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ALASKA SAR FACILITY (ASF)
SAR COMMUNICATIONS (SARCOM)
DATA COMPRESSION SYSTEM

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INTRODUCTION

The basic technical goal of the Alaska SAR Facility SAR Communications system (ASF SARCOM) is to provide a real-time operational, applications demonstration of the transmission of spaceborne synthetic aperture radar (SAR) imagery of Arctic ice over a bandwidth-limited communications satellite link.

The imagery is to be transmitted from the ASF located at the University of Alaska in Fairbanks to the National Oceanic and Atmosphere Administration (NOAA) Ice Center (NIC) in Suitland, Maryland via the DOMSAT link.

The SARCOM system will be designed to handle the spaceborne SAR imagery of the three following non-U.S., polar orbiting platform/sensors:

1. E-ERS-1 (European Space Agency) April, 1990 Launch
2. J-ERS-1 (Japan) 1992 Launch
3. RADARSAT (Canada) 1994 Launch

The SARCOM system will be able to handle the spaceborne SAR imagery in all high and low resolution modes of the three SAR systems over their operational lifetimes.

The need for data compression in the SARCOM system is driven by two factors:

a) the need to transmit in a real-time operation the high resolution imagery of the SAR sensors with their high data rates of 40-60 megabits per second (Mbps), and

b) the constraint imposed by the bandwidth limitation of the communications satellite link, namely 1.33 Mbps maximum.

These factors imply the need for data compression techniques with effective compression ratios as high as 30-to-1 and 45-to-1, respectively. All techniques known to produce such high compression ratios for any reasonable imagery data have been traditionally categorized as irreversible or fidelity (information) reducing techniques. Furthermore, many of these techniques impose a very high arithmetic load on the real-time system used to implement the data compression coding.

This article will describe how the real-time operational requirements for SARCOM translate into a high speed image data handler and processor to achieve the desired compression ratios and the selection of a suitable image data compression technique with as low as possible fidelity (information) losses and which can be implemented in an algorithm placing a relatively low arithmetic load on the system.

OVERVIEW OF THE SARCOM SYSTEM

Figure 1 is a pictorial of the SARCOM data handling scenario. A generic, spaceborne SAR is portrayed, representing either of the three sensors, viewing a portion of the Arctic basin. It is shown operating in the customary strip map mode indicated by the dashed lines. These dashed lines represent the edges of the data collection swathwidth as the SAR footprint looks broadside to one side of the subsatellite track.

All three of the SAR platforms will be in a polar orbit providing excellent opportunities to provide synoptic coverage of the Arctic basin and land regions. Overlaps in the operating lifetimes of the three systems should provide unique, spaceborne observations of these regions at multiple frequencies, polarizations and look angles. Table 1 presents the essential descriptions of the E-ERS-1, J-ERS-1, and RADARSAT including the basic SAR characteristics, the orbit and the mission(1). In this presentation the notation high resolution or HI-RES will be used to denote a nominal ground resolution of 30 meters by 30 meters for a four-look azimuth processing, one-look range processing, while low resolution, or LO-RES, will denote a nominal ground resolution of 240 meters by 240 meters derived from an 8-by-8 averaging of the HI-RES data. The pixel spacing will be 12.5 meters square and 100 meters square for the HI- and LO-RES imagery, respectively.

Figure 1 indicates the SAR raw data collected onboard being downlinked to the ASF at the University of Alaska at Fairbanks (UAF). These raw data received at the ASF are basically, accurately time-tagged radar backscattered, amplitude returns or the so-called radar echoes from successive pulses. If these radar echoes are considered in a form of amplitude as a function of the two SAR spatial dimensions -- slant range (crosstrack) and azimuth (alongtrack) -- they represent essentially a two-dimensional amplitude interferogram which is analogous to the two-dimensional intensity hologram used in three-dimensional, coherent laser holography.

The main system at the ASF will be used to perform the technically demanding, numerically intensive two-dimensional, coherent SAR processing to convert the raw data echoes into the more familiar two-dimensional SAR images. This conversion from the raw data domain to the image domain requires not only the time-tagged radar echoes but also the radar operating parameters, the SAR platform orbit and attitude data and the earth's geoid size, shape, and motion data. The ASF will perform this SAR processing in a delayed start, near real-time mode. At the present time the start delay reflects primarily the time required to receive and input a sufficiently accurate ephemeris for the SAR platform orbit.

Figure 2 portrays the functional block diagram for the basic ASF system comprised of three major systems: the Receiving Ground System (RGS), a two part SAR Processor System (SPS), and a two part Archive and Operations System (AOS). The main system at the ASF is being funded by the National Aeronautics and Space Administration (NASA). The ASF physical site at the Geophysical Institute is being funded by the University of Alaska at Fairbanks (UAF). Jet Propulsion Laboratory (JPL) is the designer and prime contractor for providing the end-to-end main ASF system. The ASF will be operated by the UAF.

SARCOM will be a stand-alone image processing and image handling system that will be collocated with the ASF system. It will be an attachment and augmentation to the main ASF system for the primary purpose of accessing the quick turnaround, low and high resolution ice imagery processed by the ASF system to be delivered to the NOAA Ice Center. SARCOM will acquire and process these image data at real-time rates.

The end-to-end SARCOM system is depicted in the pictorial labeled Figure 3. The data "umbilical cords" to the main ASF are also displayed.

From the ASF site SARCOM will link the SAR data via a T1 microwave link to the NOAA Tracking and Data Acquisition (TDA) station at Gilmore Creek at real-time rates as shown in Figure 1. Gilmore Creek is located approximately 12-14 miles northeast of the UAF site. For the SARCOM operation the usual 1.54 Mbps T1 link bandwidth limitation will be constrained to an overall maximum transfer rate of 1.33 Mbps.

From the NOAA TDA station the SAR data will be skylifted to the domestic satellite system (DOMSAT) via another T1 microwave link and relayed in real-time to the NIC in Suitland, Maryland. The data will actually be ingested by the existing NOAA Command and Data Acquisition

(CDA) station and passed to the Ice Center under the auspices of the National Meteorological Center which are all collocated in the same building complex in Suitland.
The LO-RES data can be displayed and/or post-processed for information extraction and analysis immediately upon reception at the NIC for the original LO-RES imagery didn't need to be compressed prior to the transmission in real-time using the SARCOM 1.33 Mbps link. The 64-to-1 reduction of the 8-by-8 averaging of the HI-RES data to derive the LO-RES data corresponds to at most 0.94 Mbps for the LO-RES for even the most demanding 60 Mbps maximum HI-RES mode; thus the LO-RES data will always fit within the link bandwidth constraint. However, the HI-RES image data will have to be compressed/coded using a data compression algorithm at the SARCOM transmit end in Alaska to fit within the link bandwidth and then the image must be reconstructed by using the inverse algorithm at the NIC receive end in Suitland.

The SARCOM operational applications goal is to provide SAR ice imagery to enhance and expand the ice forecasting capabilities and services of the Ice Center. It is planned that this imagery will serve as both quick forecasting and synoptic data bases for direct ship support operating in these areas, longer term sea ice modelling and applied research areas. These data will be utilized in the determination of ice concentration, classification of ice types and the determination of ice motion for an understanding of the kinematics of ice fields and the incorporation into ice dynamics modelling.

FUNCTIONAL REQUIREMENTS OF THE SARCOM SYSTEM

The basic functional requirements for the SARCOM system at the ASF are indicated in Figure 4. The crucial input data for the SARCOM application will be the LO-RES and HI-RES Quick-Turnaround Data which will both be stored on Ampex DCRSi (Digital Cassette Recording System) cassettes.

The Quick-Turnaround Imagery is imagery processed by the main ASF

system that is less than six hours old from the time of the actual capture of the raw data echoes used to form the images. These "fresh" images are a requirement in order that the Ice Center can utilize them in their quick forecasting for direct ship traffic support.
The SARCOM maximum real-time input rate that must be sustainable over the system transfer time for the scene is 8 megabytes per second with 1 byte per pixel, up to 12,000 pixels per swathline and up to 640 swathlines per second.

Therefore, the real-time SARCOM system must have an effective throughput rate of up to 8 megapixels per second. Using the results of a data compression study conducted at the Digital Image Processing Laboratory, the algorithm(s) specified for the compression of the HI-RES data, the most demanding mode of operation for the SARCOM, will have to support an arithmetic load in the range of 20-25 real operations per input pixel or an effective arithmetic rate of 160-200 million floating point operations per second (MFLOPS).

The compressed representation of the HI-RES images and the uncompressed LO-RES images must be outputted from SARCOM in the DOMSAT/NOAA data ingest center formats at a maximum rate of 1.33 Mbps (that is 167 kilobytes per second maximum). There will be 1 byte per compressed coefficient for the HI-RES data and 1 byte per uncompressed image pixel for the LO-RES data.

The SARCOM functional components previously illustrated in Figure 3 consist of:

1. a computer subsystem which consists of a control processor (a host CPU with peripherals), and a high-speed arithmetic processor (an array processor or a bank/grid of processing elements)

2. a data storage subsystem

3. an image/data display subsystem

4. a microwave link subsystem to couple SARCOM to Gilmore Creek

The LO-RES SAR data can be handled by the SARCOM control processor and high-speed bus at real-time rates without exceeding the 1.33 Mbps maximum satcom link rate and without being compressed by the arithmetic processor. The HI-RES SAR data will be handled by SARCOM at real-time rates by utilizing not only the control processor and high-speed bus but also the high-speed arithmetic processor to compress the data by compression ratios as high as 30-to-1 or 45-to-1 at real-time processing rates to fit within the 1.33 Mbps maximum.

A data storage subsystem consists of a high-speed, high-capacity disk drive and its interface to the real-time input/output bus. The data storage subsystem can provide for interim storage of a single image frame or as a stacker of image frames prior to being forwarded to the satcom link at Gilmore Creek.

The seven functional components of the SARCOM end-to-end system in Alaska and in Maryland are indicated in Figure 5.

Figure 6 shows a more detailed system interconnections diagram between the SARCOM and the main ASF systems. It includes four of the seven SARCOM functional components contained at the UAF.

There will be basically only two interconnections between the two systems. The critical LO-RES and HI-RES Quick Turnaround Data interface between the ASF Digital Cassette Recorder System (DCRS) and the SARCOM high speed Input/Output bus is depicted by the wide path running parallel to the bottom of Figure 6. The only other system interconnect will be a low speed network connection, designated DECNET, which will couple the SARCOM CPU and two of the ASF CPUs.

A preliminary design of the hardware subsystems which will achieve the SARCOM objectives is indicated in Figure 7 which includes possible manufacturers and models. The rationale for the system design was to incorporate off-the-shelf hardware subsystems with significant existing subsystem software (drivers, high speed mathematics library and diagnostics) and already demonstrated successful interfacing between hardware subsystems wherever possible.

Several candidates for the hardware subsystem designated as the array processor have been identified. This subsystem has as its principal function the responsibility to perform the data compression of the HI-RES data in real-time. However, a cost-effectiveness trade-off study of these processor candidates has not been finalized yet. Apparently, the significantly high, sustainable arithmetic load of 160-200 MFLOPS required for the most demanding modes of SARCOM hovers around the present technological limit of moderately priced ($0.25M-$0.50M) array processors.

SARCOM DATA COMPRESSION TECHNIQUES

A consideration of the various modes of operation for the three spaceborne SAR systems for which the SARCOM was designed establishes a range of design compression ratios which set the framework for the selection of a data compression algorithm(s). The real-time SARCOM design compression ratios for the extreme swathwidths and quantization levels (bits/sample) selectable for the three systems are given below. The values derived are based on a maximum link bandwidth of 1.33 Mbps and a pixel spacing of 12.5 meters.

SWATHWIDTH (KM)	BITS/SAMPLE	REAL-TIME IMAGE RATE (Mbps)	DESIGN COMPRESSION RATIO
150	8	61.4	46.2
100	8	41.0	30.8
50	4	10.4	7.7

Therefore, the range of SARCOM design compression ratios is from approximately 8-to-1 to approximately 30-to-1 for the E-ERS-1 and J-ERS-1 systems while the upper end of the range is extended to approximately 45-to-1 when the RADARSAT system is included.

Within this design compression ratio range, several data compression techniques were evaluated at the Digital Image Processing Laboratory (DIPL) using SEASAT SAR and Shuttle Imaging Radar (SIR-B) imagery of ice, land and sea(5). Some of the techniques evaluated in both non-adaptive and adaptive forms included both, a) spatial techniques such as the linear, bi-linear and quadratic interpolative techniques, a linked polynomial technique and block truncation coding (BTC), and b) transform techniques such as the discrete cosine transform (DCT) and the Hadamard Transform (HT) techniques. The evaluation criteria used were, a) the fidelity of the reconstructed image determined by the polling of subjective viewing and the quantitative measure of normalized-mean-square-error (NMSE), and b) the arithmetic burden imposed on the real-time SARCOM system.

The results of the study indicated that for the SARCOM data compression range of 8-to-1 through 45-to-1 the two transform techniques, the DCT followed by the HT, yielded the best results. Even though the DCT produced significantly better fidelity, the HT method showed potential due to the its arithmetic simplicity of being reducible to just a number of additions and no multiplications. This simplicity of the HT method may be implemented very effectively in certain system architectures.

Figure 8 presents a block diagram of the data compression schematic for the Discrete Cosine Transform (DCT) technique at both the transmit and receive ends. The schematic is a generic one which is actually applicable to any transform technique. The indicated steps in this data compression process for the non-adaptive DCT technique (or any non-adaptive transform technique) are the well-known steps for any non-adaptive transform technique[6].

In a real-time data compression process the arithmetic load of any technique can be just as important as the effectiveness of that technique in producing the highest-fidelity reconstruction of the original image after data compression.

The arithmetic load of a data compression process on the transmit end can be characterized by the figure of merit given by the number of arithmetic operations (real adds and real multiplies) required to implement the data compression algorithm. In the DIPL study, the DCT technique was selected as the best performance non-adaptive technique based on spaceborne SAR ice imagery from SEASAT when both the arithmetic load and the effectiveness of the reconstructed image were considered.

Figure 9 presents plots of the number of additions and the number of multiplications per input pixel of the scene as a function of the compression factor are plotted for the non-adaptive DCT data compression technique. The curve parameter, N, in the figure is the block size of the square used as the subscene size for the application of the technique. For example, using a subscene size of 128-by-128 pixels as a block size, the non-adaptive DCT technique requires approximately 11 additions per input pixel and approximately 4 multiplications per input pixel or a total of 15 operations per input pixel for the most demanding SARCOM compression factors of 30-to-1 and 45-to-1. It is interesting to note that the number of operations per input pixel is essentially independent of the compression factor above a compression factor of approximately 10-to-1 for a fixed block size. Furthermore, for a constant compression factor the number of additions and multiplications per input pixel for the whole scene and thus the total arithmetic load increases as a slow function of N, the block size of the subscene used.

The actual selection of a subscene block size is usually a trade-off between choosing a low value of N to reduce the total arithmetic load and choosing a higher value of N to reduce the subscene block edge effects when the subscenes are mosaicked together to form the full scene.

The use of an adaptive technique was found to significantly increase the fidelity of the reproduced image after data compression for SAR ice imagery. For the SARCOM range of compression factors the arithmetic load imposed by the adaptive DCT technique could be bounded by 20-25 operations per input pixel for compromise subscene block sizes of N=128. This was the arithmetic load which was used in the design criteria for the SARCOM real-time operations.

The non-adaptive DCT algorithm selected is a combination of, a) a variation of the fast DCT algorithm of B.G. Lee[4] to achieve the forward (or inverse) DCT, and b) decision criteria developed at the DIPL based on the scene statistics to produce the actual data compression.

The adaptive DCT algorithm selected is a combination of, a) the same variation of Lee's fast DCT method to perform the forward and inverse transforms, and b) the very effective technique of Chen and Smith[2,3] implemented to accomplish the actual data compression.

An example of the very effective adaptive discrete cosine transform (ADCT) technique is displayed in Figure 10. It is an example of the reconstructed image (compression factor = 32) side-by-side with the original at a map scale of 1:500,000. The scene is a SEASAT SAR ice image of a portion of the Beafort Sea in the Arctic basin with Banks Island occupying the left one quarter of the image from top to bottom and the remainder of the image being pack ice near the island and much more mobile ice in the right half of the image. Figure 11 emphasizes the fidelity of the reconstructed image by presenting a 64-to-1 zoom of the previous figure with a more demanding map scale of 1:64,000. It is a blow-up of just a small portion of the ice floe region just to the right of image center in the complete scene.

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2) Chen, W., C.H. Smith and S.C. Fralick, "A Fast Computational Algorithm for the Discrete Cosine Transform", IEEE Transactions on Communications, Vol. COM-25, pp. 1004-1009, September 1977.

3) Chen, W. and C.H. Smith, "Adaptive Coding of Monochrome and Color Images", IEEE Transactions on Communications, Vol. COM-25, pp. 1285-1292, November 1977.

4) Lee, B. G., "A New Algorithm to Compute the Discrete Cosine Transform", IEEE Trans. Acoust., Speech, Signal Processing, vol. ASSP-32, pp. 1243-1245, December 1984.

5) Mango, S.A., K.W. Hoppel, P.B. Bey and M.R. Grunes, "Case Study : Data Compression Techniques for Synthetic Aperture Radar (SAR)", Scientific Data Compression Workshop, Snowbird, Utah, May 1988.

6) Pratt, W. K., "Digital Image Processing", Wiley (Interscience), New York, 1978.

TABLE 1
SAR SENSOR MISSION DESCRIPTIONS
ALASKA SAR FACILITY (ASF)

		E-ERS-1	J-ERS-1	RADARSAT
SAR	Frequency	C-band	L-band	C-band
	Polarization	VV	HH	HH
	Swath	80km	75km	500 to 50 km
	Resolution/looks	30m/4	30m/4	100m/8 to 10m/1
	Incidence angle	23 degrees	35 degrees	20-50+ degrees
	Orientation	Right	Right	Right
	On-Board Storage	none	about 10^{11} bits	yes
Orbit	Inclination	97.5 Degrees	97.7 degrees	98.5 degrees
	Altitude	785 km	568 km	790 km
	Repeat	3 days initially, then TBD	41days	16 days (with 3-day subcycle)
	Node	sun-synchronous	sun-synchronous	sun-synchronous
Mission	Launch	4/1990	2/1992	1994
	Lifetime	2-3 years	2 years	5 years
	Status	Approved	Approved	Approved
Other Instruments		Radar Altimeter, Wind/Wave Scatterometer, Along-Track Scanning Radiometer	Optical Sensor	TBD

[FROM CARSEY, 1988]

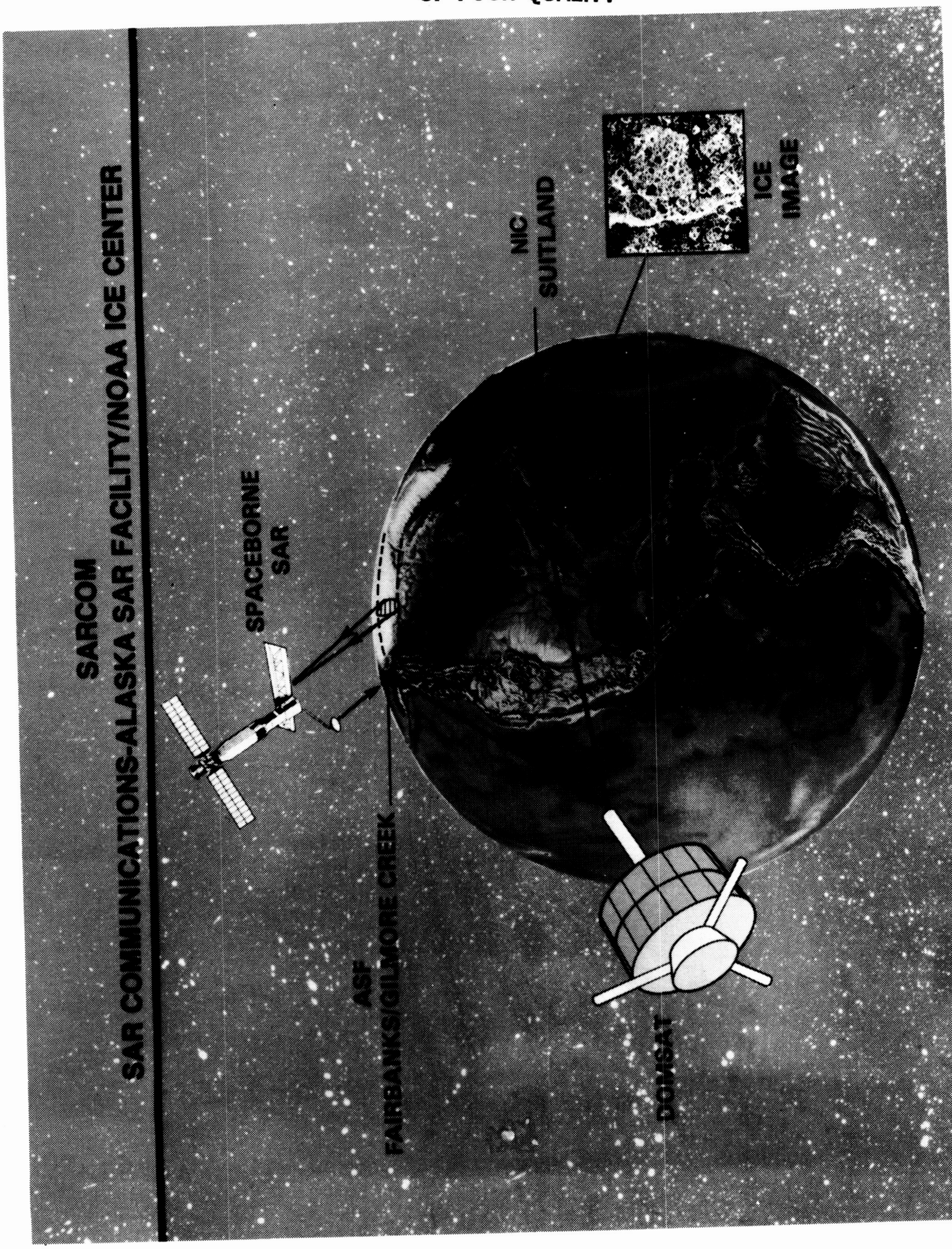
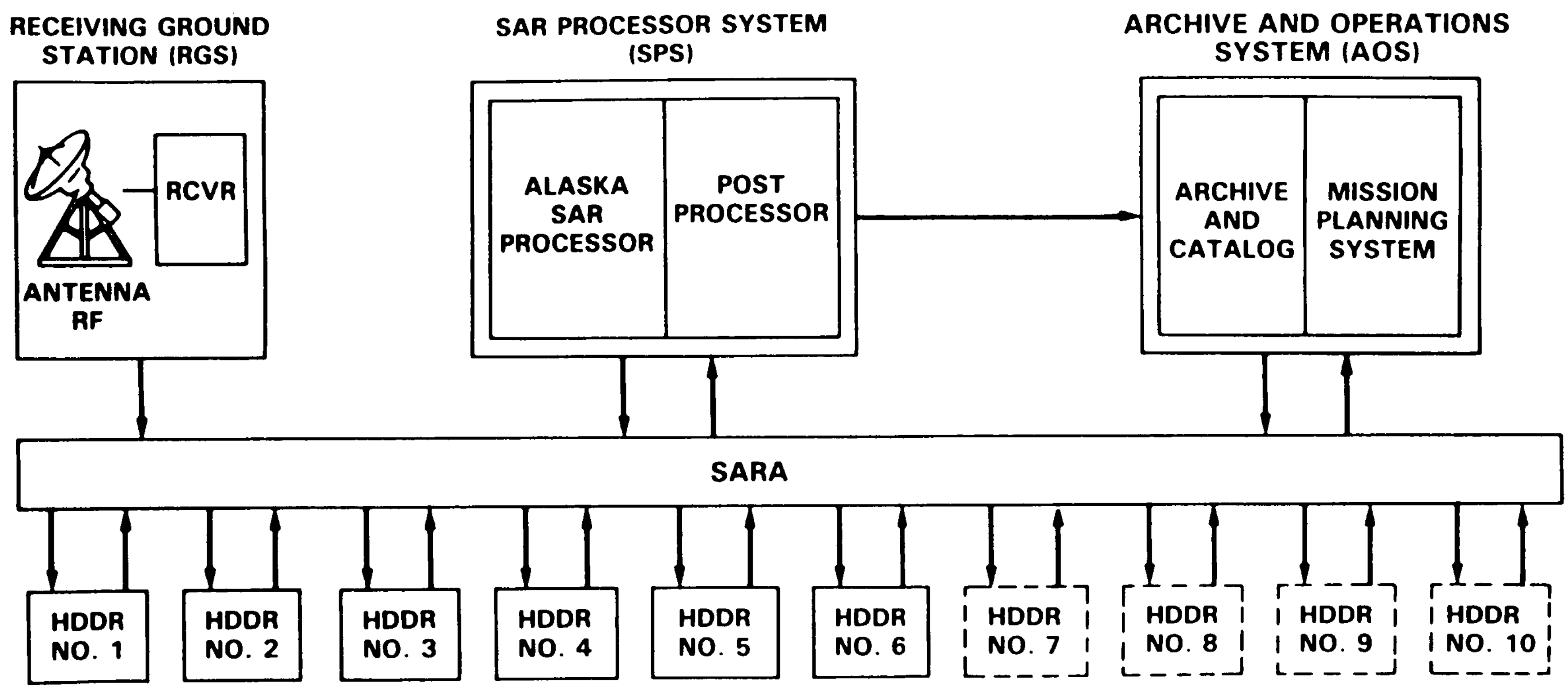

SARCOM
SAR COMMUNICATIONS-ALASKA SAR FACILITY/NOAA ICE CENTER
SPACEBORNE SAR
ASF
FAIRBANKS/GILMORE CREEK
NIC
SUITLAND
ICE
IMAGE
DOMSAT

Figure 1

ALASKA SAR FACILITY (ASF) FUNCTIONAL BLOCK DIAGRAM



[FROM JPL ASF DESIGN REVIEW, JUNE 1987]

FIGURE 2

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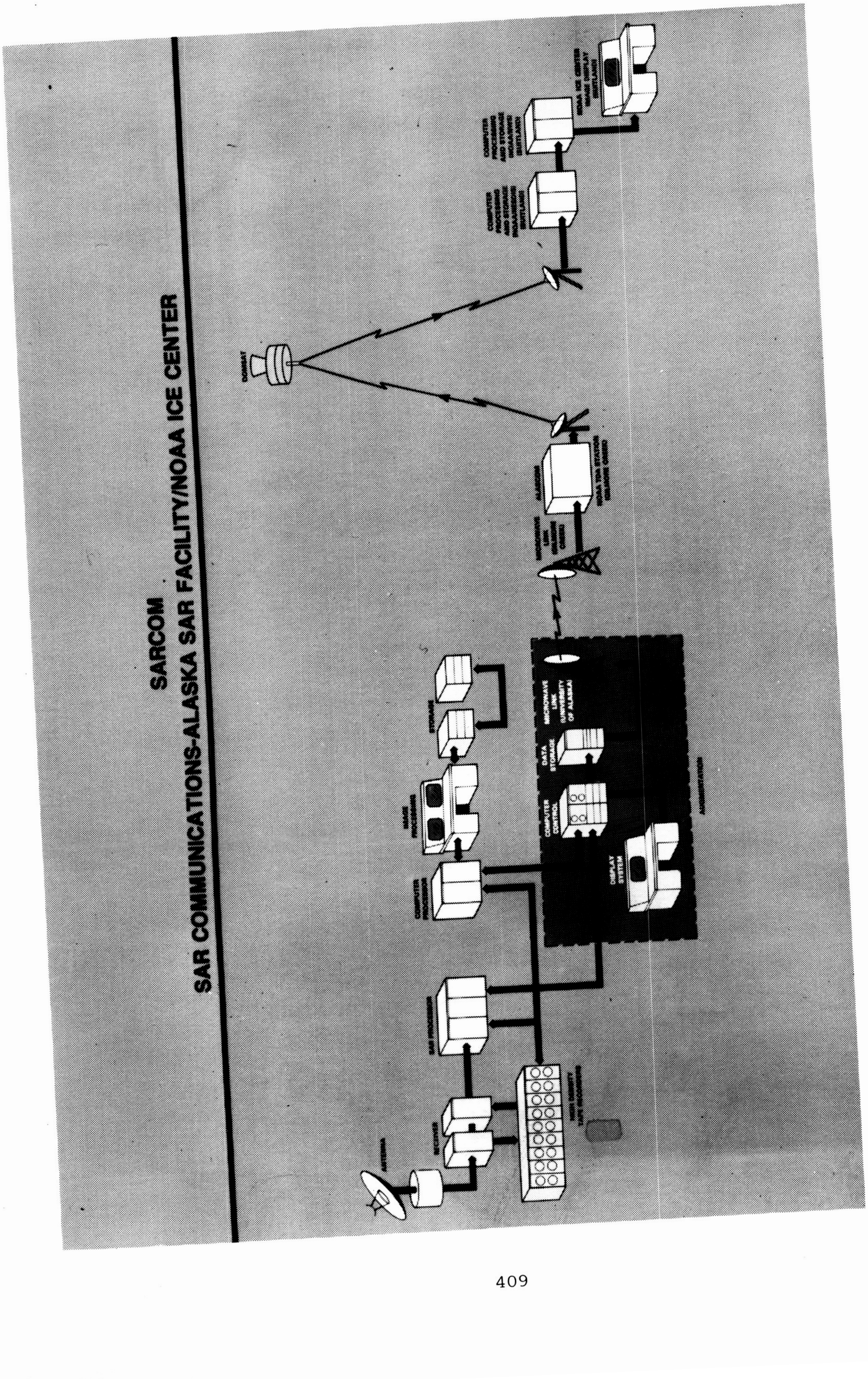


Figure 3

SARCOM FUNCTION AT ASF

- LO-RES OR HI-RES
  QUICK-TURNAROUND DATA
  < 6 HOURS "OLD"
- MEDIUM-AMPEX DCRSi
  CASSETTES (AMPEX/JPL FORMAT)
- REAL-TIME RATE
  8 MBYTES/SEC MAX.
  1 BYTE/IMAGE PIXEL
  12,000 PIXELS/SWATHLINE MAX
  640 SWATHLINES/SEC MAX

- EFFECTIVE THRUPUT RATE
  8 MEGAPIXELS/SEC
- ARITHMETIC LOAD
  20-25 REAL OPERATIONS
  PER INPUT PIXEL
- EFFECTIVE ARITHMETIC RATE
  160-200 MFLOPS

- HI-RES (OR LO-RES)
  COMPRESSED REPRESENTATION OF IMAGE
  (OR UNCOMPRESSED IMAGE)
- DOMSAT/NOAA DATA INGEST
  FORMAT
- REAL-TIME RATE
  167 KBYTES/SEC MAX
  (1.33 Mbps)
  1 BYTE/COMPRESSED
  COEFFICIENT
  (OR UNCOMPRESSED
  IMAGE PIXEL)

FIGURE 4

ASF SARCOM FUNCTIONAL COMPONENTS

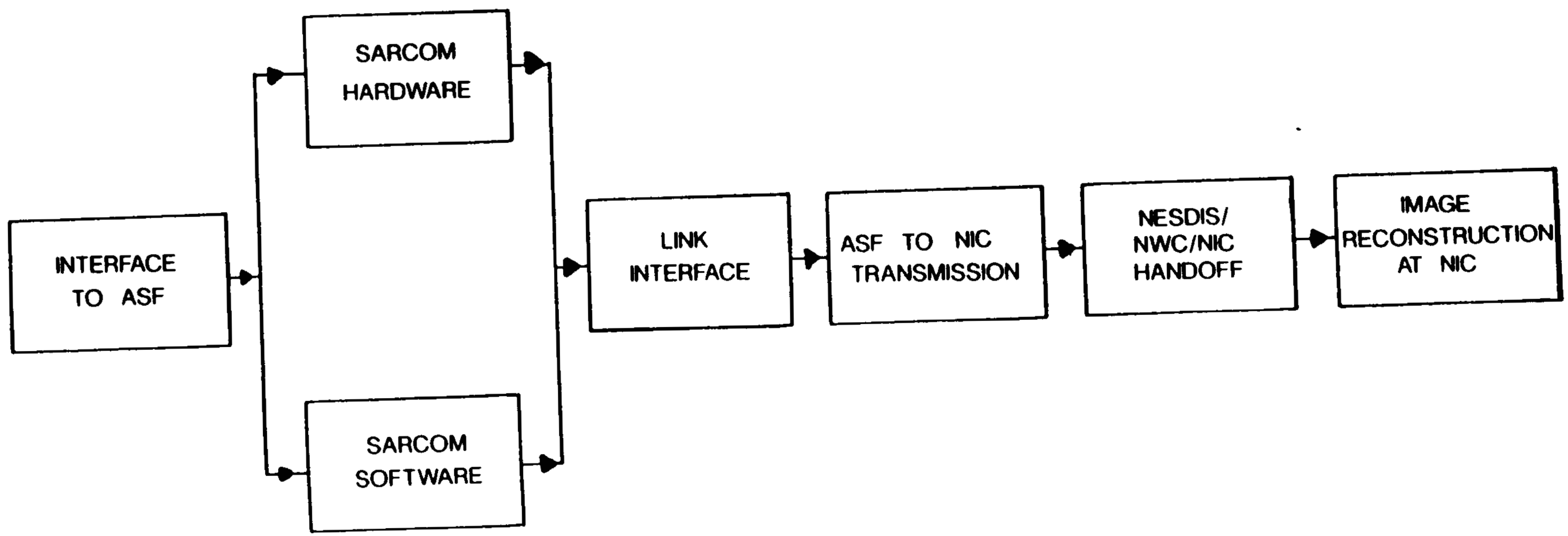


FIGURE 5

SYSTEM INTERCONNECTIONS

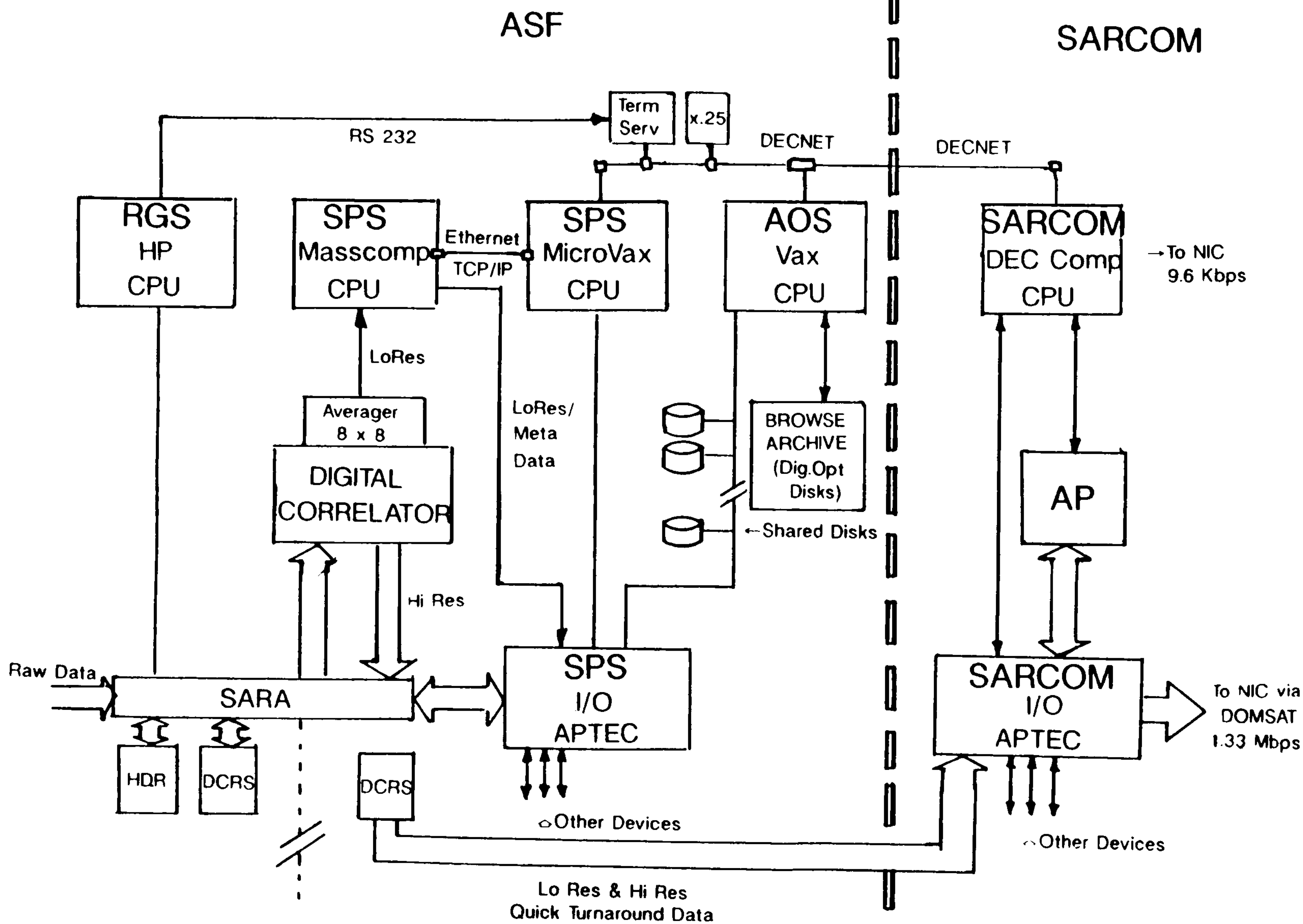


FIGURE 6

ASF SARCOM
HARDWARE SUBSYSTEMS

(BY MANUFACTURER/MODEL)

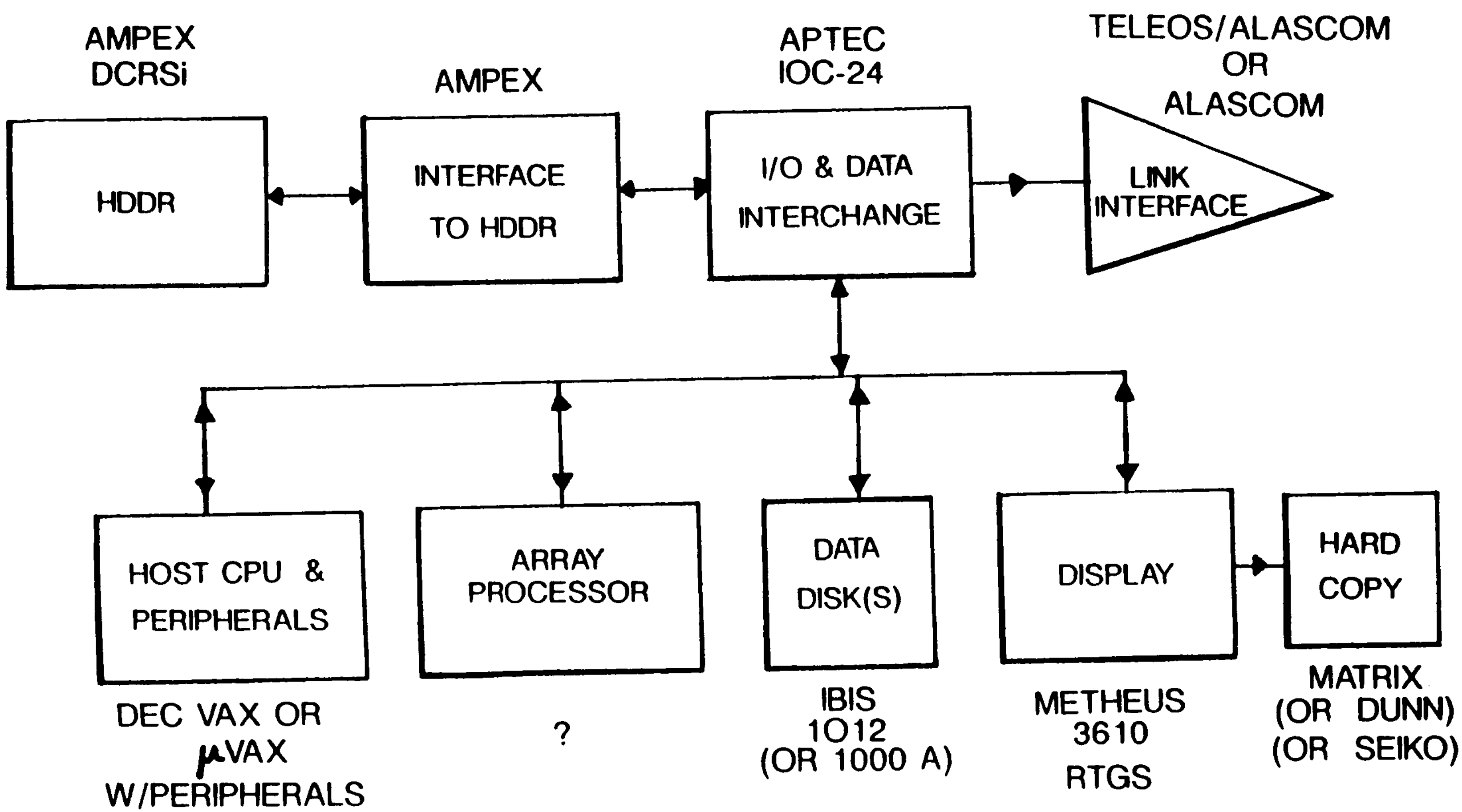


FIGURE 7

DATA COMPRESSION SCHEMATIC FOR DISCRETE COSINE TRANSFORM (DCT) TECHNIQUE

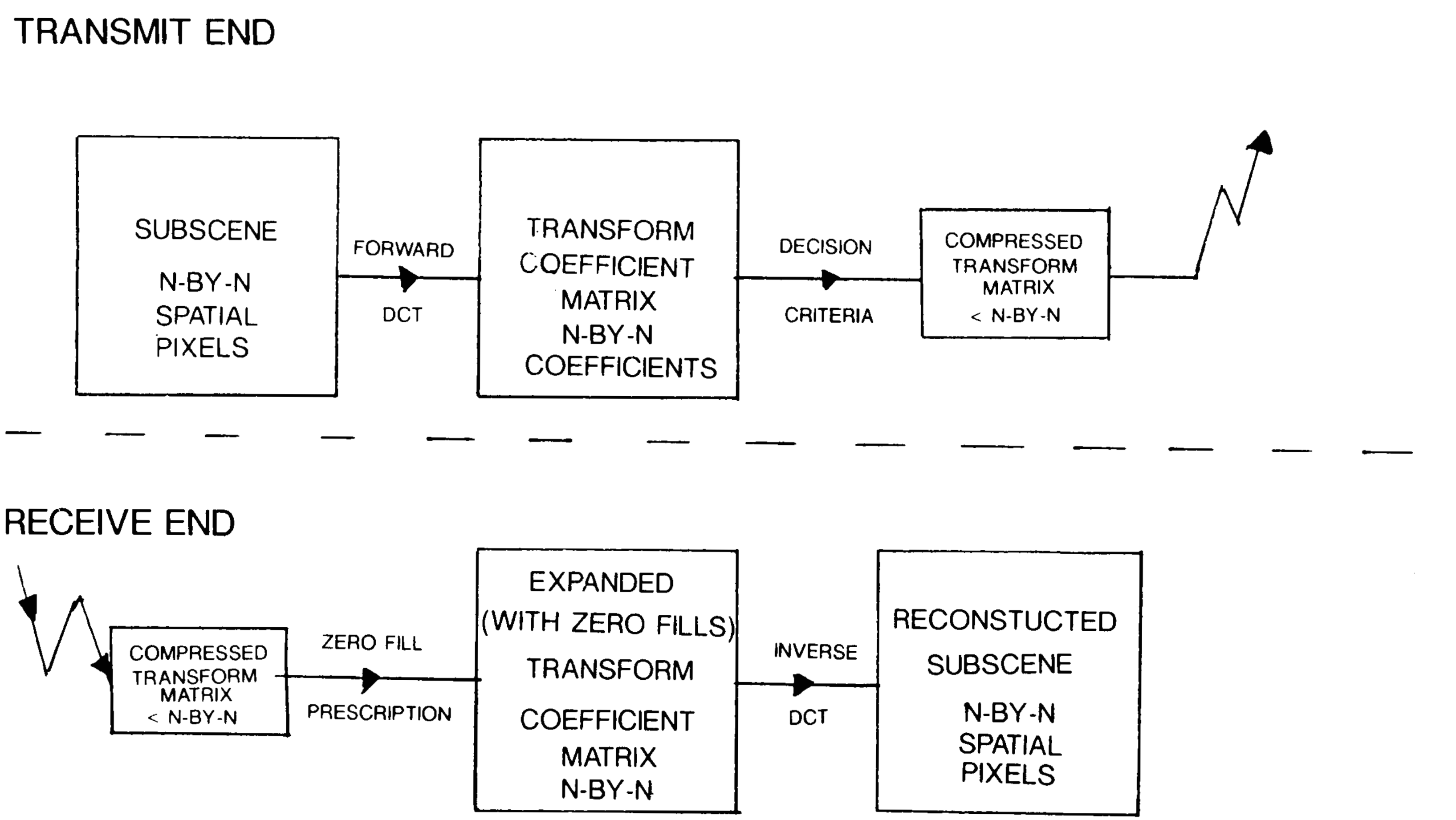
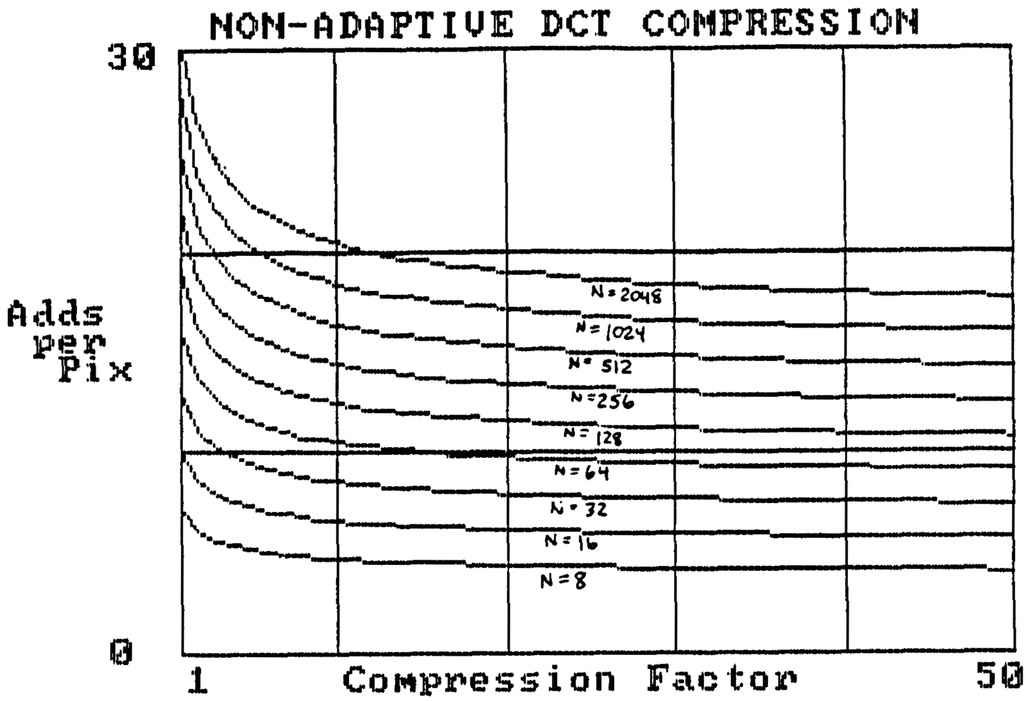


FIGURE 8

SARCOM ARITHMETIC LOAD
NON-ADAPTIVE DISCRETE COSINE TRANSFORM (DCT)

N = BLOCKSIZE (N-BY-N PIXELS)



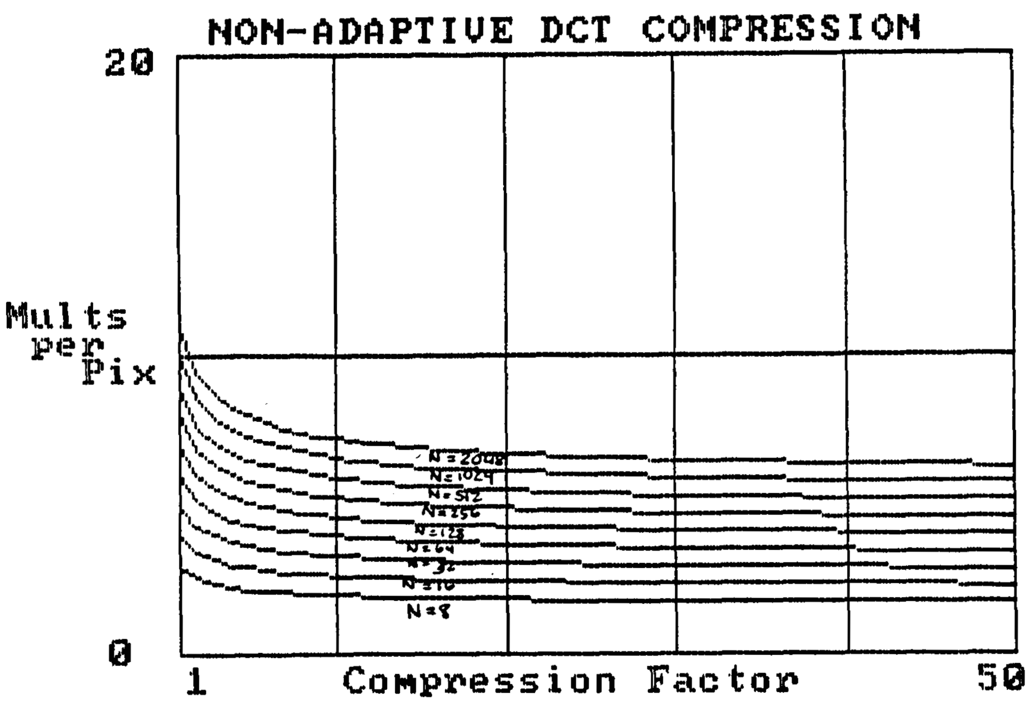


FIGURE 9

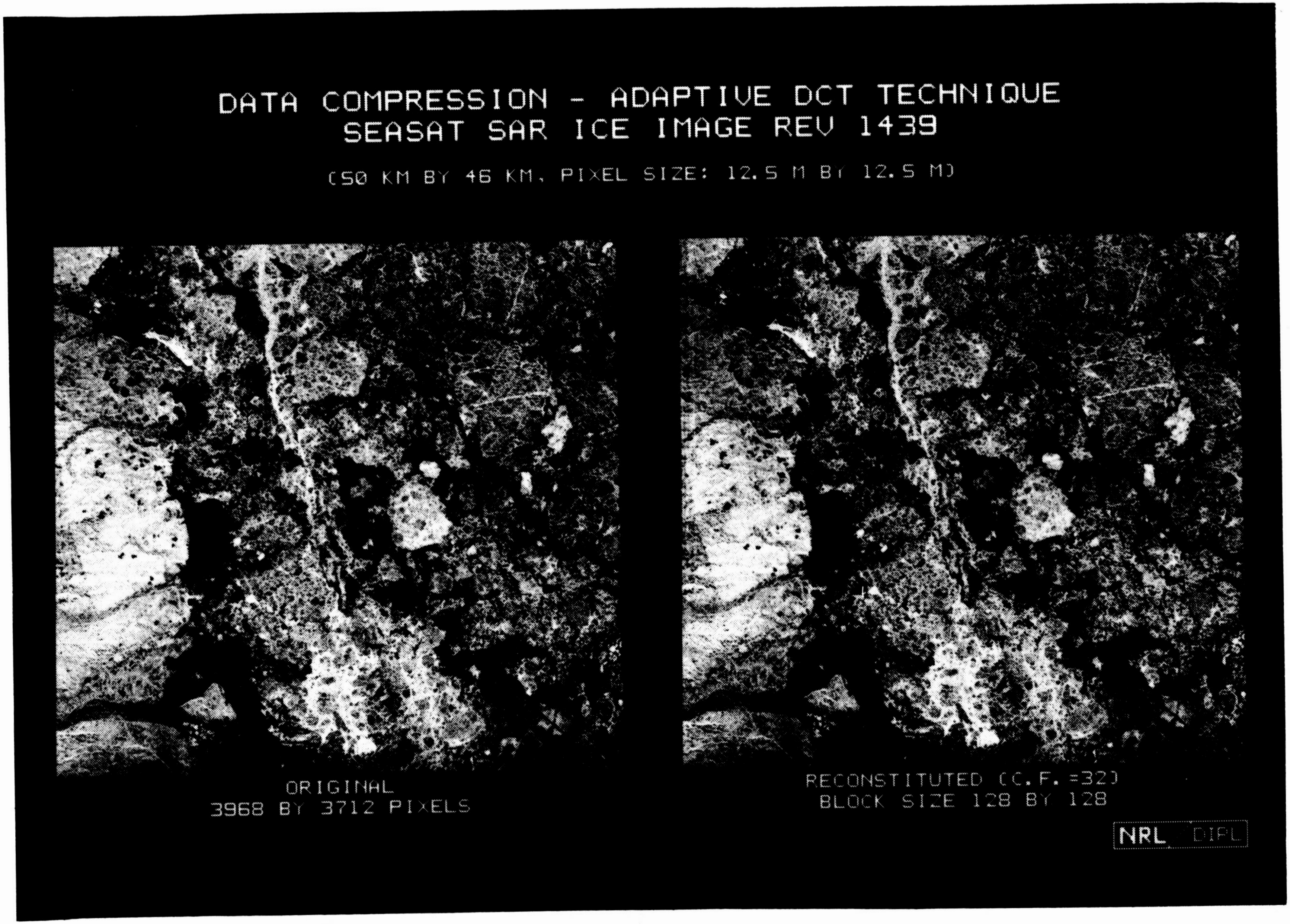

DATA COMPRESSION - ADAPTIVE DCT TECHNIQUE
SEASAT SAR ICE IMAGE REV 1439
(50 KM BY 46 KM, PIXEL SIZE: 12.5 M BY 12.5 M)
ORIGINAL
3968 BY 3712 PIXELS
RECONSTITUTED (C.F.=32)
BLOCK SIZE 128 BY 128
NRL DIPL

Figure 10

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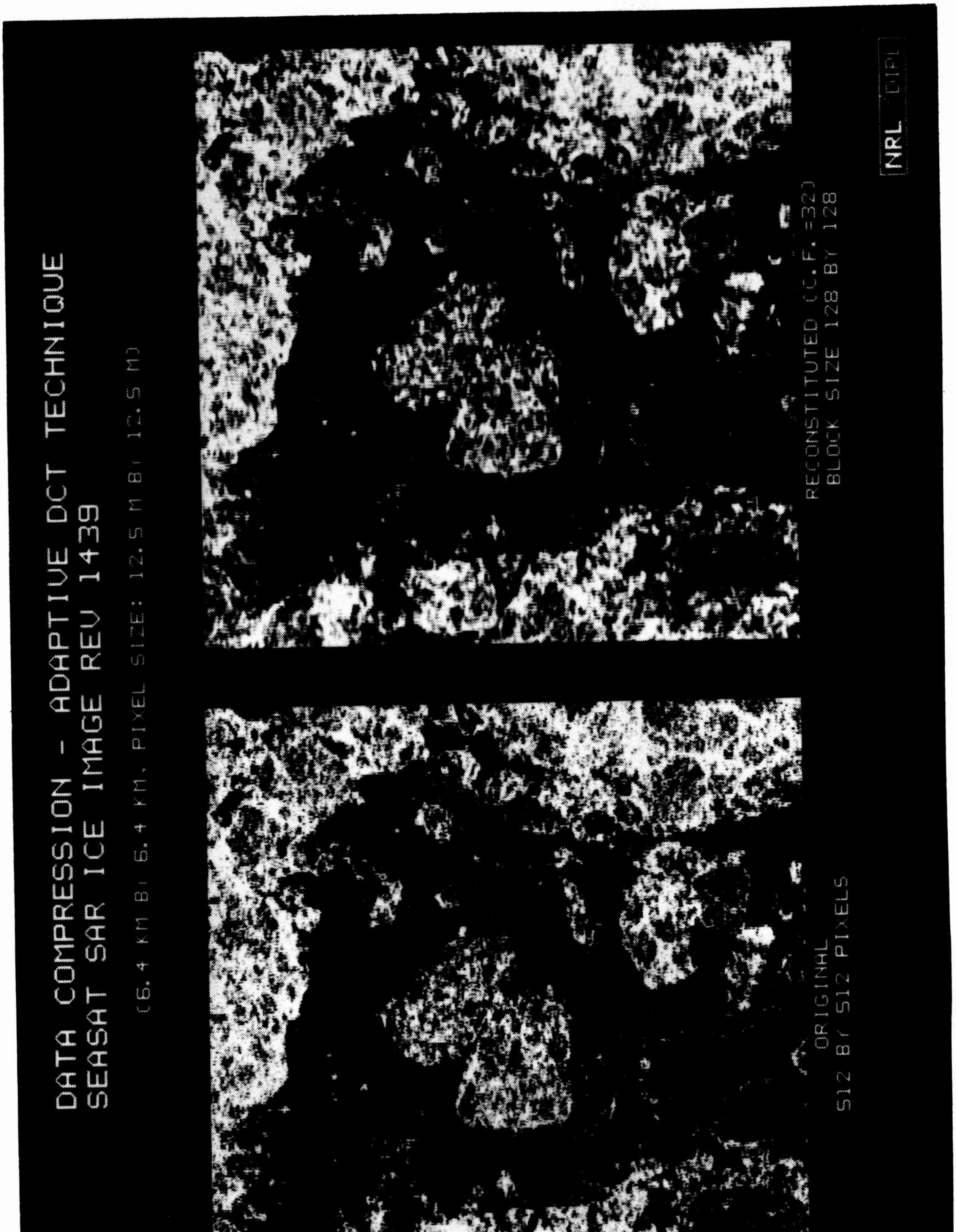

Figure 11