DATA REDUCTION USING REAL-TIME ON-BOARD SATELLITE SAR PROCESSING

Laurens Bierens, Rob van Heijster, Hans van Bezouwen

TNO Physics and Electronics Laboratory
P.O.Box 96864, 2509 JG The Hague, The Netherlands
phone: -31-70-3264221, fax: -31-70-3280961

1 Introduction

In satellite Synthetic Aperture Radar (SAR) huge amounts of data are involved, typically in the order of 100 Mbytes for imaging a 100 × 100 km surface. This figure will increase more and more in future SAR systems. The communication system and the intermediate storage must handle this increasing amount of data as well. Furthermore, ground stations must process, broadcast and archive the SAR data and therefore show the tendency to become more and more expensive and time-consuming due to this data increment.

An attractive solution to reduce the communication requirements is to perform SAR processing on-board the satellite. It is the most rigorous kind of raw SAR data reduction. For example, an E-ERS-1 SAR image contains 63 Mbytes whereas a batch of raw E-ERS-1 SAR data contains 300 Mbytes. Moreover, standard image compression techniques can be used to achieve an even higher data reduction ratio.

The advantages of data reduction by using on-board SAR processing and image compression can be summarized as follows:

Intermediate data storage: As a result of the compression rates achieved, more data can be stored on-board and less ground stations will be required. Moreover, the SAR can collect data from parts of the earths surface which are not within the reach of a ground station at that moment.

Direct broadcast facility: Since the satellite transmits the end-product down to earth, the end-user has directly available the SAR image. This means that a processing and broadcasting facility at the ground station is not required. The end-user also receives the most up-to-date information.

Efficient archiving: The image received by a ground station can be monitored immediately and, as a consequence, can be archived immediately.

The success of an on-board processor mainly depends on two criteria:

- the image quality must fulfill the demands of the end-user,
- the hardware must have low power consumption, low volume and high processing capacity.

The first item completely depends on the usage of the SAR image. It will not be possible to satisfy the requirements of all end-users. However, end-users can be clustered into market segments (environmental research, defense market, oil industry, etc.) each served by their own satellite SAR system setting. Depending on their specific needs, the performance of the on-board SAR processor and the quality of the images can be specified.

The second item depends on the state of the art in DSP hardware technology. Nowadays on-board satellite SAR processing is feasible, due to the on-going progress in VLSI technology and design methodologies of DSP hardware for complex algorithms. This statement is based on our experience with the on-board real-time airborne SAR processing activities for PHARUS, a fully polarimetric active phased array C-band SAR which is currently developed at TNO-FEL [5].

A key requirement for on-board real-time SAR processing is that the system must have a limited volume and low power consumption. These requirements will be met by hardware miniaturization of the critical processing steps and by optimizing algorithms for hardware implementations. As a result we achieve a really efficient implementation of the SAR processing algorithms in hardware. A typical example is the fast convolution algorithm developed at TNO-FEL, used for range and azimuth compression [2, 3]. The hardware implementation of this algorithm is smaller and has lower power consumption than conventional hardware implementations with an equivalent performance.

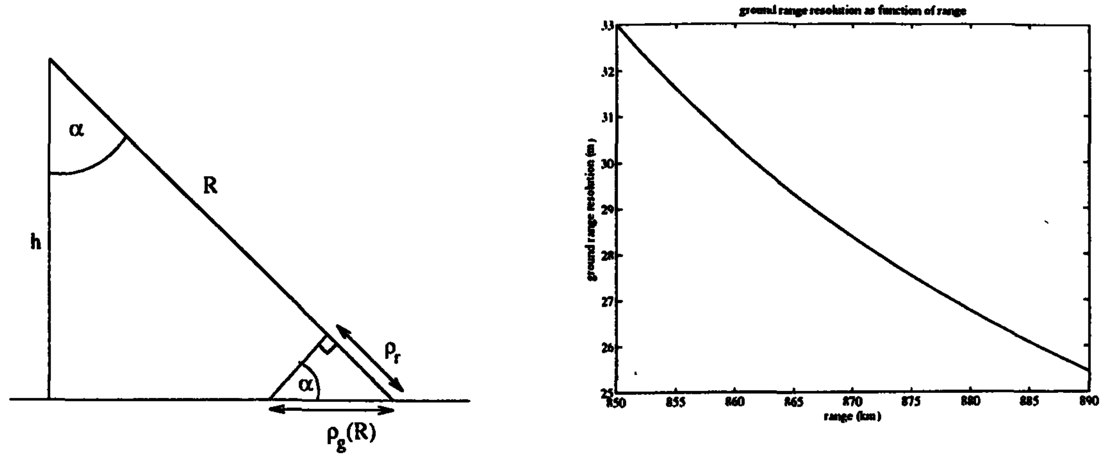
In this paper we will derive the specifications of a demonstrator real-time on-board SAR processor. The objective is to optimize the function specifications and the processing performance parameters given the requirements and the specified SAR parameters. In section 2 we will derive the required SAR parameters. From this we determine the optimum processing parameters. The basis of the SAR parameters will be the fast delivery image requirements from ESA [1]. In section 3 we will derive the real-time SAR processor parameters from the required SAR parameters. Data rates, amount of data samples, data reduction factors, etc. will be considered. In section 4 we will globally specify the hardware architecture of a demonstrator real-time on-board SAR processor. The required amount of hardware and the power consumption will be estimated. The architecture will be based on standard DSP components.

2 SAR Parameter Specifications

The derivation of the requirements will be described briefly for the different steps in SAR processing. Experience with software airborne SAR processing has shown that these steps are sufficient for C-band SAR processing. The definitions of the SAR parameters are given in

λ	wavelength	v	nominal speed
B	bandwidth	h	nominal height
B_d	Doppler bandwidth	f_r	range sample frequency, complex
β_{ant}	azimuth antenna beam width	f_a	azimuth sample frequency (PRF)
τ_p	pulse width	ρ_r	slant range resolution
R_{min}	minimal range	ρ_g	ground range resolution
R_{max}	maximal range	ρ_a	azimuth resolution, single look

Table 1: SAR parameter definitions.



(a) (b)

Figure 1: Relation between the ground range resolution and the slant range resolution (a) and the ground range ρ_g as function of the range R (b).

table 1.

The specifications of the real-time SAR processor are based on the E-ERS-1 product specifications [1]. Typical SAR parameters are listed in table 2. Based on the defined parameters we can give the specifications of a real-time SAR system. For the on-board processing we will consider the so-called "fast delivery" product specifications:

- ground range resolution: $\rho_g \leq 33$ m
- azimuth resolution: $\rho_a = 33$ m
- no. of looks: $N_{look} = 3$
- ground range swath width: $W_g = 100$ km

Range Resolution

From the specified bandwidth B we can derive a slant range resolution $\rho_r = 9.6$ m. From figure 1 the ground range resolution ρ_g can be determined as

$$\rho_g \leq \rho_r / \sin \alpha \qquad (1)$$

where $\cos \alpha = h / R_{min}$. Hence the worst ground range resolution is then given as 30 m which meets the specifications.

λ	0.057 m	τ_p	37.1 μsec	R_{min}	850 km	f_r	19 MHz
B	15.5 MHz	β_{ant}	0.3°	R_{max}	890 km	f_a	1700 Hz
B_d	1300 Hz	h	800 km	v	7000 m/s		

Table 2: Typical E-ERS-1 parameters.

Azimuth Resolution

The required aperture length for given azimuth resolution ρ_a at range R is given as [4]

$$L = \nu \frac{\lambda R}{2\rho_a} \tag{2}$$

where ν is the increment factor that allows weighting to increase the peak-sidelobe ratio (PSLR). We shall assume that $\nu = 1.5$ (Hamming window). A three look image requires three successive apertures of length L. Let B_a be the equivalent Doppler bandwidth per aperture, then B_a is determined by [4]

$$B_a = \frac{2vL}{\lambda R} = \nu \frac{v}{\rho_a} \tag{3}$$

Since $B_a < B_d$, for each look the bandwidth (and thus the sample frequency) can be reduced. With $\rho_a = 33$ m the required Doppler bandwidth per look is given as $B_a = 320$ Hz.

Range Migration

The echo signal of a point target after range compression has a quadratic range difference during its transit through the antenna beam, which effect is known as range curvature. Let $dr = \frac{1}{2}c/f_r$, with c the speed of light, be the sample distance in slant range. Let $d\theta$ be the squint angle and let v_{earth} be the velocity of the earth perpendicular to the satellite orbit. Then the phase history will pass N_{mig} range gates, where N_{mig} is given as [4]

$$N_{mig} = \left\lceil \frac{L(v_{earth}/v + \frac{1}{2}\sin d\theta + L/8R)}{dr} \right\rceil \tag{4}$$

Observe that $L^2/8R$ is negligible and since the squint angle for E-ERS-1 is $d\theta \approx 0$, the most important cause of the range migration is v_{earth}. The velocity of the earth is maximum at the equator, which means in case of E-ERS-1 that $v_{earth} \leq 450$ m/s. Hence the range migration is given as $N_{mig} \leq 75$.

3 SAR Processor Specification

In this section we will translate the specifications of the SAR pprototypearameters into processor specifications. The main parameters are the number of required data samples and the bandwidths in range and azimuth and the data rates. The processor parameters will be optimized with respect to the requirements, such that a minimum hardware architecture can be determined.

Range Compression

The number of complex pulse samples is given as $N_p = \tau_p f_r = 700$. Let $W_r = R_{min} - R_{max}$ be the swath width in slant range, then the number of range samples is given as $N_r = N_p + W_r/dr = 5700$. After the range compression, the effective number of samples that must be written in the corner turning memory is $N_r - N_p$. The effective data rate required for the range compression is defined as the number of range samples that is processed within the inter-pulse time: $D_r = N_r f_a = 9.7$ MHz.

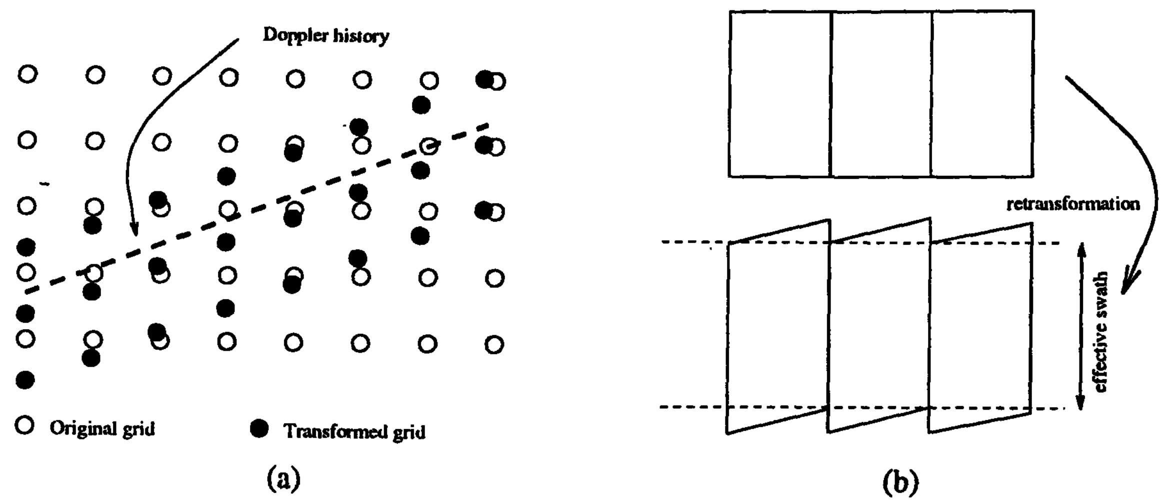


Figure 2: Rotation of the rectangular grid before azimuth compression (a) and rectification on image data (b).

Range Migration Correction

In our case the range migration is a result of the velocity of the earth only, and is therefore assumed linear. The Doppler history of one point target will traverse through many range cells, see figure 2.a. The compensation can be done by rotation of the rectangular grid after range compression such that the Doppler history will traverse through only one range cell. The resulting azimuth lines can be processed with the conventional one dimensional azimuth compression algorithms.

After the azimuth compression the grid must be retransformed, such that the geometrical distortion due to the rotation is rectified, see figure 2.b. Since this is only a geometrical correction it can be combined with the slant-to-ground conversion of the image.

Azimuth Compression

A three look image requires three successive apertures. The critical sampling frequency required for the processing is determined by the required Doppler bandwidth per aperture B_a. The decimation factor after proper bandfiltering, γ_a, is given as $\gamma_a = \lceil f_a/B_a \rceil = 5$. However, in general standard decimation hardware components require powers of 2, and therefore we will set $\gamma_a = 4$.

Let $da = v/f_a$ be the inter pulse distance (azimuth sample distance). The azimuth compression is performed using an overlap-discard fast convolution algorithm [4], which implies an utilization factor. Let U be the utilization of the azimuth compression, then U is defined as

$$U = \frac{N_a}{N_a - N_{look} N_{app}} \tag{5}$$

where N_a is the number of azimuth samples that is written into the azimuth compression and N_{app} is the maximum number of samples per aperture $N_{app} = L_{max}/da = 280$, with L_{max} is the aperture length at $R = R_{max}$. I.e. U is the ratio of required input samples and effective output samples of the azimuth compression.

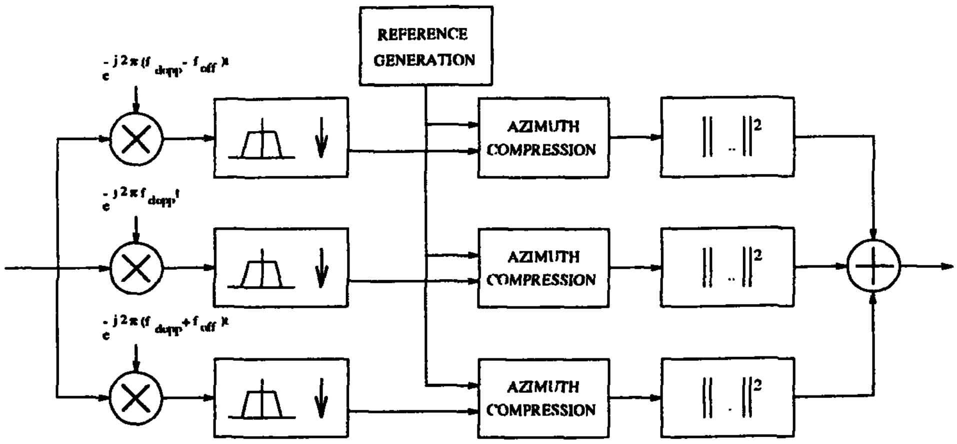


Figure 3: Multilook azimuth compression with frequency translation over $-(f_{dopp} - f_{off})$, $-f_dopp$, and $-(f_{dopp} + f_{off})$, respectively, lowpass filtering, decimation with a factor γ_a and multilook summation.

Maximum utilization implies large N_a, which is unacceptable because all samples must be stored before the azimuth compression. Minimum utilization implies small N_a, which is also unacceptable because the processing capacity of the azimuth compression will drop dramatically. Optimizing for both aspects results in an acceptable utilization of $U = 0.75$ %. In this case the data rate for azimuth compression after the data reduction is given as $D_a = N_{look}(N_r - N_p)f_a/U\gamma_a = 8.5$ MHz. The complete multilook azimuth compression structure is shown in figure 3. The maximum number of samples required per aperture after data reduction is given as $N_{app}/\gamma_a = 70$.

To reduce the required hardware we propose the azimuth structure shown in figure 3. Let the center frequencies of the three successive looks be $-(f_{off} - f_{dopp})$, $-f_{dopp}$ and $-(f_{dopp} + f_{off})$, respectively, where f_{dopp} is the known Doppler centroid. The spectra of the three data paths are frequency translated to baseband, such that real FIR lowpass filters and decimators can be used. After the azimuth compression the absolute values of the complex data samples are calculated and the images are summed.

Azimuth processing can be performed with one reference function at baseband. The depth of focus is given as [4]

$$depth\ of\ focus = \frac{2\rho_a^2}{\lambda} \tag{6}$$

Substituting the parameters shows that the depth of focus is 38 km, which is almost the complete slant range swath. Therefore a few reference functions can be used, which reduces the reference generation hardware.

Corner Turning Memory

The size of the corner turning memory is determined in range by the effective number of samples in range $N_r - N_p = 5000$. Then the number of effective output samples is given as $UN_a = N_a - N_{look}N_{app}$. Hence, with $U = 75$ % this results in $N_a = 3360$. To ensure a constant azimuth data flow, a ping-pong construction is required with $N_{look}N_{app}$ overlap. Hence

function	size (# U6)	mean I/O data rate (Msamples/sec)	power (W)
range compression	4	9.7/9.7	60
corner turning memory	1	9.7/11.3	10
range migration correction	1	11.3/11.3	10
data reduction	1	11.3/8.5	10
azimuth compression	4	8.5/8.5	60
post processing	1	8.5/0.28	10
total	12	9.7/0.28	160

Table 3: The estimated requirements of a demonstrator on-board real-time SAR processor.

the corner turning memory size in azimuth is 5880 samples. Assuming that a complex sample consists of 4 bytes, a memory size of approximately 120 Mbyte is required.

Slant-to-Ground Conversion

The pixel size in azimuth is determined as $da/\gamma_a = 16$ m, and thus the pixel size in ground range should also be 16 m. Therefore the slant range image must be interpolated in range to obtain the required ground range pixel size. Since the interpolation is in range direction it can be performed after the processing of all azimuth lines. Obviously this requires again a (ping-pong) memory with dimension 5000 in range and $(2N_a - N_{look}N_{app})/\gamma_a = 1470$ in azimuth. The samples size is 2 bytes (pixel), hence the required memory size is 15 Mbyte. The interpolated data is image data and can be compressed immediately after the interpolation. Using JPEG standard a compression factor of at least 20 is achievable.

4 Hardware Architecture Specification

In this section we will specify the hardware architecture for a demonstrator real-time SAR processor. The amount of required hardware will be estimated. For the demonstrator systemwe propose standard components as much as possible.

For the range and azimuth compression we have developed the so-called "Fast Convolution Module" (FCM), a single-board U6 fast convolution board, based on standard DSP components and Programmable Logic Devices (PLDs). The latter can easily be converted to ASIC devices, if needed for space qualification. The FCM is an implementation of the fast convolution algorithm, developed at TNO-FEL [2, 3], and has smaller dimensions and lower power consumption than conventional fast convolution hardware implementations with an equivalent performance. The FCM can handle data sequences with lengths up to 30 Ksamples complex with an effective data rate of 2.5 MHz. The FCM is expected to be operational end 1994.

The required memory size of the corner turning memory is 120 MHz. At the moment 32 Mbyte SIMM DRAM is available with 10 MHz data rate. Hence 4 SIMMs are required including address control hardware.

The range migration correction can be performed using DSP chips. The main operations are generation of addresses and interpolation. The data reduction (including the reference

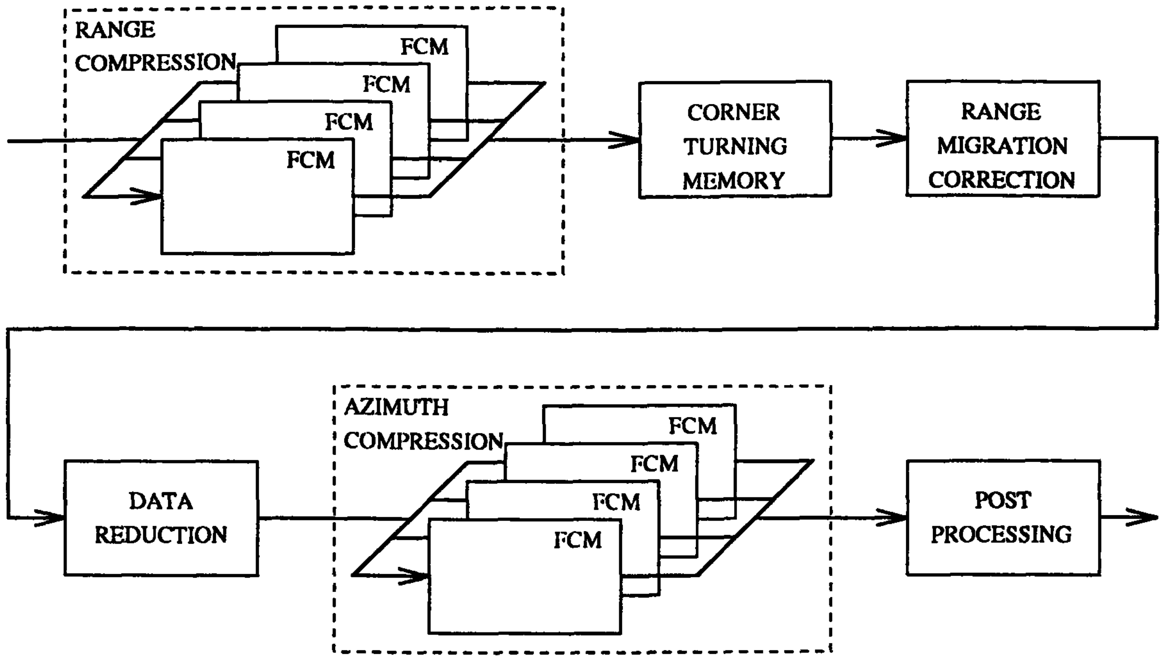


Figure 4: The global hardware architecture of the real-time on-board SAR processor.

generation) will consist of two on-chip frequency mixers, six lowpass FIR filters/decimators with real coefficients.

The multilook summation will consists of three on-chip Pythagoras processors and an adder. The sample format will be reduced to 2 byte pixels, hence 16 Mbyte DRAM SIMM is sufficient to meet the required memory. The slant-to-ground conversion and the range migration retransformation will be performed by standard image interpolation hardware. The final image will be pipelined directly into a JPEG standard compression chip.

In figure 4, the complete hardware architecture is shown and the specifications are summarized in table 3. Figure 5 shows an example of an E-ERS-1 image processed with the real-time SAR processing parameters as defined in section 3.

5 Conclusive Remarks

In this paper we have proposed real-time on-board satellite SAR processing as a rigorous kind of SAR data reduction. The specifications of the processor are derived, based on the ESA "fast delivery" image product specifications. Data reduction factors of over 140 can be achieved (including image compression according to JPEG standard), which opens up the opportunity of on-board data storage or data transmission with narrow band data-links. A total of 11 U6 Printed Circuits Boards (PCBs) are required for a demonstrator real-time SAR processor, with an estimated total power consumption of less than 160 W.

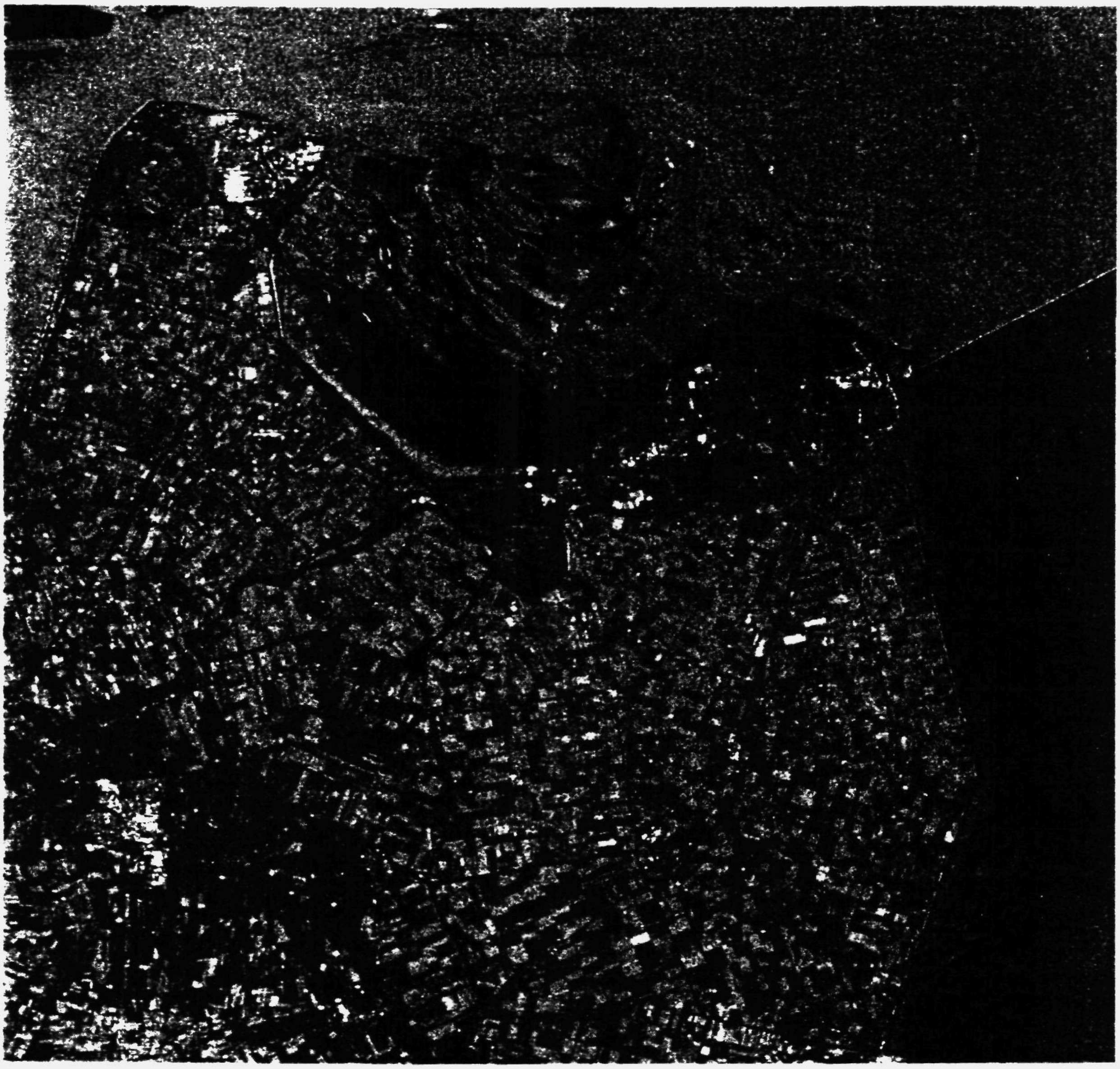


Figure 5: 3 Look E-ERS-1 ground range image of North-Holland with resolution approx. 33 × 33 m and pixel size 16 × 16 m. The processing is performed using the real-time SAR processing parameters described in section 3.

6 Acknowledgement

The authors gratefully acknowledge Rob Dekker for the useful discussions about E-ERS-1 SAR processing and his effort in adjusting the spaceborne SAR processing software for evaluating the real-time SAR processing specifications.

References

[1] ESA ERS-1 Product Specification. No. ESA SP-1149, ESA, June 1992.

[2] L.H.J. Bierens. A Real-Time Convolution Algorithm and Architecture with Applications in SAR Processing. Internal Report, No. FEL-91-B113, TNO Physics and Electronics Laboratory, Oktober 1993.

[3] L.H.J. Bierens. Real-Time SAR Processing Activities at TNO Physics and Electronics Laboratory. In *Proc. Int. Geoscience and Remote Sensing Symp. '93*. IEEE, 1993.

[4] J.C. Curlander and R.N. McDonough. *Synthetic Aperture Radar, Systems and Signal Processing*. Wiley Series in Remote Sensing, 1991.

[5] P. Hoogenboom, P. Snoeij, P.J. Koomen, and H. Pouwels. The PHARUS Project, Results of the Definition Study Including the SAR Testbed PHARS. *IEEE Transactions on Geoscience and Remote Sensing*, 30(4):723–735, July 1992.

Fourth International Workshop on Digital Signal Processing Techniques Applied to Space Communications

Organised by the European Space Agency

ESA

and

King's College London

in cooperation with

EUTELSAT

and

INMARSAT

Organizing Committee Co-Chairmen:
C. Elia & A.H. Aghvami

Technical Committee Chairman:
R.A. Harris

26-28 September 1994
King's College London, United Kingdom