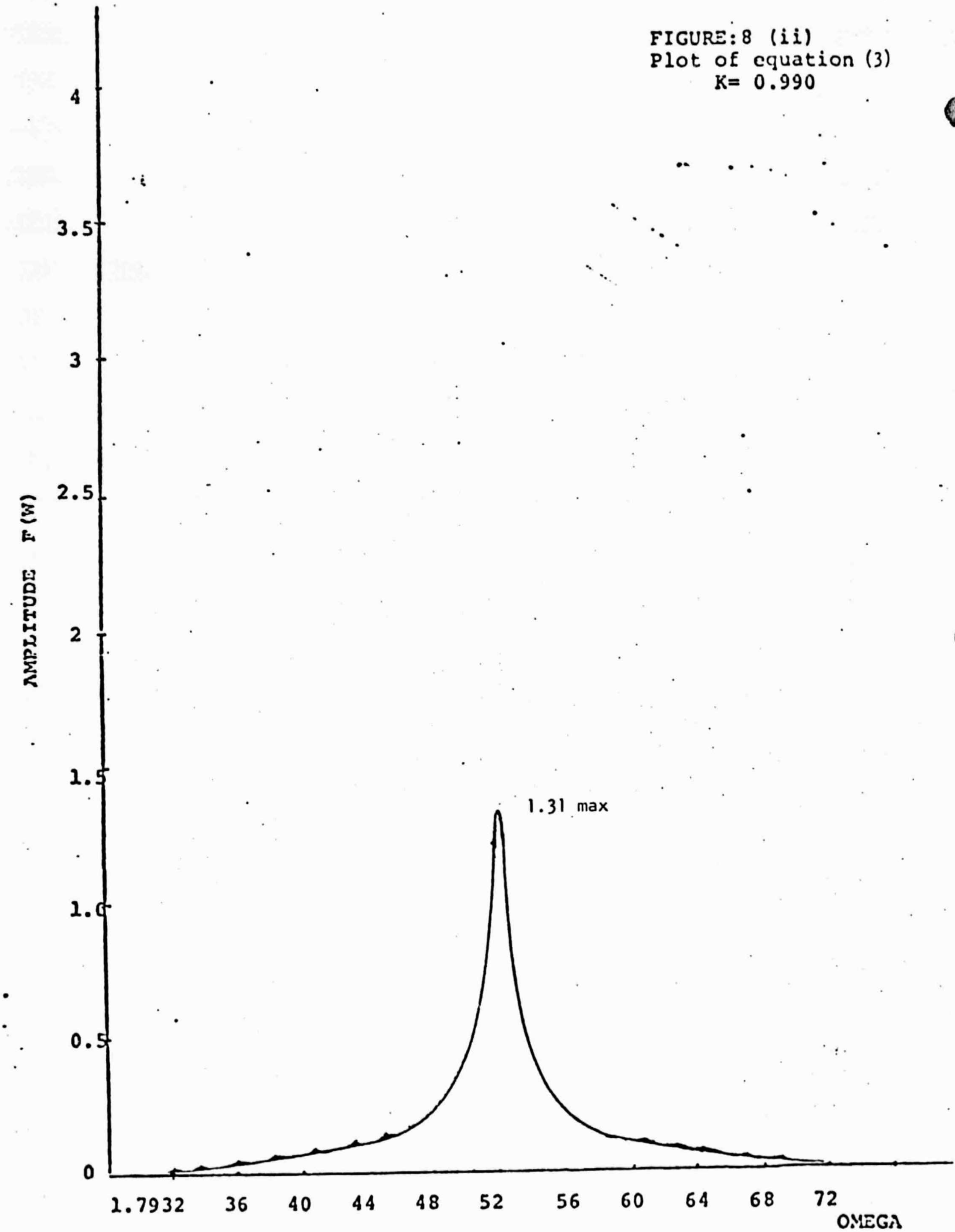


FIGURE: 8 (ii)
Plot of equation (3)
K= 0.990
AMPLITUDE F(W)
4
3.5
3
2.5
2
1.5
1.0
0.5
0
1.31 max
1.7932
36
40
44
48
52
56
60
64
68
72
OMEGA

well known. In replacing conventional analog circuits with small and reliable digital storage devices, significant improvements such as size, weight, power and reliability have been made possible.

The alternative method to recirculating systems is the use of sampling systems at a clock frequency, f_r. The sampling rate must be high enough to avoid aliasing and is usually at the pulse repetition frequency (PRF) of the radar. This method also depends on range gates, with a sample per range gate. Figure 9 illustrates a schematic of a simple unfocussed processor.

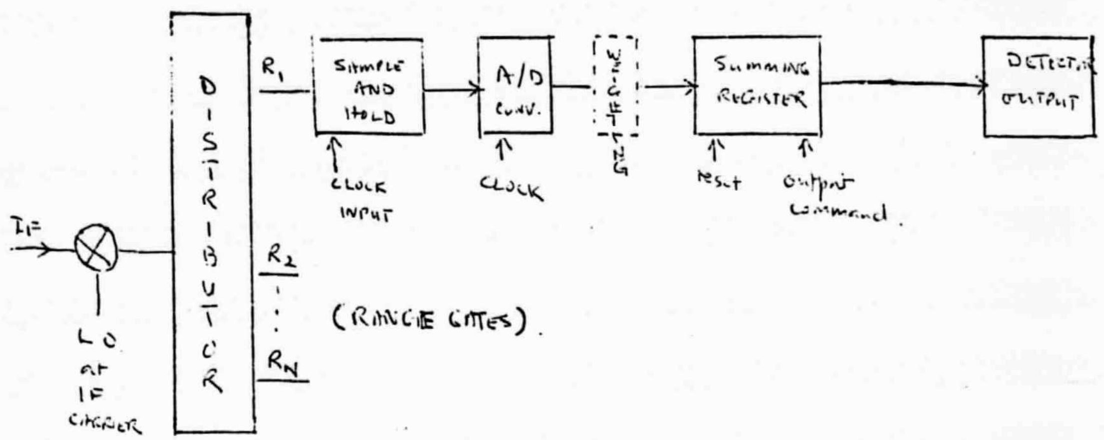


Figure 9. Unfocussed sampling processor.

The IF echo signal is distributed to the several range gates where it is sampled at least once per pulse width and converted to a digital word. N samples corresponding to the coherent integration time or desired array length are summed together in a register which is controlled by the master clock. The register, therefore, only stores the sampled signal and adds a new sample for each pulse signal per range gate.

Figure 10 illustrates the processor using I and Q channels for a zero-IF configuration. The advantage of this unfocussed processor is that it requires no multiplications at all for the single channel range gate and only output multiplications for I and Q channels. This is possible because of the recent advances in A/D conversion rates and the rapid decrease in the cost of digital storage.

To make a map, multiple range cells are required. When multiple range gates are processed similarly, an azimuth line is formed. The map is formed with successive azimuth lines laid side by side. Each azimuth line is like a sample of the synthetic array pattern. For multiple looks, replications of the system according to the number of looks will be needed with different local oscillator frequencies to

ORIGINAL PAGE IS
OF POOR QUALITY

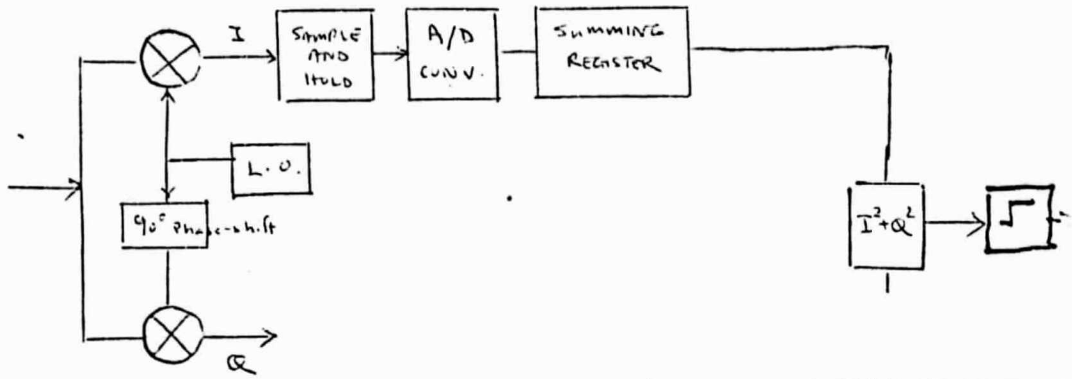


Figure 10. Digital I and Q SAR processor multiple range gate, single filter.

point the beam. [7]

In the above system, since each range gate does its own A/D conversion, the conversion can be carried out at a slow rate although a fast sample-and-hold unit is still required. If we use a single fast A/D unit before distribution, its output must go into a fast buffer for each range gate as shown in Figure 11. However, this buffer store could use fewer bits than the main register, and summing could be done still slower. The buffer memory that operates on a First-in, First-out mode is the most cost-effective way to interface two systems with different data rates.

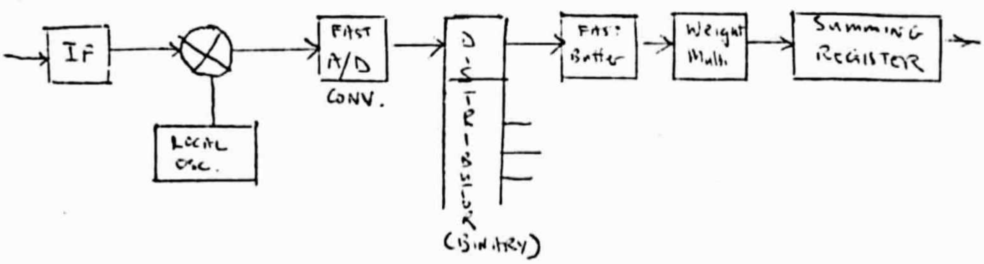


Figure 11. Fast A/D convertor before range gating of processor.

The range gate distributor can be designed according to the schematic in Figure 12. Here the sampled signal is clocked serially to the left. When the return from a zero range target is in the left-most storage location, the sampling clock is stopped, and the contents of the distributor are transferred in parallel to the output fast buffer stores, thereby sorting the radar return into range bins.

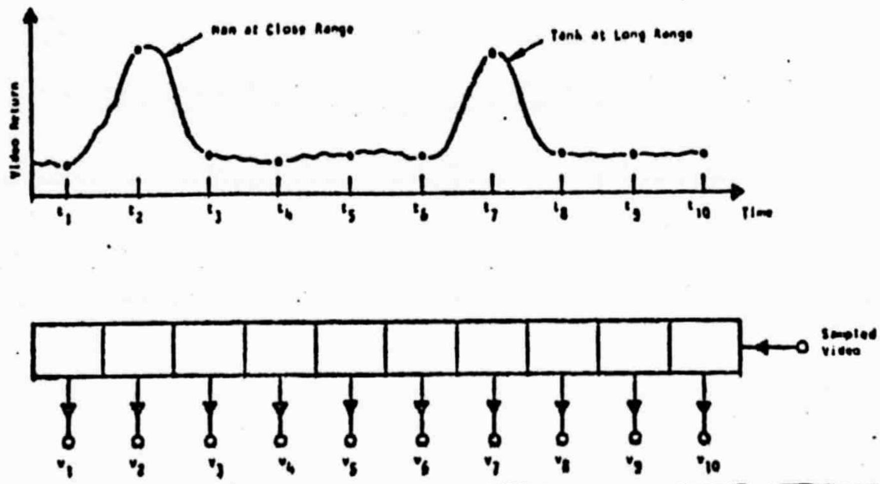


Figure 12. Schematic of the Operation of a RGF. The video return is sampled as shown, and the samples are clocked into the RGF. The man at close range results in a large signal at V_2 and the tank at longer range results in a large signal at V_7.

A common criterion for optimization is to find a weighting function which will provide a minimum main-lobe widening for a specified side-lobe level. Proper amplitude weighting of the received pulse train can improve the signal-to-clutter ratio in many situations. Some examples of weighting are the Taylor, Cosine, Hamming functions.

In summary, sampled-data systems depend on range gating first whereas the comb-filter techniques do the inverse and Doppler filter on the complete signal and then separate the range cells.

To illustrate the advantage of the unfocussed multi-look SAR processor from a hardware aspect, let us consider the following example which compares it with a focussed system using a fast Fourier transform (FFT) processor.

The SAR system has the following parameters:

Altitude of spacecraft	435 km
Ground velocity	7.2 km/sec

Wavelength	0.063 meters
Swath	138 km
Bandwidth	4.8 kHz
Aperture length	3 meters
Look angle	7^o
Number of looks	4

Let us assume a cross-track resolution of 150 meters. Then for a swath of 138 km, we obtain the required number of range bins - 920.

Assume that a word of information can be represented by 5 bits, then the distributor shift register must be able to handle 5 x 920 = 6400 bits.

For an unfocussed multi-look system, hardware and power consumption is listed as follows:

Quantity	Item	Power
1	A/D Convertor	8.33 watts
2	Digital shift register, 6 MHz, AM 2F 25	2 x 123 μw = 246 μw
920	Buffer memories CMOS MC14014	920 x 63 nw 57.96 μw
1840	Summing Registers (I and Q) CMOS MC14008AL	1840 x 1 μw = 1840 μw
	Sub - total	8.332 watts
	for 4 looks - total	33.328 watts

For FFT focussed processor, hardware and power consumption is listed as follows:

$BT = 1.268 \times 4.8 \times 10^3 = 6090$

G = number of sub-apertures, D/2 per pixel $= \frac{150}{1.5} = 100$

Number of pulses per sub-aperture $= \frac{BT}{G} = 60.9$

For FFT, no. of pulses must be an integer of 2

Nearest multiple of 2^m is for m = 6 where $N = 2^6 = 64$.

Memory size, including corner turning is $= \frac{5}{4} \times 64 \times 920 \times 5 = 368$ k bits.

Quantity	Item	Power
1	A/D Convertor	8.33 watts
	100 ns, Datel ADC-UH6B	
2	Digitai Shift Register	2 x 123 μw =
	6 MHz, AM 2825	246 μw
368	RAM Intersil CMOS IM6508A-1	$368 \times 10^3 \times 9.8 \times 10^{-6}$ = 3.6 watts
	(plus corner-turning memory)	
920 x 4	Adder/Subtractor register	3680 x 1 μw
	CMOS MC14008AL	3.68 mw
920 x 4	Multiplier	3680 x 100 nw =
	CMOS MC14554AL	0.360 mw
	Total	12.0 watts

It is interesting to note that the application of a CCD transversal filter for an image processor [8] could provide a power consumption of a similar order of magnitude: (7 watts for 10 km swath width with 50 m resolution from an altitude of 800 km) as the unfocussed processor.

5.0 CONCLUSION

Unfocussed signal processing produces images with considerably poorer along-track resolution than fully or partially focussed systems. However, the unfocussed signal processor is very much simplified enabling a reduction in hardware for the system so that it can be placed on-board the aircraft or spacecraft.

This advantage also enables the reduction of the required telemetry channel capacity and the ground-based processing facilities significantly.

It is necessary that multi-looks be applied to unfocussed signal processing to provide an image which can be useable. This is at the expense of additional hardware, however.

Since the azimuthal resolution r_x for a fully focussed system is related to the total Doppler bandwidth, it is possible to provide more coverage per orbit by employing unfocussed systems at the sacrifice of azimuthal resolution. This in addition to multi-looks may provide the necessary parameters for a mission which does not require high resolution.

APPENDIX A

SAR SPECIFICATIONS: PRF = 7.2 kHz. ; Δf_d = 26 Hz.

Therefore: N, number of pulses $= \frac{PRF}{\Delta f_d} = 277$

$$T_p = \frac{1}{PRF} = 140 \ \mu secs.$$

$$\Delta_t = \frac{T_p}{1000} = 0.14 \ \mu secs.$$

$$w_o = \frac{2\pi m}{T_p} = 1.7951957 \text{ MHz} \quad \text{for } m=40$$

$$A = 10^5$$

$$k = 0.995 \quad \text{and} \quad = 0.99$$

Width of comb: $\frac{2\pi}{NT_p}$ = 162 Hz.

Spacing between combs: $\frac{2\pi}{T_p}$ = 44880 Hz

Width of envelope: $\frac{2\pi}{\Delta t}$ = 4,488,000 Hz.

Program for K =1.

```
DATA PI/1.7951957/
WRITE(6,850);850 FORMAT (2X,'OMEGA',5X,'FW')
DO 100 I=44800,250000; W=4.0E-5*I
TEMP 1= 0.7E-2*SIN(19390*W)/SIN(70*W)
IF(W.EQ.0.0) TEMP 1=0.7E-2* 1.0
X1 = (W-PI)*0.07
X2 = (W+PI)*0.07
80 TEMP 2 = SIN(X1)/X1 + SIN(X2)/X2
IF(X1.EQ.0.0) TEMP 2 =1.0+SIN(X2)/X2
FW =TEMP1*TEM
          P2
WRITE (6,900) W,FW
900 FORMAT (1X,F8.6,3E12.3)
100 CONTINUE;STOP;END
```

Print-out for K= 1

OMEGA	EW
1.792000	-0.473E-01
1.792040	-0.634E-01
1.792080	-0.427E-01
1.792120	0.327E-02
1.792160	0.486E-01
1.792200	0.669E-01
1.792240	0.469E-01
1.792280	-0.766E-03
1.792320	-0.493E-01
1.792360	-0.706E-01
1.792400	-0.516E-01
1.792440	-0.203E-02
1.792480	0.501E-01
1.792520	0.747E-01
1.792560	0.567E-01
1.792600	0.519E-02
1.792640	-0.509E-01
1.792680	-0.792E-01
1.792720	-0.623E-01
1.792760	-0.872E-02
1.792800	0.518E-01
1.792840	0.842E-01
1.792880	0.687E-01
1.792920	0.127E-01
1.792960	-0.526E-01
1.793000	-0.897E-01
1.793040	-0.759E-01
1.793080	-0.173E-01
1.793120	0.536E-01
1.793160	0.960E-01
1.793200	0.841E-01
1.793240	0.227E-01
1.793280	-0.546E-01
1.793320	-0.103E 00
1.793360	-0.936E-01
1.793400	-0.289E-01
1.793440	0.557E-01
1.793480	0.112E 00
1.793520	0.105E 00
1.793560	0.363E-01
1.793600	-0.569E-01
1.793640	-0.122E 00
1.793680	-0.118E 00
1.793720	-0.453E-01
1.793760	0.584E-01
1.793800	0.134E 00

OMEGA	FW
1.793840	0.135E 00
1.793880	0.563E-01
1.793920	-0.621E-01
1.793960	-0.148E 00
1.794000	-0.155E 00
1.794040	-0.703E-01
1.794080	0.621E-01
1.794120	0.168E 00
1.794160	0.181E 00
1.794200	0.886E-01
1.794240	-0.648E-01
1.794280	-0.193E 00
1.794320	-0.217E 00
1.794360	-0.114E 00
1.794400	0.685E-01
1.794440	0.229E 00
1.794480	0.269E 00
1.794520	0.151E 00
1.794560	-0.739E-01
1.794600	-0.284E 00
1.794640	-0.350E 00
1.794680	-0.210E 00
1.794720	0.826E-01
1.794760	0.378E 00
1.794800	0.495E 00
1.794840	0.323E 00
1.794880	-0.100E 00
1.794920	-0.580E 00
1.794960	-0.835E 00
1.795000	-0.619E 00
1.795040	0.154E 00
1.795080	0.134E 01
1.795120	0.261E 01
1.795160	0.355E 01
1.795200	0.385E 01
1.795240	0.340E 01
1.795280	0.236E 01
1.795320	0.107E 01
1.795360	-0.510E-01
1.795400	-0.711E 00
1.795440	-0.815E 00
1.795480	-0.489E 00
1.795520	0.186E-02
1.795560	0.384E 00
1.795600	0.492E 00

OMEGA	FW
1.795640	0.365E 00
1.795680	0.146E-01
1.795720	-0.256E 00
1.795760	-0.352E 00
1.795800	-0.246E 00
1.795840	-0.233E-01
1.795880	0.197E 00
1.795920	0.274E 00
1.795960	0.202E 00
1.796000	0.283E-01
1.796040	-0.145E 00
1.796080	-0.223E 00
1.796120	-0.173E 00
1.796160	-0.316E-01
1.796200	0.115E 00
1.796240	0.188E 00
1.796280	0.151E 00
1.796320	0.340E-01
1.796360	-0.941E-01
1.796400	-0.162E 00
1.796440	-0.135E 00
1.796480	-0.357E-01
1.796520	0.778E-01
1.796560	0.141E 00
1.796600	0.123E 00
1.796640	0.370E-01
1.796680	-0.649E-01
1.796720	-0.125E 00
1.796760	-0.113E 00
1.796800	-0.380E-01
1.796840	0.544E-01
1.796880	0.112E 00
1.796920	0.104E 00
1.796960	0.356E-01
1.797000	-0.457E-01
1.797040	-0.101E 00
1.797080	-0.973E-01
1.797120	-0.393E-01
1.797160	0.383E-01
1.797200	0.914E-01
1.797240	0.912E-01
1.797280	0.398E-01
1.797320	-0.320E-01
1.797360	-0.832E-01
1.797400	-0.858E-01
1.797440	-0.401E-01

K = 0.990

```
DATA PI/1.7951957/
WRITE(6,850);850 FORMAT (2X,'OMEGA',5X,'F(W)')
DO 100 I=44830,45000;W=4.0E-5*I
X1=(W-PI)*0.07
X2=(W+PI)*0.07
IF(X1.GT.0.0001) GO TO 80
TEMP1=0.7E-2*(1.0+SIN(X2)/X2); GO TO 90
80  TEMP1=0.7E-2*(SIN(X1)/X1+SIN(X2)/X2)
90 F1=70.0*W;F2=19390.0*W
F3=0.938205*COS(F2)
F4=1.061795*SIN(F2)
TEMP2=SQRT(F3**2+F4**2)
F5=0.01*COS(F1)
F6=1.99*SIN(F1)
TEMP4=SQRT(F6**2+F5**2)
FW=TEMP1*TEMP2/TEMP4
WRITE(6,900) W,FW
900 FORMAT (1X,F8.6,3E12.3)
100 CONTINUE;STOP;END
```

K = 0.995

```
DATA PI/1.7951957/
WRITE(6,850);850 FORMAT (2X,'OMEGA',5X,'F(W)')
DO 100 I=44830,45000;W=4.0E-5*I
X1=(W-PI)*0.07
X2=(W+PI)*0.07
IF(X1.GT.0.0001) GO TO 80
TEMP1=0.7E-2*(1.0+SIN(X2)/X2); GO TO 90
80  TEMP1=0.7E-2*(SIN(X1)/X1+SIN(X2)/X2)
90 F1=70.0*W;F2=19390.0*W
F3=0.7505*COS(F2)
F4=1.2495*SIN(F2)
TEMP2=SQRT(F3**2+F4**2)
F5=0.005*COS(F1)
F6=1.995*SIN(F1)
TEMP4=SQRT(F6**2+F5**2)
FW=TEMP1*TEMP2/TEMP4
WRITE(6,900) W,FW
900 FORMAT (1X,F8.6,3E12.3)
100 CONTINUE;STOP;END
```

Print-out for K= 0.99

OMEGA	F(W)
1.793200	0.516E-01
1.793240	0.494E-01
1.793280	0.509E-01
1.793320	0.563E-01
1.793360	0.563E-01
1.793400	0.528E-01
1.793440	0.553E-01
1.793480	0.614E-01
1.793520	0.619E-01
1.793560	0.581E-01
1.793600	0.605E-01
1.793640	0.675E-01
1.793680	0.686E-01
1.793720	0.646E-01
1.793760	0.670E-01
1.793800	0.750E-01
1.793840	0.769E-01
1.793880	0.727E-01
1.793920	0.750E-01
1.793960	0.844E-01
1.794000	0.874E-01
1.794040	0.830E-01
1.794080	0.854E-01
1.794120	0.966E-01
1.794160	0.101E 00
1.794200	0.966E-01
1.794240	0.993E-01
1.794280	0.113E 00
1.794320	0.120E 00
1.794360	0.115E 00
1.794400	0.119E 00
1.794440	0.136E 00
1.794480	0.147E 00
1.794520	0.143E 00
1.794560	0.148E 00
1.794600	0.171E 00
1.794640	0.188E 00
1.794680	0.188E 00
1.794720	0.196E 00
1.794760	0.232E 00
1.794800	0.263E 00
1.794840	0.270E 00
1.794880	0.291E 00
1.794920	0.358E 00
1.794960	0.430E 00

OMEGA	F(W)
1.795000	0.473E 00
1.795040	0.548E 00
1.795080	0.745E 00
1.795120	0.102E 01
1.795160	0.123E 01
1.795200	0.131E 01
1.795240	0.120E 01
1.795280	0.959E 00
1.795320	0.694E 00
1.795360	0.524E 00
1.795400	0.465E 00
1.795440	0.417E 00
1.795480	0.341E 00
1.795520	0.283E 00
1.795560	0.270E 00
1.795600	0.259E 00
1.795640	0.223E 00
1.795680	0.192E 00
1.795720	0.188E 00
1.795760	0.187E 00
1.795800	0.166E 00
1.795840	0.145E 00
1.795880	0.144E 00
1.795920	0.146E 00
1.795960	0.132E 00
1.796000	0.116E 00
1.796040	0.116E 00
1.796080	0.120E 00
1.796120	0.110E 00
1.796160	0.974E-01
1.796200	0.976E-01
1.796240	0.101E 00
1.796280	0.943E-01
1.796320	0.838E-01
1.796360	0.839E-01
1.796400	0.877E-01
1.796440	0.826E-01
1.796480	0.736E-01
1.796520	0.734E-01
1.796560	0.773E-01
1.796600	0.735E-01
1.796640	0.656E-01
1.796680	0.653E-01
1.796720	0.691E-01
1.796760	0.663E-01
1.796800	0.593E-01

Print-out for K= 0.995

OMEGA	F(W)
1.793200	0.565E-01
1.793240	0.400E-01
1.793280	0.478E-01
1.793320	0.654E-01
1.793360	0.622E-01
1.793400	0.442E-01
1.793440	0.510E-01
1.793480	0.709E-01
1.793520	0.690E-01
1.793560	0.493E-01
1.793600	0.550E-01
1.793640	0.776E-01
1.793680	0.771E-01
1.793720	0.556E-01
1.793760	0.598E-01
1.793800	0.857E-01
1.793840	0.871E-01
1.793880	0.635E-01
1.793920	0.660E-01
1.793960	0.959E-01
1.794000	0.997E-01
1.794040	0.737E-01
1.794080	0.740E-01
1.794120	0.109E 00
1.794160	0.116E 00
1.794200	0.873E-01
1.794240	0.848E-01
1.794280	0.126E 00
1.794320	0.138E 00
1.794360	0.106E 00
1.794400	0.100E 00
1.794440	0.151E 00
1.794480	0.170E 00
1.794520	0.134E 00
1.794560	0.123E 00
1.794600	0.139E 00
1.794640	0.220E 00
1.794680	0.179E 00
1.794720	0.162E 00
1.794760	0.255E 00
1.794800	0.310E 00
1.794840	0.264E 00
1.794880	0.241E 00
1.794920	0.394E 00
1.794960	0.519E 00

OMEGA	F(W)
1.795000	0.484E 00
1.795040	0.474E 00
1.795080	0.891E 00
1.795120	0.148E 01
1.795160	0.194E 01
1.795200	0.209E 01
1.795240	0.187E 01
1.795280	0.136E 01
1.795320	0.776E 00
1.795360	0.446E 00
1.795400	0.503E 00
1.795440	0.505E 00
1.795480	0.357E 00
1.795520	0.229E 00
1.795560	0.280E 00
1.795600	0.307E 00
1.795640	0.234E 00
1.795680	0.154E 00
1.795720	0.191E 00
1.795760	0.220E 00
1.795800	0.175E 00
1.795840	0.117E 00
1.795880	0.144E 00
1.795920	0.171E 00
1.795960	0.141E 00
1.796000	0.941E-01
1.796040	0.114E 00
1.796080	0.140E 00
1.796120	0.118E 00
1.796160	0.792E-01
1.796200	0.943E-01
1.796240	0.118E 00
1.796280	0.103E 00
1.796320	0.688E-01
1.796360	0.797E-01
1.796400	0.102E 00
1.796440	0.907E-01
1.796480	0.610E-01
1.796520	0.687E-01
1.796560	0.896E-01
1.796600	0.814E-01
1.796640	0.551E-01
1.796680	0.600E-01
1.796720	0.797E-01
1.796760	0.741E-01
1.796800	0.505E-01

REFERENCES

1. Harger, R. O., "Synthetic Aperture Radar Systems, Theory and Design," 1970.
2. Moore, R. K. et al., "Microwave Remote Sensors," Chapter 9 in Manual of Remote Sensing, Vol. 1, Robert G. Reeves, editor, American Society of Photogrammetry, Falls Church, Virginia, 1975.
3. Burenin, N. I., "Radars With Synthesized Antenna," JPRS-59391, Arlington, Virginia, June 1973.
4. Space Shuttle Synthetic Aperture Radar - Final Report to Goodyear, Jet Propulsion Laboratory, California Institute of Technology, August, 1975.
5. Gerchberg, R., "Synthetic Aperture Radar and Digital Processing," (Ph. D. Thesis), University of Kansas Center for Research, Inc., Remote Sensing Laboratory, RSL Technical Report 177-10, September 1970.
6. Di Franco and Rubin, "Radar Detection," 1968.
7. Kirk, "A Discussion on Digital Processing for Synthetic Aperture Radar," IEEE Transactions on Aerospace and Electronic Systems, May 1975.
8. Bailey, W.,W. Eversole, J. Holmes, W. Hoover, J. McGehee, R. Ridings, W. Arens, "CCD Applications to Synthetic Aperture Radar," .