DIGITAL PROCESSING OF SEASAT SAR DATA

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ABSTRACT

The Synthetic Aperture Radar (SAR), on board the Seasat-A satellite, provides an all-weather imaging capability which should prove useful in a number of remote sensing applications. Unlike optical (Landsat) data, the SAR data requires extensive two-dimensional, space variant signal processing before an image is formed.

This paper describes the signal processing operations in a digital processor which has been built to produce images from the Seasat-A SAR data. It describes the operations of real-to-complex data conversion, range compression via fast convolution, matrix transformation of 40 MB disk arrays, range cell migration correction, look extraction via bandpass filtering, azimuth compression via fast convolution, interpolation and detection.

1. INTRODUCTION

1.1 <u>What is Synthetic Aperture Radar</u>
Synthetic Aperture Radar or SAR, is an active microwave imaging system for all-weather terrain mapping. SAR differs from "normal aperture" radar in that the beam aperture in azimuth is synthetically reduced by processing the Doppler frequency information in the return radar signal. In this way, a sharply focussed beam is synthesized from a normal length antenna, and high resolution is achieved. A growing body of literature has developed since the 1960's in the SAR area, summarized in a reprint volume[1] and a recent SAR conference[2].

1.2 <u>Spaceborne SAR</u> Until recently, SAR systems have operated form airborne platforms, using L and X band microwave energy and obtaining resolutions of the order of a few metres to 50 m at ranges from 5 to 50 km. The year 1978 saw the launch of the first spaceborne SAR system, as one of the sensors on board NASA's Seasat-A Ocean Studies satellite. The beam geometry of the spaceborne SAR is such that, compared with airborne SAR's, the change in range that a ground radar reflector (point target) experiences while it traverses the beam is large in relation to the range resolution. In Seasat, the average range is 850 km, the azimuth beam width on the ground is 17 km, and the change of a target's range varies from 90 m to 1400 m while the range resolution is only 10 m. This leads to the spaceborne-unique problem of Range Cell Migration, discussed below.

Unlike aerial photography or a scanning system such as Landsat, the received SAR data requires extensive two-dimensional, space-variant signal processing before an image is produced. This paper describes the signal processing operations in a software digital processor which has been built to produce images from recorded Seasat-A SAR signal data.

2. THE NATURE OF THE RECEIVED SAR SIGNAL

The radar signal is transmitted from a 10 metre linear antenna which gives a ground footprint approximately 100 km long in the cross-track direction and 17 km long in the along-track direction (the -3 dB contour is shown in Figure 1). The centre of the beam is perpendicular to the satellite heading and is inclined 20° to the vertical. The beam tranverses the ground at a speed of about 7000 m/s.

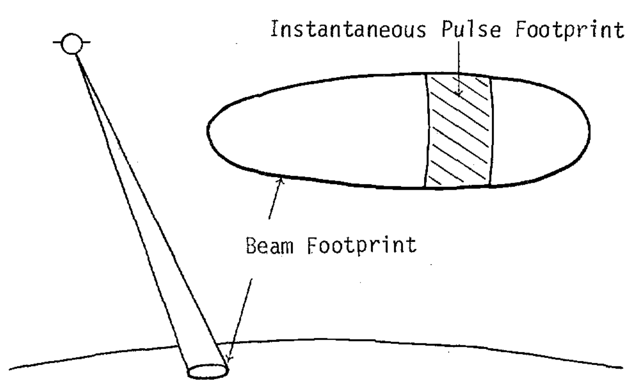

FIGURE 1 <u>Beam Footprint on Earth's Surface</u>

The radar signal is a swept linear FM pulse of duration T = 33.9 μs, FM rate of 0.562 MHz/μs and a bandwidth of 19 MHz, shown in Figure 2. The pulses are repeated at a rate of 1647 Hz, called the pulse repetition frequency or PRF. Between pulses, the transmitter is turned off and the antenna and RF electronics become a reception system.

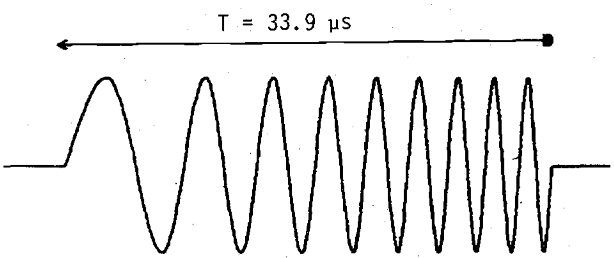

FIGURE 2 Transmitted Radar Pulse Waveform

The transmitted radar energy is contained between two expanding concentric spheres, representing the leading and trailing edge of the 33.9 μs pulse. At any instant in time, the ground terrain contained between the spheres contributes to the reflected radar energy which is received at the antenna (to allow for the fact that the received energy must traverse the distance from the satellite to the ground and back, the expanding spheres have a radius difference of ½ cT metres and expand at a speed of ½ c m/s, where c is the speed of light.) This ground area is called the instantaneous pulse footprint and is illustrated in the enlarged portion of Figure 1.

The instantaneous pulse footprint traverses the 100 km beam footprint in about 300 μs, and during this time the received radar return signal is digitized and recorded on high density digital tape (HDDT). Ultimately, in the processing computer, this 300 μs duration signal forms one range line in signal memory, with succeeding radar pulse returns filling up successive range lines in signal memory. After 4096 range lines have been received, signal memory contains enough data to begin forming an image of the ground terrain.

We have seen that a single point in signal memory contains contributions from a large collection of ground reflections represented by the area of the instantaneous pulse footprint in Figure 1. By the same principle, the received signal from a single reflector or point target on the ground will be spread through a large area of signal memory. A diagram of signal memory is shown in Figure 3, illustrating the spread of energy from a single point target. The coordinates of signal memory are slant range and azimuth or alternately radar signal return time (range) and pulse transmission time (azimuth). The length of the range axis is 300 μs and the length of the azimuth axis is 4096/PRF = 2.5 seconds. The large disparity in durations of the two axes leads to the terms "fast time" for the range axis and "slow time" for the azimuth axis, and allows the effective decoupling of the coordinates in signal processing operations.[10]

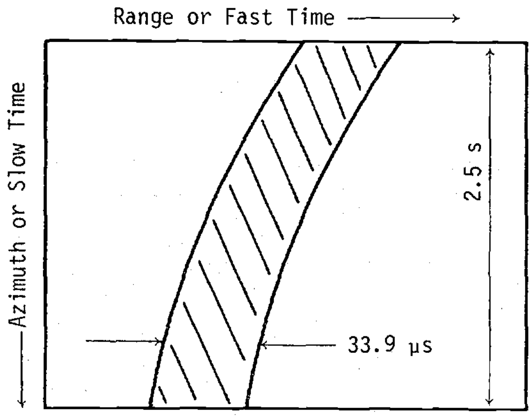

FIGURE 3 Point Target in Signal Memory

Notice in Figure 3 how the range of the point target response varies with azimuth. This is because the instantaneous slant range from the satellite radar antenna to the point target on the ground varies appreciably during 2.5 s compared to the scaling of the range axis. Typical differences in range over 2.5 s are 90 to 1400 m, compared to the range cell separation of 6.6 m. Thus the point target undergoes a migration across range cells as a function of azimuth, a phenonemon known as Range Cell Migration (RCM).

Imagining for the moment that the transmitted radar signal were a single frequency CW signal, the received signal would exhibit a Doppler frequency shift proportional to the slant range rate. It is this Doppler frequency shift upon which the SAR principle is based. A geometrical analysis of the satellite and point target motions shows that the slant range rate varies approximately linearly with time (i.e., the target region border in Figure 3 is approximately a parabola). This means that the received radar signal Doppler shift varies linearly with time, or has a linear FM modulation.

As the transmitted radar signal is pulsed, and itself has a swept linear FM waveform, the Doppler shift is manifested by a changing phase angle of the received pulse from the same point target, as a function of pulse number or slow time. The FM rate of the azimuth Doppler signal is about 500 Hz/s which is a factor of 10^9 smaller than the FM rate of the transmitted pulse (i.e., the range signal). This large disparity of the range and azimuth FM rates is further evidence of the decoupling of the range and azimuth signals.[10]

Thus the point target response in signal memory (the 2-dimensional impulse response of the point target) consists of a linear FM waveform in both the range and azimuth directions. The response in one dimension is decoupled from the other because of the large difference in time scales. The responses in each dimension are not orthogonal, but can be made so with RCM correction.

3. SIGNAL PROCESSING OVERVIEW

The function of signal processing is to focus or compress the energy of each point target, which is spread through signal memory in the manner described above, into single points on the image product. A software SAR digital processor has been written for an Interdata 8/32 computer with 512 KB core store, floating point double precision hardware and two 67 MB disks. A block diagram showing the sequence of signal processing operations is given in Figure 4. The sequence is divided into four data passes, because certain operations like corner turning and range cell migration correction must have access to all the data at once. Between passes, the data is stored on 42 MB disk files. The operations are described briefly below, with more detail on the items of interest to signal processing engineers given in later sections.

3.1 Pass 1 Range Compression The Range Compression pass takes the data stored in signal memory (disk or tape), unpacks the 5-bit data elements, converts to floating point words and then to complex numbers by means of an FFT. After generating the matched filter coefficients, the range compression is done by a fast convolution with the range matched filter.

3.2 Pass 2 Corner Turning and Azimuth Transform Corner Turning takes the data from disk Store 1, which is written in range line order, and rearranges it so that it can be read in azimuth line order. Corner turning uses a modified version of the algorithm of Eklund[6]. It is modified

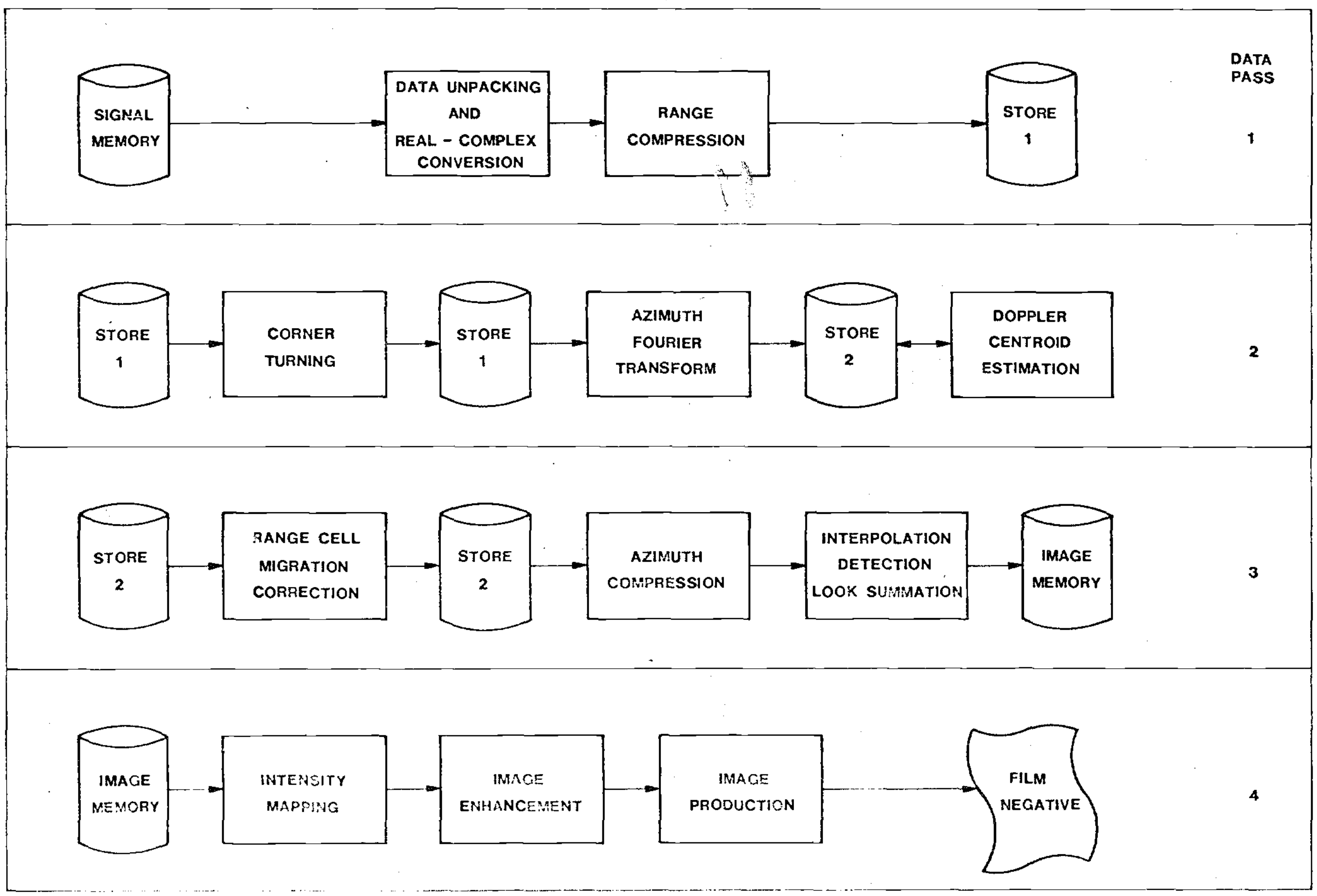

FIGURE 4 BLOCK DIAGRAM OF SAR SIGNAL PROCESSING OPERATIONS

to use large in-core buffers to further minimize the number of disk transfers, and to handle non-square matrices whose dimensions are not a power of two.

The data is then Fourier transformed with a 4096 point FFT. This is really the first step of the Azimuth Compression fast convolution, but is done at this stage so that Range Cell Migration correction can be done in the frequency domain.

3.3 Pass 2 Doppler Centroid Estimation The data in Store 2 represents the distribution of azimuth doppler energy as a function of range. This energy has a maximum in the azimuth direction depending on the orientation of the beam. The Doppler Centroid Estimator estimates the azimuth frequency at which the maximum occurs as a function of range, and then expresses it in terms of how many seconds it takes for a point target to pass from its closest point of approach to the satellite to the centre of the beam.

3.4 Pass 3 Range Cell Migration Correction At this point, the data in Store 2 is similar to that in Signal Memory, Figure 3, with two exceptions. Firstly, Pass 1 has taken the point target energy, which was originally spread out in range by 33.9 μs, and compressed it into essentially a single cell in range. Secondly, the azimuth Fourier Transform of Pass 2 has done an inversion and circular shift of the azimuth axis (this is an approximate property of high time-bandwidth product linear FM signals[10]). The resulting point target trajectory is shown as the solid line in Figure 5.

The function of Azimuth Compression is to compress the energy in this trajectory to a single cell in the azimuth direction. But as the lines are stored in azimuth line order, the Azimuth Compression algorithm can only achieve its compression if the point target trajectory lies parallel to an azimuth line. The Range Cell Migration Correction algorithm rearranges the data in Store 2

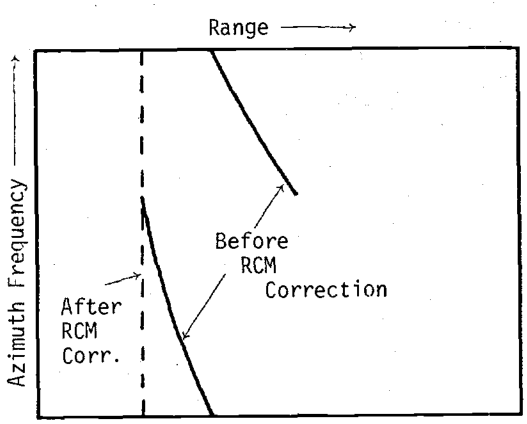

FIGURE 5 Point Target in Store 2

to straighten the solid trajectory in Figure 5 into the dotted trajectory.

In the example above, the solid trajectory represented the energy of a single point target, but it also represents the trajectory of a family of point targets, each with the same range but different azimuth (the azimuth spectra of each member of the family differ only by a linear phase rotation term). Thus the same RCM Correction operation corrects not only for the single point target, but for each member of the family as well. Thus a block processing efficiency is achieved by doing RCM Correction in the frequency domain rather than the time domain.

3.5 Pass 3 Azimuth Compression After RCM Correction, the energy from the point target lies in a single range cell in Store 2. This energy is compressed in the azimuth direction to a single point by convolving the data with an azimuth matched filter. The Azimuth Compression module generates the matched filter coefficients and then applies the matched filter with a fast convolution operation. The data is now in the form of an image as energy from a single point on the ground is stored in a single point in the processor memory.

3.6 Pass 3 Interpolation and Detection As the SAR signal and matched filter are complex, the image data resulting from azimuth compression is in the complex form. The detection operation converts the complex data to power so that it can be displayed as intensity by an imaging device. As the detection operation can increase the bandwidth of the signal, the image points are interpolated in two dimensions with a cubic convolution operation prior to detection. The interpolator increases the data rate by a factor of about 1.4 in each dimension and serves the purpose of changing the image to standard coordinates (12.5 m pixel spacing).

3.7 Pass 3 Look Summation Instead of compressing the entire azimuth signal trajectory (Figure 5) in one operation, the trajectory may be divided up into several parts (four in the Seasat case), and each part is compressed into a single point in a separate image submemory. The resulting separate images are called "looks" because of the analogy of dividing the radar beam into (four) sections in azimuth, each subbeam representing a different look at the target. The Look Summation operation adds the intensities of each subimage to form a single image, achieving the effect of reducing the speckle inherent in coherent wavefront imaging systems. The resulting summed image is stored in image memory, and is written to magnetic tape as a standard SAR processor output product.

3.8 Pass 4 Image Production As the processed radar image can exhibit an intensity dynamic range of up to 50 dB, while imaging devices can generally only display 20 dB in a linear mapping, an intensity mapping is done to display that part of the image intensity range of interest. At this point, image enhancement operations can be included to enhance image features and correct for radiometric variations. The image is then produced on a CRT monitor and recorded on film.

4. RANGE COMPRESSION

4.1 Received Radar Signal In its simplest form, the received demodulated radar signal from a single point target can be expressed as:

$$f(t) = \mathrm{Re}[\ \mathrm{rect}(\tfrac{t}{T})\ \exp(2\pi j(\phi_a(t)+f_0 t + \tfrac{1}{2} K_r t^2))] \quad (4.1)$$

where T = pulse duration (33.9 μs)

K_r = range FM RATE (.562 MHz/μs)

f_0 = range offset frequency (11.38 MHz)

$\phi_a(t)$= return signal phase angle in cycles

For convenience, the time origin t=0 is placed in the middle of the received pulse. The return signal phase angle is introduced by the number of cycles of the radar wavelength which have occurred from the time of transmission of the radar pulse to the time of reception of the received pulse. Thus:

$$\phi_a(t) = \frac{2\ r(t)\ f_c}{c} = \frac{2r(t)}{\lambda}\ \text{cycles} \quad (4.2)$$

where f_c = L band radar carrier frequency (1274.83 MHz)

λ = L band radar wavelength (0.23515 m)

c = speed of light ($2.9979\ 10^8$ m/s)

$r(t)$= instantaneous slant range from radar antenna to point target (typically $850{*}10^3$ m)

Now, it can be shown that with the Seasat parameters, and with a maximum satellite roll, pitch and yaw of one degree, the maximum change in $\phi_a(t)$ during the reception of one radar pulse (33.9 μs) is only 0.10 cycle. Thus $\phi_a(t)$ can be considered constant in equation (4.1), and then $\phi_a(t)$ only varies with the transmitted pulse number. In fact, $\phi_a(t)$ is the azimuth phase modulation on the received signal, which is why the subscript "a" is used. The fact that $\phi_a(t)$ is constant in the range direction means that the range and azimuth signal processing operations can be decoupled.

4.2 Real → Complex Conversion If B_r and B_a Hz are the bandwidths of the range and azimuth signals respectively, 2-dimensional sampling theory states that the 2-dimensional sampling rate must be at least $2B_rB_a$ real samples per second. The sampling rates in Seasat conform to this rule as:

B_r = 19.0 MHz
B_a = 1300 Hz (6 dB point)
Range sampling rate 45.52 MHz
Azimuth sampling rate 1646.8 Hz

However, as the range and azimuth signal processing functions are to be separated, the one-dimensional sampling theorem must also hold during the respective range and azimuth signal processing operations. That is, the real sampling rate must be at least twice the bandwidth, or the complex sampling rate must be at least as large as the bandwidth. It is noted that for real signals the range sampling rate is adequate, but that the azimuth rate is not.

The solution to this problem is to convert the data from real to complex before azimuth processing so that the sampling theorem is satisfied in azimuth. As range compression is done with FFT's which operate most efficiently with complex data, it is most efficient to make the conversion to complex before range compression. With the conversion, the range sampling rate can be halved while still conforming to the sampling theorem in range.

The conversion to complex and sample rate reduction is achieved by taking the FFT of the real range signal, and then taking the inverse transform of the first half of the spectral samples. If the real signal has no energy at DC or at half the real sampling frequency, it can be shown that this process results in a complex time series of half the sampling rate with the following properties:

a) the real parts of the complex signal equal the original signal at each time point (i.e., at every second sample of the original sequence),

b) the discrete spectrum of the complex signal equals the discrete spectrum of the real input signal at all frequencies between 0 and the complex sampling rate.

Note that the radar range signal has only noise components at 0 and 22.76 MHz, and so it is convenient to set these terms to zero during the complex conversion. Thus the real to complex conversion is equivalent to removing the Re [·] operand in equation (4.1).

Noting that an FFT and an IFFT are the first and last steps of a fast convolution operation, the complex conversion and sample rate reduction are actually done as part of the fast convolution -- that is, no extra computation is needed explicitly for the conversion.

4.3 Generation of Matched Filter Coefficients The design of coded pulse radars and associated pulse compression techniques are discussed in References 3 and 4. The standard matched filter for the signal of equation (4.1) is:

$$h(t) = \mathrm{Re}[\ \mathrm{rect}(\tfrac{t}{T})\ \exp(2\pi j(f_0 t - \tfrac{1}{2}K_r t^2))] \quad (4.3)$$

which in fact is simply the signal f(t) reversed in time. This means that the convolution of f(t) with h(t) is equivalent to cross-correlating the received signal with a replica of the transmitted signal.

4.4 Fast Convolution The FFT is taken of the real signal (4.1) and the matched filter (4.3), using the Even/Odd Separate and Half Cell Shift method of taking the FFT of a real signal with a complex FFT. Only the first half of the spectrum is computed as that is all that is needed for further processing because of the conversion to complex signals at this stage (see Section 4.2). The real matched filter length is 1543 samples and a 4096 point real signal sequence is used as input to the FFT, which is the minimum length needed to give acceptable fast convolution efficiency[5].

The 2048 point complex signal and matched filter spectra are multiplied together and then shifted left by 1024 points (circular shift) to eliminate the offset carrier (f_0t) component in equations 4.1 and 4.3. A 2048 point complex IFFT is then taken to achieve the desired range compression.

When applied to the point target (4.1), the matched filter output is approximately given by:

$$s(t) = e^{2\pi j\phi_a} K_r T^2 \frac{\sin(\pi K_r Tt)}{\pi K_r Tt} \qquad (4.4)$$

The approximation is good for high time bandwidth products.

Several points are interesting about the expression (4.4) for the compressed pulse output. Firstly, apart from the exponential term, the signal is real. This means that the azimuth phase angle ϕ_a is encoded in the range compressed signal in a simple and easily extractable manner. It is simply a constant phase rotation applied to the compresses pulse envelope.

Secondly, the envelope of the compressed pulse is given by $\sin(\pi K_r Tt)/(\pi K_r Tt)$, which is the narrow pulse shown in Figure 6. The pulse has first nulls at $[t] = 1/(K_r T)$ s and a 3 dB width of $0.886/(K_r T)$ s. Thus the energy of the received signal, which covered a time span of T s, has been compressed in time by approximately the ratio of $K_r T^2$, or the time-bandwidth product.

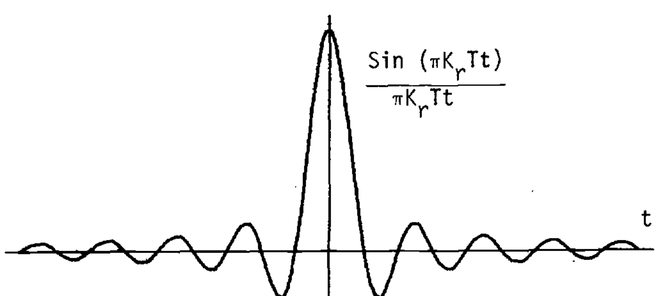

FIGURE 6 Envelope of Unweighted Compressed Pulse

4.5 Time Response Smoothing The compressed pulse response in Figure 6 has high gain and narrow main lobe width, but suffers from a rather high side lobe level. The standard solution to this problem is the application of weighting. The method used is the normal spectral analysis application[7], but with the time and frequency domains reversed. In spectral analysis, weighting is applied in the time domain to achieve smoothing (i.e., side lobe reduction) in the frequency domain. In the radar fast convolution, weighting is applied in the frequency domain to achieve smoothing of the time response.

The application is different from the classical radar approach of applying weighting in the time domain before the compression operation[4]. However, as there is a close equivalence between the time and frequency domains for high time-bandwidth product linear FM signals, the results are similar.

All one's personal ingenuity can be applied to the art of choosing smoothing weights, but many standard windows provide adequate control of side lobes in the current application.

Low-order Taylor weights are often used in radar, and are quite satisfactory here. A modified second order weighting was used, and the 2-dimensional integrated side lobe level was reduced to about -14 dB after azimuth compression.

5. AZIMUTH COMPRESSION

The Azimuth Compression signal processing operations are similar to those of Range Compression, with three exceptions. Firstly, real to complex conversion is not necessary because the signals entering Azimuth Compression are already complex. Secondly, the operation of Look Extraction is added. Thirdly, the FM rate and frequency offset of the azimuth matched filter varies with range.[12]

5.1 Look Extraction As discussed in Section 3.7, Look Extraction is the process of dividing the azimuth signal energy into four essentially independent parts, so that when the compressed answer from each part is added after detection, the coherent wavefront radar speckle effect is reduced. This is done in the present processor by frequency domain band pass filtering in the middle of the fast convolution operation. In fact, the time response smoothing operation can be considered as a digital filter applied in the frequency domain, and can be combined with the band-pass look extraction filter into a single filter.

The azimuth fast convolution begins with a 4096 point FFT of a 1300 Hz bandwidth signal (Section 3.2). As the look extraction filter output has a bandwidth of about 300 Hz, the inverse transform length at the end of the fast convolution is reduced to 1024 points to divide the output sample rate by four. Thus the combined look extraction and smoothing filter must have only 1024 nonzero frequency domain coefficients out of the total of 4096.

A digital filter design method which can explicitly equate a subset of the frequency domain coefficients to zero is the linear programming method[8]. As that program was not available, the Remez exchange algorithm[9] was used to design a filter with frequency domain coefficients nearly zero in the desired region, and then setting them exactly to zero. This technique worked well as the stop-band intersample ripple specification was only -35 dB.

The 1024 point look extraction and smoothing filter can be multiplied by 1024 contiguous points of the 4096 point matched filter to obtain a combined filter in the frequency domain. The four looks only differ in the selection of which 1024 matched filter (and signal) points to use in the convolution. Having designed the combined filter, the look extraction, smoothing and matched filters are applied simultaneously with one array multiply with the frequency domain signal data. An inverse FFT then completes the Azimuth Compression operation.

6. EXAMPLE OF A SAR IMAGE

At the time of writing (November 28, 1978), only a single look image is available, because the Look Summation algorithm (Section 3.7) is still undergoing system integration tests in the MDA Seasat Software SAR Processor. A sample image is shown in the final figure. Further examples, including four look imagery, will be shown at the conference.

The image was created on an Optronics P1500 Film Recorder from 8-bit data. The 8-bit data was obtained from the floating point output of Pass 3 using a dynamic range compression algorithm to display about 40 dB of image intensity in the 21 dB 8-bit intensity store.

The resolution of the image can be deduced by measuring the -3 dB width of discrete point targets in the image. This was found to be approximately 23 m in azimuth and 25 m in range which meets the Seasat specification of 25 m.

7. DIGITAL VS. OPTICAL SAR PROCESSING

7.1 Optical SAR Processing The classical method of SAR processing uses coherent laser beam illumination and the Fourier Transform properties of lenses to compress the SAR signal data simultaneously in 2-dimensions[10,11]. Input and output information formats are analogue film strips, which are motor driven through the optical system at synchronized speeds.

7.2 Advantages of Optical Processing The prime and very significant advantage of optical SAR processing is speed, because the throughput is only limited by the rate that film negatives can be exposed and processed. When the time for recording signal film, for adjusting the lens positions and for developing and printing the image file is included, optical processing rates for Seasat run at approximately 100 times real time. This is compared with the MDA Software Processor which runs at about 40,000 times real time (a 40 km square full resolution image requires about 10^{10} real multiplies and adds, and corresponds to the data collected in 2.5 seconds). While this time may be reduced by a factor of 10 with the addition of higher speed hardware (array processor, larger disks, high density tapes) and some software optimization (microcoding), significant advances in the speed of digital processing will only be made with the design of special purpose hardware processors.

7.3 Advantages of Digital Processing As experience is gained with the digital processing of satellite-borne SAR signals, several advantages are becoming apparent. Most of the advantages pertain to the quality of the output image.

1. The optical signal film recorder is avoided. Unless very carefully designed, the film recorder may not record the full signal bandwidth, and may introduce antifacts and radiometric distortion.
2. The accuracy of the matched filter, including the addition of nonlinear FM terms, can be closely controlled. In particular, automatic FM rate fine tuning can be incorporated into the digital algorithm.
3. The accuracy of RCM correction can be controlled. It is currently set to +/- ½ range cell, but can be improved if necessary. This point, combined with the one above, tends to achieve better image focussing over the whole image than the optical processing.
4. Digital schemes can be contrived to eliminate certain unwanted signal components as the pilot tone, DC offset, and demodulator artifacts.
5. Floating point processing preserves the full dynamic range of the image, which can be as high as 50 dB.
6. The image can be stored on CCT which is convenient for further computer processing such as scene classification and image enhancement. The CCT stores the full image dynamic range, and has no geometric or radiometric distortion.
7. Dynamic range compression techniques can be used to display a wider range of image detail on film products.

8. CONCLUSIONS

An application has been presented which makes use of many of the modern digital signal processing techniques. The capability of producing a high-quality image has been demonstrated, but at a severe throughput penalty. A clear challenge is presented to develop more efficient signal processing algorithms and hardware devices so that digital SAR imagery can be produced on a large scale.

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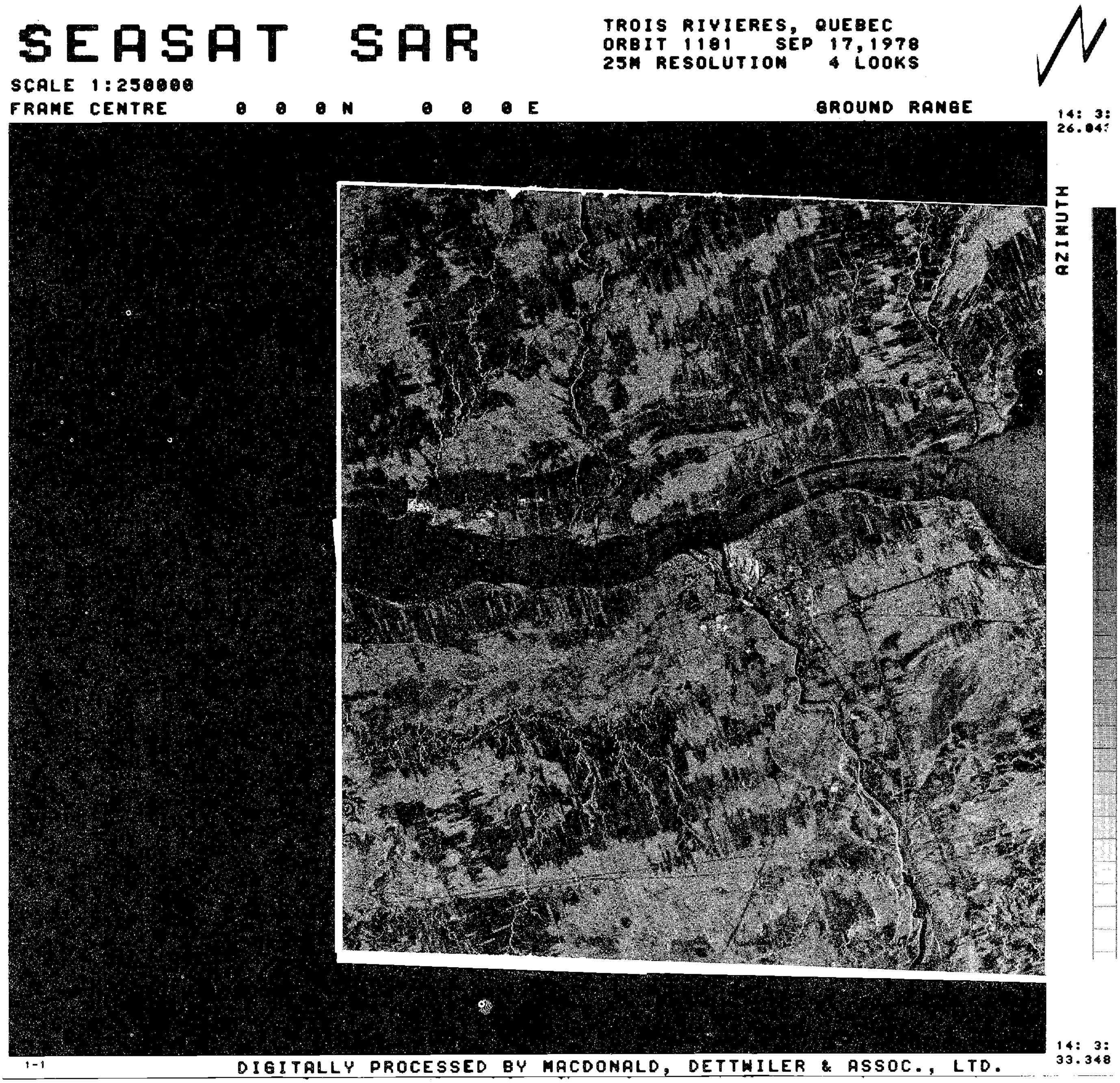

FIGURE 7 Example of Digitally Processed SEASAT SAR Image