SIR-C GROUND DATA SYSTEM AND PROCESSING ALGORITHM DESIGN

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Abstract

The Shuttle Imaging Radar-C (SIR-C) is the third in a series of space shuttle based synthetic aperture radars (SAR) sponsored by the National Aeronautics and Space Administration (NASA). The SIR-C ground data processing system is to process the playbacked SAR signal data into a variety of data products for distribution to the science community. This paper presents an overview of the end-to-end ground data processing system with emphasis on the unique characteristics involved in the system design. Included in the discussion are science requirements, radar system specifications, input data format specifications, system operations design, data products design, processing algorithm design, hardware architecture design and software design.

Key Words: *Algorithm, Image Processing, Radar, Systems, SAR*

1. INTRODUCTION

The Shuttle Imaging Radar-C (SIR-C) will for the first time provide simultaneous data acquisition of eight radar channels (two radar frequencies: L and C, each comprised of two like-polarized and two cross-polarized channels) from a spaceborne synthetic aperture radar (SAR) [Curlander, 91a], [Curlander, 91b], [Jordan, 91]. This instrument is accompanied by a VV-polarized, X-band SAR (X-SAR) which will operate simultaneously with SIR-C. The SIR-C/X-SAR is currently scheduled for three space shuttle flights, the first being in late 1993. Each flight is planned for a six to eight day data acquisition period. Table 1 summarizes the SIR-C science requirements on the image quality of output products. Table 2 shows the orbit characteristics and the radar specifications.

Resolution broadening	≤ 20%
Integrated Sidelobe Ratio	≤ -14 dB
Peak Sidelobe Ratio	≤ -17 dB
Ambiguity to Signal Ratio	≤ -20 dB
Swath Width	15 Km to 90 Km
Radiometric Accuracy (Science Goal)	
- Relative Cross-Swath (1σ)	± 1.0 dB
- Relative Band-to-Band (1σ)	± 1.5 dB
- Relative Channel-to-Channel (1σ)	± 1.0 dB
- Absolute Each Channel (3σ)	± 3.0 dB
- Phase Error	≤ 10°
Geometric Accuracy (3σ)	
- Absolute Location	≤ 100 m
- Channel-to-Channel Registration Error	≤ 1/8 pixel
- Scale error	≤ 0.1%
- Skew error	≤ 0.1%

Table 1: SIR-C science requirements on the image quality of output data products.

This paper presents the system design of the SIR-C ground data processor, which is being developed at the Jet Propulsion Laboratory (JPL) under contract with NASA [Curlander, 91b]. There are two European space agencies working on the X-SAR processor development: the German Aerospace Research Establishment (DLR) and the Italian Space Agency (ASI) [Runge, 90].

The major challenge to the SIR-C processor design is to cope with a large number of radar modes. Nominally the SIR-C science team has selected seventeen data acquisition modes from all the possible combinations with eight radar channels (See Table 3), two pulse bandwidths and three data quantization formats. Additionally, data will be collected in two nominal attitudes over incidence angles from 17^o to 63^o with a variety of antenna elevation patterns controllable to provide beam spoiling at the steep incidence angles. The large number of radar modes complicates the logics in handling different types of data format and increases the scope of testing the integrated processor software.

SAR Orbit	
- Nominal Altitude	215 ± 25 Km
- Eccentricity	≤ 0.002°
- Inclination	57°
Attitude Measurement Error(3σ)	
- Roll	±1.24°
- Yaw	±1.43°
- Pitch	±1.78°
Attitude Drift Rate Error(3σ)	
- Roll	±0.03°/sec
- Yaw	±0.03°/sec
- Pitch	±0.03°/sec
Transmitter frequency	
- L-Band	1.25 GHz
- C-Band	5.30 GHz
Polarization	HH, HV, VH, VV
Pulse bandwidth	20, 10 MHz
Pulse duration	33.8, 16.9, 8.44 usec
Sampling rate	45, 22.5 MHz
Data quantization format	4-bit, 8-bit, (8,4) BFPQ
Pulse Repetition Frequency	1344, 1395, 1440, 1488, 1512, 1620, 1674, 1736 Hz
Antenna Dimension	
- L-Band	12.1 m x 2.8 m
- C-Band	12.1 m x 0.74 m
Incidence Angle	17° to 63°

Table 2: SIR-C orbit characteristics and radar specifications.

MODE	CHANNEL-1	CHANNEL-2	CHANNEL-3	CHANNEL-4
1	LHH	LHH	LHV	LHV
2	LVH	LVH	LVV	LVV
3	CHH	CHH	CHV	CHV
4	CVH	CVH	CVV	CVV
5	LHH	LHH	LVV	LVV
6	CHH	CHH	CVV	CVV
7	LHH	LHH	CVV	CVV
8	LHH	LHH	CHH	CHH
9	LVV	LVV	CVV	CVV
10	LVH	LVH	CVH	CVH
11	LHH	LHV	CHH	CHV
12	LVH	LVV	CVH	CVV
13	LHH	LVV	CHH	CVV
14	LHH	LVH	LHV	LVV
15	CHH	CVH	CHV	CVV
16	LVH, LHH	LVV, LHV	CVH, CHH	CVV, CHV
23 Tape 1	LHH	LVH	LHV	LVV
23 Tape 2	CHH	CVH	CHV	CVV

Table 3: SIR-C radar data aquisition modes.

The second challenge to the SIR-C processor design is to cope with the large attitude uncertainties and high attitude drift rates of the space shuttle platform as shown in Table 2. The large attitude uncertainties create PRF ambiguity problem in Doppler centroid estimation and large Doppler errors for data acquired over high terrain relief areas. Special techniques (multiple PRF technique and attitude steering technique, respectively) are required to resolve the problems [Chang, 92a], [Chang, 92b]. The high attitude drift rates induce fast Doppler drifts in both cross-track and along-track dimensions. Frequent Doppler update is required to maintain the image quality, which complicates the geometric rectification procedure to produce a seamless image.

The third challenge to the SIR-C processor design is to produce radiometrically calibrated and geometrically registered multi-band, polarimetric SAR image [Freeman, 89], [Klein, 92]. For radiometric calibration, the built-in-test-equipment (BITE) data are designed for probing the health of the antenna, receive only noise data for estimating the noise power, calibration tone signal for monitoring the receiver gain and temperature measurements and T/R module failure information transmitted via the downlink telemetry. These ancillary data and calibration site data are essential to derive radiometric calibration parameters which are applied during the data processing to produce calibrated image product. For geometric registration, special consideration is required in the processor design to ensure that the output images are registered in both cross-track and along-track dimensions.

The remaining paper presents an overview of the SIR-C end-to-end ground data processing system design, which includes input data format specifications, system operations design, data products design, processing algorithm design, hardware architecture design and software design. At the end of the paper, we give a brief summary of the status and plan for the processor development.

2. INPUT DATA FORMAT

The signal data is recorded across four recorder channels on the High Density Digital Cassette (HDDC). The data rate for each recorder channel is 45 Mbps for a total of 180 Mbps. The signal data is quantized into one of three types of format: 4-bit, 8-bit or (8, 4) block floating point quantization (BFPQ). Nominally, the data is collected over a period called data take using the same set of commanded radar parameters. The length of the data take varies from 3 minutes to as long as 15 minutes for ocean site data. The average length is estimated to be between 4 and 5 minutes.

The nominal SIR-C data take consists of a turn-on sequence, followed by the science data collection and a turn-off sequence as shown in Figure 1. The first four seconds of the turn-on sequence consist of (one second each): receive only noise data, caltone scan data, low noise amplifier (LNA) BITE data and high power amplifier (HPA) BITE data. These four second data are used for radiometric calibration.

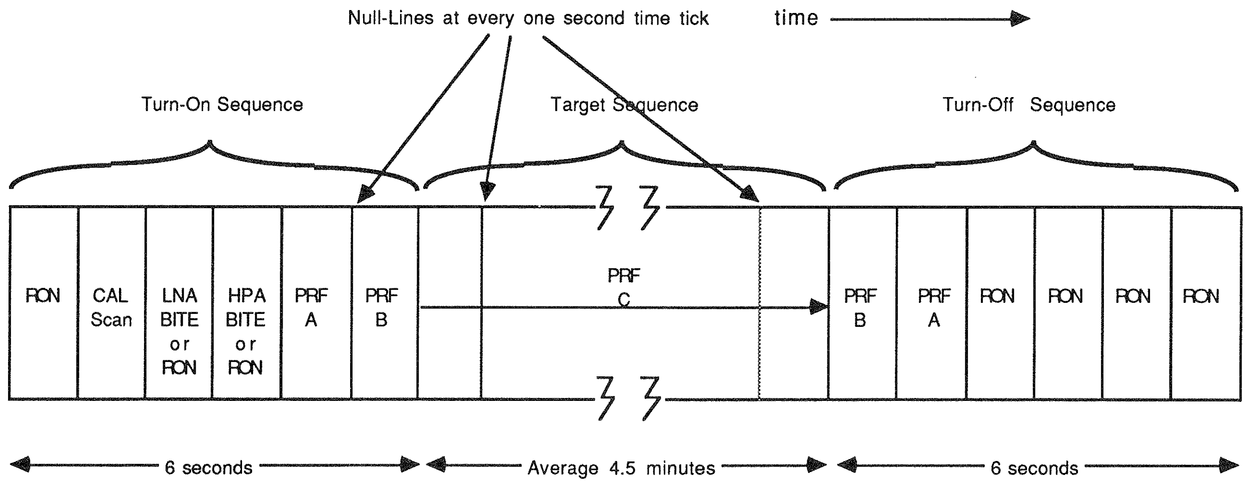

Figure 1: SIR-C input data run format. Each segment in turn-on and turn-off sequence is 1 second duration. RON: Receive Only Noise, LNA: Low Noise Amplifier, HPA: High Power Amplifier, CAL scan: Caltone Scan.

The remainder of the turn-on sequence consists of one second of PRF_A data and one second of PRF_B data which together with the first second of PRF_C data are used for resolving PRF ambiguity in estimating the Doppler centroid frequency [Chang, 92a]. The system remains on PRF_C for collection of the science data. The turn-off sequence is similar to the turn-on sequence in that the science data collection is followed by one second each of PRF_B and PRF_A. The last four seconds of the turn-off sequence are receive only noise data.

At every one second time tick, a null-line is inserted. The null-line is obtained by setting a half of the phase array elements with a 180^o phase difference to create a null around the center of the antenna elevation pattern. The null-line is used to estimate the shuttle roll angle drift.

A sinusoid waveform, called the calibration tone (caltone) signal, is injected in the receiver electronics and recorded together with the return echo data. The caltone is used to estimate the receiver gain change as the temperature varies.

3. SYSTEM OPERATIONS DESIGN

Operations of the SIR-C processor is comprised of two main phases: phase 1 survey processing and phase 2 standard processing, which last for a total of one year. During the phase 1 operations, a quick-look survey processor is employed to process single-frequency band, single-polarization channel data into low resolution strip images. These survey images will cover all the SIR-C ground sites albiet with a single radar channel. By-products of the survey processor include unambiguous Doppler centroid estimates history and roll angle estimates history. Additionally, during the phase 1 operations, some selected data segments (covering calibration sites) will be processed into single-look, full-resolution complex imagery. These data will be analyzed to derive the parameters used for antenna pattern generation and polarimetric calibration. These parameters will be applied during the phase 2 standard processing to produce phase and amplitude calibrated data products [Freeman, 89], [Klein, 92].

The system operations schedule is planned as follows. Six weeks are allocated for processor check-out upon receipt of the first signal data tape. Phase 1 operations will begin following the completion of the processor system check-out and last for a period of twelve weeks. This is followed by phase 2 operations for a period of forty weeks.

4. DATA PRODUCTS DESIGN

The SIR-C output data products include three image products: survey image, standard multi-look image and standard single-look image; and one reformatted signal data product. The throughput requirements are to produce 24 survey image products per week during the phase 1 operations and to produce 9 standard multi-look image, 1 single-look image and 1 reformatted signal data products per week during the phase 2 operations. The expected processor throughput far exceeds the requirements.

The survey image is a 4-look, single-polarization strip image, stored in the byte amplitude format. The image is deskewed to zero-Doppler and resampled to the ground range domain with a 50 meter pixel spacing. The resolution is approximately 100 meters. The length of the survey image is equal to the length of the data take. The average length is approximately 4.5 minutes or 2000 Km. The survey image will be recorded on Alden thermal prints and CD-ROMs. The CD-ROMs will be distributed to all the principal investigators (PIs).

The standard multi-look image is a multiple look, polarimetric (single-, dual- or quad-polarization) frame image. The image is deskewed to zero-Doppler and resampled to the ground range domain with a 12.5 meter pixel spacing. The azimuth resolution is chosen to be 25 meters. The range resolution is chosen to be 25 meters or the natural resolution if greater than 25 meters. The image data is stored in a compressed cross-product format [Dubois, 89]. The basic frame size is chosen to be 100 Km. The image will be recorded on Kodak prints and CEOS formatted tapes.

The standard single-look complex image is a single-look, polarimetric (single-, dual- or quad-polarization) frame image. The image is processed to full-resolution, deskewed to zero-Doppler and presented in the slant range domain in natural pixel spacing. The image data is stored in a compressed scattering matrix format. The basic frame size is chosen to be 50 Km. The image will be recorded on CEOS formatted tapes and a reduced, detected image will be printed by the Kodak printer.

The reformatted signal data contains the signal data reformatted in the range line byte format. The signal data together with the decoded radar parameters will be stored on CEOS formatted tapes.

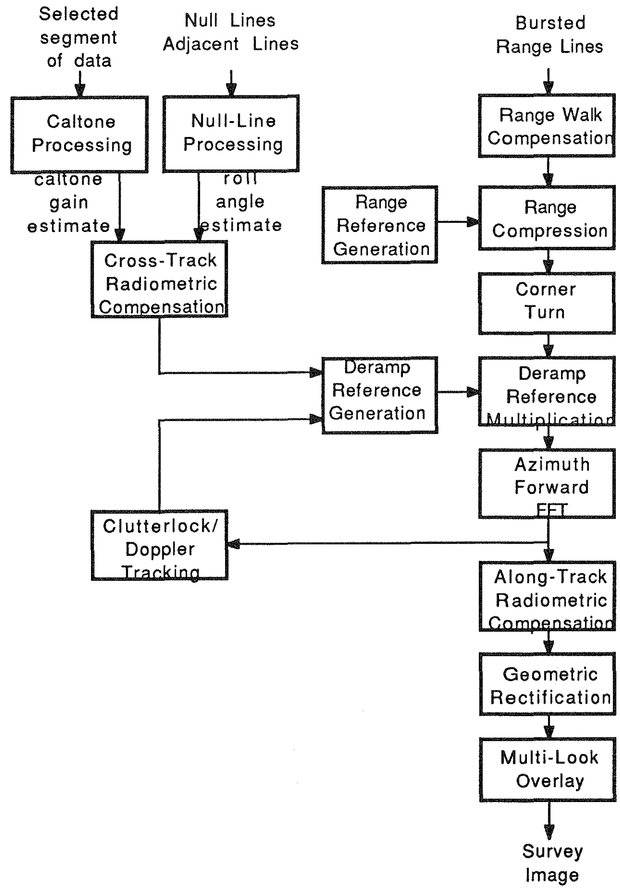

Figure 2: Survey processing algorithm flowchart.

5. PROCESSING ALGORITHM DESIGN

5.1 Survey Processing Algorithm

The SIR-C survey processor utilizes a burst mode processing algorithm [Sack, 85], [Curlander, 91b]. The algorithm flow chart is shown in Figure 2. The survey processor is designed to process an entire data take into a strip image in approximately one-seventh the real time data collection rate. To attain high throughput rate, the data is bursted in azimuth (slow time) with a one-quarter duty cycle factor. The data volume is further reduced by a factor of four in range (fast time) by processing the data using only one-quarter of the range chirp bandwidth. The azimuth compression is performed using the spectral analysis (SPECAN) algorithm which requires fewer azimuth FFT's than the traditional matched filtering algorithm. Following azimuth compression, radiometric correction is applied to compensate for the along-track radiometric modulation. This is followed by a geometric rectification step that resamples the slant range-Doppler image into the ground range cross-track and along-track domain. The rectified burst images are then overlaid to produce the final multi-look strip image.

For the survey processor, the initial Doppler centroid frequency is determined using a clutterlock routine and a ambiguity resolution technique that requires a multiple PRF data collection at the start of each data take [Chang, 92a]. The unambiguous Doppler centroid frequency is then tracked by a burst mode clutterlock algorithm during the data processing. The Doppler frequency rate is solely derived from the ephemeris parameters. Analysis results show that the accuracy of the ephemeris is sufficient for generation of survey products without employing the autofocus routine.

5.2 Standard Processing Algorithm

Prior to standard processing, preprocessing is employed to iteratively refine the Doppler centroid frequency and the Doppler frequency rate estimates using clutterlock and autofocus techniques [Li, 85]. Doppler centroid frequency is estimated from the azimuth spectrum by locating the energy centroid. Doppler frequency rate is estimated from the look registration error by azimuth cross-correlating the look-1 and look-4 images obtained by spectral division. Identical Doppler parameters are used for processing all polarimetric data channels to ensure the phase coherency required for the polarimetric data analysis. This approach will result in some increase in azimuth ambiguities if the antenna beams are not exactly aligned.

The range-Doppler processing algorithm (i.e., the rectangular algorithm) with secondary range compression and frequency domain range cell migration compensation was selected by SIR-C for standard processing [Wu, 82], [Jin, 84], [Curlander, 91a]. The algorithm flowchart is shown in Figure 3. The range compression and azimuth compression matched filtering operations are performed using the frequency domain fast convolution technique. All the signal data, independent of the final products, are initially processed to single-look, complex imagery using the full azimuth processing bandwidth. This is followed by an azimuth deskew operation where the resulting deskewed, single-look complex image is then radiometrically corrected.

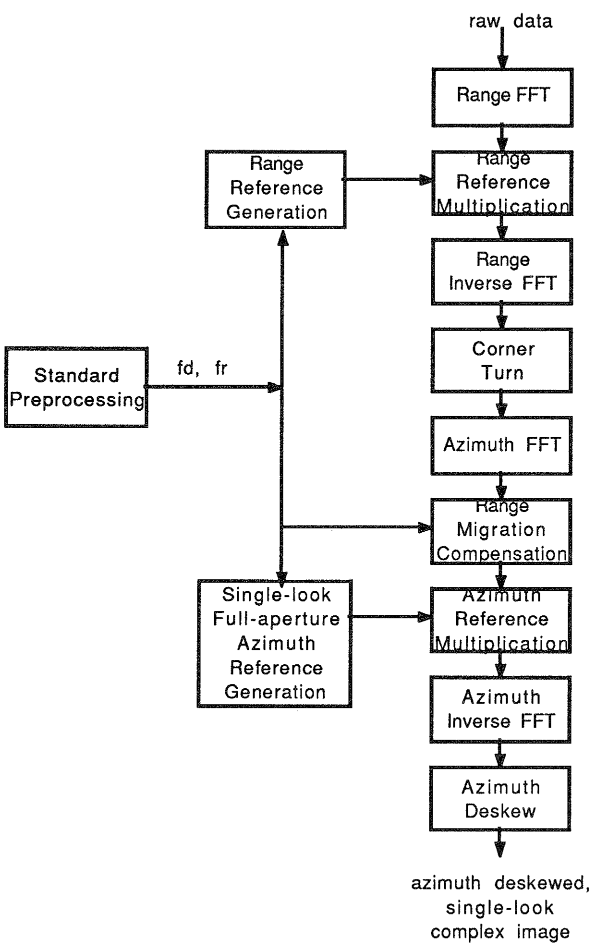

Figure 3a: Standard processing algorithm flowchart.

Following standard processing, postprocessing is employed to generate the final image product [Curlander, 91b]. Data reduction is the only postprocessing function for generation of single-look image products, where the data reduction function is applied to the scattering matrix. Major postprocessing functions for generation of multi-look image products include cross-product generation, multi-look filtering and data reduction where the multi-look filtering combines multi-looking as well as geometric rectification functions. For SIR-C, all the multi-look images will be filtered to a 25 m

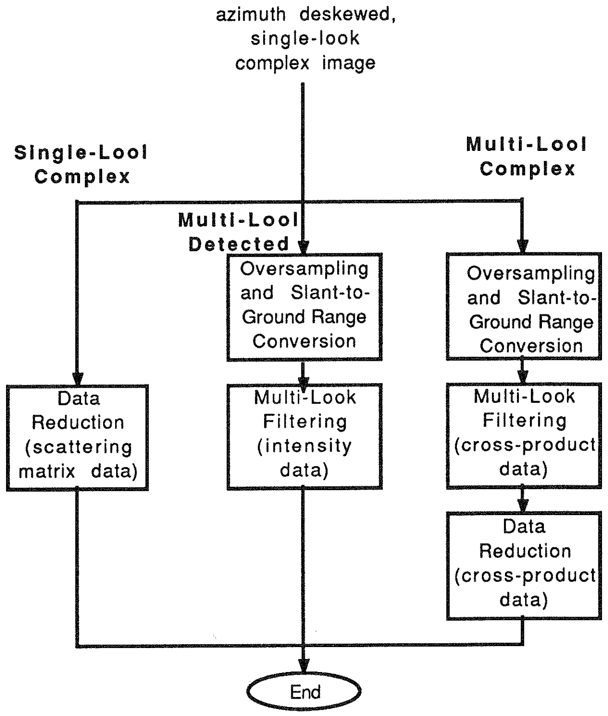

Figure 3b: Standard postprocessing algorithm flowchart.

resolution in azimuth and a 25 m or natural resolution in range. The pixel spacing is selected to be 12.5 m in both range and azimuth. The filtering is applied to the cross-products. The data reduction function is then applied to the multi-look filtered cross-products data.

6. HARDWARE ARCHITECTURE DESIGN

Figure 4 shows the hardware architecture design of the SIR-C ground data processor. The entire processor system is composed of seven subsystems. The Data Transfer Subsystem (DTS) performs raw data reformatting and line synchronization. The SAR Correlator Subsystem (SCS) processes the SAR signal data into survey and standard image data. The Output Products Subsystem (OPS) performs image data reformatting, recording and display. The Control Processor Executive (CPX) controls the processing sequence of the above three subsystems. The Catalog Subsystem (CAS) stores the information concerning the processing request and processor status into database. The Calibration Subsystem (CAL) is used for generation of calibration parameters and analysis of calibration site image quality. The Radar Data Center (RDC) archives all the output data products.

The SCS consists of a STAR array processor with three computational modules, an Alliant FX/8 mini-supercomputer with eight compute elements and an Alliant FX/2800 mini-supercomputer with twelve i860-based CPU's. The STAR array processor is the main compute engine for survey proces-

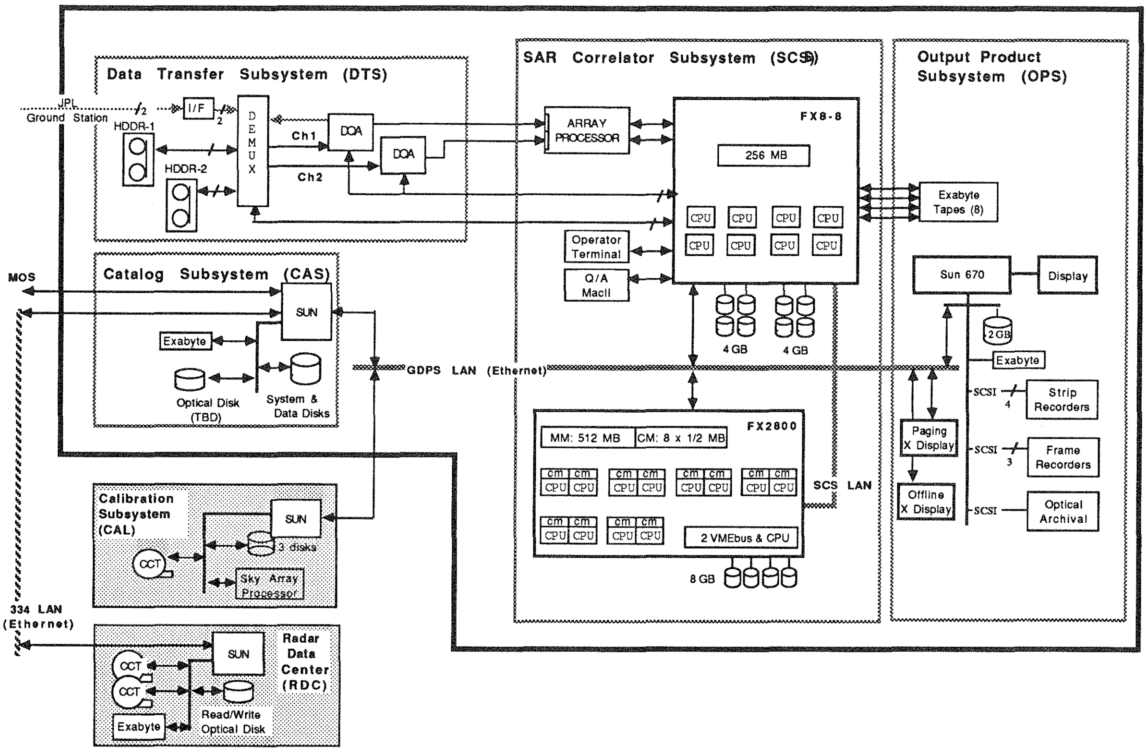

Figure 4: SIR-C ground data processing system hardware architecture.

sor. Its FFT performance is measured at 120 MFLOPS using three computational modules. The Alliant FX/8 is primarily used for standard postprocessing functions. Its aggregate FFT performance nears 20 MFLOPS. Two SKYBOLT accelerator boards are installed to speed up the FX/8 computer, which provide additional 100 MFLOPS compute power. The FX/2800 is the main compute engine for standard processor and standard preprocessor. Its aggregate FFT performance is measured at over 300 MFLOPS. Computational tasks are distributed over computers for concurrency processing in order to provide maximum processor throughput.

The DTS consists of a high density digital recorder, a DEMUX and two data quality analyzers (DQA). The DEMUX is used for selection of recorder channel for data processing. The DQA is used for line synchronization and verifying the data quality and integrity. The OPS consists of Exabyte tape drives, Alden thermal printers and Kodak color printers. Three subsystems, OPS, CAS and CAL, run on three separate SUN Sparc workstations. The image display and operator interface display are handled via X-terminals.

7. SOFTWARE DESIGN

There are a variety of software packages used for developing the SIR-C processor due to the need of specific applications. The major part of the signal processing software is written in FORTRAN while the input and output formatting software is written in C. The image display software is developed using X-library routines. The operator interface software is developed using a graphics user interface software called Teleuse which runs on top of MOTIF. The image annotation is created using a commercially available software package called PV-WAVE. The catalog subsystem software uses both FORTRAN and INGRES.

8. SUMMARY

Design and implementation of the SIR-C ground data processing system is quite a challenge due to the large number of radar modes and the large attitude errors/high attitude drift rates. In addition to the correlation software, there are many software programs required for deriving parameters from the ancillary data in order to ensure that the output image products are radiometrically calibrated and geometrically registered. Another challenge to development of this large software based system is its complex interfaces among the many software programs. Clear interface definitions are essential to successfully deliver the operational system on schedule.

Currently, we are in the middle of developing all the processor software. Major computer hardware will be installed by summer 1992. The end-to-end system integration will take place in early 1993. The entire system is scheduled to begin operations in late 1993.

Development of the SIR-C processor inherits a great deal of experience from the previous and existing spaceborne and airborne SAR processors, such as SEASAT, SIR-B, and JPL AIRSAR. Experience accumulated from the SIR-C processor will certainly benefit future processor design and development, such as EOS SAR and RADARSAT.

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