INTERAGENCY ARRAYING

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ABSTRACT

Voyager ground aperture requirements for Neptune encounter in August 1989 exceed the expected capabilities of the Jet Propulsion Laboratory's Deep Space Network (DSN) 70- and 34-meter antennas. Agreements have been consummated with the National Science Foundation to array the National Radio Astronomy Observatory's Very Large Array in New Mexico and with the Commonwealth Scientific and Industrial Research Organization's Parkes Radio Telescope in Australia with the DSN. This technique, which was demonstrated during Voyager's Uranus encounter, will provide a greater return of imaging and non-imaging science data. The arrays consist of the normal facility receiving equipment at each location, augmented by special receiving, combining, recording, and monitor and control equipment. This equipment has been designed, is being implemented, and will be operated during the Neptune encounter to effectively double the available antenna aperture over the western United States and Australia.

Keywords: Telemetry arraying, baseband combining, symbol stream combining, effective aperture, very long baseline combining.

INTRODUCTION

Voyager Project experimenters hope to characterize Neptune's interior, atmosphere, rings, satellites, and magnetosphere as they did at Jupiter, Saturn, and Uranus--but they face formidable obstacles. Because Neptune's distance from the sun (4.5×10^9 km, 30 A.U.) reduces available light, images take longer. Because of greater distance from Earth, radio signals are attenuated more (down 3.5 dB from signals received from the spacecraft at Uranus). These considerations caused studies to be performed, negotiations entered, and trade-offs made to match requirements with capabilities. These activities and their outcome are described in this paper.

Requirements on Ground Aperture

The requirements on ground aperture, in terms of data reception, can best be explained using two categories: (1) a general, all-purpose, continuous data requirement, general science and engineering (GS&E); and (2) a specific, instrument-oriented, episodic, data requirement, equivalent full-frame images (EFFI). The GS&E contains spacecraft engineering, science instrument health, and low-data-rate science instrument data. EFFI contain actual imaging frames (800-by-800 eight-bit pixels) or the equivalent (5 Mb) in high-data-rate science instrument data, such as the Plasma Wave and Planetary Radio Astronomy Subsystems.

The established requirement for GS&E data is continuous, 24 hours per day, at 4.8 kb/s during the Neptune encounter period--5 June through 2 October 1989. The requirement for EFFI, in EFFI/day, varies from the time in days of closest Neptune approach (N), as follows: from N-80 to N-15 and N+5 to N+30 days - 50 EFFI/day; from N-15 to N-1 and N+l to N+5 - 225 EFFI/day; and from N-1 to N+l days - 300 EFFI/day. These requirements specify 90 percent confidence in the telecommunications link.

DSN Capabilities

Neptune encounter data will be collected and sent to the Voyager Project at Jet Propulsion Laboratory (JPL) from the three DSN deep space communications complexes (DSCC) in Madrid, Spain (MDSCC); Goldstone, CA (GDSCC); and Canberra, Australia (CDSCC). The maximum elevation angle and spacecraft pass duration at these complexes affect the share of data each can provide. These are, at Neptune encounter: MDSCC 27.5 degrees and 8.3 hours; GDSCC - 32.6 degrees and 8.9 hours; and CDSCC 76.9 degrees and 13.3 hours. The Voyager Project designed the mission accordingly. Neptune closest approach will occur during GDSCC tracking; Triton closest approach and occultations of Neptune and Triton will occur during CDSCC tracking.

The DSN has three antennas available for Voyager support at each complex--one 34-meter standard (34 STD), one 34-meter high-efficiency (34 HEF), and one larger antenna, currently being upgraded from 64-meter (64m) to 70-meter (70m) aperture. Any combination of antennas at a complex can be arrayed (1). Using the 64m-antenna gain and system noise temperature at 8.4 GHz as a reference for DSN aperture units (APU), the antennas and arrays produce the following performance:

Element(s)	APU	Equivalent dB
70m	1.55	+1.9
34 HEF	0.35	-4.6
34 STD	0.25	-6.0
70m + 34 HEF	1.9	+2.8
70m + 34 HEF + 34 STD	2.15	+3.3

With this capability, the GS&E requirement could be met, except for short periods caused by lack of sufficient overlap between complex view periods, but the EFFI requirement could not. Only about 150 EFFI per day could be received.

Other Agencies' Capabilities

The National Radio Astronomy Observatory's Very Large Array (NRAO VLA), in Socorro, New Mexico, is a Y-shaped array of 27 25-meter Az-El antennas. This represents a significant aperture in the approximate longitude of Goldstone. However, there were two difficulties. First the VLA did not use the 8.4-GHz frequency used by Voyager. Second, the installation uses a control technique in antenna pointing which causes a 1.6-ms gap in the received signal each 52 ms. NASA proposed solving the first problem by installing 8.4-GHz low noise amplifiers (LNA), and software simulations indicated that the concatenated convolutional and Reed-Solomon coding used for Voyager telemetry data transmission could bridge the gaps (2)(3)(4).

A more straightforward situation existed in Australia. The Australian Commonwealth Scientific and Industrial Research Organization (CSIRO) operates a 64-meter Az-El radio telescope at Parkes. This antenna supported 63 passes during the Voyager Uranus encounter. The Parkes station had been outfitted with a European Space Agency (ESA) 8.4-GHz maser front end and a microwave link installed to Canberra (still in place) (5)(6). The Parkes station was used for tracking ESA's Giotto spacecraft to Halley's Comet and for telemetry real-time arraying with the three CDSCC antennas. Personnel from the CDSCC had operated the newly installed receiving and data processing equipment during a very successful encounter. The use of the Parkes facility contributed approximately 2250 EFFIs to the science data return.

Coverage Agreement

In February 1985, NASA and NSF signed a Memorandum of Agreement which stated that the VLA would support the Voyager Neptune encounter during 40 spacecraft passes. (The National Science Foundation funds the NRAO, which operates the VLA, while JPL is funded by NASA.) NASA stated that it would assist in the implementation of twenty-seven

8.4-GHz feed horns and LNA, additional power facilities, and all interfacing requirements (7)(8).

In September 1986, NASA and CSIRO signed a Memorandum of Understanding stating that Parkes would support the Voyager Neptune encounter during 80 spacecraft passes. NASA would reinstall the ESA maser and approximately the same complement of data processing equipment as used for Uranus encounter.

With these two radio astronomy observatories (RAO) augmenting the DSN capabilities, the full EFFI requirements could be met--provided the design, implementation, and operations were successful.

SYSTEM DESIGN AND CONFIGURATION

The arraying technique was developed for point-to-point microwave installations to provide increased communications performance by frequency and space diversity reception. The technique was adapted for deep space missions during the Voyager Saturn encounter to increase the apparent ground antenna aperture. By combining the data from two or more antennas, at either the baseband or symbol stream detection level, in proportion to their signal-to-noise ratios (SNR), a composite signal can be obtained which is approximately the sum of the individual SNRs (9)(10).

The overall interagency arrays have been given the designations Very Large Array-Goldstone Telemetry Array (VGTA) and Parkes-Canberra Telemetry Array (PCTA). These arrays have the same function and share some common subsystems, but the arrays differ in a few particulars. A breakdown into subsystems reveals these aspects. Figure 1 is a block diagram of the VTGA and PCTA. Facilities at the Goldstone and Canberra DSCCs are generally the same except for the video link terminal and the combiner. The principal differences at the RAOs lie in antennas (and antenna phasing at VLA), antenna control, front-end equipment, interfaces with the DSN array, and the video link to the DSCC.

The principal equipment designed to effect the array are the Receiver Subsystem (Receiver) at the RAOs, the Combiner Subsystem (Combiner) at the DSCCs, the Monitor and Control Subsystem (Monitor/Controller) whose elements are split between RAO and DSCC, and the Symbol Stream Recording and Combining Subsystem (Recorder) at all sites. In addition, primary power, frequency and timing references, intersite communications, and logistics and operational support are part of the design--but their details will not be described here. The antennas, antenna pointing, and microwave equipment design at the RAOs and DSCCs are functions of the existing facilities--as are the processing of the combined telemetry output of the array (convolutional decoding, formatting, transmission, frame synchronization, Reed-Solomon decoding, decommutation, and further distribution).

Receiver Subsystem

The Receiver at VLA and Parkes provides the intermediate frequency demodulation to telemetry baseband. Its major capabilities are to track spacecraft signals with signal dynamics encountered during planetary flybys, coherently detect the telemetry data, and provide signals for determining carrier amplitude. The Receiver controller configures the Receiver to acquire the carrier signal to determine precise tuning, after using frequency predictions to get within range of the acquisition feature. The Receiver major interfaces are with the RAO microwave subsystem, Monitor/Controller, and timing subsystem. The Receiver can be operated by its controller (from the Monitor/Controller or from a local terminal) or, in emergency, by fully manual means.

The Receiver accepts an intermediate frequency signal from the RAO microwave subsystem and outputs a baseband signal containing the spacecraft subcarrier (nominally 360 kHz) and data (nominally 21.6 kb/s). The input frequency is centered around 315 MHz at Parkes, 18.75 MHz at VLA; the VLA input is upconverted to 315 MHz. The microwave system uses a fixed local oscillator adjusted for the mid-point of the dynamic range expected during the pass. The Receiver tracks the received signal over the ranges and rates expected for spacecraft cruise (<20 kHz per pass, 1 Hz/s) and Neptune encounter (<200 kHz, 75 Hz/s). The carrier tracking loop bandwidth is selectable to 10.8 Hz (cruise) or 21.6 Hz (encounter). The telemetry output, which has a 6-MHz bandwidth, is routed via the Monitor/Controller to the Recorder and the video link.

Receiver configuration, status, and performance signals are presented to the Monitor/ Controller. These signals include carrier signal level and loop static phase error measurements. Control information, including frequency predictions, are received from the Monitor/Controller. A 1 pulse per second timing and a 5-MHz frequency reference are received from VLA or PCTA equipment. An internal test signal generator (TSG) provides a signal with adjustable levels of carrier, subcarrier, data, and noise, at the microwave interface frequency, to verify receiver performance. Provision is made for accepting an external test signal and a VLA gap simulation.

Combiner Subsystem

The Combiner is located at the DSCCs. Equipment consists of a Long Baseline Combiner (LBC) at CDSCC for the PCTA and a Very Long Baseline Combiner (VLBC) at GDSCC for the VGTA. The differences are required by the nature of the video link: a 260-kilometer microwave link at PCTA and a synchronous satellite link at VGTA. The

Combiner design is patterned after equipment developed for DSN complex arrays but with capabilities enhanced to accommodate the different baseline characteristics. The DSCC combiner experiences delays of <100 μs, the PCTA LBC ~2 ms, and the VGTA VLBC ~260 ms. The longer baselines also affect the dynamics: the VLBC will accommodate a delay range of ±2400 μs, a 240 ns/s rate of change and an acceleration of 0.02 ns/s/s. The maximum combining loss will be <0.2 dB. Lock-up time will be <30 s.

The Combiner accepts two real-time inputs: (1) the 70M or DSCC- arrayed signal from the DSCC combiner and (2) the telemetry signal received from the RAO via the video link. The input signals consist of the 360-kHz subcarrier, symbols (typically 43.2 ksym/s), and noise. The Combiner performs the cross-correlation, tracking, and summing functions to coherently combine the input. The combining process provides for automatic weighting of the summing function, including the ability to suppress a noncontributing input in real time. The resultant data output is an eight-bit soft-quantized symbol stream. The output is presented to the DSCC telemetry subsystem for decoding and further processing. Prior to the start of the pass, tracking station locations and operating parameters and spacecraft operating mode and ephemeris have been input via the array controller. The Combiner configuration, status, and performance parameters (including the SNR of the inputs and combined output) can be monitored at the array controller, at the DSCC, and at JPL.

Monitor and Control Subsystem

The Monitor/Controller provides the switching, interfacing, combining, monitor, and control functions for the real-time and non-real-time arrays. It also provides test signals for test and calibration of the total system, including the Receiver, Recorder, and video link equipment. Equipment at all sites includes array and communication controllers, switching assemblies, TSG, Subcarrier SNR Estimators, and commercial test equipment.

The Monitor/Controller performs the central control, configuration, interconnection, combining, testing, and monitoring functions necessary to coordinate all the capabilities of the array.

Control and monitoring is effected via communications controllers which interface with the assemblies and array controllers. The array controllers interface with the communications controllers, with each other, and with operations personnel at either terminal of the array. The array controllers are used to control, configure, operate, and monitor the array.

A switching assembly is operated via the array controller or manually to select the signals for combining, recording, and routing test signals for system testing.

A Monitor/Controller TSG, in conjunction with the Receiver TSG, provides the capability to simulate the relevant dynamic characteristics of the spacecraft and array with dynamic signal delays. The simulation includes the capability to synchronize the TSG at the RAO with the TSG at the DSCC.

The Monitor/Controller accepts timing and frequency reference signals at all sites and provides all interfaces with the communications terminals and the DSCC subsystems. It also provides configuration and control signals to the Recorder during non-real-time playback operations.

Recording Subsystem

The Recorder demodulates the baseband telemetry signal at each site, records the soft quantized symbols, and provides for subsequent playback and combining at the DSCC for processing through the remainder of the real-time telemetry system. The equipment at all sites is the same. Major capabilities are to detect and soft quantize the telemetry symbols from the telemetry baseband; to provide performance monitoring data; to digitally record the symbols alternately on two recorders, avoiding tape gaps; and to playback, synchronize, and combine signals from two previously recorded tapes for input into the DSCC telemetry subsystem. In the event of a real-time communication failure, tapes from the RAO will be air (VLA) or ground (Parkes) transported to the DSCC for playback. The major interfaces of the Recorder are with the Monitor/Controller.

The Recorder consists of two redundant assemblies, each composed of a demodulator/ symbol synchronizer/SNR estimator, two tape drives, and a computer/combiner. The site and spacecraft information provided to the combiner is also provided to the Recorder. During the pass, the Recorder receives the baseband output of the array receiver or the DSCC telemetry subsystem and records an eight-bit, twos-complement, soft-quantized symbol representation at 6250 bpi (2460 b/cm) on standard 2400-foot (730-m) magnetic tapes. Time data, site data, spacecraft data, and an SNR estimate are also recorded. Tape drives are alternated automatically; redundancy is provided for quick failure recovery. The SNR for each recording is provided to the Monitor/Controller for monitoring at the array controller.

During playback, two tapes are mounted on the recorder, their times synchronized, and the outputs combined. The resultant soft-quantized symbol stream is presented to the DSCC telemetry subsystem for convolutional decoding, blocking, and transport to JPL in the same manner as real-time data.

Supporting Subsystems

Power, frequency references, timing references, the inter-site communication system, and predictions generation support are provided by existing, augmented, or contracted capabilities. Power is obtained from the host organization at all sites. At VLA, existing commercial power was augmented by the installation of two diesel generators for increased reliability. Diesel power will be the prime power source during Voyager support. The 1 pulse per second timing and 5-MHz frequency references are provided by the host reference: active hydrogen maser at the DSCCs, rubidium standard at VLA, and cesium standard at Parkes. Global Positioning system receivers will be added at the RAOs to improve the knowledge of local clock offset from DSN clocks.

The communications link for VGTA is contracted from NASA Communications and provides: a 5-MHz-bandwidth satellite video link for telemetry, two 9600-baud circuits for Monitor/Controller computer links, two voice circuits, and 110-baud teletype service. PCTA requires the same service, but it uses the existing Telecom Australia microwave for the video link between Parkes and Canberra. All necessary predictions for the DSCCs, RAOs, VGTA, and PCTA are generated at JPL in the Network Support Computer. New sites identifications, coordinates, and ephemeris translations were added for these arrays.

IMPLEMENTATION

The VGTA and PCTA are required to be implemented with minimum interference to currently operational and heavily committed facilities. NASA, NSF, CSIRO, and ESA are all involved to some extent in the implementation. The VGTA implementation will be discussed first, then the differences involved with the PCTA implementation will be highlighted.

VLA-GDSCC Telemetry Array

The VGTA was assigned Project status by JPL and NRAO to ensure that the necessary resources were available for the array. Receiver, Combiner, Monitor/Controller, and Recording Subsystems, interfaces with other VLA and DSN subsystems, communications between sites, and testing will be covered in the following paragraphs. (The 8.4-GHz feedhorn and LNA implementation at VLA is discussed in a companion paper, and will not be discussed here.)

At VLA, all VGTA equipment will be installed in an area adjacent to the VLA control room. The phased, combined, analog-summed signal will be passed to the VGTA receiver at 18.75 ±4 MHz. VLA status, configuration, and performance signals will be routed to and displayed at the VLA operator’s console co-located with the array controller. The baseband output will be delivered to a ground satellite tracking terminal supplied by NASA Communications.

At GDSCC, a similar terminal is used to receive the VLA telemetry baseband and monitor signals, to send control signals from the GDSCC Monitor/Controller to its counterpart at the VLA, and to send slow-scan television images and operational traffic to VLA. The Combiner receives telemetry baseband from the combined 70m and 34m antennas at GDSCC, combines it with the VLA baseband, and delivers this signal to the DSN telemetry subsystem. The DSN telemetry subsystem provides monitoring of the Combiner input and output signals.

Parkes-CDSCC Telemetry Array

The prime differences between this array (PCTA) and the VGTA are (1) the interface between the RAO microwave subsystem and the Receiver and (2) the communications link between the RAO and the DSCC. The microwave at Parkes includes an ESA-provided 8.4-GHz feed horn and maser. This assembly, successfully used during the Voyager Uranus encounter, is being refurbished and tested at JPL. The same generic signals are distributed as at VLA, except that the telemetry nominal center frequency is 315 MHz, without carrier tracking. The PCTA communications link is furnished by the previously mentioned microwave link installed for the Voyager Uranus encounter. The same signals are exchanged with CDSCC as the VLA exchanges with the GDSCC. At Parkes, all PCTA signal processing equipment will be installed in a trailer adjacent to the radio telescope. The CDSCC installation will be identical to GDSCC, with the exception of the communications terminals (microwave at CDSCC and satellite at GDSCC).

Schedule

The overall Interagency Array schedule is shown in Figure 2. The shorter lead time for PCTA corresponds with its lesser complexity compared to VGTA and the condition of PCTA being basically a reinstallation of a proven implementation.

VGTA implementation is proceeding so as to permit development and phased integration and test of the new 8.4-GHz equipment and to permit prototype design and test of the Receiver, Combiner, Monitor/Controller, and Recorder Subsystems. The communications link will be activated in mid-1988 for testing with concurrent Voyager spacecraft tests. All implementations and acceptance testing will be complete in January 1989, to permit operations test and training to be completed by the first Voyager need date in April 1989.

PCTA implementation includes testing of the Parkes equipment at JPL prior to shipment to Australia. The signal processing equipment will be installed and tested starting six months before the first Voyager need date (for radio science) in March 1989. Because the installation of the ESA equipment curtails normal astronomy operations, this will not start until 1 March. An accelerated testing program will be mounted to meet Voyager telemetry requirements for the PCTA in April. Tracking passes, other than tests, will be supported from 8 June through 29 August by PCTA, and from 6 June through 27 September by VGTA.

OPERATIONS

The operational concept is derived from PCTA experience obtained during the Voyager Uranus encounter. From the Voyager Project viewpoint, the complex aperture has increased. From the RAO viewpoint, a user is directing the antenna pointing and receiver configuration during a track. From the DSN viewpoint, an additional antenna has been added to the complex array. Achieving this simplicity, however, requires prior support activities, realtime operations, and post-pass operations.

Support Activities

Training, testing, scheduling, communications, direction, reporting, and control are requisite to an operational facility. Training of VLA, Parkes, and DSN personnel, as well as specific DSN-supplied VGTA and PCTA personnel, will occur during the final engineering acceptance testing and specifically scheduled operational training and testing. Scheduling of resources for support during the committed passes will be accomplished through existing standard channels. Antenna pointing predictions in Right Ascension and Declination will be provided to the RAOs, as well as downlink radio frequency predictions via teletype. Downlink frequency and telemetry predictions will be sent to array control personnel via data lines. Nominal Project-supplied sequences of events, including spacecraft events, will also be transmitted. This information, together with the necessary operating procedures, will be available to array personnel prior to the pass.

Real-Time Operations

Operational control of each array will be effected through an array lead engineer at the DSCC, reporting to the complex Shift Supervisor. His overall responsibility is to ensure that the combined array signal yields the appropriate enhancement compared with the complex-only array. He will direct the array equipment operator at the complex and the array supervisor at the RAO. The latter individual will coordinate with the RAO operator and direct the local array equipment operator. Each equipment operator will monitor and control the status, configuration, and performance of his assigned equipment. He will ensure that the Recorder is writing tapes correctly, and he will change the tapes as required. Anomalies will be reported and corrected expeditiously. All personnel will keep a log of appropriate events.

Non-Real-Time Operations

If the telemetry data cannot be successfully combined in real time at the DSCC, but are captured by the RAO, the appropriate tapes will be copied on site and then transported to the DSCC. At VLA, the tapes will be taken by VGTA personnel by auto to Albuquerque, flown to Los Angeles via regularly scheduled airliner, and flown to Goldstone by the NASA aircraft based in the area. At Parkes, the tapes will be taken by PCTA personnel to CDSCC by auto.

At the DSCC, the tapes will be combined with the DSCC tapes, if available, via the Recorder. Telemetry data from the tapes will be fed, together with performance data, to the DSN telemetry subsystem for convolutional decoding and transmission to JPL in the same manner as real-time data. If no matching tape had been recorded at the DSCC, the output quality will be that obtainable from the RAO alone.

EXPECTED PERFORMANCE

Comparing the performance of the array based on APU, the comparison of arrays against the 64m performance is as follows:

Element(s)	APU	Equivalent dB
VLA	2.54 (1.78)	+4.0 (+2.5)
70m + 34 HEF + VLA	4.44 (3.68)	+6.5 (+5.7)
GDSCC + VLA	4.69 (3.93)	+6.7 (+5.9)
Parkes	0.88	-0.6
70m + Parkes	2.43	+3.9
70M + 34 HEF + Parkes	2.78	+4.4
CDSCC + Parkes	3.03	+4.8

The numbers in parentheses would apply if high electron mobility transistors, currently used in the VLA low noise amplifiers, should prove to be unreliable. The backup plan is to use another field effect transistor with resultant increase in system noise temperature.

Because available Voyager spacecraft data rates (8.4, 12.8, 14.4, and 21.6 kb/s) can be accommodated without the 34 STD antenna, it is planned to release this resource for tracking other spacecraft. This decreases the available margin only slightly (0.2 to 0.4 dB).

Coding Limits at VLA

The previously mentioned gaps in VLA data will have effects on the combined VGTA data which depend on the spacecraft coding scheme. Some spacecraft formats, and parts of formats, have concatenated convolutional outer and Reed-Solomon (R-S) inner coding; others have only convolutional coding. The effect of gaps on R-S data is much less: from 0 to 0.5 dB extra symbol SNR is needed to achieve the required (l x 10E-5) bit error rate (BER) after decoding. For non-R-S data the effect is greater: from 0.5 to 1.5 dB extra SNR is required. VLA data alone at 0.0 dB yield <1.5 x 10E-2 BER. Voyager mission planners will take these effects into consideration when estimating which telemetry data rates and formats to employ over the VGTA.

CONCLUSION

The design and planned operation of the interagency arrays in support of the Voyager spacecraft encounter with the Neptunian system promises to permit a deeper and more comprehensive investigation than would otherwise be possible.

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NOMENCLATURE

BER	bit error rate
CDSCC	Canberra Deep Space Communications Complex
CSIRO	Commonwealth Scientific and Industrial Research Organization
DSCC	deep space communications complex
DSN	Deep Space Network
EFFI	equivalent full-frame images
ESA	European Space Agency
GDSCC	Goldstone Deep Space Communications Complex
GS&E	general science and engineering (data)
JPL	Jet Propulsion Laboratory
LBC	Long Baseline Combiner

LNA	low noise amplifier
MDSCC	Madrid Deep Space Communications Complex
NRAO	National Radio Astronomy Observatory
NSF	National Science Foundation
PCTA	Parkes-Canberra Telemetry Array
RAO	radio astronomy observatory
SNR	signal-to-noise ratio
TDA	Telecommunications and Data Acquisition
TSG	test signal generator
VGTA	Very Large Array-Goldstone Telemetry Array
VLA	Very Large Array
VLBC	Very Long Baseline Combiner
34 HEF	34-meter high-efficiency (antenna)
34 STD	34-meter standard (antenna)
64m	64-meter (antenna)
70m	70-meter (antenna)

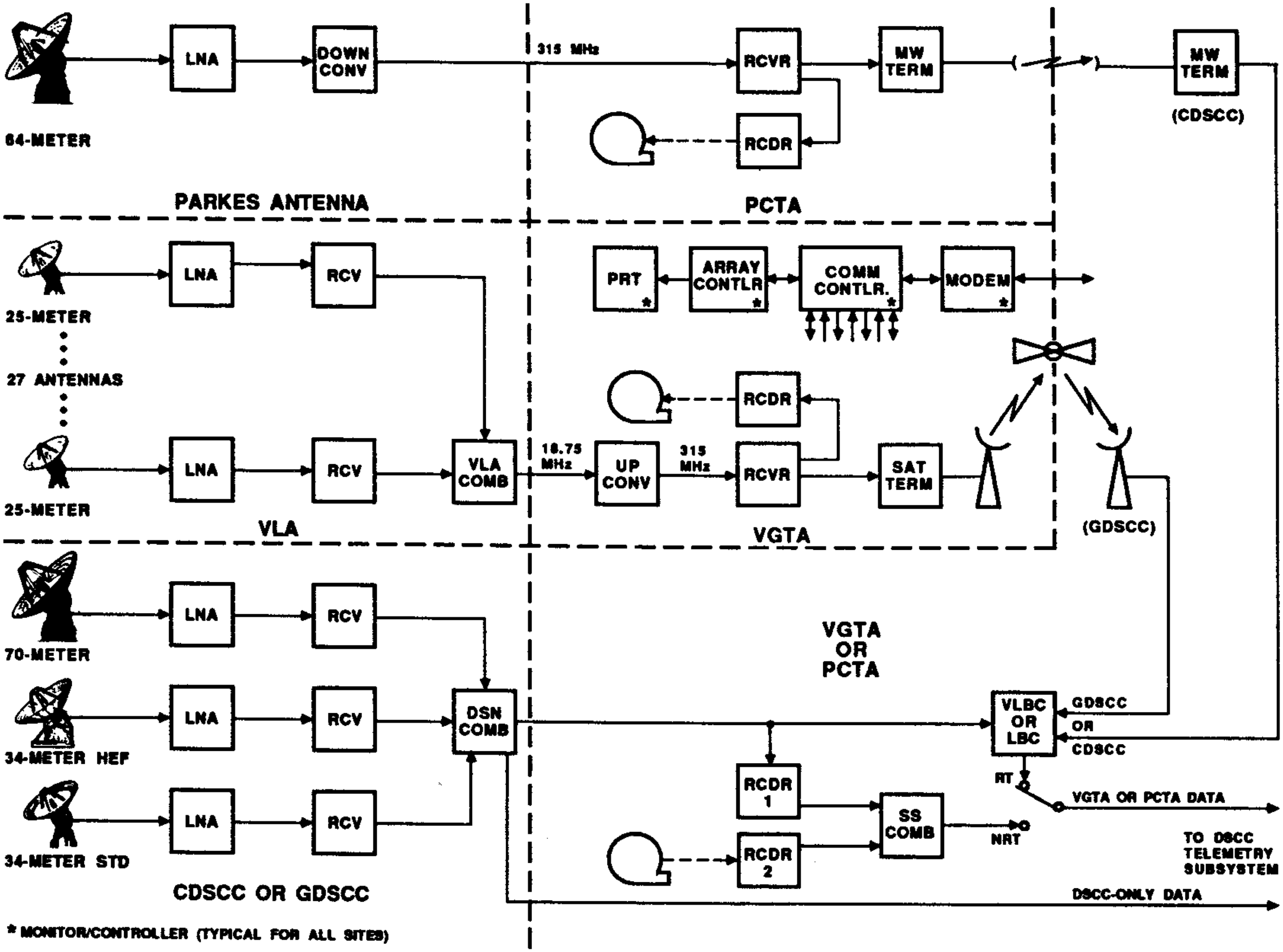

Figure 1. Interagency Arrays

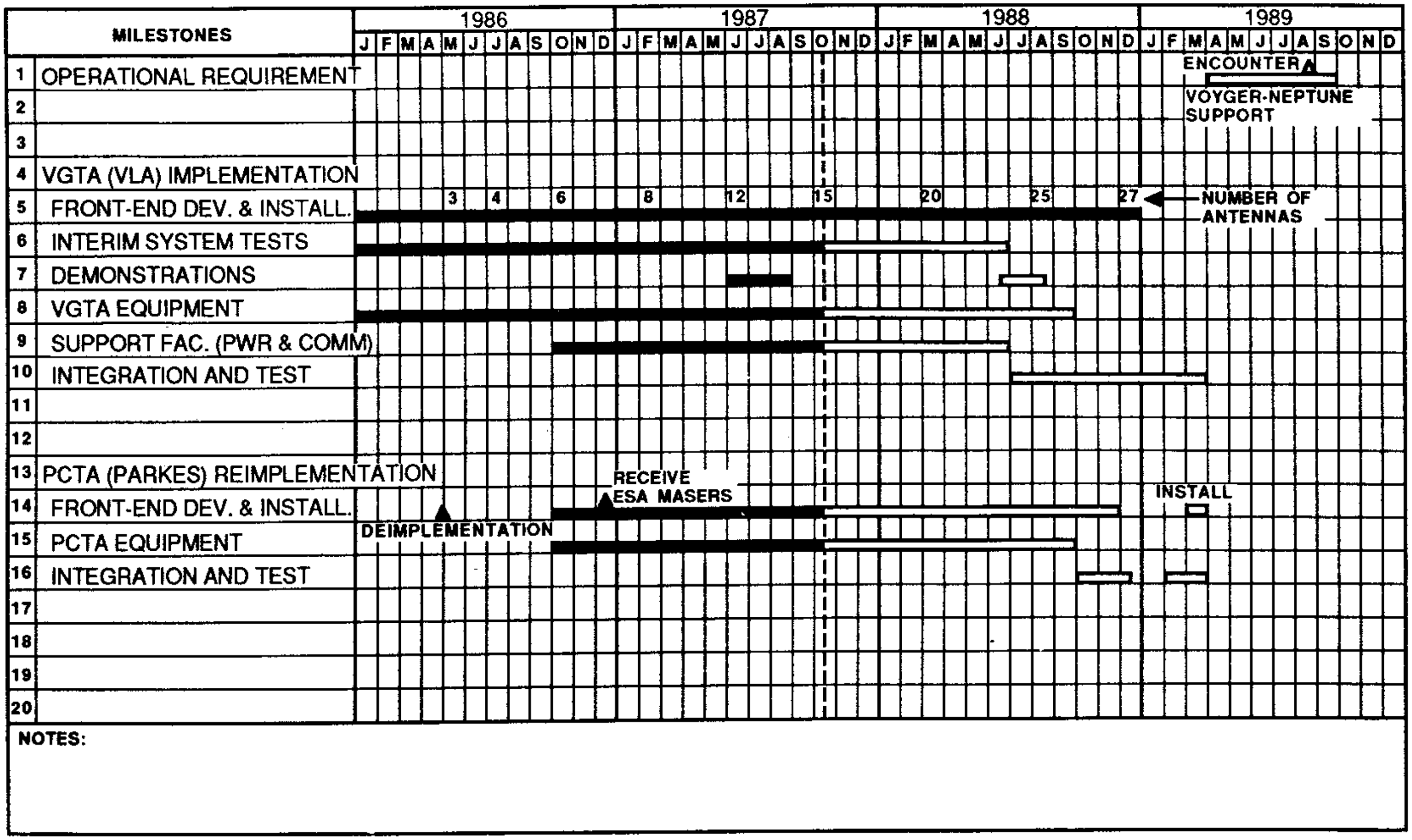

Figure 2. Implementation Schedule